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Towards the Development of Low Cost Calibration Apparatus for 3D Reconstruction of Spine

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Abstract
Three-dimensional reconstruction of the human spine is very much essential in diagnosis, planning of surgery and treatment of several spinal deformities. This can be achieved using stereo-radiographic methods. Calibration of a stereo-radiographic setup is a necessary step in this process. It provides metric information from 2D images. Many calibration methods that are available in literature result in cumbersome calibration objects. Hence difficult to use in the clinical valuation of spinal deformities. 3-D reconstruction without calibration or with small calibration objects is considered to be unreliable. It also results in large reconstruction errors. A review of different calibration techniques is performed and compared. The best suitable technique is proposed which gives least reconstruction error and produces minimum undesirable objects in radiographs.

Keywords: *Stereo-radiography, calibration, self-calibration, 3-D spine reconstruction, scoliosis*

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INTRODUCTION

Three dimensional reconstruction of the human spine is used in numerous scientific evaluations of pathologies. For example, assessment of the spine recovery after applying braces [1], evaluation of effect of surgery [2], and the evolution of deformities like scoliosis [3].

They are also essential in clinical and biomechanics research for obtaining postural and morphometric information [4]. Advanced imaging modalities such as; CT and MRI have limitation for 3-D modelling of the spine. They are obtained with the patient in sleeping position which alters the real anatomy.

The presence of surgical implants, heavy radiation dose and high cost make them inappropriate for spinal diagnosis. Hence stereo-radiographic three dimensional reconstruction of the human spine from an antero-posterioir (AP) and lateral (LAT) x-rays is the most frequently used approach. Presently, 3-D modelling of the pelvis [5], spine [6], distal and proximal femur [7, 8] is possible. It requires minimal radiation as it requires only two x-rays. All these approaches need to know the geometry of the clinical setup to compute 3-D data from the biplanar x-rays.

This is achieved using calibration techniques. They use explicit apparatus and standard radiographic setup which in turn increases the cost [9]. Several methods were proposed to use minor calibration articles [10–12]. Some of them tried to eliminate the calibration objects which resulted in less accurate models [13–15].

These methods can be broadly classified as direct linear transformation (DLT) method, explicit calibration method and self-calibration method and are discussed later in the paper in separate sections. Section below gives the analytical description of the calibration and last section discusses the results obtained from these methods and presents the conclusion of this work.

RADIOGRAPHIC CALIBRATION

In case of biplanar radiographic setup, the parameters that represent the properties of the system are formulated using a set of linear equations. The projection of a 3-D point on each of the x-rays can be formulated as:

$$\begin{bmatrix} w_i.u_i \\ w_i.v_i \\ w_i \end{bmatrix} = N_i . \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \text{ for i = 1 and 2} \qquad (1)$$

In above formulation, for every data acquisition i, N represents the calibration matrix. It defines the projection of the 3-D point into image. A scaling of w is also used. X-ray detectors of flat type can be modelled as matrix N given by:

$$\begin{bmatrix} f_i/s & 0 & u_{pi} & 0 \\ 0 & f_i/s & v_{pi} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} R_i & t_i \\ 0_3^T & 1 \end{bmatrix} = M_i, \text{ for i=1,2} \qquad (2)$$

Here focal length f is the distance between the radiographic source and its detector, sampling pitch is represented by s, (u_p, v_p) represents the principal point.

The geometrical transformations R and t are represented by a 4 x 4 matrix. It is mainly used for coordinate mapping of the x-ray source and patient's coordinates. More precisely, 0_3^T represents $(0, 0, 0)^T$, t represents the translation vector. It can be decomposed in to matrix $(t_x, t_y, t_z)^T$. R represents a 3x3 rotation matrix. The Rodrigues' formula [15] can be used to solve this form of matrix which gives a 3-D vector $\omega = (\omega_x, \omega_y, \omega_z)^T$. It represents the rotation around an axis having direction ω along with the magnitude of the vector.

