Validation of the non-stereo corresponding points stereoradiographic 3D reconstruction technique

A. Mitulescu[1] **I. Semaan**[2] **J. A. De Guise**[4,5] **P. Leborgne**[1]
C. Adamsbaum[3] **W. Skalli**[1]

[1]Laboratoire de Biomécanique, ENSAM, Paris, France
[2]Service d'orthopédie, Hôpital Longjumeau, Longjumeau, France
[3]Service de radiologie, Hôpital St. Vincent de Paul, Paris, France
[4]Ecole de Technologie Supérieure, Montreal, Canada
[5]Laboratoire de recherche en imagerie et orthopédie (LIO), Centre de Recherche du CHUM, Montreal, Canada

Abstract—*Several 3D reconstruction techniques deriving from stereoradiographic DLT have been presented during the last 15 years, but these techniques have usually been limited in accuracy because of the small number of corresponding anatomical landmarks identified on both radiographs. A new technique has recently been proposed to perform 3D reconstruction of the spine using not only the stereo-corresponding anatomical landmarks (seen on both frontal and sagittal X-ray films) but also some non-stereo-corresponding ones. This technique (called non-stereo-corresponding points or NSCP) has already been used for cervical dry vertebrae. In the present study, we focus on the validation of this technique for lumbar vertebrae by comparing four techniques: direct measurement, CT scan, 3D reconstruction by stereoradiography using a direct linear transformation (DLT) algorithm and the NSCP technique. The accuracy of the NSCP technique was also evaluated on different vertebral regions. The global results show mean errors of 1.1 mm and maximum of 7.8 mm with regard to direct measurements. These mean errors are close to those obtained using 3D reconstructions from CT scan using 1 mm cuts.*

Keywords—*Stereoradiography, Three-dimensional reconstruction, Vertebra quantitative morphology*

Med. Biol. Eng. Comput., 2001, **39**, 152–158

1 Introduction

SPINAL PATHOLOGIES have been widely studied and several authors have agreed on the importance of the three-dimensional aspect of vertebral deformations (PERDRIOLLE, 1979; DANGERFIELD, 1992; DRERUP, 1992; DUBOUSSET, 1992). The difficulty of corrective surgery planning usually comes from a lack of *a priori* information concerning the way that each specific patient would react to the treatment. Surgery planning is still mostly based on examination of planar X-ray films while three-dimensional (3D) shape analysis is possible using CT scan (computer tomography) reconstruction of some vertebral levels. These two techniques are far from perfect methods: planar X-ray films neglect the three-dimensional aspect; CT scans require a great number of CT slices to visualise the whole spine, which results in a non-negligible risk concerning the irradiation dose (LEVY *et al.*, 1996). Furthermore, clinical investigation by CT scan is performed on the patient in a lying position, which sometimes may bias the clinical interpretation.

Several authors have proposed 3D geometrical and mechanical models to describe the behaviour of the healthy and/or pathologic spine (SHIRAZI *et al.*, 1985; UENO and LIU, 1987; GOEL *et al.*, 1988; LAVASTE *et al.*, 1992; SKALLI *et al.*, 1993; KOUBAA *et al.*, 1995). Accurate personalised geometrical and mechanical information concerning one given patient would allow such models to be used for surgery planning.

Stereoradiographic 3D reconstruction techniques (PEARCY, 1985; DANSEREAU and STOKES, 1988; HATZE, 1988; GAZZANI, 1993; NYSTRÖM *et al.*, 1994), usually based on the DLT algorithm (direct linear transformation) (ABDEL-AZIZ and KARARA, 1972; MARZAN, 1976), can provide a compromise between irradiation risk and improvement of the evaluation. Furthermore, adding the kriging technique using the reconstructed points as control points yields good visualisation of the vertebral geometry (DELORME, 1996). However, because of the very small number of reconstructed control points, these techniques are still not accurate enough to be used on a large scale in geometric modelling and in surgery planning (AUBIN *et al.*, 1997). The NSCP (non-stereo corresponding points) technique was developed to improve the accuracy of the 3D

Correspondence should be addressed to Dr A. Mitulescu; email: Anca.Mitulescu@paris.ensam.fr

First received 4 September 2000 and in final form 1 December 2000

MBEC online number: 20013547

reconstruction by using more information contained in the X-ray film, i.e. anatomical landmarks that are seen on only one film. However, even though the results of this technique seem to be satisfactory for isolated dry cervical vertebrae (VÉRON, 1997; MITTON *et al.*, 2000), one cannot extrapolate the accuracy of the 3D reconstruction obtained on upper cervical vertebrae to lumbar vertebrae, since the geometry and size of the lumbar vertebrae are quite different from the upper cervical vertebrae. Moreover, as the anatomical landmarks are easily identifiable on X-ray films when dealing with dry lumbar vertebrae, it was considered necessary to evaluate NSCP on frozen specimens in order to be as close as possible to *in vivo* conditions. Thus, the purpose of this study is to validate this new technique on cadaver non-pathologic lumbar spines.

