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3D Reconstruction of the Human Spine From Radiograph(s) using a Multi-Body Statistical Model

Jonathan Boisvert[a], Farida Cheriet[b], Xavier Pennec[c], and Nicholas Ayache[c]

[a] School of Computing, Queen's University, Kingston, ON, CANADA;
[b] Dept. of Computer Engineering, Ecole Polytechnique de Montréal, QC, CANADA;
[c] Asclepios Project Team, INRIA, Sophia Antipolis, FRANCE

ABSTRACT

Three-dimensional models of the spine are very important in diagnosing, assessing, and studying spinal deformities. These models are generally computed using multi-planar radiography, since it minimizes the radiation dose delivered to patients and allows them to assume a natural standing position during image acquisition. However, conventional reconstruction methods require at a minimum two sufficiently distant radiographs (e.g., posterior-anterior and lateral radiographs) to compute a satisfactory model. Still, it is possible to expand the applicability of 3D reconstructions by using a statistical model of the entire spine shape. In this paper, we describe a reconstruction method that takes advantage of a multi-body statistical model to reconstruct 3D spine models. This method can be applied to reconstruct a 3D model from any number of radiographs and can also integrate prior knowledge about spine length or preexisting vertebral models. Radiographs obtained from a group of 37 scoliotic patients were used to validate the proposed reconstruction method using a single posterior-anterior radiograph. Moreover, we present simulation results where 3D reconstructions obtained from two radiographs using the proposed method and using the direct linear transform method are compared. Results indicate that it is possible to reconstruct 3D spine models from a single radiograph, and that its accuracy is improved by the addition of constraints, such as a prior knowledge of spine length or of the vertebral anatomy. Results also indicate that the proposed method can improve the accuracy of 3D spine models computed from two radiographs.

Keywords: 3D Reconstruction, Personalized Spine Model, Statistical Method, Radiograph

1. INTRODUCTION

Three-dimensional models of the spine are important tools in the study of spinal deformities. They can be used to diagnose, document, evaluate the severity, simulate the progression or plan the treatment of those deformities.[1–4] The three-dimensional capability of such models enables analysis that would be impossible to perform directly on radiographs. For example, clinical indices, such as the orientation of the plane of maximal curvature or the spine torsion,[5] rely on the availability of 3D spine models.

Such three-dimensional models of the spine can theoretically be computed from a large variety of imaging modalities. However, they are most often computed using multiple radiographs. The small exposure of the patients to harmful ionizing radiations associated with radiographs is one of reasons motivating this choice. However, the primary reason is that 3D models must be computed while the patient is assuming a "natural" standing posture. Otherwise, deformities could be underestimated since a significant part of the spine's curvature is lost when a patient reclines. However, it is sometimes difficult or even impossible to acquire enough radiographs with sufficient disparity to apply traditional 3D reconstruction methods (for example, during bending tests or surgeries).

Current reconstruction methods require two or more radiographs to produce a usable 3D spine model.[6–13] The only notable exception is a method proposed by Novosad et al.[14] in which an *ad hoc* alignment constraint enabled the reconstruction of 3D spine models from only one radiograph. However, this alignment constraint might not be valid for large deformations and cannot be generalized readily to other applications.

Further author information: (Send correspondence to Jonathan Boisvert)
Jonathan Boisvert: E-mail: boisvert@cs.queensu.ca

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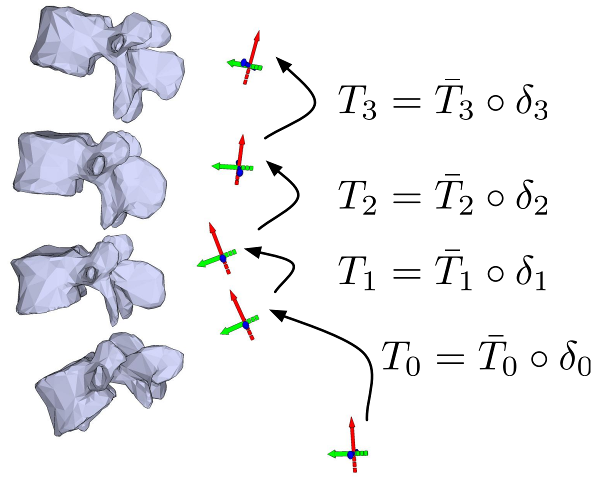


