Biomedical Signal Processing and Control 31 (2017) 181–188

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Quantification of spinal deformities using combined SCP and geometric 3D reconstruction

Sampath Kumar [a,*], K. Prabhakar Nayak [a], K.S. Hareesha [b]

[a] Department of Electronics and Communication, Manipal Institute of Technology, Manipal, India
[b] Department of Computer Applications, Manipal Institute of Technology, Manipal, India

ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 23 July 2016
Accepted 10 August 2016
Available online 13 August 2016

Keywords:
Stereo-radiography
3D reconstruction of spine
Generic spine model
Scoliosis

ABSTRACT

Three dimensional reconstruction is essential in accurate diagnosis of numerous spinal deformities which are 3D in nature. The stereo-radiographic reconstruction involving bi-planar X-rays is one of the most commonly used methods. Algorithms with stereo-corresponding point (SCP) or non-stereo-corresponding point (NSCP) can be used to achieve this 3D reconstruction. But, the NSCP method is slower and needs manual identification of many anatomical landmarks. Hence it suffers from observer variability and has restricted usage in normal clinical setup. Thus, a hybrid method is proposed in which the SCP reconstructed model is refined using the geometric features from the X-rays to achieve the accuracy closest to NSCP method. The SCP model is constructed using the X-rays on a calibration bench from the scoliotic subject. From these X-rays the vertebral features are extracted automatically. The SCP model structure is refined using the geometric transformations according to the extracted features. The 3D model thus formed is called combined SCP and geometric (CSCPG) reconstruction. By considering the NSCP model as a reference, both qualitative and quantitative approaches are followed to validate the proposed model. The CSCPG method has lesser observer variability as it needs only six anatomical landmarks per vertebra. Further, it is faster and the reconstruction error is within the acceptable limits. To quantify the deformities like axial vertebral rotation and spinal curvature novel methods have been proposed. The axial vertebral rotation is measured using simple vertebra vector parametric computations. It needs identification of only two landmarks per vertebra for angle measurement. The apical vertebra gives the plane of maximum curvature. The actual spinal curvature has to be computed on this plane. A semi-automatic method is proposed to compute this curvature using a new projection technique. The deformity quantification methods are validated using manual measurements as well as the results from standard approaches. Hence, a fast, simple and economic 3D diagnostic method is developed for quantification of the spinal deformities.

1. Introduction

Spine deformities are three dimensional in nature. Hence, their diagnosis using 2D imaging techniques is error prone. The 3D reconstruction provides the diagnostic information to the physicians and surgeons for clinical diagnosis, better visualization and planning of medical procedures. These 3D models are obtained using Magnetic Resonance Imaging (MRI), Computed Tomography (CT) and stereo-radiographic 3D reconstruction. The stereo-radiographic 3D reconstruction of the spine is established based on two orthogonal (posterior-anterior or anterior-posterior and lateral plane) X-rays. This allows the 3D rendering of the entire vertebral column in an upright position [1]. CT and MRI methods cannot be immensely relied on, as the images are acquired with the patient in a supine position which changes the actual deformation of the spine [2]. Also, the cost of these procedures is very high. Therefore, stereo-radiographic 3D reconstruction is commonly used for reconstruction of the human spine [3].

In earlier techniques, stereo-radiographic 3D reconstruction was based on triangulation of corresponding landmarks identified on both the X-rays, known as stereo-corresponding points (SCP) technique [4,5]. Here six corresponding points (top and bottom of vertebral endplates; and extremities of pedicles) were identified on orthogonal X-rays. Reconstruction was done after calibrating the radiological environment. A calibration bench was used for this purpose. Since the number of reconstructed points was less

* Corresponding author.
E-mail addresses: kumar.sampath@manipal.edu (S. Kumar), kp.nayak@manipal.edu (K.P. Nayak), hareesh.ks@manipal.edu (K.S. Hareesha).

http://dx.doi.org/10.1016/j.bspc.2016.08.004
1746-8094/

in this process, the resulting model was less accurate. Hence, more anatomical landmarks were identified on the X-rays for reconstruction. Since the availability of SCPs was limited, points present in only one of the X-rays, known as non stereo-corresponding points (NSCP), were used for 3D reconstruction. This method was known as NSCP method [6,7]. In this method, though the accuracy was improved due to increased number of points, it ignores easily available vertebral orientation and pedicle features in the X-rays. Also, it involves the digitization of numerous landmarks available on the X-rays which requires a lot of human intervention. Hence the method had restricted usage in clinical applications and more suitable for research purposes. The NSCP method also suffers from inter and intra-observer variability [8]. To reduce the observer variability several automated processes have been developed. Many image features were also incorporated to reduce the number of manually identified points.

Pomero et al. [9] used geometrical and statistical inferences from the spinal X-rays to develop an automated 3D reconstruction process. Humbert et al. [10] added longitudinal inferences to this approach. Dumas et al. [11] developed a semi-automated process in which vertebral contours of few vertebrae were interpolated and optimized for reconstruction. All these methods use a specialized and dedicated radiograph acquisition system which facilitates simultaneous acquisition of two orthogonal X-rays. However, neither the clinical indices nor the accuracy of vertebrae location was evaluated completely in these studies.

In current approaches, Zhang et al. [12] used the spine midline and vertebral body contour matching technique for 3D reconstruction. The epipolar geometry constraints limit this model to a projective reconstruction. Also, the vertebral deformations were not addressed. Zhang et al. enhanced their previous technique by applying pedicle projections to match the vertebral orientations [13]. But, the vertebral centers were manually identified which causes observer variability. Also, the study was restricted to in vitro experimentation. Recently, Moura et al. [14] developed a new uncalibrated method to reduce the obstructions formed by calibration objects on the X-rays. The average geometrical parameters acquired from a laser rangefinder were used for this purpose. It assumes that the radiological settings and the patient positions were stationary during radiograph acquisition, which is improper in a typical clinical environment. Further, the resulting model was not a morphorealistic model.

