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3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences

L. Humbert [a,b,*], J.A. De Guise [b], B. Aubert [a], B. Godbout [b], W. Skalli [a]

[a] Laboratoire de Biomécanique, Arts et Métiers ParisTech - CNRS, Paris, France
[b] Laboratoire de recherche en Imagerie et Orthopédie, ETS-CRCHUM, Montréal, Canada

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ABSTRACT

Reconstruction methods from biplanar X-rays provide 3D analysis of spinal deformities for patients in standing position with a low radiation dose. However, such methods require an important reconstruction time and there is a clinical need for fast and accurate techniques. This study proposes and evaluates a novel reconstruction method of the spine from biplanar X-rays. The approach uses parametric models based on longitudinal and transversal inferences.

A first reconstruction level, dedicated to routine clinical use, allows to get a fast estimate (reconstruction time: 2 min 30 s) of the 3D reconstruction and accurate clinical measurements. The clinical measurements precision (evaluated on asymptomatic subjects, moderate and severe scolioses) was between 1.2° and 5.6°.

For a more accurate 3D reconstruction (complex pathologies or research purposes), a second reconstruction level can be obtained within a reduced reconstruction time (10 min) with a fine adjustment of the 3D models. The mean shape accuracy in comparison with CT-scan was 1.0 mm. The 3D reconstruction method precision was 1.8 mm for the vertebrae position and between 2.3° and 3.9° for the orientation.

With a reduced reconstruction time, an improved accuracy and precision and a method proposing two reconstruction levels, this approach is efficient for both clinical routine uses and research purposes.

1. Introduction

The clinical interest of tri-dimensional (3D) imaging to understand, quantify and predict the evolution of deformities of the spine has been well-known for a long time [12,31,32]. 3D CT-scan analysis provides accurate local diagnoses for pathologies such as congenital scoliosis [29] or for surgical planning [22]. Nevertheless a global analysis of the whole spine morphology would require a number of slices leading to a considerable radiation dose for the patient [26]. Moreover Yazici et al. [40] showed that the study of patients in supine position underestimates scoliotic curves and thus biases the morphological analysis of scoliosis.

Therefore studies were performed to develop 3D reconstruction methods from biplanar X-rays. These approaches provide 3D subject-specific models of the whole spine of patients in standing position with a low radiation dose.

Many authors proposed 3D reconstruction methods of vertebrae [1,2,9,23] which rely on the digitalization of a few corresponding points in both X-rays. To take more information from the radiographs into account, a method using non-corresponding points digitalized only in one of the X-rays [27,28,39] considerably improved the reconstruction accuracy. This method was used by other authors with different approaches [3,11]. Nevertheless such methods require an important reconstruction time to get the 3D models and have been restricted for a long time to clinical research.

With the development of biplanar radiography in a routine clinical use, there is a need of both accurate and fast 3D reconstruction methods.

To automate the reconstruction process, methods based on image processing and 2D/3D registration of statistical deformable models [5,16] were developed. However the image processing is limited by the superimposition of bony structures and the quality of the X-rays and is dependent on a good initialization [5].

Dumas et al. [14] proposed a semi-automated reconstruction method of the spine based on an interpolation technique which allows the 3D reconstruction of the position and the scale of vertebrae. However the method does not include any deformation of the vertebral shape which is an important limitation for 3D reconstruction of severe scolioses.

The semi-automated approach proposed by Pomero et al. [33] relies on parametric models of vertebrae using transversal statistical inferences. The transversal inferences are based on the relationships between geometric descriptors of a given vertebra.

* Corresponding author at: Laboratoire de Biomécanique, Arts et Métiers ParisTech, 151, Boulevard de l'Hôpital, 75013 Paris, France. Tel.: +33 1 44 24 63 64; fax: +33 1 44 24 63 66.
E-mail addresses: ludovic.humbert@netcourrier.com, wafa.skalli@paris.ensam.fr (L. Humbert).

