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A. Mitulescu
W. Skalli
D. Mitton
J. A. De Guise

Three-dimensional surface rendering reconstruction of scoliotic vertebrae using a non stereo-corresponding points technique

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A. Mitulescu (✉) · W. Skalli · D. Mitton
Laboratoire de Biomécanique, ENSAM,
151, Bd. de l'Hôpital, 75013 Paris, France
e-mail: anca@argos-europe.com,
Tel.: +33-1-44246364,
Fax: +33-1-44246366

J.A. De Guise
Ecole de Technologie Supérieure,
Montréal, Quebec, Canada

A. Mitulescu · J.A. De Guise
Laboratoire de recherche en imagerie
et orthopédie (LIO),
Université de Montréal,
Centre de recherche du CHUM,
Hôpital Notre-Dame,
Montreal, Québec, Canada

Abstract The medical imaging techniques that allow a three-dimensional (3D) surface rendering reconstruction, which is usually required by the clinician when dealing with scoliotic patients, are computed tomography (CT) and stereoradiography. However, CT cannot provide a 3D rendering of the whole spine because of the high irradiating dose, while the stereoradiographic 3D reconstruction techniques, which use an algorithm derived from the direct linear transformation (DLT), are usually limited in accuracy because of the small number of corresponding anatomical landmarks identifiable on both radiographs. The purpose of the present study is to validate a recent biplanar 3D surface rendering reconstruction technique on scoliotic vertebrae. This technique, called "non stereo-corresponding points" (NSCP), has already been tested on non-pathologic dry cervical vertebrae and frozen lumbar specimens, and the results have proved very encouraging. Since scoliosis is a 3D deformity of the vertebrae and of the global spine, such a technique could be a very useful clinical tool for the diagnostic, follow-up and surgical planning when dealing with scoliotic patients. The validation of the NSCP technique on scoliotic patients was performed on 58 scoliotic vertebrae in 14 patients, by comparison with the CT scan 3D rendering technique. The results of this study show mean errors of 1.5 mm. On the basis of this study, we can conclude that the NSCP 3D reconstruction technique is a definite improvement over existing techniques, and can serve as a useful diagnosis tool in scoliosis. However, the results of the technique still need to be optimized for use in geometrical modeling.

Keywords Scoliosis · 3D reconstruction · Surface rendering · Stereoradiography

Introduction

As scoliosis is a three-dimensional (3D) local and global deformation of the spine [5, 9, 10, 23], 3D computerized rendering of scoliotic vertebrae is required for surgical planning as well as for finite element modeling of this spinal pathology [3, 16].

Because of the high irradiating dose [17] and of the patient having to adopt a lying position, computed tomography (CT), although quite accurate [7, 14, 20], is an inappropriate 3D reconstruction method when dealing with scoliotic patients. Thus alternative radiological 3D reconstruction techniques, using 3D surface rendering algorithms, are necessary in order to provide the surgeon with the same 3D information. Such alternative techniques are all based on the stereoradiography method, which is also called biplanar radiography.

Stereoradiographic 3D reconstruction techniques are divided into two classes. The first of these use an algorithm that allows reconstruction only where there are stereo-corresponding points, i.e., points for which the projection is easily identifiable on both frontal and sagittal radiographs. These techniques are mostly based on the direct linear transformation (DLT) algorithm [1], optimized [18] or modified [2, 4, 6, 11, 12, 21, 22], making it possible to reconstruct a point using its projections on two X-ray films. Although quite accurate on the vertebral body of non-pathological vertebrae, these techniques are far from being optimal on scoliotic vertebrae [3, 20], because of the lack of identifiable stereo-corresponding points in certain vertebral regions, e.g., the posterior arch. In the second class is a recently developed technique that allows 3D reconstruction of both stereo-corresponding and non stereo-corresponding points, the latter being a set of points for which the projection is visible on only one radiograph. This technique is based on the DLT and on the non stereo-corresponding points (NSCP) algorithm [19, 26]. Because it uses more information from the radiograph – i.e., anatomical landmarks that are seen on only one film – the NSCP algorithm has been shown to provide a considerably more accurate 3D reconstruction of vertebrae, when compared to the DLT technique, when it was tested on non-pathological cervical and lumbar vertebrae [20].

However, as the NSCP technique has been validated only on non-pathologic vertebrae [19, 20, 26], the purpose of the present study was to validate the NSCP technique on scoliotic patients.