Therefore, a calibrated approach is proposed for 3D spine reconstruction. It creates least occlusions in the X-rays and yields morphorealistic model. Epipolar geometry is used to estimate the occluded landmark positions. In our previous work [15] we have developed a geometric reconstruction technique that uses SCPs and vertebral orientation data to deform a feature based generic spine model to obtain the personalized 3D reconstruction. In the proposed method, the generic model in geometric method is replaced with SCP reconstructed model to observe the improvement in reconstruction accuracy. This method is named as combined SCP and geometric (CSCPG) reconstruction. The technique proposed by Aubin et al. [4] is used to obtain the SCP model whereas NSCP model is reconstructed using the technique proposed by Mitton et al. [7]. The proposed reconstruction is validated with reference to the NSCP reconstruction.

Using CSCPG model, a novel spinal deformity quantification method is proposed. It includes axial vertebral rotation (AVR) and spinal curvature measurements. AVR is one of the most important features in the assessment of spinal deformity. Numerous methods have been developed to precisely measure AVR [16–18]. They were mainly based on determining the relative positions of the vertebrae, which is erroneous. Though, Perdriolle torsiometer [18] is the most conventional method, it cannot accurately quantify AVR. Also, it has limited reproducibility [19]. The recent technique proposed by Tamaís et al. [20], used in present EOS-systems [21], uses vertebra vectors. It is a new low dose radiographic device that performs 3D spine reconstructions using full body bi-planar X-rays in standing position. Though it is highly accurate, it requires precise knowledge of acetabulum positioning and a new coordinate system. Hence, it is hard to achieve in standard clinical setups. Therefore, a semi-automatic AVR measurement technique is proposed. It needs identification of only two landmarks/vertebra on the pedicles to compute AVR.

Among the numerous 2D methods [22–24] to compute the spinal curvature, Cobb method [22] is widely used due to its superior reproducibility. Since the real deformity is in 3D, the 2D evaluations give inaccurate results. Therefore, an automated method is proposed in which the spinal curvature on frontal view of the 3D spine model is computed first. Then it is projected onto the plane of maximum curvature to measure the actual spinal curvature. For validation, the spine model is manually rotated by an angle equal to maximum AVR and spinal curvature is computed. These results are validated using the method proposed by Tamaís et al. Therefore, a low cost, semi-automatic stereo-radiographic 3D reconstruction and deformity quantification procedure is proposed for the proper evaluation of spinal deformities in a normal clinical setup.

2. Materials and methods

2.1. SCP reconstruction

The stereo-corresponding points (SCP) reconstruction method requires orthogonal X-rays of the spine acquired in a calibration bench. A low cost, patient-friendly calibration bench is designed and the technique proposed by Dansereau et al. [25] is used for calibrating the radiological environment. The proposed calibration bench is shown in Fig. 1(a). Compared to the self-calibration methods the reconstruction error is lesser [26] and it produces least occlusions in the X-rays. If the landmarks are occluded, then they are identified by applying the epipolar constraints that exist between the acquired bi-planar X-rays. To calibrate the radiological environment, Direct linear transformation (DLT) [27] technique is used. It is preferred due to the low computational complexity and linearity. Also, it is independent of setup and is the radiographic technician skills. But the error computed by this process is an insignificant algebraic error. Therefore, retro-projection error is minimized using the iterative Levenberg-Marquardt optimization method [28].

Ten subjects suffering from idiopathic scoliosis with a Cobb angle ranging from 41° to 78° have come forward to this study. The subject's age group is between 9 and 15 years. Prior approval was taken from the local ethical committee. From these subjects, the X-rays are obtained on the calibration bench. Six SCPs per vertebra are identified on these X-rays using a semi-automatic method proposed in our previous work [29]. This procedure reduces observer variability in identifying these landmarks. The optimized calibration parameters are used to linearly triangulate these points and 3D positions of all the landmarks are computed [30]. The above procedure is repeated on all the vertebrae (T1 to L5) of the scoliotic spine to obtain the SCP reconstruction. Fig. 1(b) shows the result obtained from subject-1 X-rays.

The resulting SCP model fails to represent the complex anatomy of the human spine. Thus, to make it more realistic, a generic spine model has to be deformed in accordance with the SCP model. A cadaveric spine is used to develop a generic model from its CT-scan slices. A generic model of the spine is developed using the method described by De Guise [31] by applying the marching cube algorithm on 1 mm thick CT scan slices. Such models have shown an