2 Materials and methods

Six frozen non-pathologic lumbar spines (53 to 73-year-old men) were taken from *the Service du don des corps, Laboratoire d'Anatomie des St. Pères*, Paris.

A 3D reconstruction of each vertebra was obtained using four modalities (previous stereo X-rays DLT + kriging technique and the new stereo X-rays NSCP + kriging technique, CT scan and direct measurement) as described below:

2.1 *Stereo X-rays*

The six cadaver lumbar spines were X-rayed (PA-0: postero-anterior 0° and LAT: lateral views) in a stereoradiographic device at the Longjumeau Hospital in Paris.

The 3D reconstruction is obtained using the DLT algorithm and a kriging technique (TROCHU, 1993; DELORME, 1996, AUBIN *et al.*, 1997) (previous reconstruction technique) and using the NSCP algorithm and a kriging technique.

For stereoradiography, a calibration object derived from one described by ANDRÉ *et al.* (1994) was used (Fig. 1*a*); it is composed of: (1) two Plexiglas plates that contain 45 calibrating metallic spherical beads (3 mm diameter), of known 3D co-ordinates, previously measured using a 3D measuring device (accuracy ± 0.01 mm); (2) a rotating plate that allows rotation of 90°(accuracy ± 0.1°). The calibration is a necessary step to calculate the geometrical parameters of the radiological environment.

2.1.1 *Previous reconstruction technique (DLT + kriging):* This technique consists in reconstructing an object (i.e. vertebra, pelvis, etc.) by using two or three X-ray films of different incidences (in our case PA-0 and LAT views). Then the DLT algorithm is used to obtain the 3D spatial location of six points per vertebra that can be identified on both X-ray films, termed stereo-corresponding points. Details of the DLT algorithm have been published elsewhere by several authors (PEARCY, 1985; DANSEREAU and STOKES, 1988; HATZE, 1988; ANDRÉ *et al.*, 1994; CHEN *et al.*, 1994; NYSTRÖM *et al.*, 1994). Up to now the technique has used the 3D reconstruction of only six points per vertebra, which can be identified on two X-ray films: superior and inferior points of the median transverse section of the pedicles and the centres of the endplates (ANDRÉ *et al.*, 1994).

The final step in the 3D reconstruction using this method is the kriging of a generic shape of vertebra for each level using as control points the six stereo corresponding points reconstructed by DLT, to obtain a complete set of 178 points which entirely describe the vertebral topology (TROCHU, 1993; DELORME, 1996). The generic object considered for each level was the average of the geometry of 30 vertebrae per vertebral level previously obtained by direct measurement (SEMAAN, 1997). The vertebrae used to derive the generic objects were different from those used in the present protocol.

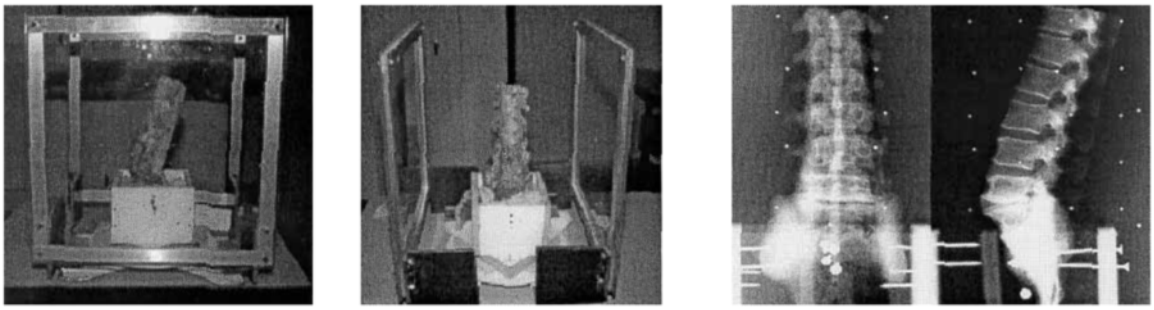
A geometric model is then constructed for each vertebra, using basic geometric surfaces, such as triangles and quadrangles that link the 178 points.

2.1.2 *3D reconstruction using NSCP + kriging technique:* The aim is to obtain complementary control points to improve the vertebral shape reconstruction using kriging. The NSCP technique is based on the standard stereoradiographic technique (DLT) significantly improved by adding new reconstructed landmarks that are usually seen on only one view (19 points) termed non-stereo-corresponding points.

The principle of this method consists in taking into account the 3D positions of DLT reconstructed landmarks, considered as fix points, then searching the 3D spatial location of non-stereo-corresponding points by considering that the topology of the vertebra to be reconstructed is consistent with the observations made on each X-ray film. i.e. it respects anatomical landmarks for which the projection is known from only one of the X-ray films.