Materials and methods

Fourteen scoliotic patients of Ste Justine Hospital in Montreal, Canada, participated in this study. Most of the patients were adolescents, ranging from 11 to 21 years old; all were female. They all had idiopathic thoracic or thoraco-lumbar scoliosis, with Cobb angles ranging from 24° to 71°.

As the surgical planning for these patients had required CT scans of some strategic vertebrae to obtain 3D reconstructions, we analyzed only these vertebrae.

Table 1 summarizes the specific characteristics of each patient, and the 58 vertebrae that were used for our study.

Three-dimensional reconstruction using the DLT+NSCP+kriging algorithms

The patients were X-rayed (postero-anterior 0° and lateral views) in a stereoradiographic device at the Ste Justine Hospital in Montreal.

For the 58 vertebrae that had previously been reconstructed in 3D by CT scan, two new sets of 3D reconstructions were obtained The first using only the DLT and a kriging algorithm, and the second using the DLT+NSCP and a kriging algorithm [8, 25].

The calibrating object, necessary to calculate a set of geometrical parameters of the radiological environment, was the one described by André et al. [2]. It is composed of three Plexiglas plates, containing 63 calibrating metallic spherical beads (0.7 mm in diameter) of known 3D co-ordinates, previously measured by means of a 3D measuring device with an accuracy of ±0.2 mm [2].

The NSCP 3D reconstruction technique is based on the standard stereoradiographic technique using the DLT algorithm, significantly improved by adding new reconstructed landmarks that are seen on only one X-ray image, i.e., non stereo-corresponding points.

The NSCP algorithm is based on two assumptions:

1. That the anatomical landmark to be reconstructed is situated on the line defined by the source point and the projection of the anatomical landmark on the X-ray image
2. That this anatomical landmark is also situated on the vertebra to be reconstructed

The reconstruction algorithm uses the 3D reconstructed stereo-corresponding points resulting from the DLT and an optimization based on the previously mentioned assumptions. It works on the basis that the topology of the vertebra to be reconstructed resembles the topology of a generic vertebra and is consistent with the 3D location of the stereo-corresponding points.

The details of the reconstruction algorithm have already been presented by Véron in 1997 [26] and Mitton et al. in 2000 [19].

The reconstruction protocol consisted of digitizing 25 anatomical landmarks per vertebra and the calibrating points on the X-ray films.

The 3D co-ordinates of the 25 anatomical landmarks were obtained as described below:

- Six stereo-corresponding points (Fig. 1) were reconstructed using the DLT algorithm; these points correspond to the projection on both X-ray images of the upper and lower extreme points of the medium section of the pedicles and the centers of the vertebral endplates.

Table 1 Specific characteristics of the patients: type of scoliotic curve, apex vertebra, Cobb angle

Patients	Scoliosis type	Apex vertebra	Cobb angles (°)	Available CT scan reconstructed vertebrae
1193...	Thoracic	T8	43	T8, T9, T10, L1
1222...	Thoracic	T9	44	T6, T7, T8, T9, T10, T11
1525...	Thoracic	T9	51	T6, T7, T8, T9, T10, T11
1725...	Thoracic	T8	68	T7, T8, T9, T10, T11
1736...	Thoracic	T9	50	T8, T9, L3
1746...	Thoracic	T9	50	T9, T10, T11
1826...	Thoracic	T9	57	T7, T8, T9, T11
1828...	Thoracic	T9	50	T6, T7, T8, T9, T10
1275...	Thoracic	T8	52	T10, T12
1143...	Thoracic	T9	59	T7, T8, T9, T10, T11, T12
1803...	Double Major	T9	48/40	T7, T8, T9, T12, L2
1749...	Lumbar	L1	31	L2, L3
1788...	Lumbar	L1	58	T11, T12, L1, L3
1152...	Double Major	L2	68/70	T10, T12, L1