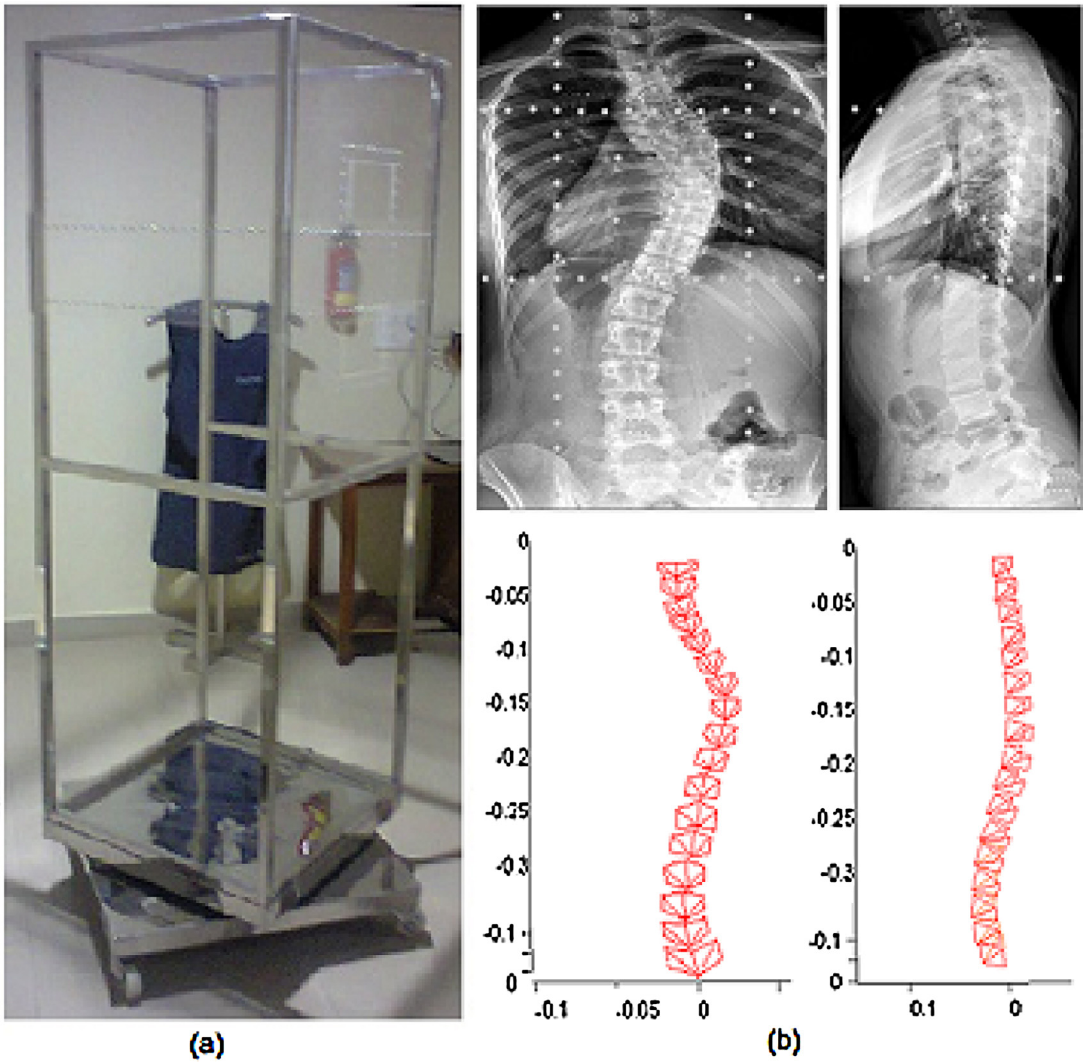

Fig. 1. (a) Calibration bench (b) Two views of X-rays and corresponding 3D spine model of subject-1.

accuracy of 1.1 ± 0.8 mm [4]. A free form deformation technique known as dual kriging [32] is applied to deform the generic model to obtain a personalized model. The entire process is explained in detail in our previous work [33]. Fig. 2 shows the personalized model of subject-1 spine using SCP reconstruction.

Since only six points are used to deform the generic model, it results in uneven vertebral deformation. To improve this model, the NSCP algorithm proposed by Mitton et al. [7] is applied to the X-rays by choosing 19 more points which are available in only one of the X-rays (NSCPs). They are the extreme points of the transverse processes, the posterior point of spinous process, the left and right extreme points of the median transverse section of the pedicles, the left, right, anterior and posterior extreme points of the end plates and of the median transverse section of the vertebral body. The brief review of this algorithm is stated below:

- First, the line joining the source and the projection of each NSCP in the radiograph is drawn
- Using the generic model, the NSCPs are initialized on these lines to form a deformable mesh
- Optimization (conjugate gradient) technique is used to find the 3D position of these points using the shape resemblance with the generic model

Using these algorithms, the SCP and NSCP models of all the ten subjects are developed. The NSCP reconstruction is considered as the reference model for validation. Though the accuracy of NSCP method is superior, the computational complexity is much higher. Because, 19 points/vertebra need to be identified and reconstructed. This adds lots of observer variability leading to ambiguities. Hence, combined SCP and geometric (CSCPG) method is proposed.

2.2. CSCPG reconstruction

In this method along with the points from SCP reconstruction, vertebral orientation features are used to deform the generic spine model to obtain the 3D model of the spine. Fig. 3 shows the flowchart of the entire process.

The entire procedure is divided into the following steps.

Step 1: The multiscale mathematical morphology [34] is used to enhance the X-rays and gradient vector flow active contour algorithm [35] is used to segment the vertebral contours. In the X-rays, the bright and dark features are unequally distributed. Thus, multiscale mathematical morphology is used to enhance the local contrast. The structuring element used is multiscale that extracts the bright and dark features from the X-rays. Gradient vector flow (GVF) snake algorithm is used for segmenting vertebral body con-

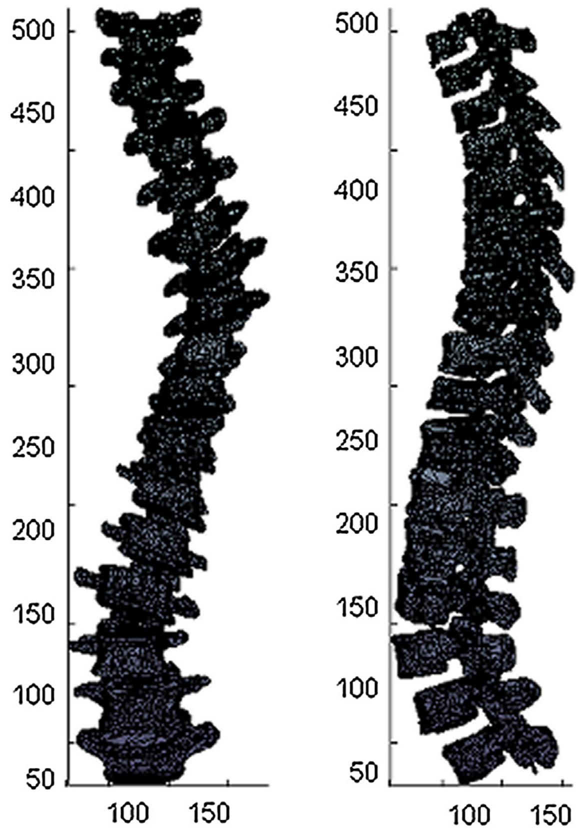

Fig. 2. SCP reconstruction of subject-1 spine.

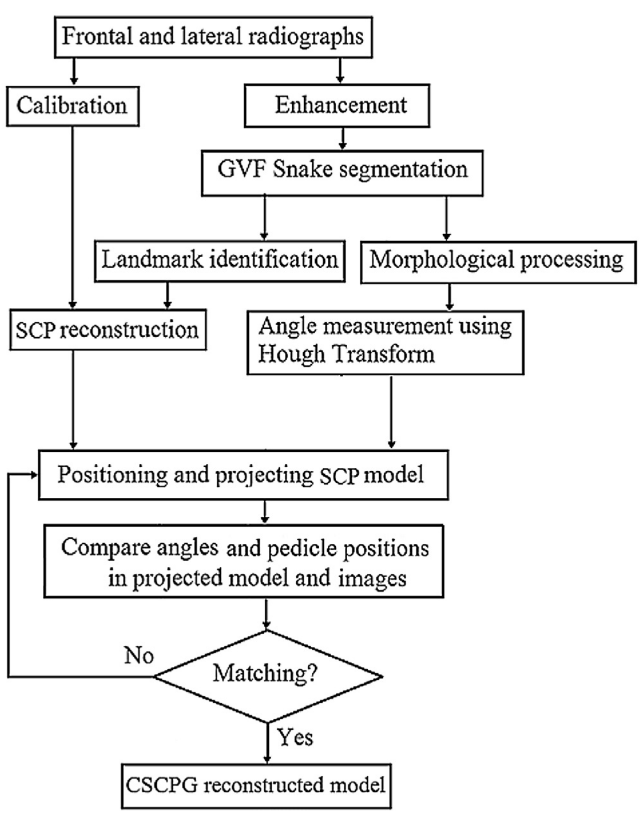

Fig. 3. Geometric 3D spine reconstruction procedure.