Figure 1. Inter-vertebral rigid transformations used to describe the spine shape

One approach to alleviating some of the limitations found in current methods is to take advantage of a statistical model of the spine to constrain the reconstruction process. Benameur et al.[15] and Fleute et al.[16] proposed two approaches in which the shape of individual vertebrae were constrained by a statistical model during a model registration procedure. However, the shape of the entire spine was not statistically modeled. Pomero et al.[8] used a statistical model to compute the axial rotation of the vertebrae and increase the number of digitized points in their 3D models. Once again, however, the shape of the entire spine was not used to constrain the reconstruction.

Recently, Boisvert et al. proposed a statistical model of the spine based on an articulated description[17] and a reconstruction method based on this statistical model.[18] These approaches model and reconstruct not only the shape of individual vertebrae, but they also consider the shape of the entire spine through the use of relative rigid transformations between neighboring vertebrae.

In the present paper, we describe a simple reconstruction method that extends an existing method.[18] The specific contributions of this paper are to propose methods to integrate prior knowledge of the spine length or of the vertebral anatomy in the reconstruction process, to validate the accuracy of the reconstruction method when only a single radiograph is available using real and synthetic data, and to demonstrate using simulations that the proposed method outperforms a commonly used reconstruction method in clinically relevant bi-planar radiography setups.

2. MATERIAL AND METHODS

2.1 Multi-Body Statistical Spine Model

Typically, three-dimensional spine models are simple collections of 3D anatomical landmarks, which are computed using manually identified anatomical landmarks on radiographs. However, this representation discards completely the articulated nature of the spine. Because vertebrae are bony structures, it is instead logical to model the shape of the spine using rigid transformations between neighboring vertebrae and anatomical landmarks measured in the vertebrae's natural frame of reference. This allows us to take into account variances in the shape of vertebrae and in the "inter-vertebral articulations" state.

The description of the spine used in this paper is thus a combination of the *inter-vertebral rigid transformations* $T_0, T_1, T_2, \ldots, T_N$ (see Figure 1) and of the *local anatomical landmarks* $p_{1,1}, p_{1,2}, \ldots p_{1,M} \ldots p_{N,M}$ (where N is the number of vertebrae studied and M is the number of landmarks digitized for each vertebra). The average spine shape can be computed by finding the Fréchet mean on this Riemannian manifold. Moreover, the covariance of the shape of the spine can be computed in the tangent space of the Fréchet mean.[17] Both the average spine shape and its covariance were estimated from a large group of 3D spine models (261 models from different patients).

2.2 Reconstruction Method

To take advantage of the statistical model, it is more convenient to use the departure from the mean spine shape rather than the shape of the spine itself to describe the reconstruction algorithm. This departure is given by:

$$S = (s_1, s_2, \ldots, s_N)$$

$$\text{with} \quad s_i = (\delta_i, p_{i,1} - \bar{p}_{i,1}, p_{i,2} - \bar{p}_{i,2}, \ldots, p_{i,M} - \bar{p}_{i,M}) \quad \text{and} \quad \delta_i = \bar{T}_i^{-1} \circ T_i,$$

where $\bar{T}_i$ and $\bar{p}_{i,j}$ are respectively the mean intervertebral transformations and the mean local landmarks. The 3D reconstruction problem then is to estimate the vector S that best fits the prior statistical model and the anatomical landmarks visible on the radiographs. These anatomical landmarks are noted $p_{2D}^{i,j,k}$ where i is a vertebra index, j is a landmark index, and k is the radiograph index.

The anatomical landmarks on the radiographs and the statistical model of the spine can be combined in a single cost function, such as:

$$C(S) = S\Sigma^{-1}S^T + \alpha \sum_{i=0}^{n} \sum_{j=0}^{m} \sum_{k=0}^{o} \| p_{2D}^{i,j,k}(S) - \hat{p}_{2D}^{i,j,k} \|^2 \tag{1}$$

$$\text{and} \quad p_{2D}^{i,j,k}(S) = M_k(\bar{T}_0 \circ \delta_0 \circ \bar{T}_1 \circ \delta_1 \circ \ldots \circ \bar{T}_i \circ \delta_i \star p_{i,j}) \tag{2}$$

where α is the relative weight of the landmark error with respect to prior knowledge of the spine shape, Σ is the covariance estimated in the tangent space of the Fréchet mean, and M_k is the linear projection associated with the k^{th} radiograph.