When calibration objects are used, the calibration process computes the unknown calibration parameters ζ:

$$\zeta = (f_i, u_{pi}, v_{pi}, t_{xi}, t_{yi}, t_{zi}, \omega_{xi}, \omega_{yi}, \omega_{zi}) \text{ for i =1 and 2} \qquad (3)$$

If calibration articles are not used, this is achieved by minimising the re-projection error of a set of corresponding points identified in two x-rays. Thus, the problem can be expressed as a minimisation using the least squares technique.

$$\min_{\zeta_1^*, \zeta_2^*} (\sum_{i=1}^{2} \sum_{j=1}^{n} ||p_{ij} - prj[\zeta_i, tri(\zeta_1, \zeta_2, p_{1j}, p_{2j})]||^2 \qquad (4)$$

Here, n represents corresponding points, p_{ij} is the j^{th} point identified in the image I. Terms ζ_1^*, ζ_2^* represent the optimised factors for image 1 and 2. Term *prj* represents the 2-D projection of a 3-D point as described in Eqs. (1) and (2). Term *Tri* represents a triangulation process that computes the 3-D coordinates for a corresponding point.

Process of calibration is achieved using a nonlinear least squares minimisation technique. The procedure requires an initialization for the calibration factors. These factors are updated iteratively to reduce Euclidean distances among the given and re-projected points.

DLT METHOD

Three dimensional reconstruction of the spine with biplanar X-rays needs a calibration structure that is closed and includes the complete subject. Allowing for these requirements of a radiographic environment, stereo-radiographic setup is subjected to movement when unused. Additionally, due to personal movement, it may be used by several operators. Hence, the 3-D modelling procedure should be independent of the skills of X-ray technicians and should not rely on a fixed setup. Due to these limitations, Direct Linear Transformation, popularly known as DLT, was selected as 3-D reconstruction procedure [9]. Important motives for this selection were as follows. The exact configuration of the radiographic setup was not needed. The algorithm computes indirectly all required parameters using a calibration method. Also, the procedure is well documented and widely used. The radiographic system consists of a radiation source and a film. Though the placement of source, object and film differ from that of the pinhole camera, the mathematical model remains the same. DLT procedure requires the locations of points with known coordinates situated on a calibration article. Calibration article (Figure 1) contains of 55 steel pointers of fixed diameter fixed in two parallel plates made up of acrylic. 3-D coordinates of every pointer were calculated with the finest accuracy by means of a coordinate measuring machine. The patient will be asked to stand on the adjustable marked floor and two radiographs (PA and LAT) were acquired. The pointers were identified and paired on the x-ray views. The DLT method calculates the features of projection matrices N_i by solving the system of linear equations obtained by Eq. (2) and the measured 3-D and 2-D coordinates of the steel beads. Once matrix N_i are computed, 3-D coordinate of any unknown point can be obtained by triangulation. For spine reconstruction, six anatomical landmarks per vertebra were considered. They were the tips of both particles and centres of superior and inferior endplates. These vertebral landmarks were identified and matched on each radiograph and 3-D reconstructed using DLT method. Using the reconstructed 3-D pointers as control points, the 3-D Dual Kriging method [16] is used for modelling. They are used to deform the structural models of vertebrae. This results in a personalized 3-D vertebral model that can be used to build the complete spine.