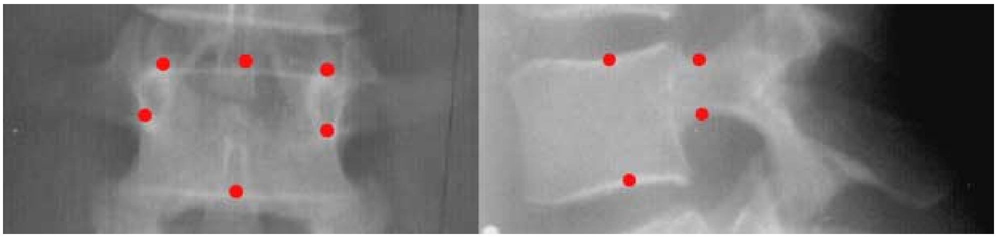

Fig. 1 Stereo-corresponding anatomical landmarks

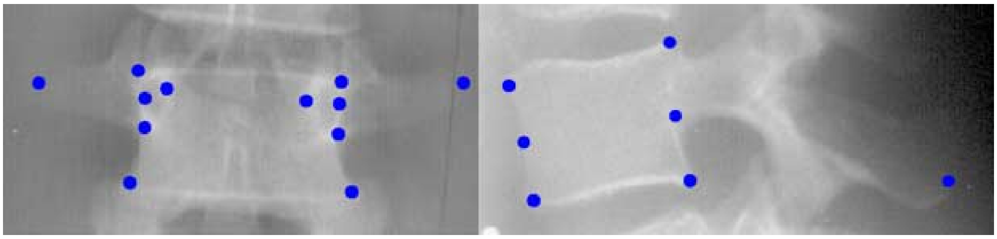

Fig. 2 Non stereo-corresponding anatomical landmarks

- Nineteen non stereo-corresponding anatomical landmarks (Fig. 2) were reconstructed using the NSCP algorithm. These anatomical landmarks correspond to the projections on the X-ray images of the posterior point of the spinous process; the extreme points of the transverse processes; the left, right, anterior and posterior extreme points of the endplates and of the median transverse section of the vertebral body; and the left and right extreme points of the median transverse section of the pedicles.

Even though 25 points may give much better information on the geometry of the reconstructed vertebra than the 6 stereo-corresponding points would provide, in order to quantify the accuracy of the global 3D reconstruction of the scoliotic vertebrae using the DLT+NSCP algorithm, we need more than 25 points per vertebra.

Hence the need to using a kriging technique, in order to obtain a set of 120–178 points per vertebra. Kriging consists in matching and deforming a generic object with regard to a set of control points. The deformation of the generic object is obtained using extrapolation and interpolation algorithms, and yields an approximate global shape of a given vertebra that is consistent with the 3D co-ordinates of the control points. In our specific case, the control points are either the 25 anatomical landmarks reconstructed by DLT+NSCP, or only the 6 anatomical landmarks obtained from DLT.

The generic vertebra, for each vertebral level, was obtained by direct measurement of 120–178 points per vertebra on 30–40 vertebrae per vertebral level [13, 24]. The direct measurements were made using the electromagnetic device Fastrak [15], allowing 3D direct measurement of complex shape objects, by means of a pointer.

The number of points varies with regard to the morphology of the typical vertebra for each vertebral level (Fig. 3):

- For T1 to T10, 140 points/vertebra
- For T11, 130 points/vertebra
- For T12, 120 points/vertebra
- For L1 to L5, 178 points/vertebra

Thus, a specific generic object was used for each vertebral level, based on the average of the geometry of 30–40 vertebrae previously obtained by direct measurement.

After having kriged the generic vertebrae with regard to the reconstructed anatomical landmarks, we obtained two personalized geometrical models for each vertebra of our sample:

- Model 1 was obtained by kriging the generic object using only the six stereo-corresponding points as control points (DLT+kriging model)
- Model 2 was obtained by kriging the generic object using all 25 stereo-corresponding and non stereo-corresponding anatomical landmarks as control points (DLT+NSCP+kriging model)

Each vertebral model contains 120–178 points per vertebra, as shown in Fig. 3.

CT scan reconstruction

The 14 patients were scanned in a CT scan device at the Ste Justine Hospital in Montreal, Canada, at strategic vertebral levels as recommended by the surgeon for the surgical planning. Fifty-eight scoliotic vertebrae in all were reconstructed using the CT scan slices (2 mm cuts).

The 3D reconstruction from the CT scan slices was obtained using SliceOmatic software [7, 14]. This software provides very accurate reconstructions (±1 mm; [20]) due to the automatic segmentation corrected and completed by a manual segmentation of the objects in each CT scan slice.

A set of 120–178 anatomical landmarks per vertebra (corresponding to those obtained after kriging) is extracted from each reconstructed vertebra using an infographic method described by Landry et al. in 1997 [14].

A personalized geometrical model is then constructed using this set of points. As the CT scan reconstruction technique is quite accurate, the geometrical models obtained by this technique were used as the reference 3D reconstructions in order to evaluate the accuracy of the stereoradiographic 3D reconstruction technique using the DLT+kriging (model 1) and the DLT+NSCP+kriging (model 2) algorithms.

