Visualization of scoliotic spine using  
ultrasound-accessible skeletal landmarks

Ben Church1, Andras Lasso1, Christopher Schlenger2,   
Daniel P. Borschneck3, Parvin Mousavi4, Gabor Fichtinger1,3, Tamas Ungi1,3

1. Laboratory for Percutaneous Surgery, School of Computing, Queen’s University, Kingston, ON, Canada
2. Premier Chiropractic, Stockton, CA, USA
3. Department of Surgery, Queen’s University, Kingston, ON, Canada
4. Medical Informatics Laboratory, School of Computing, Queen’s University, Kingston, ON, Canada

**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 as skeletal landmarks are accessible by means of ultrasound and are sufficient for quantifying scoliosis, but do not provide an intuitively comprehendible visualization of the spine. **METHODS:** We created a method for visualization of the scoliotic spine using a 3D transform field, resulting from thin-spline interpolation of a landmark-based registration between the transverse processes that we localized in both the patient’s ultrasound and an average healthy spine model. Additional anchor points were computationally generated to control the thin-spline interpolation, in order to gain a transform field that accurately represents the deformation of the patient’s spine. The transform field is applied to the average spine model, resulting in a 3D surface model depicting the patient’s spine. We applied ground truth CT from pediatric scoliosis patients in which we reconstructed the bone surface and localized the transverse processes. We warped the average spine model and analyzed the match between the patient’s bone surface and the warped spine. **RESULTS:** Visual inspection revealed accurate rendering of the scoliotic spine. Notable misalignments occurred mainly in the anterior-posterior direction at the first and last vertebra, which is immaterial for scoliosis quantification. The average Hausdorff distance computed for 4 patients was 2.4 mm. **CONCLUSIONS:** We achieved qualitatively accurate and intuitive visualization to depict the 3D deformation of the patient’s spine when compared to ground truth CT.

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

# INTRODUCTION

Scoliosis is a pathological, coronal curvature of the spine, typically greater than 10o. This quantification of the disease is in terms of the Cobb angle, the maximum angle between the endplates of any two vertebrae. Scoliosis typically manifests during adolescence and develops with growth until skeletal maturity. If left untreated, this curvature can become sufficiently severe that back pain or respiratory problems develop. Once scoliosis is detected, continued monitoring and quantification is required to ensure that its progression is met with the appropriate treatment. Continued observation is required for Cobb angles less than 20o. Bracing can be used to slow the progression of the disease for Cobb angles between 20o and 40o. Any curvature in excess of 40o is often treated with surgical vertebral fusing.

X-ray imaging is still considered the gold standard for scoliosis quantification and visualization. The health risks associated with repetitive exposure to ionizing radiation during adolescence have motivated research [Cheung 2015a, Cheung 2015b, Ungi 2014, Wang 2015, Wang 2016, Zheng 2015] into the use of spatially tracked ultrasound as an alternative imaging modality. [Purnama2010] demonstrated that the vertebral transverse processes can be located with tracked ultrasound. [Ungi2014] showed that this method of transverse process location is suitable for quantifying the curvature of a scoliotic spine.

Despite these methods’ utility in quantifying the severity of scoliosis, they do not provide clinicians or patients with a comprehensible visualization of the spine. For example, Figure 1 shows the result of placing a sequence of parasagittal, tracked ultrasound images in virtual anatomic space. [Ungi2014] showed that the transverse process locations extracted from these images are sufficient for scoliosis quantification, although their method does not provide a readily comprehensible visualization of the spine.   
  
The visualization used for landmark identification and subsequent curvature quantification by [Zheng2015] is shown in Figure 2. As [Zheng2015] showed, this image is sufficient for scoliosis quantification, and to some extent, visualization in the coronal plane. However, as a single, consolidated, 2D image, it cannot depict 3D deformation.

Figure : Posterior view of spine reconstructed from tracked ultrasound image sequence. Taken from [Zheng2015].

