Scoliotic spine visualization using   
ultrasound-accessible anatomic landmarks

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**ABSTRACT**

**PURPOSE:** Ultrasound imaging is an attractive alternative to X-ray for scoliosis diagnosis and monitoring due to its safety and inexpensiveness. The transverse processes provide landmarks which are accessible by means of ultrasound, and are sufficient for quantifying scoliosis, but, own their own, do not provide an intuitively comprehensible visualization of the spine. **METHODS:** We created 3D visualizations of pediatric patients’ scoliotic spines using 3D transform fields resulting from thin-spline interpolations of the landmark-based registrations between the transverse processes from the patients’ anatomies and the corresponding points from an average-shaped, healthy spine model. Anchor points were added to both the patients’ and models’ landmarks prior to registration such that the resulting transform fields accurately represented the deformation of the patients’ spines. The transform fields were then applied over the surface of the average-shaped spine model, resulting in 3D surface models visualizations of the patients’ spines. CT scans of the patients’ spines were used as a ground truth against which to compare our registration-derived visualizations, since the CT-derived models accurately depict the patients’ transverse process locations and spinal shapes. **RESULTS:** Hausdorff distances, Dice similarity coefficients, and model-to-model distance maps were computed to evaluate the quality of the registration-derived visualizations compared to ground truth models. Misalignment occurs mainly at upper and lower-most vertebrae, and in the anterior-posterior directions, which is immaterial in scoliosis quantification. **CONCLUSIONS:** This method is shown to be capable of producing qualitatively accurate visualizations which depict the 3D deformation of the patients’ spines when compared to ground truth CT scans.

**Keywords:** Spine**,** scoliosis, modelling, ultrasound, landmark, visualization

# BACKGROUND AND PURPOSE

Scoliosis is a pathological curvature of the spine which typically develops during adolescence. If left untreated, scoliosis can progress to the point that back pain or respiratory problems develop. Management of the disease requires monitoring the deformation’s progression. Scoliosis is quantified in terms of the Cobb angle, the maximum angle between the endplates of any two vertebrae. Continued observation is typically indicated for patients exhibiting a Cobb angle of less than 20°. Bracing can be used to prevent further progression of the disease for a Cobb angle between 20° and 40°. Any curvature in excess of 40° is often treated with surgical vertebral fusing [Frerich 2012]. X-ray is considered the gold-standard for scoliosis quantification and visualization. The risks of repetitive exposure to ionizing radiation during adolescence have motivated investigation into the use of tracked ultrasound as an alternative [Berton 2016]. Ultrasound, however, can only visualize parts of the posterior surface of the spine, which, despite being sufficient to determine the Cobb angle, does not the physician with a comprehensible visualization of the patient’s spine. We present a novel method to deform an average healthy spine to match sparse skeletal landmarks localized in the patient’s ultrasound, thereby allowing three-dimensional visual inspection of the scoliotic spine.

# NEW OR BREAKTHROUGH WORK

We have developed a method to create 3D visualization of the scoliotic spine, based on the locations of transverse processes as skeletal landmarks, by computationally deforming an average healthy spine model to match the landmarks. We have shown that the method produces an excellent qualitative visual representation of the spine that is appropriate for inspection of the extent and nature of the curvature. Besides scoliosis evaluation, applications of this method may include automatic structure labelling, the initial alignment for registration in surgical navigation.

# METHODS

Landmark-based registration requires two sets of points, one to be registered to the other. In our case, the first set of points consists of the transverse processes from an average healthy spine model, while the second set of points are transverse processes segmented in the patient’s ultrasound images. In each point set, the transverse processes align along two nearly parallel curves. The sparsity and peculiar distribution of the points make it extremely challenging to deform an average spine model to the patient’s skeletal landmarks in an anatomically accurate fashion. We propose to remedy this by computationally adding matching anchor points in both point sets, in a manner that preserves the deformation field. The anchor points are added at offsets normal to the curvature of the spines, in the anterior direction. To compute this normal direction consistently, vector cross products of right-left, and superior-inferior vectors are used to compute an anterior-posterior vector. This method defines piece-wise volumes, rather than the original curves. Since each piece of the volume corresponds to one vertebra, the registration algorithm imposes most of the deformation inter-vertebrally, rather than continuously along the curves. We account for the scale in length between average spine and the patient’s spine by scaling the magnitude of the offset distance by the ratio of the length of the patient’s spine to length of the average spine. To add the anchor point anterior to point P(i,j), where i denotes the vertebra (the superior-most being at i = 0), and where j denotes right versus left (j = 0 for left, j = 1 for right), the right-left vector was computed as:

(1)

where angled brackets denote vectors. Superior-inferior vectors are computed as the average of two possible vectors:

(2)

At the superior and inferior extremities of the spine, where only one vertebra existed below or above the one to which an anchor point is being added, only the existing vector is used in equation (2). Finally, to determine the location of the anchor point, the anterior-posterior vector is computed as the cross product of the vectors from equations (1) and (2), normalized by dividing it by its length, and scaled by a vertebral scaling factor times the ratio of the length of the patient’s spine to that of the average spine:



Figure 1: A segment of the average spine model with transverse process points, anchor points, and illustrations of the vectors used to locate one anchor point.   
The superior-inferior vector is the result of an average and therefore does not point to P(9,0). Vectors are added for illustration and therefore are not necessarily exact.   
Right-sided anchor points are occluded by the model.