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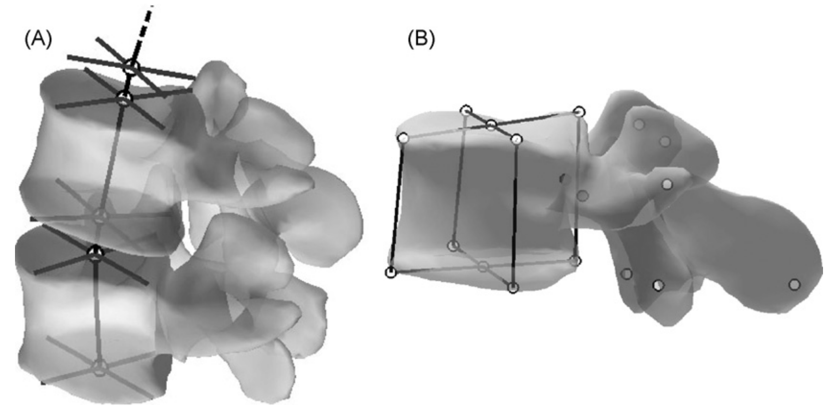

Fig. 1. (A) Parametric spine model (only L4 and L5 are represented) and (B) parametric vertebra model for L4.

This technique provides 3D reconstructions (with adjustments of both position and shape) of the spine with a quite good accuracy and allows to reduce the number of anatomical landmarks to be digitalized. In fact, only eight points per vertebra (the four corners of the vertebral body in each X-ray) need to be identified. However the manual identification of information related to each vertebra is still necessary.

To avoid this time-consuming manual identification of each vertebra and to go further into automation, the purpose of this study is to propose a novel semi-automated 3D reconstruction method of the thoracic and lumbar spine from biplanar X-rays. This method relies on parametric models of vertebrae using transversal inferences (approach proposed by Pomero et al. [33]) and also on a parametric model of the whole spine using longitudinal inferences. These longitudinal inferences are based on the relationships between descriptors of one vertebra with regard to another one and aims to reduce the reconstruction time. Two reconstruction levels are proposed. The first reconstruction level aims to get a fast estimate of the 3D reconstruction and accurate clinical measurements. If a more accurate 3D reconstruction is required, a second reconstruction level can be obtained by performing a fine adjustment of the 3D models.

2. Materials and methods

2.1. Parametric models and inferences

2.1.1. Parametric spine model for longitudinal inferences

The parametric spine model is described by the length of a curve passing through the vertebral bodies centers (spinal curve), the depth, the width and the position along the spinal curve of each vertebral endplate (Fig. 1A). All these parameters were measured on a database of 175 subjects (91 asymptomatic subjects, 47 moderate idiopathic scolioses and 37 severe idiopathic scolioses) whose 3D reconstructions of the spine were obtained from biplanar X-rays (low dose imaging device EOS [13] (Biospace med, Paris, France) and conventional imaging devices) using the method described by Pomero et al. [33]. The longitudinal inferences rely on this database to estimate, from the knowledge of some parameters of the spine, the other parameters (for example the estimation of the L3 upper endplate width from the L2 and L1 upper endplate widths). These longitudinal estimations are based on multi-linear regressions [7].

2.1.2. Parametric vertebrae models for transversal inferences

The parametric vertebrae models (from the study of Pomero et al. [33]) are described by eight specific measurements of the vertebral body (the depth and the width of each endplate and the anterior, posterior, left and right heights of the vertebral body) and by the 3D coordinates of 19 anatomical points (Fig. 1B). These parameters were measured on a database of 1628 dry isolated vertebrae of non-scoliotic and scoliotic spines using a direct 3D measurement device (Fastrack®, Polhemus, VT). These data were available from previous studies [20,24,30,34]. The transversal inferences rely on this database to estimate the 19 anatomical points from the eight specific measurements of a given vertebra using multi-linear regressions [7].

2.2. Reconstruction process

From the biplanar X-rays, a first reconstruction level aims to get a fast estimate of the 3D reconstruction providing clinical measurements. This requires the identification in the X-rays of three anatomical features of the spine. Next, this fast estimate can be iteratively improved by the adjustment of more descriptors of the spine to finally obtain a "level two" reconstruction. This process is detailed below.