Each landmark to be reconstructed is situated on the line joining its projection on the X-ray film and the source. It is also situated on the vertebra to be reconstructed. The 3D locations of the landmarks are then found by an optimisation technique based on the additional assumption that the topology of the vertebra to be reconstructed resemble the topology of a generic vertebra. Details of reconstruction algorithm have been presented by MITTON *et al.* (2000). The reconstruction protocol consisted in digitising the anatomical landmarks and the calibration points on both X-ray films (Fig. 1*b*; Fig. 2), then applying the NSCP algorithm (MITTON *et al.*, 2000). Twenty-five points per vertebra were reconstructed as follows:

- six corresponding points: the DLT points, already described above;
- nineteen non-corresponding points: the posterior point of the spinous process; the extreme points of the transverse



a b

Fig. 1 *Stereoradiographic protocol: (a) Calibration object for stereoradiographic; (b) Stereo X rays: PA-0 and LAT X-ray films of lumbar specimen*

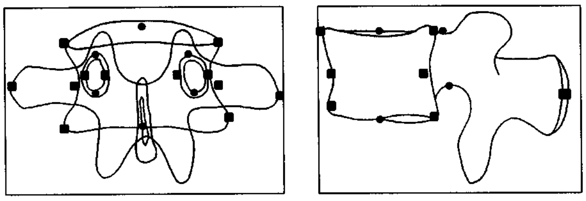


Fig. 2 *Anatomical landmarks reconstructed by NSCP: (●) stereo corresponding landmarks; (■) stereo non-corresponding landmarks*

processes; the left, right, anterior and posterior extreme points of the endplates and of the median transverse section of the vertebral body; the left and right extreme points of the median transverse section of the pedicles.

Then the kriging technique is applied using all 25 points as control points to obtain a set of 178 points, as described above.

A similar geometric model to that described earlier was then obtained for each vertebra. Reconstructions from both techniques were evaluated by comparison with the reconstructions of the same samples using two complementary modalities.

2.2 *CT scan*

The six cadaver lumbar spines were scanned in a CT scan device at the Longjumeau Hospital in Paris (thickness of slices: 1 mm). The 3D reconstruction was made by piling the CT slices of the vertebrae (DE GUISE and MARTEL, 1988; LANDRY *et al.*, 1997) using SliceOmatic® software. This software allows one to automatically segment the CT scan slices and then to correct the automatic segmentation manually to distinguish the different objects in the initial image.

The accuracy of this technique is evaluated at ±1 mm (LANDRY *et al.*, 1997) and it allows a 3D reconstruction of the vertebrae containing up to 4000 points: an infographic method, described by VERON (1997) was used to identify the 178 points corresponding to those defined above among the 4000 points obtained by CT scan. The extraction is made in two steps:

- manual extraction of about 20 easily identifiable landmarks (e.g. the same anatomical landmarks that were identified on stereo X-rays);
- automatic extraction of 158 anatomical landmarks.

This extraction is performed as follows: an approximate set of 178 points is obtained by kriging the generic vertebra and using the 20 manually extracted landmarks as control points. Then each of the 158 approximate points obtained are projected onto the 3D reconstructed surface to obtain their real location.

After this semi-automatic extraction of the whole set of anatomical landmarks corresponding to those contained in the generic objects, a similar geometric model to that described earlier was then obtained for each vertebra using the 178 subset points.

2.3 *Direct measurement*

Finally, the cadaver lumbar spines were dried and each vertebra was directly measured by means of an electromagnetic device, the Fastrak® (Fig. 3) (LEBORGNE *et al.*, 1995), allowing direct 3D measurement of complex shaped objects by means of a pointer. The three-dimensional co-ordinates of the pointer are recorded in a specific reference system.

As the accuracy of the Fastrak device is evaluated at ±0.2 mm for our protocol (SEMAAN *et al.*, 1997), these measurements are considered as the reference for the evaluation of the different

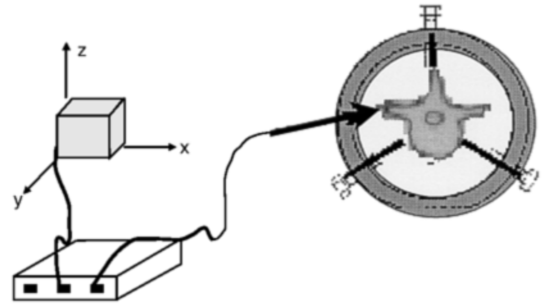


Fig. 3 *Fastrak device: 1–transmitter; 2–Fastrak electronic module; 3–measuring pointer*

X-ray methods. Since some vertebrae were damaged during the drying process, they were excluded. Thus only 26 vertebrae out of 30 were finally used in the study (5 L1, 6 L2, 5 L3, 5 L4, 5 L5).

The same 178 anatomic landmarks mentioned above, were measured using this electromagnetic device, for each vertebra. A similar geometric model to that described above was then obtained for each vertebra.

2.4 *Comparison protocol*

For each of the 26 vertebrae, 178 points and a geometric model were obtained by each of the four different methods (previous stereo X-ray method, current stereo X-ray method, CT scan, direct measurement). Since the four sets of points have been obtained by different techniques, each reference system is different. To compare them, the three-dimensional co-ordinates of all reconstructed points were first expressed in a common local vertebral reference system (Fig. 4), which was defined as described below:

- let Ops and Opi be the 'centres' of the superior and inferior endplates, defined in the sagittal plane, at 1/3 of the posterior vertebral wall. The origin of the vertebral reference is situated at the middle of the line defined by the two geometrical centres of the vertebral endplates (Ops and Opi);
- the z axis (vector $k\bar{v}$), joining the two centres of the vertebral endplates, is oriented upwards;
- the transverse plane is defined as the plane perpendicular to the z axis;
- the x axis (vector $i\bar{v}$) is the intersection between the transverse and sagittal planes, with a postero-anterior orientation;
- the y axis (vector $j\bar{v}$) is defined using the cross-product $j\bar{v} = k\bar{v} \otimes i\bar{v}$.