tours due to its accuracy and better convergence properties. Then morphological operators like dilation and erosion are applied to retain only the vertebral boundaries. Sobel edge detectors are then used to retain vertebral edges. In order to measure the vertebral orientations Hough transform [36] is used. Thus the angular features of T1 to L5 vertebrae are automatically extracted from both frontal and lateral X-rays.

Step 2: SCP reconstruction as explained in the previous section.

Step 3: SCP model is retro-projected on frontal and lateral planes and the orientation features from each vertebra are extracted using the Sobel operator.

Step 4: First, T1 vertebra is deformed using the geometric transformations. The rotations equal to the orientation of the vertebra in frontal and lateral X-rays (obtained in *step 1*) are applied to this vertebra.

Step 5: Using *step 3* the orientation feature of deformed vertebra is extracted. Perform *step 4* until these features matches with the features obtained from the X-rays (*step 1*). The histogram of the gradients is used to match the orientation features. The projection of pedicles are also used to refine the vertebral orientations.

This algorithm is applied to all the remaining vertebrae (T2 to L5) of the SCP model to obtain the combined SCP and geometric (CSCPG) reconstructed model. Fig. 4 shows the CSCPG reconstructed models of the subject-1 and subject-2 along with the X-rays.

2.3. Quantification of spinal deformity

First, the axial vertebral rotation (AVR) is computed by applying a new semi-automated procedure for the CSCPG model. The current approach to measure AVR needs the precise position of the acetabulum to define the x-axis of the coordinate system [20]. It is possible only in the present EOS system that can perform low dose full body scanning [21]. Due to the limited size of X-ray films, imaging the aceTable is not possible along with the complete spine in the standard clinical setup. Therefore, the proposed method uses the positioning system of the calibration bench for aligning the subject along the x-axis. As an example, Fig. 5 shows AVR measurement of L3 vertebra.

From the generic model of L3 vertebra (Fig. 5(a)), two points on the inner side of either pedicles are manually selected. The line joining pedicular points is taken as the x-axis. The midpoint of inter-pedicular line is point $A(x_1, y_1)$. A vertebra vector is drawn from this point tangential to the upper vertebral endplate. The point $B(x_1, y_2)$ of vector AB is found by the intersecting this line with the ventral surface of the vertebral body. The vector AB represents the y-axis. Similarly for the deformed L3 vertebra (Fig. 5(b)), the midpoint of inter-pedicular line $A(x_1, y_1)$, the terminal point $B'(x_2, y_2)$ and the vector AB' is are computed. The angle between these vectors is found using the tangent function given in equation (1) which is nothing but the AVR of L3 vertebra.

$$\theta = \tan^{-1}\frac{AB_x}{AB_y} \quad (1)$$

where,

θ = angle of axial vertebral rotation

$AB_x = B_{x2} - A_{x1}$

$AB_y = B_{y2} - A_{y1}$

Similarly, AVR of all the vertebrae are computed. The method is simple as it involves the identification of only two landmarks per vertebra. After quantifying the AVR, spinal curvature is evaluated using a new semi-automatic method. Fig. 6 shows the steps involved in this process.

Initially the CSCPG model is projected on frontal plane and subjected to thresholding to get a clear surface structured image of the vertebra. Later, the top and bottom end plates of the most tilted