Comparison protocol

In order to evaluate the accuracy of the 3D reconstructions of the 58 scoliotic vertebrae by DLT+NSCP+kriging, and the influence of the non stereo-corresponding points on the accuracy of the vertebral models, we compared the set of 120–178 points per vertebra obtained by DLT+kriging and by DLT+NSCP+kriging to the corresponding ones obtained from the CT scan.

In order to compare the two reconstructions of the same vertebra, we defined a common referential, called vertebral referential [20].

Qualitative evaluation

The geometrical models of the vertebrae obtained by CT scan and DLT+NSCP+kriging were visualized using a computer graphic workstation. For each vertebra of our sample, the two models ob-

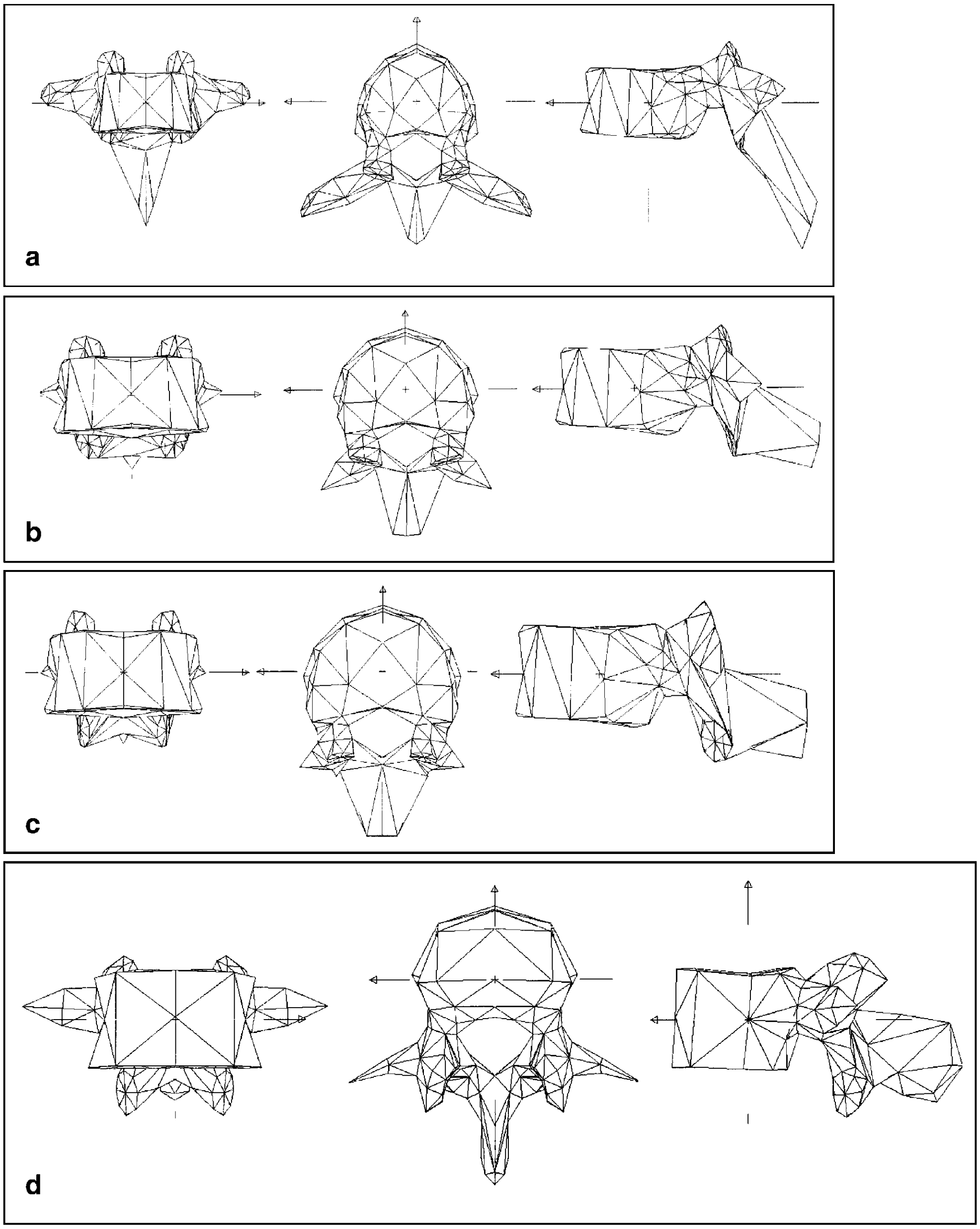

Fig. 3 Geometrical models of vertebrae: **a** T1–T6, **b** T11, **c** T12, **d** L1–L5

tained by these two 3D reconstruction techniques were superimposed using two colors, in order to make a preliminary qualitative evaluation of the accuracy of the DLT+NSCP+kriging reconstruction with regard to the CT scan reconstruction.