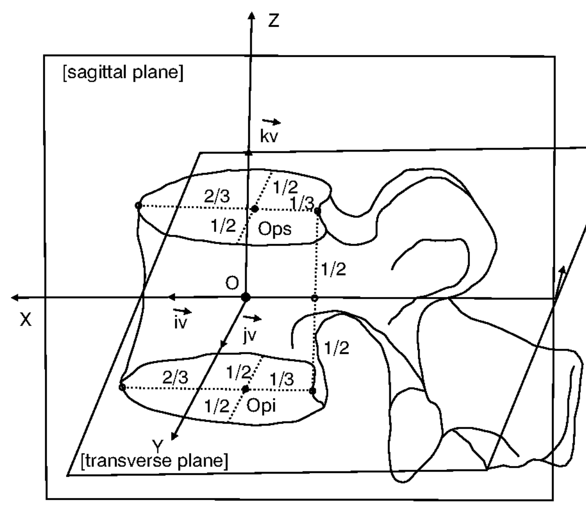


Fig. 4 *Common referential used for the comparisons*

After drying, some transverse and spinous processes and some osteophytes were slightly broken. Also the cartilage situated on the spinous process deteriorated. As these two phenomena may have biased the comparison, points where vertebrae were damaged (maximum five points per damaged vertebra out of 178) were excluded from the comparison.

2.4.1 *Qualitative comparison:* A preliminary qualitative evaluation of the different reconstruction methods is possible by visualising the different models. Thus each vertebra reconstructed using a radiographic method (stereo X-rays or CT scan) is represented using the basic geometrical model described above and is then superimposed on the corresponding vertebra reconstructed using the direct measurement method.

This step is very useful as it allows us to gain an idea of how adequate the reconstructed shape is, when compared to the reference vertebral topology; visualisation of superimposed reconstructions of the same vertebra also makes visible the vertebral regions where maximum deviations may occur.

2.4.2 *Quantitative comparison:* To quantify the accuracy of each technique with regard to direct measurements, the results of the comparisons will be expressed as '*point to surface*' distances, that is each point reconstructed by one technique is projected onto the surface of the corresponding vertebra reconstructed by another technique and the point–surface distance is calculated.

Global comparison: The global comparison consists in calculating the mean *point to surface* distance, the 2RMS and the maximum distance values. The 2RMS distances represent the maxima for 95% of all points, while the maximum distance values represent isolated extreme values obtained for the entire sample. This comparison was processed on the entire set of 178 points per vertebra, for all vertebrae of our sample and for each 3D reconstruction method with respect to the direct measurement using the Fastrak device.

Local comparison: A complementary analysis aims to define the vertebral regions for which the 3D reconstruction is able to give detailed geometric information. As most of the anatomical landmarks reconstructed by NSCP, considered as control points for the kriging algorithm, are situated on the vertebral body and on the pedicles, the set of 178 points obtained after kriging was divided into two subgroups:

- vertebral body and pedicles: 78 points;
- posterior arch: 100 points.

To quantify the difference in accuracy between the two subgroups, the 3D reconstructions of these vertebral regions obtained by previous stereo X-rays, NSCP stereo X-rays and CT scan techniques were compared with the direct measurements by Fastrak. This comparison allows not only quantification of the variability of accuracy among different vertebral regions, but also verification of how NSCP can improve geometric modelling of vertebrae in comparison with the DLT + kriging technique.

2.4.3 *Parametrical evaluation of the NSCP technique:* A global analysis of the accuracy of morphometric parameters obtained from 3D reconstructions by stereoradiography is in progress. For the entire sample, 12 morphometric linear parameters were calculated from the direct measurements and from the 3D reconstructions obtained by NSCP + kriging. These parameters are related mostly to the dimensions of the vertebral body and the spinal canal. The focus here was on only three of them, as they are three-dimensional parameters and therefore cannot be obtained directly from 2D X-ray images:

- two parameters (CA_larg and CA_prof) describe the geometry of the foramen (spinal canal);
- one parameter (VE_ped_prof) represents the transpedicular length for the left and right sides.

The definitions of these parameters (Fig. 5) have been explained in SEMAAN (1997) and LAPORTE *et al.* (2000).

To strengthen the quantitative evaluation of the NSCP technique, the three parameters obtained from NSCP + kriging reconstruction were compared with those obtained from the direct measurement and the mean and maximum errors calculated.

3 Results

The NSCP technique allowed the reconstruction of 25 points on each vertebra (six corresponding points and 19 non-corresponding points). After kriging 178 points/vertebra were obtained.