If one assumes a normal distribution for S, then $C(S)$ leads to a *maximum a posteriori* estimation. Furthermore, the gradient of Equation 1 was analytically differentiated to accelerate the optimization procedure, which was performed using a gradient descent procedure.

The image coordinates of the anatomical landmarks $p_{2D}^{i,j,k}(S)$ (see Eq. 2) are computed by first calculating the absolute 3D coordinates of all given anatomical landmarks. This is done by composing the inter-vertebral rigid transformations to obtain the absolute pose of the vertebra, and then by applying the obtained rigid transformation to the local anatomical landmark. Then, the absolute 3D coordinates of the anatomical landmark are projected onto the radiograph image plane by a linear transformation (M_k) in homogenous coordinates. The Mahalanobis distance regularizes the cost function and reduces the number of local minima. However, there is no guarantee that the optimization will not be trapped by a local minimum. One could choose a robust optimization method, such as simulated annealing, because of potential local minimums. In practice, however, a simple gradient descent procedure was sufficient.

2.3 Integrating Prior Knowledge of Spine Length

The integration of a statistical model of the entire spine allows the reconstruction method to make the best use of information available to estimate a complete 3D spine model. It reduces the effect of measurement noise and compensates for missing information. When only one radiograph is available; however, it is almost impossible to differentiate a large spine located far away from the X-Ray source from a smaller spine located closer to that source.

At the same time, the length of the spine can be estimated independently using the patient's height and/or an external measurement of the length of the patient's back. Therefore, we would like to assess whether this additional information could improve reconstruction results. The integration of the spine length in the reconstruction method is performed with an additional term in the cost function that weights the deviation of the reconstructed 3D model from the estimated spine length. The cost function then becomes:

$$C_L(S) = C(S) + \alpha_L \left(\sum_{i=0}^{N} \|Tr(T_i \circ \delta_i)\| - L_0 \right)^2 \tag{3}$$

where Tr is a function returning the translation vector associated with a given rigid transformation, L_0 is the prior spine length estimate, and α_L is the weight of the new term.

2.4 Prior Vertebrae Shape Models

The proposed articulated model description of the spine S includes both inter-vertebral rigid transformations and local anatomical landmarks. Therefore, both are normally estimated in the reconstruction process. However, the shapes of the vertebrae do not change significantly in a short amount of time, and a previous model of the vertebrae's shapes can be used to enhance the accuracy in a difficult situation (only one radiograph available and/or very noisy radiographs). Thus, if a recent and reliable 3D model of the patient's vertebrae is available, either from a computed tomography or from a previous stereo-radiographic examination, then the local anatomical landmarks $p_{3D}^{i,j}$ can be estimated from that prior model, and only the inter-vertebral rigid transformations will require estimation via the current radiograph(s). This situation is especially common for surgical cases, where pre-operative imaging is performed anyway.

3. RESULTS AND DISCUSSION

3.1 Single View Reconstruction

Three different albeit common scenarios were analyzed: reconstruction from one PA radiograph, reconstruction from one PA radiograph with prior knowledge of the spine length, and reconstruction from one PA radiograph and prior vertebral models. The landmark coordinates of thirty-seven patients were recorded from PA radiographs by a qualified technician and were used to compute 3D reconstruction using the proposed method. The resulting 3D models were then compared to the models reconstructed from the conventional stereo-radiographic method[12] using a PA and a LAT radiograph. Two experiments were performed for each scenario. First, thirty-seven randomly selected 3D spine models were analytically projected. These 2D landmarks coordinates were then used to reconstruct an articulated description of the spine, which was then compared with the real articulated description. Second, the landmark coordinates for the same thirty-seven patients were recorded from PA radiographs by a qualified technician and were used to compute 3D reconstruction using the proposed method. The resulting 3D models were then compared to the models reconstructed from the conventional stereo-radiographic method[12] using a PA and a LAT radiograph. The Table 1 summarize the results of the comparisons for each vertebral levels.