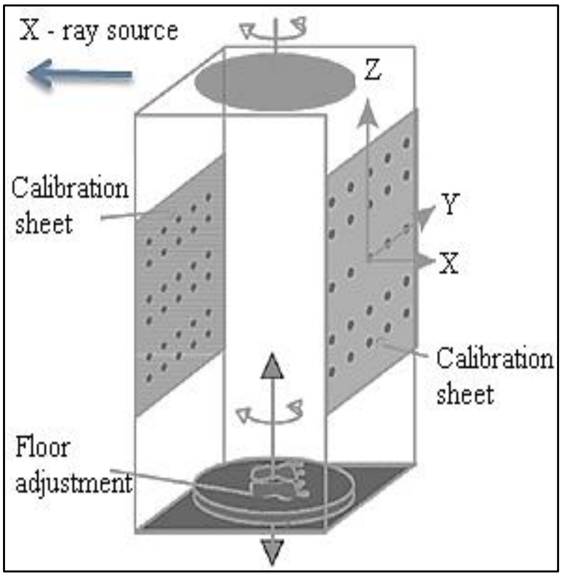

Fig. 1: *Calibration Object Incorporated to the Positioning Apparatus [17].*

It is difficult to exactly detect the corresponding pointers on both AP and leteral views as the bony landmarks are not clear on x-rays. The landmarks reconstructed from the erroneous points will result in the biased morphological modelling of spine. The research of Andre et al. [18] revealed that in the case of axis parallel to the stereo base, reconstruction error is about two and a half times the identification error. The DLT method also has significant extrapolation errors [19]. Thus, a huge calibration article was built to contain all the essential structures to be reconstructed properly. The application of the calibration article in a practice leads to numerous restrictions. The subject is forced to position in between acrylic sheets of the calibration system. It frequently generates inconvenience and fear. The object must be adjusted for objects of dissimilar heights. The design cost is also high. Further, the measurement of 3-D coordinates with high accuracy is not possible. The accuracy of DLT calibration and reconstruction was reported to be 2.6$\pm$2.4 mm [18].

EXPLICIT CALIBRATION METHOD

To overcome the limitation of the implicit DLT method, several explicit calibration methods were proposed. Methods developed by Dumas et al. [20], Moura et al. [21] and Cheriet et al. [22] are discussed in this section. A method developed by Dumas et al. [20] uses simplified geometric modelling of the radiographic setting. The knowledge about the radiographic setup produces four calibration equations that relate the horizontal and vertical planes of the two visions. This leads to a specific device and calibration method (Figure 2). Additionally, the system is attached to the stereo-radiographic system that consists of a turntable. This enables the clinical use of this system. It consists of control points with known coordinates. One of these control points was marked specifically and set at the origin. These control points were spread along all the three axes. It uses lines of 2 x m; 2 x n and p steel beads. They are fixed in bars which easily allow x-rays. Three parallel lines were composed of m = 8 markers. They are evenly dispersed along X-axis every 20 mm apart. Along Y-axis p = 11 markers are evenly dispersed every 25 mm and two perpendicular lines containing n = 32 markers evenly dispersed every 50 mm. These points were scattered in order to incorporate the complete system. Some of these control points were made visible depending on its sizes and location.

During this procedure, the rotation of the calibration device and the rotation of the one view to the other were equal. These are considered as known factors and intrinsic to the stereo-radiographic technique. The resulting system is an open structure and patient friendly in nature. The whole system was calibrated with the help of these control landmarks. They do not come into the view of the structure that are radiographed. The mean precision of the stereo-radiographic reconstruction was reported to be 1.2 mm.

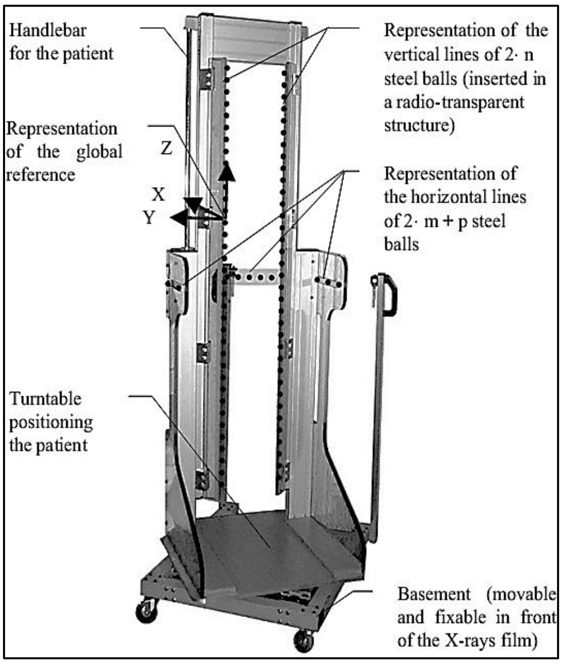

Fig. 2: *Stereo-radiographic Device [20].*

A method developed by Moura et al. [21] targets in reducing the influence of calibration articles on the content of x-rays and remains inexpensive. For accomplishing this goal an inexpensive rangefinder was used. It allows to guess some of the geometrical features. For correcting the scale a small calibration article was also required as shown in Figure 3.