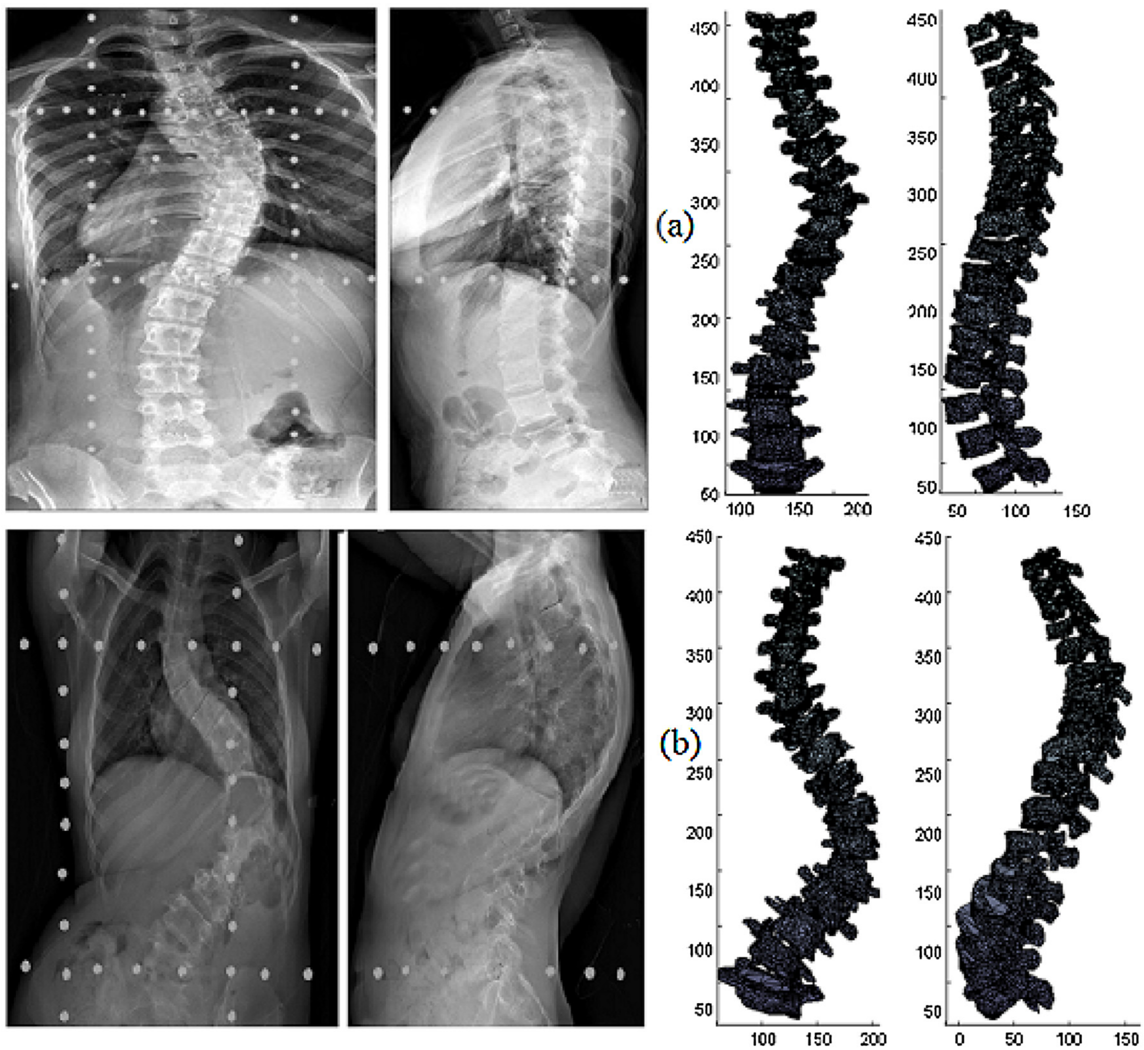

Fig. 4. Bi-planar X-rays and corresponding CSCPG reconstruction (a) subject-1 (b) subject-2.

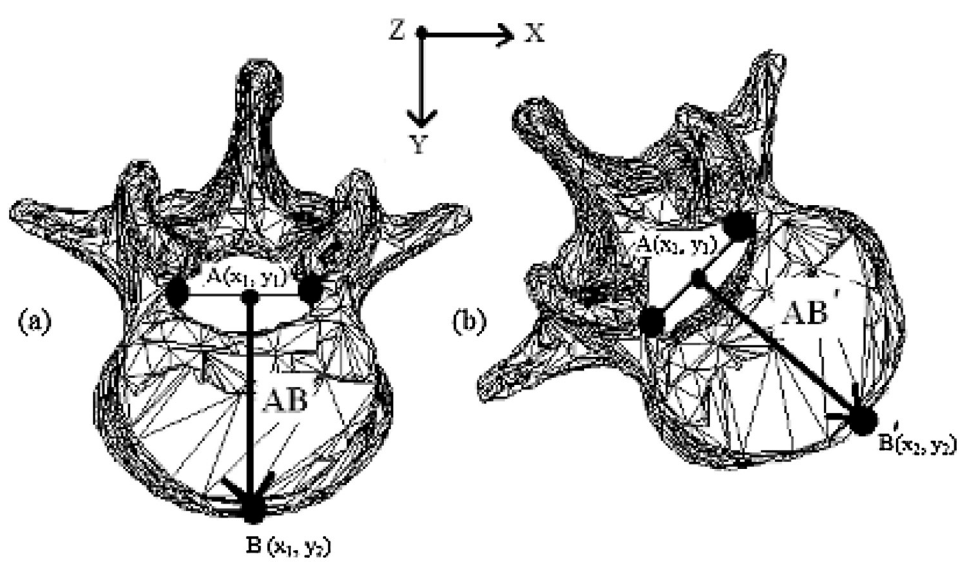

Fig. 5. AVR measurement of L3 vertebra (a) with 0^0 AVR (b) with 60^0 AVR.

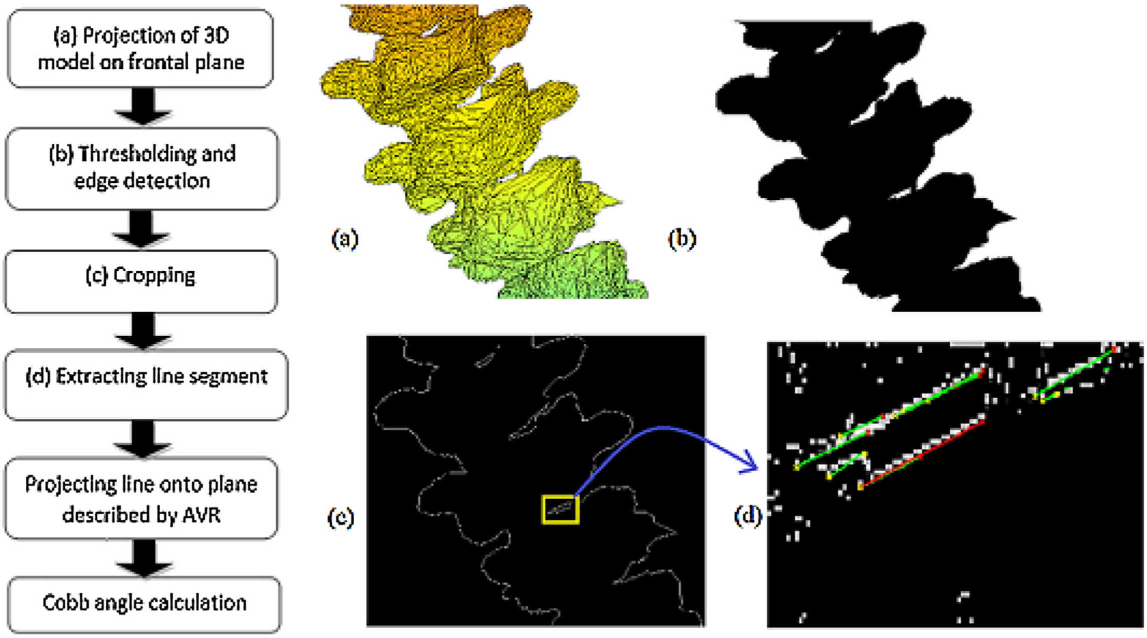

Fig. 6. Spinal curvature measurement algorithm.

inferior and superior vertebrae are cropped. Using the Hough transform the vertebral endplates edges are extracted. To compute the actual spinal curvature, it should be measured on plane of maximum curvature (PMC). Therefore, the frontal plane is rotated by an angle equal to maximum AVR around the z-axis using the rotation matrix given in Eq. (2).

$$R_z(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Projection matrix corresponding to the projection of a vertebra from the frontal plane to PMC can be obtained using the relationship

$$P = A(A^T A)^{-1} A^T \tag{3}$$

where A is the matrix with columns containing orthonormal basis of the PMC.