The reconstruction of an articulated description of the spine from a single posterior-anterior radiograph is an incredibly difficult problem. In general, reconstructing the 3D shape of an object from a single view is not possible; essentially, an infinite number of 3D objects can lead to the same projected image. However, a statistical model of the possible objects makes it feasible to compute the most likely object. The validation experiments performed with real landmarks suggest that the accuracy of such a procedure is about 13 mm (mean error). The addition of a prior knowledge of spine length reduced this error to 12 mm. Moreover, the difference between the results obtained with real and synthetic data suggest that the obtained errors are not primarily caused by landmark identification errors but by a lack of information about the spine geometry. This degree of accuracy is, of course, insufficient for surgical guidance, but it is still useful for surgical planning, diagnosis and personalization of biomechanics models. However, the accuracy obtained with prior vertebral models (5 mm) could be compatible with surgical assistance and clearly shows that large performance gains can be realized with additional constraints or measures. This result is particularly interesting since it is similar to reconstruction accuracy currently achieved with a PA and a PA-20 radiograph using a conventional reconstruction method. Moreover, in this case, the difference between real and synthetic data experiments may indicate that further

Table 1. Mean absolute errors (mm) on the reconstructed anatomical landmarks (difference between ground truth and landmarks reconstructed using the proposed method).

	PA		PA + Length		PA + Prior Shapes	
	No noise	Experimental data	No noise	Experimental data	No noise	Experimental data
L5	16	14	14	13	0.8	5.6
L4	15	13	13	12	0.8	5.3
L3	15	13	12	12	0.6	5.1
L2	15	13	12	13	0.6	4.7
L1	15	13	12	13	0.5	4.5
T12	15	13	12	11	0.6	4.6
T11	15	13	13	11	0.5	4.7
T10	15	13	13	12	0.4	4.9
T9	14	13	13	13	0.5	5.1
T8	14	13	13	13	0.6	5.1
T7	14	13	13	12	0.6	5.1
T6	14	13	12	12	0.6	5.1
T5	14	13	12	11	0.7	5.2
T4	14	13	12	11	0.6	5.4
T3	14	13	12	13	0.6	5.4
T2	15	13	11	12	0.7	5.5
T1	15	14	11	12	0.8	5.8

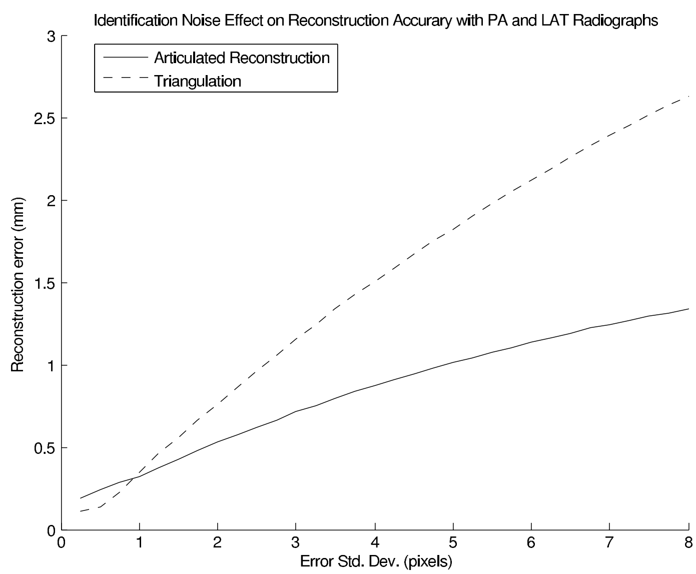


Figure 2. Simulation of the noise effect on the 3D reconstruction of spine models from two radiographs (a lateral and a posterior-anterior) using the proposed method (articulated reconstruction) and using triangulation.

improvements could be obtained by optimizing the imaging protocol. Finally, beyond immediate applications, these results provides a substantive illustration of the strength of our prior model, which is very flexible and can be combined with a variety of imaging modalities.