3.1 *Qualitative comparison*

A qualitative evaluation of two reconstructed vertebrae is shown in Fig. 6. Examples are shown of typical 'bad' and 'good' reconstructions using DLT + kriging and NSCP + kriging.

3.2 *Global comparison*

The average *point to surface* comparison results (26 lumbar vertebrae, 178 points per vertebra) corresponding to DLT, NSCP and CT scan techniques versus Fastrak are presented in Table 1 as mean, 2RMS and maximum values per vertebral level and for the entire sample of 26 vertebrae. For the maximum values of the CT scan versus direct measurements, values are presented corresponding to the maximum errors obtained without taking into account the isolated errors due to shape defaults or due to damage during drying.

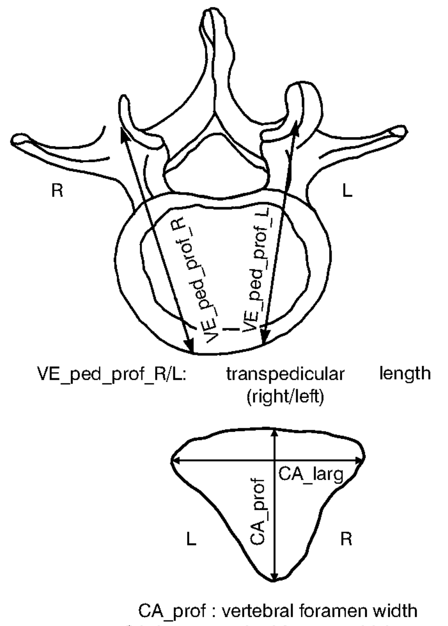


Fig. 5 *Description of morphometric parameters (SEMAAN, 1997)*

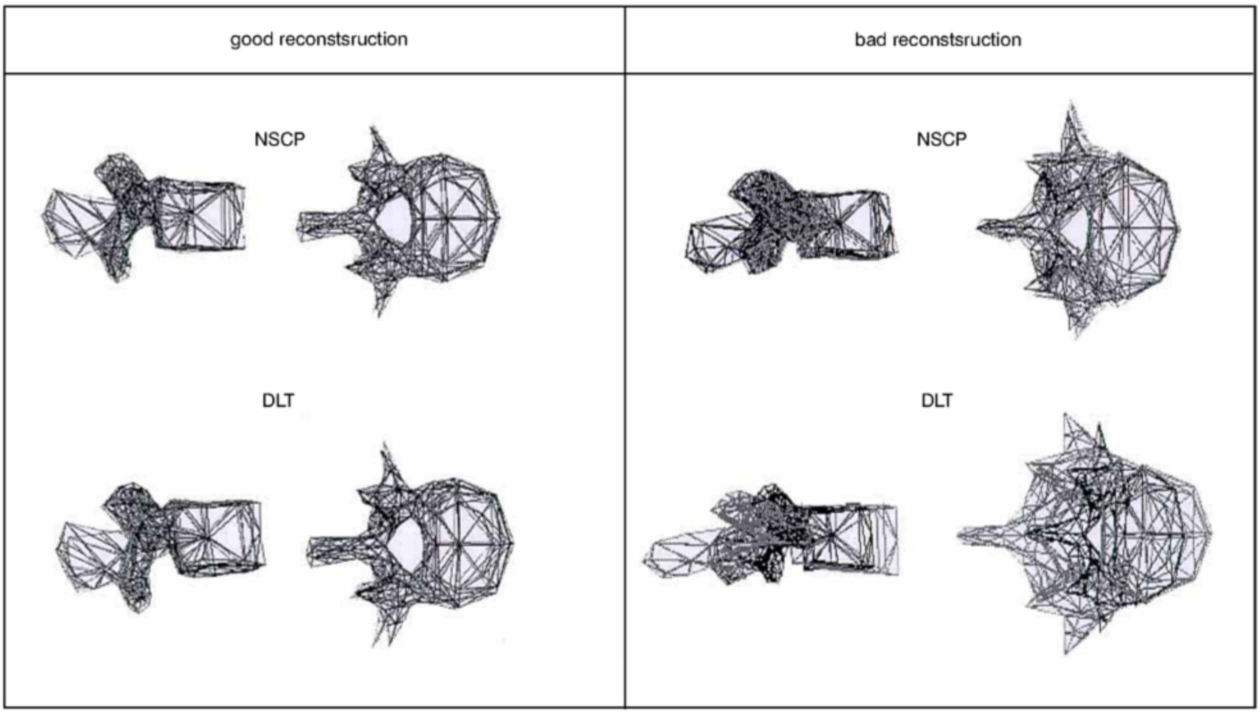


Fig. 6 *Examples of qualitative evaluation of 3D reconstruction: NSCP and DLT (grey lines) against Fastrak (black lines): good and bad 3D reconstruction for the 26 vertebrae (comparison NSCP and DLT against Fastrak for the same vertebra)*

Table 1 NSCP, DLT and CT scan against direct measurements (Fastrak)