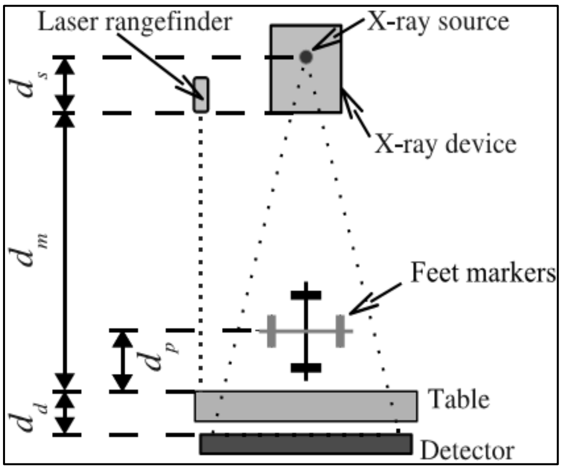

Fig. 3: *Stereo-radiographic Setup [21].*

Laser rangefinder was used to compute focal length. It also gives an initial prediction of the distance between the X-ray source and object and. Figure 3 demonstrates the attachment of devices to the X-ray device.

The device was only able to measure the distance between the table (d_m) and the X-ray device. To compute the focal length, two more factors have to be identified. One of the parameters is, the distance from the X-ray device to the plane where the X-rays are generated.

The other one is, the distance from the X-ray detector to the table. Since these factors were static for an X-ray system they are hard to measure. Therefore, they were measured using a radiopaque plane by giving dimensions.

This step is required only once for an X-ray system. A small calibration object was necessary for correcting the scale. Since only two markers were required, this calibration article shows lesser impact on resulting X-rays. The 3-D reconstruction obtained with this setup has an accuracy comparable with that of previous method [20].

Explicit methods discussed so far [20, 21] does not handle the error due to unintentional movement of the patient in the calibration article during the delay between the radiograph acquisitions (PA and LAT). A method using jacket with calibration articles and categorical calibration procedure was suggested by Cheriet et al. [22] to compensate this error. This method had twofold benefits. A new jacket containing calibration article was proposed that the patient must wear during radiography (Figure 4).

This object experiences the same translation between x-ray radiation as the patient. Thus the translation is compensated by this calibration technique. Also, a novel categorical calibration procedure was projected that reduces the errors due to extrapolation.

Two anterio-posterior (AP-0^0 and angled AP-20^0) and one lateral (LAT) radiographs were taken with the arrangement displayed in Figure 4. It shows the 3-D modelling of the human spine and ribs.

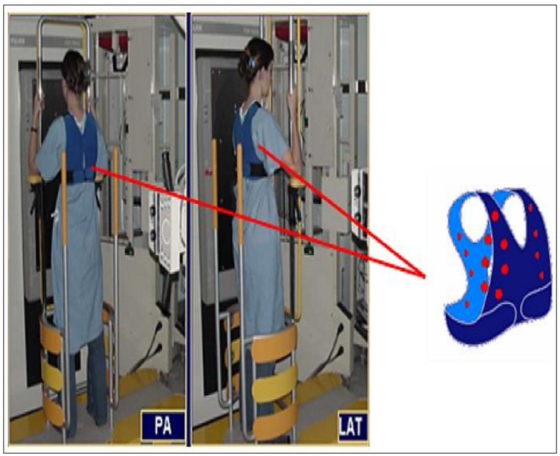

Fig. 4: *Radiographic Arrangement with Calibration Apparatus [22].*

It consists of a programmed revolving table that brings the subject to be radiographed from lateral location to AP location. The calibration article is a jacket with sixteen embedded markers. The patient must wear this jacket during radiography. The system comprises of a peripheral calibration article. It is prepared using six coplanar pellets which are opaque to radiography. Their 3-D coordinates are computed. These pellets describe the universal reference plane for reconstruction in three dimensions. Geometric parameters of the radiological environment were obtained using a nonlinear minimization procedure. A set of stereo-corresponding points are identified on two views of the radiograph. The root mean square distance among the analytical and observed projections of these corresponding points are used for optimization. The clinical indices obtained with this technique were comparable to the standard techniques.