2.2.1. Biplanar X-rays

The 3D reconstruction method relies on biplanar calibrated X-rays performed either using conventional X-ray imaging devices with specific calibration systems [8,9,15] or using the low dose imaging device EOS [13]. In this case, the system is self-calibrated and the X-rays are performed simultaneously.

2.2.2. Preliminary step: digitalization of the pelvis

In order to provide pelvic clinical measurements, anatomical primitives are digitalized on the pelvis. The method was proposed by Baudoin et al. [4] and require the identification in biplanar X-rays of two spheres on the acetabuli and a segment on the sacral endplate (Fig. 2).

2.2.3. Level 1: fast 3D reconstruction of the spine and clinical measurements

2.2.3.1. Step 1.1: first estimate. The spinal curve, the T1 upper endplate and the L5 lower endplate are first digitalized on both X-rays (Fig. 2A, white parameters). The length of the spinal curve, the width and depth of the T1 and L5 endplates, which are descriptors of the parametric spine model, are used as predictors. From these predictors, the longitudinal inferences are used to statistically estimate the other descriptors of the parametric spine (Fig. 2A, black parameters) which are the depth, the width and the position along the spinal curve of each vertebral endplate.

From the descriptors of the parametric spine model, the eight specific measurements of the vertebral body (Fig. 1B) are directly calculated for each vertebra. From the eight spe-