(3)

where the \* denotes an anchor point being added, VSF is a vertebral scaling factor used to constrain registration deformation in the anterior-posterior direction, • denotes scalar multiplication, LP is the length of the patient’s spine, LA is the length of the average spine model, × denotes a vector cross product, and |V| denotes the length of vector V. A VSF of 30 mm was empirically chosen to represent typical inter-landmark spacing.

Figure 1 shows the average spine with the transverse process points, the anchor points, and the vectors locating an anchor point. The registration is as a thin-plate spline transformation between the two sets of points [Bookstein 1989], as implemented in the Visualization Toolkit ([www.vtk.org](http://www.vtk.org)). The thin-plate spline transformation maps each transverse process and anchor point of the average spine to its corresponding point in the patient’s spine with a smooth interpolation. This yields a continuous 3D transform field that we apply to the average spine model, thereby deforming it to match the patient’s spine.

To validate this method, we apply ground truth CT data sets from pediatric scoliosis patients. We reconstructed their spine surface from CT and we marked their spinous processes which are clearly visible in the CT images. Using the spinal processes as input, we computed the anchor points, computed the deformation field from thin-plate spline registration and deformed the average spine model. In addition to qualitative visual inspection, we evaluated the outcome of registration quantitatively by computing the average and maximum Hausdorff distances and Dice similarity coefficients.

# RESULTS AND DISCUSSION

Quantitative registration evaluation metrics are shown for in Table 1. These results are potentially misleading, as they are from the entire spine, including the vertebral bodies, where no anatomic landmarks were placed. Figures 2 and 3 show the actual visualizations generated for two patients, demonstrating that most of the misalignment is in the vertebral bodies and spinous processes, that is, in structures anterior and posterior to the landmarks This misalignment is of minor importance for scoliosis visualization, which requires only right-left deformation. It is unsurprising that misalignment occurs in locations far from landmark points, especially at the outer-most vertebrae, where the transform field had fewer landmarks to constrain it. Moreover, this misalignment is of minor importance for scoliosis visualization, which is well depicted by the posterior vertebral faces.

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| --- | --- | --- |
|  | | **Registration Metric** |
| **Avg. Hausdorff Distance (mm)** | **Max. Hausdorff Distance (mm)** | **Dice Similarity Coefficient** |
| **Patient #** | **1** | 2.1 | 13.2 | 0.695 |
| **2** | 2.9 | 28.7 | 0.673 |
| **3** | 2.3 | 18.8 | 0.682 |
| **4** | 2.5 | 19.1 | 0.643 |

Table 1: Registration evaluation metrics

The accuracy of the rest of the registration (particularly in the anterior-posterior direction) is likely sensitive to the particular value used for the vertebral scaling factor, the VSF. As a possible refinement to the method, we will investigate the effects of calculating this value for individual vertebrae based on the distances between the local landmark points. The factor representing the ratio of the lengths of the spines could be refined similarly; by scaling each offset in proportion to local inter-vertebral distances, rather than for the entire spines, further improvements to these results may be achieved.



Figure 2: Results for Patient #1. The left three images are, from left to right: the average spine model, transverse process landmarks on CT-derived ground truth, and the registration-based visualization with a heat map showing the distance between it and ground truth, viewed from the posterior direction. The right three images are the same as the left three, viewed from the left.

The results depicted in Figures 2 and 3 demonstrate that the method achieves the intended purpose of producing intuitive, 3D visual representations of scoliotic spines as qualitative aids to clinicians. This purpose is served on the basis of the registration accuracy of the posterior vertebral anatomy. Furthermore, this method is not limited to scoliosis visualization, transverse processes, or ultrasound imaging. Any spine can be visualized in this way, however scoliosis served as a good trial since its associated deformation constitutes difficult anatomy upon which to register models. Our aim is to use ultrasound for the reasons outlined earlier. This meant the method was designed on the basis of symmetry and relative locations of the ultrasound-accessible landmarks, the transverse processes. However, other landmarks could be retrieved from any imaging modality, and the method adapted to suit their geometric properties.



Figure 3: Results for Patient #2. The left three images are, from left to right: the average spine model, transverse process landmarks on CT-derived ground truth, and the registration-based visualization with a heat map showing the distance between it and ground truth, viewed from the posterior direction. The right three images are the same as the left three, viewed from the left.

# CONCLUSIONS

The landmark-based registration method presented in this paper is capable of producing visualizations displaying the 3D deformation of patients’ spines using just two ultrasound-accessible landmarks per vertebra as input. Most of the registration’s misalignment occurs anterior and posterior to the vertebral faces, in the vertebral bodies and spinous processes, respectively. This misalignment is the result of being distant from the landmarks used for scoliosis quantification and as input to our method, and as such, is of little clinical significance.

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