3.2 Low Disparity Bi-Planar Reconstruction

We already mentioned that obtaining a PA and a LAT radiograph is difficult or impossible in many circumstances (bending tests or per-operative imaging, for example). However, the acquisition of a pair of similar radiographs with a small stereo base might be a good compromise between convenience and 3D model accuracy in certain applications.

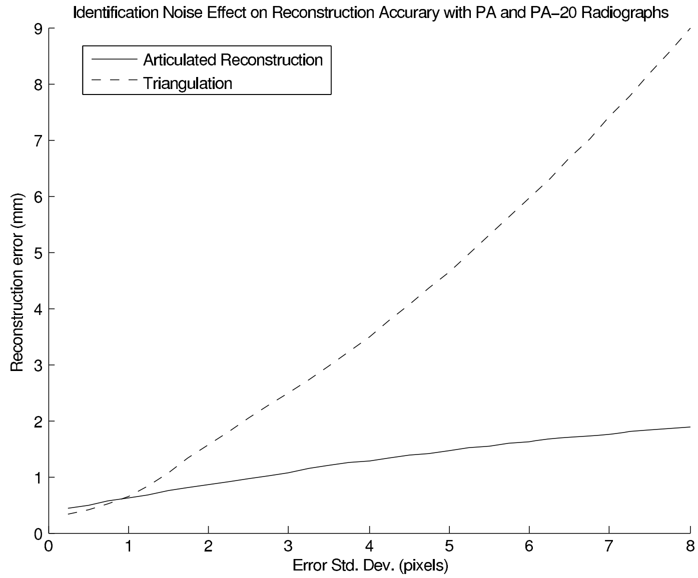


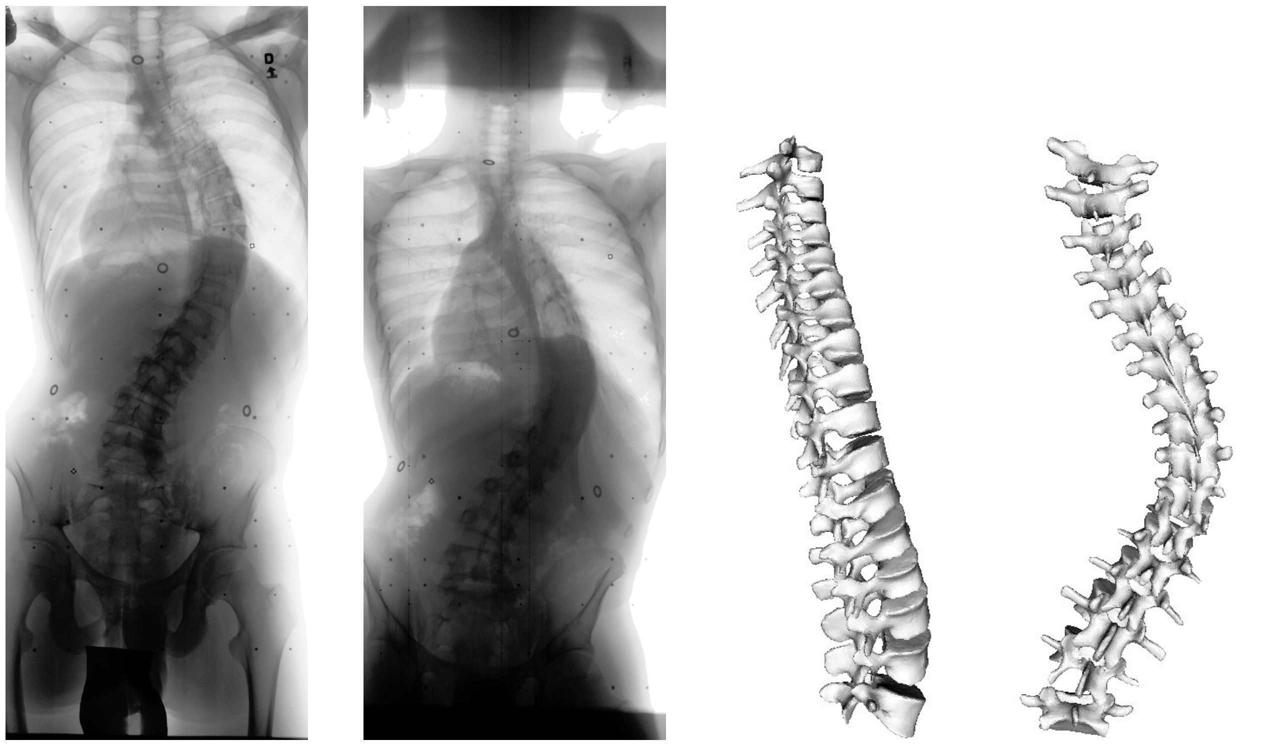
Figure 3. Simulation of the noise effect on the 3D reconstruction of spine models from two radiographs (a posterior-anterior with no elevation and a posterior-anterior with 20 degrees of elevation) using the proposed method (articulated reconstruction) and using triangulation.