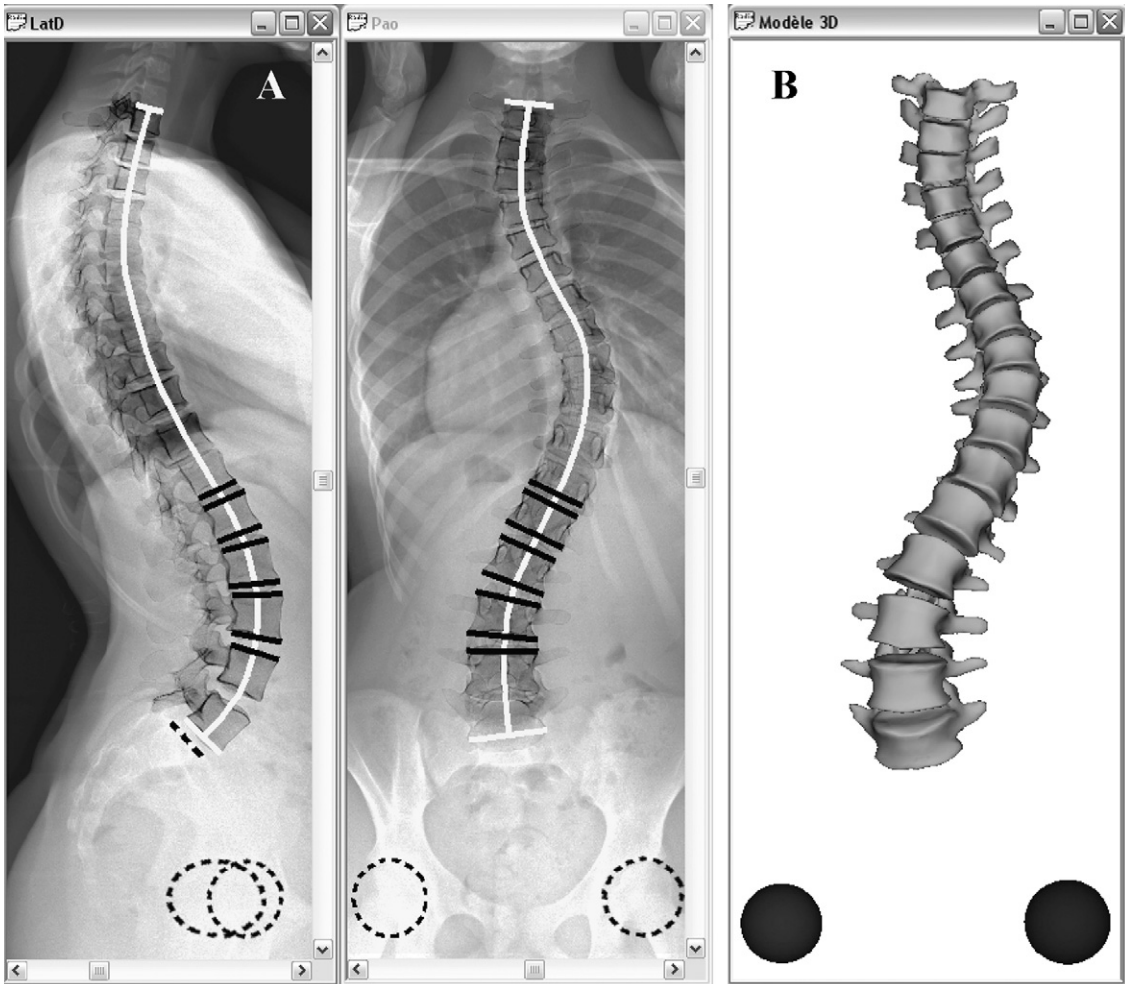

Fig. 2. (A) The digitalization of a few descriptor parameters of the parametric spine (white parameters) allows to estimate the other descriptors (black parameters) using longitudinal inferences. The estimate of the 3D reconstruction (B) is projected on the biplanar X-rays (A). The digitalization of the pelvis is drawn in black dotted line (A).

cific measurements, the transversal inferences are used to estimate the 19 anatomical 3D points for each parametric vertebra.

Finally a highly detailed ∼2000 points model [25] is generated from the above-mentioned 19 control points using an interpolation algorithm [10,38]. These models are projected on both X-rays so that the operator can visualize the 3D reconstruction of the spine in the radiographs (Fig. 2).

2.2.3.2. Step 1.2: adjustment of the 3D reconstruction for clinical measurements. Using control points on the vertebral bodies and the pedicles, the operator is asked to adjust the anatomical features of the 3D reconstruction involved in the calculation of clinical measurements. For kyphosis and lordosis, the upper endplates of T1, T4 and L1 and the lower endplates of T12 and L5 have to be adjusted. To calculate clinical measurements related to scoliosis, the operator is also asked to adjust the position and the shape of the apical vertebra and the two end vertebrae.

As soon as these anatomical features are corrected, the parametric models “self-improve” (Fig. 3): the descriptors associated to adjusted features become predictors to reestimate the whole set of descriptors of the parametric spine model (using longitudinal inferences) and consequently the descriptors of the parametric vertebrae models (using transversal inferences). In addition to statistical inferences, constraints on the spinal curve allow to ensure a geometrical continuity in terms of position and rotation of the vertebrae. In the same way, constraints on a curve passing through the vertebral canal ensure a geometrical continuity on the axial vertebral rotation.

This “level 1” reconstruction process provides a fast estimate of the spine with clinical measurements.

2.2.4. Level 2: full 3D reconstruction of the spine

If a more accurate 3D reconstruction is required, the operator is asked to check and, if necessary, to perform a fine adjustment of the position and the shape of the vertebrae (from T1 to L5) using control points on the vertebral bodies, the pedicles and the posterior arches (articular, spinal and transverse processes). As for the “level 1” reconstruction process (step 1.2), this “fine adjustment” step (described by Pomero et al. [33]) is accelerated in the current study by the use of the parametric models based on longitudinal inferences: the model “self-improves” as soon as anatomical features are corrected.

2.3. Method evaluation

The shape accuracy, the position precision, the clinical measurements precision and the reconstruction time were evaluated for both reconstruction levels. None of the subjects used in the databases for statistical inferences was included in the method evaluation.