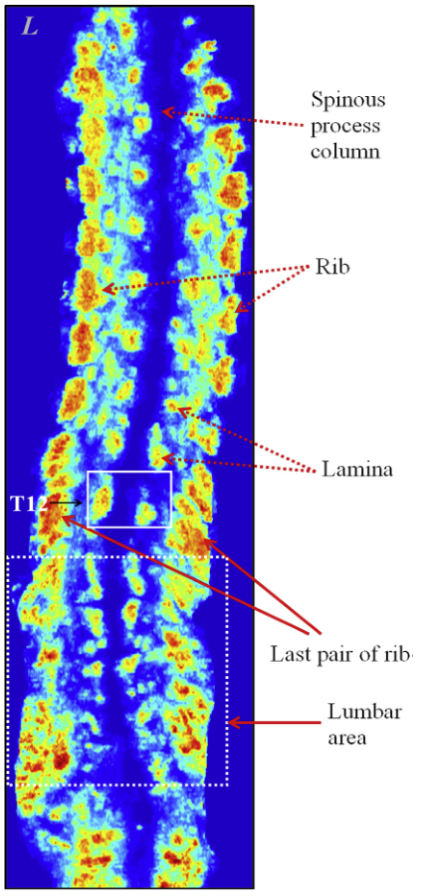
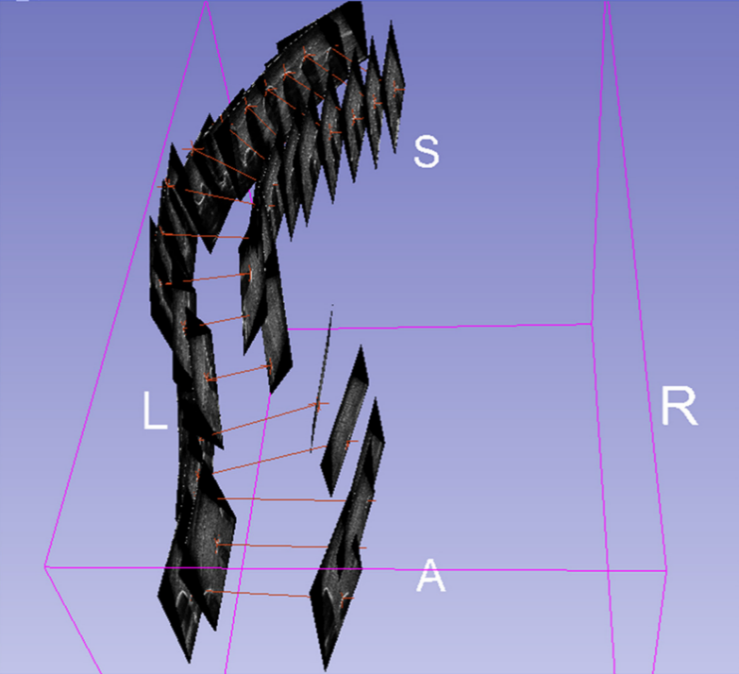


Figure : Sequence of tracked ultrasound snapshots shown in virtual anatomic space. Taken from [Ungi2014].



It is because of the lack of a method using ultrasound to produce comprehensible visualizations of spinal anatomy, scoliotic or otherwise, that we propose a method to produce such visualizations. The method uses the transverse process locations (those used by [Ungi2014] for quantification), and a 3D model of a spine with normal anatomy. The result is a 3D volume models suitable for visual inspection of the scoliotic spine, to aid the physician in visual assessment of the extent and nature of the scoliosis.

# 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 warping 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, or 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, while the second set of points are the transverse processes localized 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 warp 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 the 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 the 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 3: A piece 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 relate the size of the current vertebra’s local anatomy to the corresponding anatomy of the model, • denotes scalar multiplication, ASF is an anatomic scaling factor representing the scale of the current vertebra, × denotes a vector cross product, and |V| denotes the length of vector V.

The VSF for vertebra i on side j is computed as:

Figure 3 shows a piece of 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 warping 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 transverse processes that are clearly visible in the CT images. Using the transverse processes as input, we computed the anchor points, computed the deformation field from thin-plate spline registration and warped 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.