This step allowed us to have an idea of how adequate the reconstructed shape is when compared to the reference vertebral topology that is obtained by CT scan. Moreover, the visualization of the superimposed reconstructions of the same vertebra will make visible the vertebral regions where maximum deviations may occur.

Quantitative evaluation

To quantify the accuracy of each stereoradiographic technique (model 1 and model 2) with regard to the reference technique (CT scan), the results of the comparisons are expressed as point-to-surface distances. That means that the reference vertebra and the model of the same vertebra obtained from stereoradiography were first superimposed (i.e., set in the same referential), then each point of the model was projected onto the surface defined by the reference in order to calculate the point-to-surface distance [19, 20].

Global comparison

The global comparison consisted in calculating the mean point-to-surface distance, the 2RMS (root mean square) and the maximum distance values. (The 2RMS distances represent the maxima for 95% of all points, while the maximum distance values represent the isolated extreme values obtained for the entire sample.) This comparison was processed on the entire set of 120–178 points per vertebra for all vertebrae of our sample, for the model 1 and for the model 2 reconstruction methods with regard to the CT scan 3D reconstruction.

Local comparison

A complementary analysis aims to define the vertebral regions for which the 3D reconstruction by DLT+NSCP+kriging (model 2) is able to give detailed geometric information. As most of the anatomical landmarks reconstructed by DLT and NSCP, considered as control points for the kriging algorithm, are situated on the vertebral body and on the pedicles, we divided the set of 120–178 points obtained after kriging in two subgroups:

- Vertebral body and pedicles
- Posterior arch

In order to quantify the difference in accuracy between the two subgroups, we compared the 3D reconstructions of these vertebral regions obtained by the DLT+NSCP+kriging to those obtained by CT scan technique. This comparison allowed us to quantify the variability of accuracy among different vertebral regions.

Evaluation of the influence of image quality and of axial rotation on 3D reconstruction of scoliotic vertebrae

As the landmarks identification process is the first step in our stereoradiographic 3D reconstruction protocol, it is very important to make sure that the information collected by marking the digital radiograph using a cursor pointing function is correct. It is well known that two X-ray films belonging to two different patients will not show the same visibility or quality of the image, i.e., the anatomical landmarks will be more or less visible, depending on the patient's age, weight, degree of scoliosis, etc. André et al. have already shown that even small identification errors may yield large reconstruction errors [2].

In order to estimate the influence of the quality of the image and of the severity of the scoliotic deformation on the 3D reconstruction, we made a classification of the vertebrae with regard to these two parameters.

The quality of the image was considered:

- Good (score 1), if the extreme posterior point of the spinous process was visible on the sagittal view and the extreme lateral points of the transverse processes were visible on the frontal view
- Medium (score 2), if either the spinous process or the transverse process were barely visible on the corresponding view
- Poor (score 3), if both the spinous process and the transverse process were barely visible on the corresponding view

As for the degree of scoliosis, we classified the vertebrae into three classes, as described below (Fig. 4):

- Small (score 1), when the projections of the pedicles on the front view are asymmetrical but do not touch the lateral borders of the vertebral body, remaining inside these borders (Fig. 4a)
- Medium (score 2), when the projections of the pedicles are asymmetrical and one of the pedicles is projected onto the lateral border of the vertebral body, remaining inside the lateral borders of the vertebral body (Fig. 4b)
- High (score 3), when the projections of the pedicles are asymmetrical and one of the pedicles is projected outside the lateral border of the vertebral body (Fig. 4c)

Using the scores described above, and the results of the comparisons of the DLT+NSCP+kriging technique versus CT scan, we studied the correlation between the maximum, RMS and mean errors and the two parameters described above, i.e., the degree of scoliosis or axial rotation and the quality of the image or visibility. The correlation study was performed using StatView software.

Results

The DLT+NSCP technique allowed us to reconstruct 25 points on each of the 58 vertebra, and after kriging we obtained personalized geometrical models containing 120–178 points per vertebra.