Thus, we compared the proposed method to the linear triangulation used in most conventional methods[12] when a PA and a PA angulated by 20 degrees (PA-20) were available (see Figure 4). To do this, 37 randomly selected 3D spine models were projected using known projection matrices and a gaussian noise of variable standard deviation was added to the pixel coordinates. The resulting 2D coordinates were then used to reconstruct the 3D spine models. The mean differences between the original 3D models and the reconstructed models are illustrated by Figure 3. The proposed method is associated with smaller errors when the standard deviation of the noise is greater than 1 pixel. The same patients were also used to analyze a more conventional radiographic setup (PA and LAT). The proposed method also outperformed the triangulation method with this setup when the standard deviation of the noise was greater than a pixel. The improvement realized by using the proposed method was however larger with the low-disparity setup (PA and PA-20). Since the standard deviation observed in clinical setups is usually much more than a pixel, the proposed method should outperform the triangulation method in most cases.

4. CONCLUSION AND FUTURE WORK

In this paper, we presented a flexible method for the estimation of 3D models of the spine based on a statistical model of the entire spine. This reconstruction method is based on minimization of both the Mahalanobis distance and the reprojection error of anatomical landmarks. We demonstrated that this method can be used on one or more radiographs, and that it can integrate additional constraints, such as prior vertebral models or previous knowledge of the length of the spine. We analyzed three single view reconstruction scenarios using real and synthetic data. We also compared the performance of the proposed method with a commonly used method for different levels of noise when a PA and a PA-20 were available. The results obtained suggest that single view reconstruction is possible and that the proposed method can outperform the conventional reconstruction methods when two radiographs are available and an identification error of more than 1 pixel (std. dev.) is present.

Three-dimensional spine models are often used to initialize biomechanics models or to compute clinical indices, which are used to diagnose and evaluate spinal deformities. Therefore, we plan to analyze the effect of the new reconstructions on those methods. Moreover, the proposed method can be applied to situations in which it was previously impossible to obtain 3D spine models. New clinical applications, such as surgical assistance during minimally-invasive spine surgeries, will thus be explored in the future.



(a) (b) (c) (d)

Figure 4. Example of a reconstruction of a 3D spine model from two radiographs. (a) Posterior-anterior radiograph. (b) Posterior-anterior radiograph angled down by 20 degrees. (c) Lateral view of the reconstructed 3D spine model. (d) Posterior view of the reconstructed 3D spine model.

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REFERENCES

[1] Vijvermans, V., Fabry, G., and Nijs, J., "Factors determining the final outcome of treatment of idiopathic scoliosis with the boston brace: a longitudinal study.," *J. Pediatr. Orthop. B* **13**, 143–149 (2004).

[2] Papin, P., Labelle, H., Delorme, S., Aubin, C. E., de Guise, J. A., and Dansereau, J., "Long-term three-dimensional changes of the spine after posterior spinal instrumentation and fusion in adolescent idiopathic scoliosis.," *Eur. Spine J.* **8**, 16–16 (1999).

[3] Perie, D., Sales De Gauzy, J., and Hobatho, M., "Biomechanical evaluation of cheneau-toulouse-munster brace in the treatment of scoliosis using optimisation approach and finite element method," *Med. Biol. Eng. Comput. (UK)* **40**(3), 296 – 301 (2002).