The projection matrix P can be used to project the edges of the vertebral endplates extracted in the previous step onto PMC to compute spinal curvature. The cosine function shown in Eq. (4) can be used to find the angle (ω_1) made by the projection of the upper endplate edge (y) with respect to x-axis (x).

$$\omega = \cos^{-1} \frac{(x.y)}{\|x\|\|y\|} \tag{4}$$

where $(x.y)$ is the dot product of vectors. In the same way angle (ω_2) made by the projection of the lower end plate edge with respect to x-axis can be calculated. The Cobb angle is given by the sum of ω_1 and ω_2 as shown in Fig. 7. This process can be repeated in the lateral plane to find the angle of Kyphosis and Lordosis.

3. Results

The CSCPG model is validated using both qualitative and quantitative approaches. In qualitative approach, the 3D model is retro-projected on the bi-planar X-rays. The results are shown in Fig. 8. A close similarity in shape is observed in both the subject cases.

For quantitative validation, the accuracy of the proposed method is compared with the existing methods. For accuracy study,

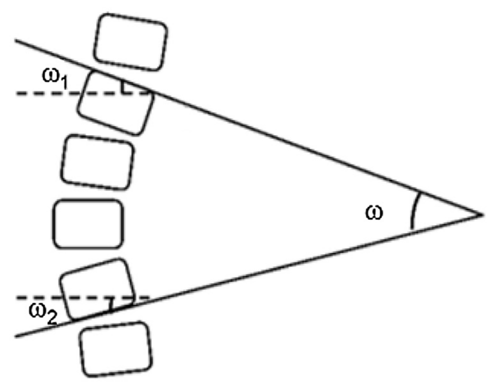

Fig. 7. Cobb angle calculation.

the RMS value of 3D reconstruction error is calculated using the point-to-point distance between the SCPs in the proposed model and the reference NSCP model. Also, the orientation error is also calculated for all the ten subjects. These results are summarized in Table 1.

The proposed method shows better accuracy compared to the recent approaches. Quantitative approaches are also followed for validation of deformity quantification methods. The method proposed by Tama's et al. [20] is used for validation of the proposed AVR measurement technique. For this purpose, line joining aceTable centers is used as the reference axis. Spinal curvatures are also validated using the measurements from manual rotation equal to AVR as well as using [20]. Table 2 summarizes these results. A close similarity between the results from different modalities show the relevance of the proposed method in the quantification of spinal deformities.

Table 1
Comparison of reconstruction accuracy.

Method	[11]	[12]	[13]	Proposed
Location (mm)	2.39	3.52	3.51	1.91
Orientation (°)	2.78	3.91	3.59	1.52

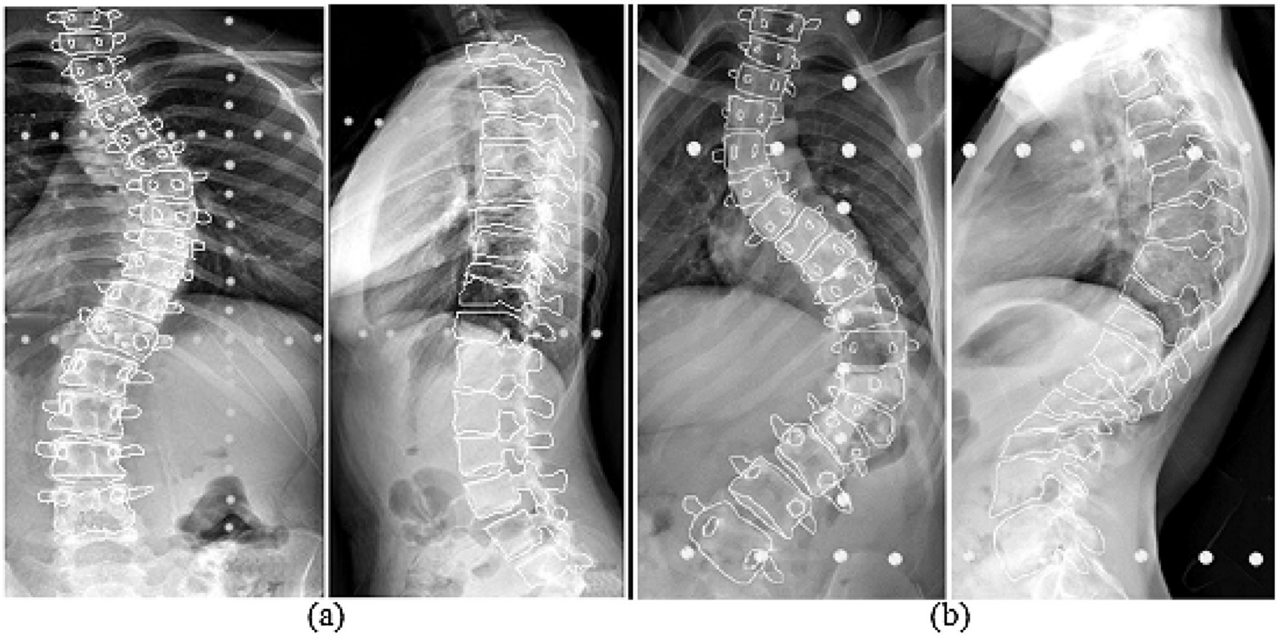

Fig. 8. Qualitative validation by retro-projecting CSCPG model on two views of the bi-planar X-rays (a) subject-1(b) subject-2.

Table 2
Comparison of deformity quantification results.

	Method	AVR (°)	Spinal Curvature (°)	Kyphosis (°)	Lordosis (°)
Subject-1	Proposed	8.5	43.0	35.5	35.0
	Manual	5–10	42.0	35.5	36.0
	[19]	9.0	42.5	35.0	35.5
Subject-2	Proposed	31	76.5	52.0	64.0
	Manual	15–30	76.0	50.5	63.0
	[19]	29.5	76.0	51.5	63.5

Table 3
The mean differences between the clinical indices of proposed method and the reference NSCP method and the p values of Wilcoxon signed rank test.