	NSCP/FA	DLT/FA	CT/FA
	Entire sample		
Mean (mm)	1.1	2.4	0.8
2RMS (mm)	2.8	7.2	2.2
Max (mm)	7.8	25.5	3.9
	Vertebral levels		
L1			
Mean (mm)	0.9	1.6	0.7
2RMS (mm)	2.3	4.2	1.9
Max (mm)	4.5	15.1	3.4
L2			
Mean (mm)	1.0	1.9	0.7
2RMS (mm)	2.3	4.8	1.9
Max (mm)	6.0	15.8	3.5
L3			
Mean (mm)	1.1	2.0	0.7
2RMS (mm)	2.8	5.8	1.9
Max (mm)	5.9	18.7	3.9
L4			
Mean (mm)	1.2	2.5	0.9
2RMS (mm)	3.2	6.9	2.6
Max (mm)	7.8	15.9	3.8
L5			
Mean (mm)	1.3	3.8	0.8
2RMS (mm)	3.2	11.8	2.0
Max (mm)	6.0	25.5	3.8
	Vertebral regions		
	Vertebral body and pedicles		
Mean (mm)	0.9	2.1	0.7
2RMS (mm)	2.6	5.3	2.0
Max (mm)	3.6	11.4	3.6
	Posterior arch		
Mean (mm)	1.4	3.3	0.8
2RMS (mm)	4.0	11.6	2.2
Max (mm)	7.8	25.5	3.9

NSCP – Non-stereo corresponding points
DLT – Direct linear transformation
CT – CT scan
FA – Fastrak

3.3 *Local comparison*

The results of the analysis concerning the difference of accuracy between the anterior and the posterior vertebral regions are also presented in Table 1, as the mean, 2RMS and maximum values for the three comparisons for the 26 vertebrae.

3.4 *Parametrical evaluation*

Finally, results of the comparison, for the entire sample, between the morphometric parameters obtained from the NSCP + kriging reconstruction and those obtained from direct measurements are presented. For all 12 morphometric linear parameters that were calculated, the maximum errors represent less than 10% and
they are all smaller than 2.3 mm.

The mean/maximum errors obtained for CA_larg are: 1 mm (4%)/2.3 mm (9%); for CA_prof: 0.9 mm (2%)/1.7 mm (8%); and for VE_ped_prof: 1.2 mm (2.2%)/2.2 mm (5%).

4 Discussion

Qualitative evaluation of the reconstructed vertebrae showed the vertebral shape for the NSCP + kriging reconstruction to be better than for DLT + kriging (Fig. 6), mainly due to the increased number of reconstructed points when using the NSCP technique. Indeed, since these points are then used as control points for kriging, the more control points that are used, the more accurate the resulting vertebral shape.

Point to surface comparisons were chosen instead of *point to point* comparisons because the Fastrak measurements and X-ray digitising were made by different operators, which may influence *point to point* comparison results, since two operators may identify the same anatomical landmark at two different locations. Even though the inter-operator error in identifying the anatomical landmarks might not be very important, *point to surface* comparison completely eliminates this error and also enables better evaluation of the real accuracy of the global shape of the 3D reconstruction.

The quantitative results of this study confirm that the new 3D reconstruction technique considerably improves the accuracy of the 3D reconstruction by NSCP + kriging over the conventional DLT + kriging technique (1.4 mm mean for NSCP, 2.4 mm for DLT in the current study and 2.6 mm obtained by AUBIN *et al.*, 1997). However, the accuracy of the reconstruction decreases for the lower vertebral levels (L4, L5), mainly due to reduced visibility on the X-ray films at these levels, especially for the L5 where we have to deal with a superimposed image of L5 and the sacrum.

Nevertheless, it is observed that the global reconstruction by NSCP is close to the CT scan reconstruction, when compared to the direct measurement (i.e. Fastrak). The CT scan reconstruction technique used is a particularly accurate one since it was performed using 1 mm cuts and a semi-manual segmentation and reconstruction method. An evaluation of the CT scan reconstruction method was necessary first of all because of the extraction step, which is based on a manual identification technique. The maximum errors obtained for the CT scan reconstructions with regard to direct measurements are due to several factors: the identification of anatomical landmarks on the 3D object and the difference in shape between the frozen specimen and the dry vertebrae. Indeed, even though intrinsic resolution of the CT scan image is high, both the 3D reconstruction technique and the passage from around 4000 'blind' points with no anatomical significance to 178 labelled points corresponding to anatomical landmarks yields a decrease in accuracy. However, as the maximum error is less than 4 mm, it is considered that the CT scan is a very accurate reference 3D reconstruction technique to use for *in vivo* evaluation of the NSCP technique.

Analysis of the difference in accuracy between the anterior and posterior vertebral regions shows that the reconstruction obtained by NSCP + kriging is more accurate than the reconstruction by DLT + kriging, due to the kriging control points situated on the posterior arch. Even though we used only a few points in this region, one may notice that the improvement in accuracy of the reconstruction is non-negligible. However, some maximum errors obtained on the posterior arch for the NSCP reconstruction are still high. Even though these maxima correspond to points with no significant role in surgery planning (extreme points of the transverse process, posterior point of the spinous process), they cannot be neglected for geometrical modelling. Better reconstruction of these points would require more visibility and probably more control points for kriging on the posterior arch.