[4] Lafage, V., Dubousset, J., Lavaste, F., and Skalli, W., "3d finite element simulation of cotrel-dubousset correction.," *Comput Aided Surg* **9**(1-2), 17–25 (2004).

[5] Stokes, I. A., "Three-dimensional terminology of spinal deformity. a report presented to the scoliosis research society by the scoliosis research society working group on 3-D terminology of spinal deformity.," *Spine* **19**, 236–248 (Jan 1994).

[6] Cheriet, F., Laporte, C., Kadoury, S., Labelle, H., and Dansereau, J., "A novel system for the 3d reconstruction of the human spine and rib cage from biplanar x-ray images," *IEEE Transactions on Biomedical Engineering* **54**, 1356–1358 (July 2007).

[7] Novosad, J., Eng, B., Cheriet, F., Delorme, S., Poirier, S., Beauséjour, M., and Labelle, H., "Self-calibration of biplanar radiographs for a retrospective comparative study of the 3d correction of adolescent idiopathic scoliosis.," *Stud. Health Technol. Inform.* **91**, 272–275 (2002).

[8] Pomero, V., Mitton, D., Laporte, S., Guise, J. A. D., and Skalli, W., "Fast accurate stereoradiographic 3D-reconstruction of the spine using a combined geometric and statistic model," *Clinical Biomechanics* **19**(3), 240–247 (2004).

[9] Mitton, D., Landry, C., Veron, S., Skalli, W., Lavaste, F., and Guise, J. A. D., "3D reconstruction method from biplanar radiography using non-stereocorresponding points and elastic deformable meshes," *Medical & Biological Engineering & Computing* **38**, 133–9 (Mar 2000).

[10] Mitulescu, A., Semaan, I., Guise, J. A. D., Leborgne, P., Adamsbaum, C., and Skalli, W., "Validation of the non-stereo corresponding points stereoradiographic 3D reconstruction technique," *Medical & Biological Engineering & Computing* **39**, 152–8 (Mar 2001).

[11] Andre, B., Dansereau, J., and Labelle, H., "Optimized vertical stereo base radiographic setup for the clinical three-dimensional reconstruction of the human spine," *Journal of Biomechanics* **27**, 1023–35 (Aug 1994).

[12] Aubin, C.-E., Dansereau, J., Parent, F., Labelle, H., and de Guise, J., "Morphometric evaluations of personalised 3d reconstructions and geometric models of the human spine," *Med. Bio. Eng. Comp.* **35**(6), 611–618 (1997).

[13] Delorme, S., Petit, Y., de Guise, J., Labelle, H., Aubin, C.-E., and Dansereau, J., "Assessment of the 3-d reconstruction and high-resolution geometrical modeling of the human skeletal trunk from 2-d radiographic images," *IEEE Trans. on Biomedical Engineering* **50**(8), 989–98 (2003).

[14] Novosad, J., Cheriet, F., Petit, Y., and Labelle, H., "Three-dimensional (3-d) reconstruction of the spine from a single x-ray image and prior vertebra models.," *IEEE Trans Biomed Eng* **51**, 1628–1639 (Sep 2004).

[15] Benameur, S., Mignotte, M., Parent, S., Labelle, H., Skalli, W., and de Guise, J., "3D/2D registration and segmentation of scoliotic vertebrae using statistical models," *Computerized Medical Imaging and Graphics* **27**(5), 321–37 (2003).

[16] Fleute, J. and Lavallée, S., "Nonrigid 3-D / 2-D registration of images using statistical models," in [*Conference on Medical Image Computing and Computer-Assisted Intervention, MICCAI'99*], *Lecture Notes in Computer Science*, 138–147, Springer (September 1999).

[17] Boisvert, J., Cheriet, F., Pennec, X., Labelle, H., and Ayache, N., "Geometric variability of the scoliotic spine using statistics on articulated shape models," *IEEE Trans. Med. Imaging* **27**(4), 557–568 (2008).

[18] Boisvert, J., Cheriet, F., Pennec, X., Labelle, H., and Ayache, N., "Articulated spine models for 3d reconstruction from partial radiographic data," *IEEE Transactions on Biomedical Engineering* **55**(11), 2565–74 (2008).