Clinical index	Mean differences	P
Spinal curvature (°)	0.62	0.71
Kyphosis (°)	0.51	0.68
Lordosis (°)	0.45	0.62
AVR (°)	1.51	0.36
Spine length (mm)	1.96	0.25
Frontal balance (°)	0.61	0.66
Sagittal balance (°)	1.82	0.31

For further validation, error between the clinical indices of the proposed model and the reference NSCP model are computed of all the ten subjects. The clinical indices like spinal curvature, kyphosis, lordosis and AVR are computed using the proposed method. The 3D length of the spine is calculated by fitting a B-spline curve to the vertebral centers. The frontal and sagittal balances are computed as described in [14]. The Wilcoxon test is performed to find if the differences between these indices are statistically significant ($p < 0.05$). These results are summarized in Table 3. The differences in clinical indices are not significant compared to the reference method.

4. Discussion

Current stereo-radiographic methods require manual identification of six or more SCPs and nineteen or more NSCPs for the 3D reconstruction of a human spine. The proposed CSCPG method needs only six SCPs and automatically extracts the required orientation features. Further NSCP landmarks on the vertebral body or on the transverse processes may be added. This can provide more detailed and refined 3D vertebral model. However, it is hard to detect the minor features such as the precise location of landmark points. It is also difficult to match them perfectly on the bi-planar X-rays. Hence, the repeatability of this process can not be assured [8]. Additionally, this procedure is error-prone, tedious and time-consuming. The quality of the 3D modelling is directly related to the accuracy of the 2D landmark identification. The errors due to manual identification of the anatomical landmarks on the 3D spine reconstruction are discussed in detail by Panjabi et al. [37]. Due to these limitations, the clinical deformity assessment during a subject's visit is often not possible with the NSCP method [6]. However, the proposed method needs only six stereo-corresponding points which are semi automatically extracted using image processing steps and epipolar geometry is applied in the case of occlusions. The orientation features are also automatically extracted. Therefore, the proposed method has lesser computational complexity and observer variability compared to the existing methods.

In terms of accuracy of 3D reconstruction, the large calibration bench is still considered as the gold-standard. The small calibration objects are economical and flexible, but are less precise. However, these calibration objects offer adequate precision for a number of clinical practices [11]. The use of calibration bench, either small or large, always have drawbacks, such as costs, overlapping anatomical landmarks and modifications in the operating protocol. Therefore, calibrating the radiological environment without using calibration bench would be a significant practice [12]. However, currently no method is able to perform accurate reconstruction without calibration objects. Thus a low cost, patient friendly, calibrated approach is proposed which causes minimum occlusions in the X-rays.

A novel semi-automated method for spinal deformity quantification is also proposed. The proposed AVR measuring algorithm does not require full body scan. Only two landmarks per vertebra need to be identified to quantity the AVR. Therefore, the process is faster and associated with the lesser observer variability. The proposed spinal curvature measuring algorithm is simple and consistent as the manual computations also give similar results.

The proposed method eliminates most of the manual computations present in the earlier methods. Also, it reduces the radiation exposure to the subject by eliminating the full body scanning. For quantitative evaluation, Wilcoxon signed rank test is conducted for the differences in clinical indices between the reference NSCP method and the proposed method. No significant difference is detected in any of these indices. The main limitation of the proposed method is the presence of inter and intra observer variability in 3D reconstruction and deformity quantification techniques. The major human interventions are minimized by introducing semi-automated procedures in these methods. If these methods are automated, the observer variability can be minimized. However, the proposed method shows much better accuracy with respect to both location and orientation compared to the existing methods. Thus, it can be used as a promising tool for quantification of spinal deformities.

5. Conclusion

A new 3D spine modelling and deformity quantification methods are proposed. CSCPG model is obtained by deforming the SCP model using the vertebral features. These features are automatically extracted from the X-rays using the several image processing steps. Hence the observer variability is reduced. The limited number of landmarks, low cost calibration bench and a simple generic model make the entire procedure very economical. Additional geometric features can be added to increase the reconstruction accuracy. A semi-automatic technique with minimum human intervention is proposed for evaluating spinal deformities. The axial vertebral rotation and spinal curvatures of the scoliotic subjects are evaluated using their CSCPG models. Both the techniques are successfully validated by comparing them with standard techniques. These techniques are simple, fast and significantly reduce the observer variability. Automating these processes can improve the accuracy. The proposed CSCPG reconstruction and quantification procedure can be implemented in any normal clinical setup for the diagnosis of spinal deformities.

Acknowledgment

The authors would like to acknowledge the Department of Science and Technology (DST), Government of India. This project is funded under a SERB-DST, Fast Track Scheme for Young Scientists (Grant No. SB/FTP/ETA-210/2012).