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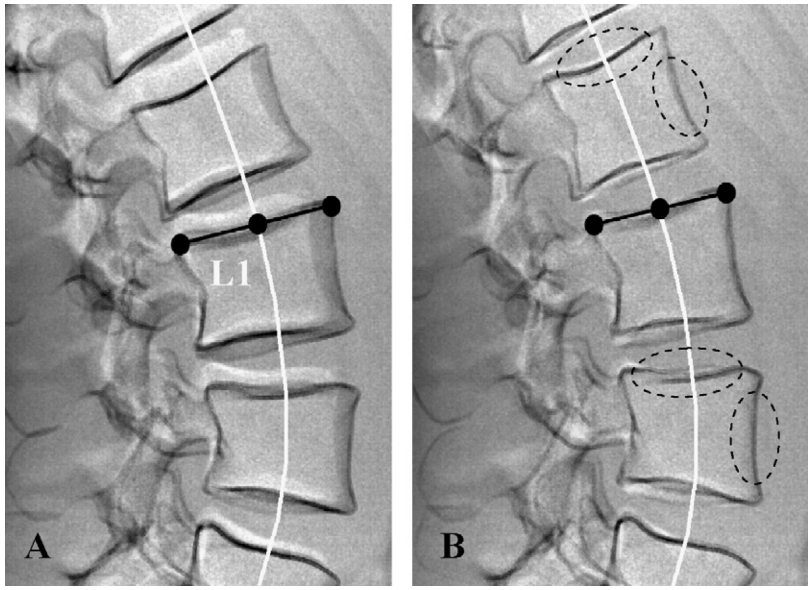

Fig. 3. Self-improvement of the 3D reconstruction of the spine: the adjustment of the L1 upper endplate position and depth (A) improves the position and the depth of the adjacent vertebrae endplates (B) thanks to statistical inferences.

2.3.1. Shape accuracy

2.3.1.1. Patients and radiographic analyses. The accuracy was evaluated by comparing 3D reconstructions of vertebrae obtained from biplanar X-rays and from CT-scan. 40 thoracic and lumbar (T11 to L5) vertebrae from 11 patients of the Erasme Hospital (Brussels, Belgium) were included in this evaluation. Biplanar X-rays of these patients were performed using a biplanar X-rays device EOS. 3D reconstructions from CT-scan were obtained for the 40 vertebrae using an automatic segmentation completed by a manual segmentation of the CT-scan slices (1 mm cuts) using the software Amira (Mercury Computer Systems, Chelmsford, MA, USA).

2.3.1.2. Shape accuracy. The reconstructions obtained from the biplanar X-rays (for both level 1 and level 2) were superimposed onto the corresponding CT-scan reconstructions (rigid registration [33]) and point-to-surface signed distances were calculated between the models. Global shape accuracy was evaluated using the mean and the standard deviation (SD) of these signed point-to-surface distances. Local shape accuracy was evaluated for two different regions of the vertebra: vertebral body + pedicles and posterior arch.

2.3.2. Position precision, clinical measurements precision and reconstruction time

2.3.2.1. Patients, radiographic analyses and operators. 60 subjects were included in this evaluation: 20 asymptomatic subjects, 20 moderate idiopathic scolioses with a mean Cobb's angle of 26° (15–37°) and 20 severe idiopathic scolioses with a mean Cobb's angle of 49° (39–71°). Biplanar X-rays of these patients were performed using biplanar X-rays devices EOS installed at the *Laboratoire de Biomécanique*, the *Saint-Vincent de Paul* Hospital (Paris, France), and the *Sainte-Justine* Hospital (Montréal, Canada). Each one of the three operators performed the 3D reconstruction process one time for the 60 subjects. Among these three operators, two were novices and followed a practical course (3 days with examinations) to become familiar with the reconstruction method.

2.3.2.2. Position calculation. A vertebral reference frame based on the definition of Stokes and the Scoliosis Research Society [37] was associated with each vertebra. The position of the vertebral bodies centers enabled to measure the position precision. The Lateral–Sagittal–Axial (L–S–A) angles [35] calculated from the vertebral reference frame allowed to estimate the orientation precision.