Validation of the NSCP technique on non-pathological vertebrae suggests that this technique might be used for clinical analyses of vertebral shape for various spinal deformities as it yields accurate 3D information on the vertebral shape. Notice that the three morphometric parameters selected for this study cannot be obtained from 2D X-rays, even though they are necessary for clinical analysis and surgical planning as well as for personalised modelling.

Nevertheless, as some spinal pathologies, such as scoliosis, are characterised not only by shape parameters but also by postural parameters, study of the evaluation of the NSCP reconstruction technique on scoliotic patients is in progress.

5 Conclusion

The aim of this study was to validate a new stereoradiographic 3D reconstruction technique using stereo-corresponding and non-stereo-corresponding points on non-pathologic lumbar specimens, to complement the study of MITTON *et al.* (2000) which focused on upper cervical vertebrae.

To compare these results for the DLT and NSCP reconstruction technique with other existing studies, the evaluation was made on non-pathologic vertebra, as no study on deformed vertebrae was available.

The point to surface comparison results presented above show that this technique is accurate for the reconstruction of cadaver non-pathologic lumbar vertebrae (mean error = 1.1 mm). Moreover, when compared to the DLT, the new technique considerably improves the 3D reconstruction of the posterior arch. Further improvements of the method can be expected if image processing is employed to obtain better quality X-ray images, as in some cases where the reconstruction of the posterior arch is still less accurate than the reconstruction of the vertebral body and the pedicles.

However, this new technique has already shown definite improvements with regard to existing methods and it should provide a significant aid to clinical studies and finite element modelling.

Acknowledgments—The authors thank the staff of the radiology service of *Longjumeau Hospital*, especially Dr D. Teboune, and of *St Vincent Hospital* in Paris for their technical assistance as well as *BIOSPACE Instruments* and the *Coopération Scientifique Franco–Québécoise* for their financial support. Special thanks to D. Mitton for the follow-up to this study.

References

ABDEL-AZIZ, Y. I., and KARARA, H. M. (1971): 'Direct linear transformation from comparator coordinates into object space coordinates in close range photogrammetry'. Proc. ASP/UI Symposium on Close-range Photogrammetry, Urbana, Illinois

ANDRÉ, B., DANSEREAU, J., and LABELLE, H. (1994): 'Optimized vertical stereo base radiographic setup for the clinical three-dimensional reconstruction of the human spine', *J. Biomech.*, **27**, pp. 1023–1035

AUBIN, C. E., DANSEREAU, J., PARENT, F., LABELLE, H., and DE GUISE, J. A. (1997): 'Morphometric evaluations of personalized 3D reconstructions and geometric models of the human spine', *Med. Biol. Eng. Comput.*, **35**, pp. 611–6184

CHEN, L., ARMSTRONG, C. W., and RAFTOPOLOUS, D. D. (1994): 'An investigation on the accuracy of the three-dimensional space reconstruction using the direct linear transformation', *J. Biomech.*, **2**, pp. 493–500

DANGERFIELD, P. H. (1992): 'Scoliotic curves types should be reclassified using 3-D measurements'. Proc. Int. Symp. 3-D Scoliotic Deformities, Montréal, Québec, Canada

DANSEREAU, J., and STOKES, I. A. (1988): 'Measurements of the three-dimensional shape of the rib cage', *J. Biochem.*, **21**, pp. 893–901

DE GUISE, J. A., and MARTEL, Y. (1988): '3D biomedical modeling: merging image processing and computer aided design'. IEEE EMBS 10th Int. Conf., New Orleans, pp. 426–427

DELORME, S. (1996): 'Application du krigeage pour l'habillage et la personnalisation de modèle géométrique de la scoliose'. Mémoire de maîtrise, Ecole Polytechnique de Montréal

DRERUP, B. (1992): '3-D acquisition, reconstruction and modelling techniques applied on scoliotic deformities'. Proc. Int. Symp. 3-D Scoliotic Deformities, Montréal, Québec, Canada, pp. 2–10

DUBOUSSET, J. (1992): 'Importance of the three-dimensional concept in the treatment of scoliotic deformities'. Proc. Int. Symp. 3-D Scoliotic Deformities, Montréal, Québec, Canada, pp. 302–311

GAZZANI, F. (1993): 'Comparative assessment of two algorithms for calibrating stereophotogrammetric systems', *J. Biomech.*, **26**, pp. 1449–1454

GOEL, K. V., KIM, Y. E., LIM, T. H., and WEINSTEIN, J. N. (1988): 'An analytical investigation of the mechanics of spinal instrumentation', *Spine*, **13**, pp. 1003–1011

HATZE, H. (1988): 'High-precision and three-dimensional photogrammetric calibration and object space reconstruction using a modified DLT-approach', *J. Biomech.*, **21**, pp. 533–38

KOUBAA, W., DEFIVES, T., PIERUNEK, M., SIMONET, J., SKALLI, W., and LAVASTE, F. (1995): 'Modélisation tridimensionnelle par éléments finis de la jonction thoraco-lombaires (T12-L1)', *Rachis*, **7**, pp. 181–196