SELF CALIBRATION METHOD

The implicit/explicit calibration methods explained so far need a large calibration article. This makes the reconstruction procedure susceptible to motion of the subject in between two radiographic acquisitions. It causes variations among the patient's geometries and calibration setup. Further, it is clumsy in a normal clinical environment. Also, the linear algorithms used for optimization of geometric parameters exhibit high sensitivity to noise. The data described by the epipolar constraint can vary to a large extent of even a slight pixel level change. This constraint is very important in defining a 3-D model using linear systems [23]. To overcome these limitations self-calibration methods were proposed. Kadoury et al. developed a robust and versatile device for the analysis of spine in three dimension [10]. It can be placed in a health care clinic using normal Uncalibrated X-rays. It has a weak-perspective method and self-calibration procedure for 3-D reconstruction. Using this 3-D position of landmarks is computed that are identified on biplanar X-rays. Moreover, a planar article of known size was used to obtain a model which is precisely scaled. The procedure uses corresponding landmarks recognized on a pair of radiographs. It also uses estimated geometric constraints to calibrate the radiographs. The 3-D location of corresponding landmarks is changed repeatedly till the system meets a steady state. Due to the elimination of calibration article the patient was free to have any gesture of his freedom. Moreover, the technique does not need accurate 3-D measurements of the calibration article. Also, the method allows to assess 3-D deformities of subjects restricted to a wheelchair. Though the calibration object was eliminated, they still need a skilled person to manually recognize and match the anatomical landmarks on the biplanar radiographs. They are also needed for calibration and 3-D reconstruction of spine model. Presently, this task is implemented manually through a skilled person. It involves finding the location of landmarks on end plates of the vertebrae and on pedicles. Vertebrae from first thoracic region to last lumbar region on biplanar X-rays are used. The identification involves locating exact points with precision and matching them perfectly within biplanar radiographs. Therefore, repeatability of this technique is difficult to achieve. Additionally, the process is tedious, error-prone and time-consuming.

The excellence of the 3-D modelling is exactly related to this precision in localization of 2-D landmarks. Panjabi et al. [24] discussed these errors due manual identification of landmarks on the radiographs. In this method, the control points and detectable straight bars (Figure 5) were used to recover the 3-D model in the universal system of coordinates. Hence, it was termed as quasi self-calibration method. This method was unreliable and reconstruction error was also very large.

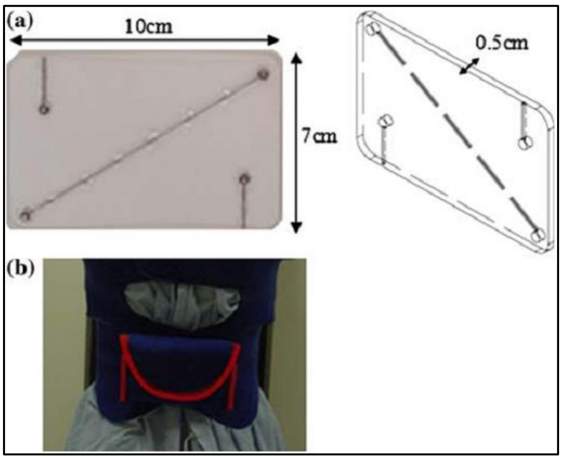

Fig. 5: *(a) Portable Calibration Object (b) Placement of the Calibration Object [10].*

Due to the drawbacks of quasi self-calibration, clinical 3-D diagnosis of the deformity in real time was not possible. Additionally, the present self-calibration methods depend on corresponding points between the biplanar x-rays. Since they offer low redundant sparse data [25], it produces multiple minima while optimizing the nonlinear equations. The corresponding points to trust on the following hypothesis. A common point on any surface looks alike in the biplanar radiographs in which it is visible. Though, this phenomenon shown by the radiographic system, these corresponding points are not essentially a consistent equivalent for a 3-D modelling. Hence, it reduces the freedom in degrees of in a linear equation system [26–28]. Additionally, the self-calibration method is a compound scientific problem. In order to improve the current self-calibration methods that uses iterative algorithms, it is essential to include extra data and mathematical constraints.