References

[1] C.M. Daniel, Jonathan Boisvert, G.B. Jorge, Hubert Labelle, Joao Manuel RST, Fast 3D reconstruction of the spine from biplanar X-rays using a deformable articulated model, Med. Eng. Physics. 33 (2011) 924–933.
[2] Jonathan Boisvert, Farida Cheriet, Xavier Pennec, Articulated spine models for 3D reconstruction from partial radiographic data, IEEE Trans. Biomed. Eng. 55 (2008) 11.
[3] L. Seoud, F. Cheriet, H. Labelle, J. Dansereau, A novel method for the 3D reconstruction of scoliotic ribs from frontal and lateral X-rays, IEEE Trans. Biomed. Eng. 58 (2011) 5.
[4] C.E. Aubin, J. Dansereau, et al., Morphometric evaluations of personalized 3D reconstructions and geometric models of the human spine, J. Med. Biol. Eng. Comput. 35 (1997) 611–618.
[5] B. Andre, J. Dansereau, H. Labelle, Optimized vertical stereo base radiographic setup for the clinical three dimensional reconstruction of the human spine, J. Bio. Mech. 27 (1994) 1023–1035.
[6] A. Mitulescu, W. Skalli, et al., Three-dimensional surface rendering reconstruction of scoliotic vertebrae using a non-stereo-corresponding points technique, Eur. Spine J. 11 (4) (2002) 344–352.
[7] D. Mitton, C. Landry, S. Verson, W. Skalli, J. de Guise, 3D reconstruction method from biplanar radiography using non-stereo corresponding points and elastic deformable meshes, J. Med. Biol. Eng. Comput. 38 (2000) 133–139.
[8] Samuel Kadoury, Farida Cheriet, Hubert Labelle, Personalized X-ray 3-D reconstruction of the scoliotic spine from hybrid statistical and image-based models, IEEE Trans. Med. imaging 28 (9) (2009) 1422–1434.
[9] V. Pomero, D. Mitton, S. Laporte, J. de Guise, W. Skalli, Fast accurate stereo-radiographic 3D reconstruction of the spine using a combined geometric and statistic model, J. Clin. Bio. Mech. 19 (2004) 240–247.
[10] L. Humbert, J. de Guise, B. Aubert, B. Godbout, W. Skalli, 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences, J. Med. Eng. Physics. 31 (2009) 681–687.
[11] R. Dumas, B. Blanchard, R. Carlier, et al., A semi-automated method using interpolation and optimization for the 3D reconstruction of the spine from bi-planar radiography, J. Med. Biol. Eng. Comput. 46 (2008) 85–92.
[12] Junhua Zhang, Liang Lv, et al., 3D reconstruction of the spine from biplanar X-rays based on contour matching using the Hough transform, IEEE Trans. Biomed. Eng. 60 (2013) 7.
[13] Junhua Zhang, Xinling Shi, et al., A simple approach for 3D reconstruction of the spine from biplanar radiography, Proceedings of Sixth International Conference on Digital Image Processing (ICDIP 2014), SPIE Proceedings (2014) 9159.
[14] D.C. Moura, J.G. Barbosa, Real-scale 3D models of the scoliotic spine from biplanar radiography without calibration objects, Computerized Med. Imaging Graphics 38 (7) (2014) 580–585.
[15] Sampath Kumar, Nayak K. Prabhakar, K.S. Hareesha, 3D reconstruction of spine from partial biplanar radiographic image data, in: 2nd International Conference on Biomedical Engineering, Malaysia, 2015, pp. 1–5, http://dx.doi.org/10.1109/ICoBE.2015.7235127.
[16] C. Nash, J. Moe, A study of vertebral rotation, J. Bone Joint Surg. 51A (1969) 223.
[17] M.H. Mehta, Radiographic estimation of vertebral rotation in scoliosis, J. Bone Joint Surg. Br. 55B (1973) 513–520.
[18] R. Perdriolle, J. Vidal, Morphology of scoliosis: three dimensional evolution, Orthopaedics 10 (1987) 909–915.
[19] B.S. Richards, Measurement error in assessment of vertebral rotation using the Perdriolle torsiometer, Spine 17 (1992) 513–517.
[20] Illés Tamas, M. Tunyogi-Csapó, S. Somoskeöy, Breakthrough in three-dimensional scoliosis diagnosis: significance of horizontal plane view and vertebra vectors, Eur. Spine J. 20 (1) (2011) 135–143.
[21] J. Dubousset, G. Charpak, I. Dorion, et al., A new 2D and 3D imaging approach to musculoskeletal physiology and pathology with low-dose radiation and the standing position: the EOS system, Bull. Acad. Natl. Med. 189 (2005) 287–297.
[22] J.R. Cobb, Outline for the study of scoliosis, Instructional Course Lect. 5 (1948) 261–275.
[23] K.M. Diab, J.A. Sevastik, R. Hedlund, I.A. Suliman, Accuracy and applicability of measurement of the scoliotic angle at the frontal plane by Cobb method, by Ferguson method and by a new method, Eur. Spine J. 4 (5) (1995) 291–295.
[24] C. Yi-Lang, C. Wen-Jer, C. Wen-Ko, An alternative method for measuring scoliosis curvature, Orthopedics 30 (2007) 10.
[25] J. Dansereau, J.A. Beauchamp De Guise, H. Labelle, Three-dimensional reconstruction of the spine and rib cage from stereoradiographic and imaging techniques, in: 16th Conference of the Canadian Society of Mech Eng, Toronto, 1990, pp. 61–64.
[26] S. Delorme, Petit Y. De Guise, et al., Assessment of the 3D reconstruction and high-resolution geometrical modeling of the human skeletal trunk from 2-D radiographic images, IEEE Trans. Biomed. Eng. 50 (2003) 8.
[27] Aziz Abdel, Karara, Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry, in: Proceedings of the Symposium on Close-Range Photogrammetry, American Society of Photogrammetry, Falls Church, VA, 1971, pp. 1–18.
[28] D.M. Bates, D.G. Watts, Nonlinear Regression and Its Applications, Wiley, New York, 1988.
[29] Sampath Kumar, Nayak K. Prabhakar, K.S. Hareesh, Semiautomatic method for segmenting pedicles in vertebral X-rays, Elsevier, in: proceedings of ICCCS'12, Procedia Technology, 6, 2012, pp. 39–48, http://dx.doi.org/10.1016/j.protcy.2012.10.006.
[30] Kumar Sampath, Nayak K. Prabhakar, K.S. Hareesha, Improving visibility of stereo-radiographic spine reconstruction with geometric inferences, J. Digital Imaging 29 (2016) 226–234, http://dx.doi.org/10.1007/s10278-015-9841-1.
[31] J.A. De Guise, Y. Martel, 3D-biomedical modeling: merging image processing and computer aided design, in: Proc. Annual Int. Conf. IEEE Engineering Medicine Biology Society, New Orleans, LA, 1988, pp. 426–427.
[32] F. Trochu, A contouring program based on dual kriging interpolation, Eng. Computations 9 (1993) 160–177.
[33] Sampath Kumar, K. Prabhakar Nayak, K.S. Hareesha, 3D Biomedical modelling of human vertebrae and its deformation, in: Advances in Information Technology and Power Electronics, McGraw-Hill publishing, 2014, 2016, pp. 325–336.
[34] S. Mukhopadhyay, B. Chanda, An edge preserving noise smoothing technique using multiscale morphology, J. Signal Processing 82 (2002) 527–544.
[35] M. Kass, A. Witkin, D. Terzopoulos, Snakes: active contour models, Int. J. Comput. Vision 1 (1998) 321–331.
[36] Hough, Method and means for recognizing complex patterns, Patent 3069654, USA, 1962.
[37] M. Panjabi, D. Chang, J. Dvorak, An analysis of errors in kinematic parameters associated with in vivo functional X-rays, Spine 17 (1992) 200–205.