LANDRY, C., DE GUISE, J. A., DANSEREAU, J., LABELLE, H., SKALLI, W., ZELLER, R., and LAVASTE, F. (1997): 'Analyse infographique des déformations tridimensionelles des vertèbres scoliotiques', *Ann. Chir.*, **51**, pp. 868–874

LAPORTE, S., MITTON, D., DE FOUCHECOUR, M., LASSEAU, J. P., LAVASTE, F., and SKALLI, W. (2000): 'Quantitative morphometric study of thoracic spine. A preliminary parameters statistical analysis', *Eur. J. Orthop. Surg. Traumatol.*, **10**, pp. 85–91

LAVASTE, F., SKALLI, W., ROBIN, S., ROY-CAMILLE, R., and MAZEL, C. (1992): 'Three-dimensional geometrical and mechanical modelling of the lumbar spine', *J. Biomech.*, **25**, pp. 1153–1164

LE BORGNE, P., SKALLI, W., STOKES, I. A. F., MAUREL, N., DUVAL BEAUPÈRE, G., and LAVASTE, F. (1995): 'Three-dimensional measurement of a scoliotic spine' in D'AMICO, M. (Ed.): 'Three-dimensional analysis of spinal deformities' (IOS Press, Amsterdam)

LEVY, A. R., GOLDBERG, M. S., MAYO, N. E., HANLEY, J. A., and POITRAS, B. (1996): 'Reducing the life-time risk of cancer from spinal radiographs among people with adolescent idiopathic scoliosis', *Spine*, **21**, pp. 1540–1548

MARZAN, G. T. (1976): 'Rational design for close-range photogrammetry', Ph D thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, USA

MITTON, D., LANDRY, C., VÉRON, S., SKALLI, W., LAVASTE, F., and DE GUISE, J. A. (2000): 'A 3D reconstruction method form biplanar radiography using non stereocorresponding points and elastic deformable meshes', *Med. Biol. Eng. Comput.*, **38**, pp. 133–139

NYSTRÖM, L., SÖDERKVIST, I., and WEDIN, P. A. (1994): 'A note on some identification problems arising in roentgen stereo photogrammetric analysis', *J. Biomech.*, **27**, pp. 1291–1294

PEARCY, M. J. (1985): 'Stereo radiography of lumbar spine motion', *Acta Orthop Scand.*, **212**, pp. 1–45

PERDRIOLLE, R. (1979): 'La scoliose' in Maloine (Ed.) (Paris, 1979)

SEMAAN, I. (1997): 'Etude morphométrique des vertèbres lombaires; Mémoire de DEÁ (ENSAM, Paris)

SHIRAZI-II, A., AHMED, A. M., and SHRIVASTAVA, S. C. (1986): 'A finite element study of a lumbar segment subjected to pure sagittal plane moments', *J. Biomech.*, **18**, pp. 2–19

SKALLI, W., ROBIN, S., LAVASTE, F., and DUBOUSSET, J. (1993): 'A biomechanical analysis of short segment spinal fixation using a three-dimensional geometric and mechanical model', *Spine*, **18**, pp. 536–545

TROCHU F. (1993): 'A contouring program based on dual kriging interpolation', *Eng. Comput.*, **9**, pp. 160—177

UENO, K., and LIU, Y. K. (1987): 'A three-dimensional nonlinear finite element model of the lumbar intervertebral in torsion', *J. Biomech. Eng.*, **109**, pp. 200–209

VÉRON, S. (1997): 'Modélisation géométrique et mécanique tridimensionelle par éléments finis du rachis cervical supérieur'. Thèse de doctorat en mécanique, ENSAM, Paris

Authors' biographies

The Laboratoire de Biomécanique (LBM) in Paris and several teams in Montreal (Laboratoire d'Informatique de la Scoliose 3D (LIS 3D), Laboratoire de recherche en Imagerie et Orthopédie (LIO), Ecole de Technologie Supérieure (ETS), Ecole Polytechnique de Montréal (EPM)) have collaborated since 1991 in the field of spinal biomechanics. Their research include three-dimensional stereoradiographic reconstruction, personalised biomechanical finite element modelling and semi-automatic analysis of X-ray images. LBM research activity is conducted in close collaboration between clinicians, engineers and implant designers. It concerns the analysis of mechanical behaviour of the musculoskeletal system with the aim (1) to understand normal behaviour and mechanisms of degradation, and (2) to improve implants and provide help for surgical planning. It is mainly oriented towards geometric and mechanical modelling, with a strong link to *in vitro* experimentation and to *in vivo* quantitative clinical investigation. The LIO brings together clinicians, engineers, researchers and professors from ETS, EPM, the University of Montreal and the Research Centre of the Centre Hospitalier de l'Université de Montréal. The LIO creates a favourable climate for research and development of new technologies linked to medical imaging, 3D geometric modelling of osteo-articular structures, computer-assisted surgery and quantitative assessment of orthopaedic and surgical corrective methods.