Qualitative comparison

Figure 5 shows some examples of superimposed reconstructions for several vertebrae, obtained by DLT+NSCP+kriging and by CT scan. We present examples of typical good and unfavorable reconstructions of the vertebrae in our sample.

Quantitative comparison

The average point-to-surface comparison results, for 58 vertebrae (120–178 points per vertebra), corresponding to the model 2 versus CT scan and to model 1 versus CT scan, are presented in Table 2 as mean, 2RMS and maximum values per patient and for the entire sample (58 vertebrae).

The 2RMS distances represent the maxima for 95% of all points, which were found globally to be lower than 4.0 mm for the entire sample. The maximum distance values represent the isolated extreme values obtained for the sample, and were found to be about 7 mm for 11 patients out of 14 (47 vertebrae out of 58).

Local comparison

The results of the analysis concerning the difference in accuracy between the anterior and the posterior vertebral re-

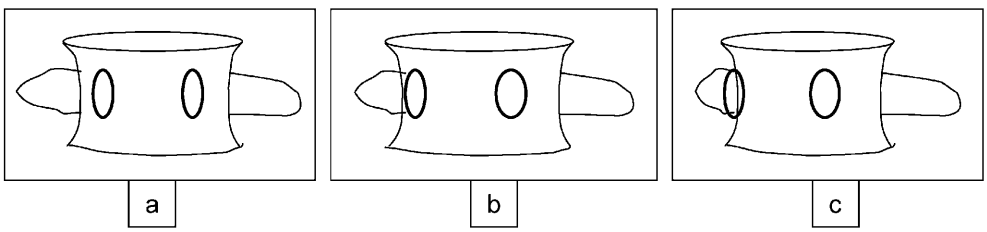

Fig. 4 Axial rotation: **a** small (score 1), **b** medium (score 2), **c** big (score 3)