2.3.2.3. Clinical measurements. The following clinical measurements were calculated from the 3D reconstructions: T1/T12 and T4/T12 kyphoses, L1/L5 and L1/S1 lordoses, pelvic incidence, pelvic tilt, sacral slope and for scoliotic subjects, Cobb's angle, axial vertebral rotation of the apical vertebra and torsion index [6]. The definition of the measurements was detailed by Gille et al. [18]. The end vertebrae and the apical vertebra were chosen for each scoliotic subject by one operator.

2.3.2.4. Statistical analysis. Descriptive statistics (simple plots and analysis of variances) were first used to observe the data and to investigate possible significant differences among the operators or the subjects' categories (asymptomatic, moderate or severe scolioses). The position and clinical measurements precision, according to Gluer et al. [19] and the ISO standard [21], was evaluated using the Root-Mean-Square (RMS) average of the standard deviations

Table 1
Shape accuracy for the two reconstruction levels: mean of absolute values and 95% confident interval (2SD) for the signed point-to-surface distances (mm) between 3D reconstructions from biplanar X-rays and from CT-scan.

Reconstruction level	*N*	Whole vertebra		Vertebral bodies + pedicles		Posterior arch	
		Mean Abs	95%	Mean Abs	95%	Mean Abs	95%
Level 1	40	1.3	3.6	1.2	3.0	1.4	3.9
Level 2	40	1.0	2.7	0.9	2.2	1.2	3.0

Table 2
Position precision (2RMS$_{SD}$) for the two reconstruction levels: the vertebral position (Anterior–Posterior, Medial–Lateral, Proximal–Distal and 3D) and orientation (Lateral, Sagittal and Axial angles) are detailed for each subject's category (asymptomatic subjects, moderate and severe scolioses).

Reconstruction level	Category	Position (mm)				Orientation (°)		
		A–P	M–L	P–D	3D	L	S	A
Level 1	Asymptomatic	1.2	1.3	0.8	1.9	2.1	2.4	3.1
	Moderate	1.3	1.3	0.8	2.0	2.7	2.6	4.3
	Severe	1.5	1.3	1.1	2.3	3.3	2.8	5.1
	All	1.3	1.3	0.9	2.1	2.7	2.6	4.2
Level 2	Asymptomatic	1.1	1.0	0.6	1.6	1.8	2.0	3.1
	Moderate	1.1	1.1	0.8	1.7	2.5	2.3	3.9
	Severe	1.4	1.2	0.9	2.1	2.8	2.5	4.6
	All	1.2	1.1	0.8	1.8	2.4	2.3	3.9

SD_j calculated for each sample j:

$$RMS_{SD} = \sqrt{\sum_{j=1}^{m} \frac{SD_j^2}{m}} = \sqrt{\sum_{j=1}^{m} \frac{\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2/(n-1)}{m}} \quad (1)$$

where m is the number of samples, n the number of repeated measurements, x_{ij} the ith measurement for the sample j and $\bar{x}_j$ the mean of all x_{ij} for the sample j. This approach allows to estimate a 95% confidence interval for the position precision given by $\pm 2RMS_{SD}$.

2.3.2.5. Reconstruction time. Finally, the reconstruction time was also evaluated from the reconstructions of the 60 subjects performed by the three operators. The computer used was a Pentium 4 with a 3.4 GHz CPU.

3. Results

3.1. Shape accuracy

The mean shape accuracy (in comparison with CT-scan) was 1.3 mm for the first reconstruction level and 1.0 mm for the second level (Table 1). The mean absolute values and the 95% confident intervals presented for different anatomical regions highlighted a better accuracy for the vertebral bodies + pedicles in comparison with the posterior arches. The mean of signed distances (not mentioned in the table) was very close to zero showing that there is no systematic error (i.e. no bias) for the shape between the biplanar X-rays and the CT-scan reconstructions.

3.2. Position and clinical measurements precision

Descriptive statistics highlighted that the vertebral position and the clinical measurements precision vary substantially between subjects' categories. On the other hand, no significant difference was found between the operators. The precision results were pooled according to these observations.