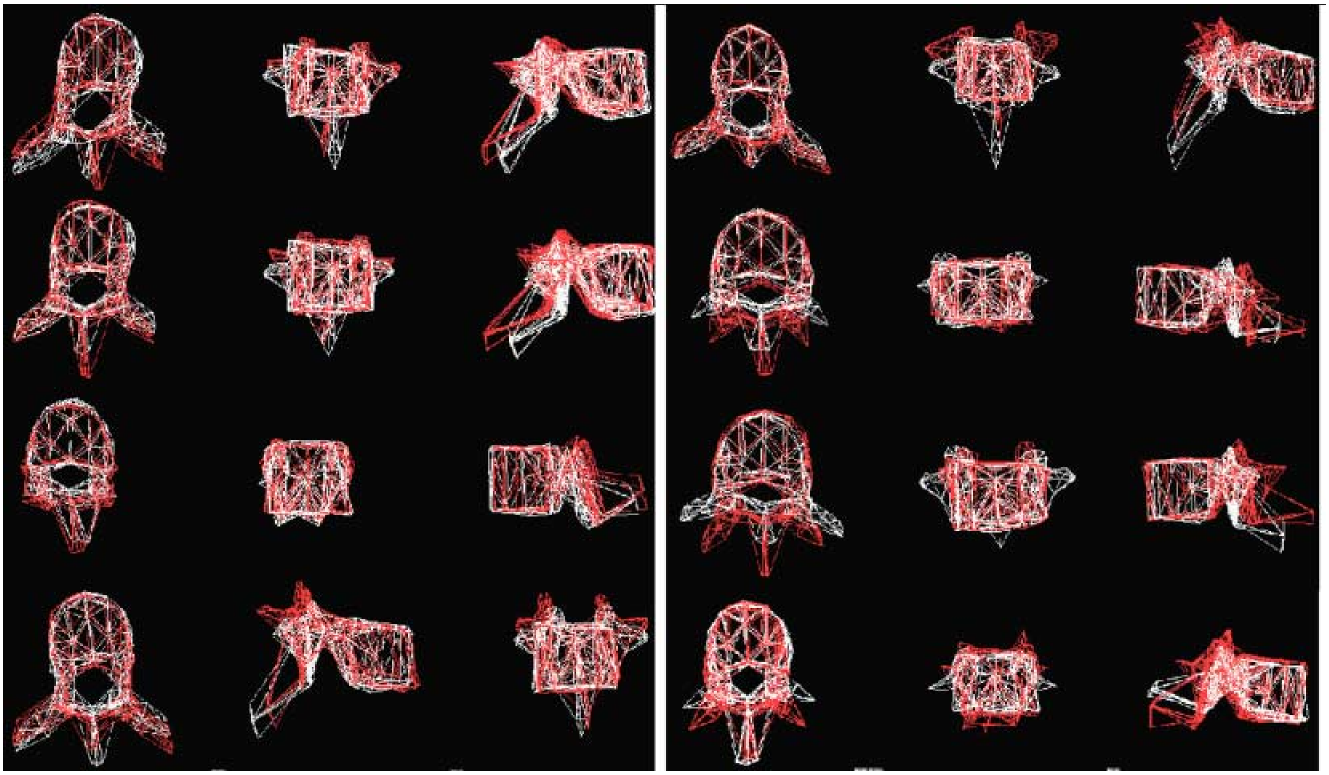

Fig. 5 Examples of superimposed 3D reconstructions. *In black*: DLT+NSCP+kriging (model 2); *in gray*: computed tomography (CT) scan model. *Left*: examples of good reconstructions; *right:* examples of unfavorable reconstructions

gions for the DLT+NSCP+kriging (model 2) are presented in Table 3 as the mean, 2RMS and maximum values obtained from the comparisons for the 58 vertebrae.

Influence of the quality of the image on the 3D reconstruction by NSCP

The results of the study on the correlation between the quality of the image and the point-to-surface distances between the model obtained by 3D reconstruction by DLT+ NSCP+kriging (model 2) and the model obtained by CT scan show correlation coefficients of –0.45, –0.52 and

Table 2 Global results of the comparisons between model 2 and the computed tomography (CT) scan model and between model 1 and the CT scan model

Patients	Reconstructed vertebral levels	Point-to-surface distances					
		Mean (mm)		2RMS (mm)		Max (mm)	
		Model 2	Model 1	Model 2	Model 1	Model 2	Model 1
1525....	T6,T7,T8,T9,T10,T11	1.4	2.3	3.8	6	6.3	10.3
1828....	T6,T7,T8,T9,T10	1.2	1.6	3.2	4.2	7.1	12.1
1826....	T7,T8,T9,T10,T11	1.2	1.8	3.0	4.8	6.0	11.9
1725....	T7,T8,T9,T10,T11	1.4	2.6	3.8	6.4	7.2	10.4
1143....	T7,T8,T9,T10,T11,T12	1.4	1.9	3.4	4.8	5.7	7.6
1803...	T7,T8,T9,T12	1.3	2.2	3.4	5.6	5.9	16.0
1193...	T8,T9,T10,L1	1.3	2.1	3.2	5.2	5.6	7.5
1152...	T10,T11,T12,L1	1.5	2.2	4.0	5.8	5.8	14.6
1746...	T9,T10,T11	1.4	2.0	3.6	5.0	5.6	6.0
1788...	T11,T12,L1	1.5	2.5	3.8	7.0	6.7	18.6
1275...	T10,T12	1.4	1.8	3.6	4.6	5.5	7.3
1222...	T6,T7,T8,T9,T10,T11	2.1	4.1	5.4	10.6	10.0	16.2
1736...	T8,T9,L3	1.7	2.2	5.2	6.2	19.7	19.7
1749...	L2,L3	1.9	3.8	5.2	10.6	11.1	18.6
Global (14 patients)	58 vertebrae	1.5	2.4	4.0	6.4	19.7	19.7

Table 3 Three-dimensional reconstruction comparison results for different vertebral regions: model 2 versus CT scan model (*VB* vertebral body)

Vertebral regions	Point-to-surface distances		
	Mean/region (mm)	2RMS/region (mm)	Max/region (mm)
VB+pedicles	1.2	3.2	5.0
Posterior arch	3.3	7.5	19.7

–0.74 respectively for the mean, RMS and maximum point-to-surface distances with regard to the quality of the image.

We classified the global results of the point to surface comparisons in three classes with regard to the quality of the image (good, medium, poor), as shown in Table 4.

Influence of the degree of scoliosis on the 3D reconstruction by NSCP

As for the influence of the severity of the scoliotic deformity on the 3D reconstruction by DLT+NSCP+kriging, the results of the correlation study show relatively small correlation coefficients, of –0.24, –0.24 and –0.53, for the correlations between the axial rotation and the mean, RMS and maximum point-to-surface distances respectively. We therefore cannot come to any conclusions on the influence of vertebral rotation on the accuracy of the 3D reconstruction and modeling.