The 95% confident interval for position precision (3D) was 2.1 and 1.8 mm respectively for the "level 1" and "level 2" reconstructions (Table 2). The clinical measurement precision was between 3° and 6° for kyphoses and lordoses, between 1° and 3° for pelvic measurements and between 3° and 4° for measurement dedicated to scoliosis (Table 3). As all the anatomical features involved in the clinical measurements calculation are adjusted during the first reconstruction level and not modified during the second level, the results of the clinical measurements precision are identical for both levels.

3.3. Reconstruction time

The mean reconstruction time evaluated from the 60 subjects was 2 min 30 s for the first and 10 min for the second reconstruction level (Table 4). The computation time was very low (about 4 s to generate the first estimate of the fast 3D reconstruction from the spinal curve, the T1 upper endplate and the L5 lower endplate (end of the step 1.1)). Most of the reconstruction time was thus dedicated to verifications and manipulations performed by the operators.

4. Discussion

The purpose of this study was to propose and evaluate a 3D reconstruction method from biplanar X-rays using parametric models based on longitudinal and transversal inferences. Two reconstruction levels were proposed: a first reconstruction level with a fast estimate of the 3D reconstruction providing clinical measurements and a second level with a complete verification of the whole vertebral shape.

4.1. Shape accuracy

3D reconstructions from CT-scan were used as a reference to perform an in vivo evaluation of the vertebral shape accuracy. For the "level 1" reconstructions, mean error was 1.3 mm and 95% of the point-to-surface distances were less than 3.6 mm. The accurate adjustments performed at "level 2" allow to bring the mean accuracy up to 1.0 mm (2.7 mm for 95% of the errors). A comparison with literature (even if the patients involved and the imaging devices

Table 3
Clinical measurements precision (2RMS$_{SD}$) (identical for both reconstruction levels).

	Asymptomatic subjects	Moderate scolioses	Severe scolioses
T1–T12 kyphosis (°)	4.6	5.5	5.6
T4–T12 kyphosis (°)	3.4	3.8	4.3
L1–L5 lordosis (°)	3.8	4.6	5.4
L1–S1 lordosis (°)	3.6	4.1	4.2
Pelvic incidence (°)	3.2	3.4	3.5
Pelvic tilt (°)	1.2	1.4	0.8
Sacral slope (°)	3.2	3.0	3.2
Cobb's angle (°)	–	3.1	3.5
Axial vertebral rotation of the apical vertebra (°)	–	3.4	3.9
Torsion index (°)	–	4.0	4.2

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Table 4
Mean reconstruction time for the different reconstruction levels and for the preliminary step (digitalization of the pelvis).

Reconstruction level	Asymptomatic subjects	Moderate scolioses	Severe scolioses	All
Preliminary step (pelvis)	1 min	1 min	1 min	1 min
Level 1	2 min	2 min 30 s	3 min	2 min 30 s
Level 1 + level 2	9 min	10 min	11 min	10 min

Table 5
Comparison of the position (Anterior–Posterior, Medial–Lateral and Proximal–Distal) and orientation (Lateral, Sagittal and Axial) precision for the current study (Level 1 and 2) and the method of Dumas et al. [14] ($2RMS_{SD}$ estimated with the formula proposed by the authors).

	N	Mean Cobb's angle [min–max]	Position (mm)			Orientation (°)		
			A–P	M–L	P–D	L	S	A
Level 1	13	30° [23–36°]	1.1	1.1	0.7	2.3	2.3	3.6
Level 2			0.9	0.9	0.6	2.1	2.0	3.3
Dumas et al. [14]	11	30°	1.8	3.8	4.0	3.0	4.0	4.0

used in these studies were different) highlights the improved accuracy of the current study: Pomero et al. [33], with a method requiring a reconstruction time of 14 min, found a mean point-to-surface distance of 1.4 mm and Delorme et al. [11] a mean distance of 2.6 mm.