Discussion

A most important aspect of the present study with regard to previous similar studies is its development in real routine clinic conditions, i.e., directly on scoliotic patients who were placed into the stereoradiographic radiological device, with all the respiration and movement biases that may occur in these circumstances.

The qualitative evaluation of the reconstructed vertebrae shows that the shape of the scoliotic vertebra was adequately reconstructed for most of the vertebrae in our sample. Even though we used a generic object obtained from non-pathological vertebrae, the visualization shows that the scoliotic deformation of vertebrae is obtained even when kriging a non-deformed generic object.

The quantitative results of the present study show that the DLT+NSCP+kriging 3D reconstruction technique is quite accurate for scoliotic vertebrae; moreover, the non stereo-corresponding points technique makes it possible to considerably improve the accuracy of stereoradiographic reconstruction with regard to techniques based only on stereo-corresponding points (2.6 mm [3]; 2.4 mm [20]). The difference in accuracy between the two stereoradiographic techniques (DLT+kriging and DLT+NSCP+kriging) is highly significant ($P<0.0001$). This difference is mainly due to an increased number of reconstructed points that are used by the NSCP algorithm (i.e., 25 points for model 2 versus six points for model 1).

For some vertebrae in our sample (11 in all, in three patients), the results are still poor for the maxima, which is mainly due to the low visibility of some anatomical landmarks, as shown by the results of the correlation between the maximum errors and the quality of the image. However, even in this worst case, the DLT+NSCP+kriging technique appeared as quite accurate for the reconstruction of vertebral bodies and pedicles (maximum error for 95% of points <3.2 mm; isolated maxima for all points <5 mm).

The analysis of the accuracy on different vertebral regions allowed us to conclude that there remains a difference in accuracy between the anterior and the posterior vertebral regions. This difference is greater in those vertebrae for which the transverse and/or spinous processes are barely visible on the X-ray images because, as we cannot correctly identify these anatomical regions, we may lose several anatomical landmarks on the posterior arch. Therefore, the maximum reconstruction errors are in all cases located in these vertebral regions, i.e., transverse and spinous processes.

As for the pragmatic way of classifying the vertebrae in our sample with regard to the quality of the image, this made it clear that the method of reconstruction is reliable in so far as the information can be extracted from the X-ray image. For example, if the surgeon needs to reconstruct a strategic vertebra that was classed as “poor” for the quality of the image (neither the spinous process nor the transverse process are visible on the X-ray images), he knows that the posterior arch, except for pedicles, of this vertebra will not be reconstructed with the same accuracy as the vertebral body and pedicles. Whether the surgeon may or may not count on this reconstruction depends on the specific requirements of the surgery.

Table 4 Classification of the global results obtained from point-to-surface comparison with regard to the quality of the image

Quality of the image	No. of patients (no. of vertebrae)	Mean (mm)		2RMS (mm)		Max (mm)	
		Model 2	Model 1	Model 2	Model 1	Model 2	Model 1
Good	7 (29)	1.35	2.0	3.6	5.2	6.0	16.0
Medium	4 (19)	1.4	2.3	3.6	6.0	7.2	18.6
Poor	3 (11)	1.9	3.4	5.4	9.0	19.7	19.7

The values obtained for the correlation coefficients between the mean errors, the RMS, and the maximum errors and the quality of the image (i.e., 0.45, 0.52 and 0.74) show that the quality of the image has a greater influence on the maximum errors than on the mean and RMS values.

Therefore, a better reconstruction of scoliotic patients using NSCP may be obtained for a better quality of the image, which would yield a better visibility of the 25 anatomical landmarks. Furthermore, a better quality of the image would probably allow the operator to identify a lot more than 25 points per vertebra.

The use of a scoliotic generic object for the kriging might also improve the accuracy of the 3D reconstruction of scoliotic spines by NSCP, and studies are in progress to provide several generic objects that would correspond to different scoliotic patterns.

Conclusion

The aim of this study was to validate a new stereoradiographic 3D reconstruction technique using stereo-corresponding and non stereo-corresponding points on scoliotic patients.

The point-to-surface comparison results presented above show that this technique is quite accurate on scoliotic vertebrae (mean error 1.5 mm).

The correlation between the quality of the image and the maximum errors proves once again the importance of the landmarks identification during the digitizing process.

Even though some maximum errors are still too high, the global reconstruction of scoliotic vertebrae using NSCP has already proved a definite improvement with regard to existing methods, and it should provide significant aid for clinical analyses as well as for finite element modeling of the scoliotic spine.

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