4.2. *Precision study*

As CT-scan and biplanar X-rays 3D reconstructions were not in the same radiological environment, it was not possible to assess the vertebral position and the clinical measurements using the CT-scan as a reference. The precision study aims to quantify in vivo the precision [19,21] of the 3D reconstructions from biplanar X-rays and to provide a 95% confident interval ($\pm 2RMS_{SD}$). We focused on the inter-rater variability which is generally an unfavorable case. Nevertheless the intra-rater variability was also evaluated (one operator performed twice the 3D reconstruction of the 60 patients) with results slightly better in comparison with inter-rater variability (95% confident intervals for intra-precision ("level 2" reconstruction) were 1.5 mm for the position (3D) and 1.9°, 2.0° and 3.5° (L–S–A angles) for the orientation).

4.2.1. *Position precision*

The results (Table 2) highlights that, despite a precision slightly lower, the "level 1" reconstruction precision was close to the precision obtained after the "level 2" process.

Dumas et al. [14] proposed a semi-automated reconstruction method of the spine from biplanar X-rays which rely on the adjustment of the position and the scale of the vertebrae. The method precision was evaluated using the calculation of the RMS_{SD}, however with a different formula in comparison with Eq. (1) used in this study. In fact, the division by $n-1$ was replaced by n, which conflicts with the recommendations of Gluer et al. [19] and the ISO standard [21] and minimizes the precision errors. To evaluated the current study in comparison with the method proposed by Dumas et al., the position precision was also evaluated using the formula used by the authors. A subsample of 13 patients, extracted from the 20 subjects with a moderate scoliosis, was used, representing the same scoliosis magnitude as idiopathic scolioses involved in the study of Dumas et al. (mean Cobb's angle of 30°). This comparison (Table 5) highlights that the current study's precision is better for both reconstruction levels. In addition, the method proposed by Dumas et al. [14] does not include any deformation of the vertebral shape to modify the posterior arches or the wedging of vertebrae, which is an important limitation for severe scolioses and calculation of clinical measurements based on vertebral endplates (Cobb's angle, kyphosis, lordosis . . .).

4.2.2. *Clinical measurements precision*

Many authors emphasized the limitation of 2D radiological measurements and the clinical interest of measurements calculated from 3D reconstruction [17,18,36]. The clinical measurements evaluated in this study are essential for the diagnosis of scoliosis [18]. Therefore the reconstruction process was especially dedicated to clinical applications, with measurements provided from the "level 1" reconstruction.

An evaluation of the clinical measurements precision of the previous 3D reconstruction method used in our laboratories was proposed by Gille et al. [18]. The results of this study on mild scoliotic subjects were comparable to those obtained with the current study.

4.3. *Reconstruction time*

Despite a fast reconstruction method (5 min), the approach proposed by Dumas et al. [14] remains less precise and presents important limitations for the study of severe scolioses and the calculation of clinical measurements.

The method used by Pomero et al. [33], with the digitalization of 8 points per vertebra, requires 14 min. To provide accurate clinical measurements, the method has to be completed with fine adjustments of the vertebral shape, bringing the reconstruction time up to 20 min [18].

The method proposed in this study provides very quickly (2 min 30 s) a 3D reconstruction and clinical measurements which are sufficient for most of clinical applications. In case of complex pathologies or for research purposes, the "level 2" reconstruction allow to get quickly (10 min) a more accurate and precise 3D reconstruction.

To go further into the reduction of the reconstruction time, our researches aim to automate the reconstruction process "level 2" by adding to the parametric models based on inferences, image processing algorithms. The accuracy and the precision of the 3D reconstruction obtained from the "level 1" make this purpose easier.

5. Conclusion

This study proposed a 3D reconstruction method of the spine from biplanar X-rays relying on parametric models based on longitudinal and transversal inferences. A first reconstruction level was dedicated to routine clinical use with a fast (2 min 30 s), quite accurate and precise 3D reconstruction providing clinical measurements (mean shape accuracy: 1.3 mm). A more accurate "level 2" reconstruction (mean shape accuracy: 1.0 mm) can be obtained in a reduced reconstruction time (10 min) by including adjustments

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of the whole vertebral shape for complex pathologies or research purposes.

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Conflict of interest

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