Added constraints reduce the degrees of freedom without additional data input. Additional geometrical primitives like ellipses, lines, curves, can considerably improve the amount of data supplied to the system. Geometric factors, for example the translation and rotation of the system, may be found depending on shape data obtained through the projection of radiographic views. Kadoury et al. [15] proposed a complete self-calibration technique which uses high level data. This data are automatically taken out from biplanar radiographs to resolve the intrinsic and extrinsic factors. A segmentation technique was proposed which considers the varying appearance and scoliotic spine geometry. From this, it isolates and extracts the silhouettes of the spinal elements. Using a priori structural data obtained from Bayesian formulation, multiscale segmentation of the spine was proposed for patients with scoliosis. A nonlinear optimization procedure was applied to improve the geometrical factors of the 3-D sight. The limitation of this method is that it requires a huge database of spine radiographs for statistics based segmentation and obtaining shape information. 3-D reconstruction accuracy of this method wascomparableto those obtained with the standard techniques.

DISCUSSION

The self-calibration method discussed in [15] is ideally suited for 3-D modelling of the human spine for clinical evaluation of spinal deformities. It is free from a dedicated calibration object and radiographic setup. Also, it is useful when a patient is using a wheelchair or lying down during surgical procedures.

The only limitation of this method is, it requires a huge database of spine radiographs for the computation of calibration parameters. When such database is not available, one has to make a choice between available explicit calibration methods. Though explicit techniques are computationally expensive, they are more robust and give precise results with badly conditioned data. Since methods discussed in [20] and [21] does not handle the error due to unintentional motion during the X-ray exposures, the method discussed in [22] can be a better choice. This method needs a calibration article to make the initial guess of the calibration parameters which can produce undesirable objects in the X-rays. Automatic segmentation procedure, landmark identification and feature matching techniques are still unsolved problems. Hence manual methods are used which are error prone and time consuming. Current methods also require a stereo-radiographic setup which consists of positioning apparatus and a rotating platform for the biplanar X-ray acquisition.

CONCLUSION

There is a need for stere-radiographic setup which has following capabilities. It should produce minimum undesirable objects in the X-rays so that landmark identification becomes more accurate. This will in turn increase the accuracy of the 3-D reconstruction. This can be achieved by removing the calibration object and using laser range finders for initial guess of calibration parameters. There is also a need for automatic landmark identification procedure to increase the accuracy of the 3-D reconstruction. Furthermore, the stereo-radiographic setup can be simplified using footmarkers instead of rotating platform and replacing acrylic sheets with detectable straight bars.

This method can be used to assess 3-D deformities of subjects restricted to a wheelchair. This method can give least reconstruction error and will produce minimum undesirable objects in radiographs.

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REFERENCE

1. H. Labelle, J. Dansereau, C. Bellefleur, *et al.* Three-dimensional Effect of the Boston Brace on the Thoracic Spine and Rib Cage, *Spine* Jan. 1996; 21: 59–64p.
2. Sawatzky B.J., Tredwell S.J., Jang S.B., *et al.* Effects of Three-dimensional Assessment on Surgical Correction and Hook Strategies in Multi-hook Instrumentation for Adolescent Idiopathic Scoliosis, *Spine* 1998; 23(2): 201–205p.
3. I. Villemure, C. E. Aubin, G. Grimard, *et al.* Progression of Vertebral and Spinal Three-dimensional Deformities in Adolescent Idiopathic Scoliosis: A Longitudinal Study, *Spine* Oct. 2001; 26: 2244–2250p.
4. Skalli W., Robin S., Lavaste F., *et al.* A biomechanical Analysis of Short Segment Spinal Fixation using a Three-dimensional Geometric and Mechanical Model, *Spine* 1993; 18(5): 536–545p.
5. Pomero V, Mitton D, Laporte S, *et al.* Fast Accurate Stereoradiographic 3D-reconstruction of the Spine using a Combined Geometric and Statistic Model, *Clin Biomech* 2004; 19: 240–247p.
6. Mitton D, Deschˆenes S, Laporte S, *et al.* 3D Reconstruction of the Pelvis from Bi-planar Radiography, *Comput Meth Biomech Biomed Eng* 2006; 9: 1–5p.
7. Laporte S, Skalli W, de Guise J, *et al.* A Biplanar Reconstruction Method based on 2D and 3D Contours: Application to the Distal Femur, *Comput Meth Biomech Biomed Eng* 2003; 6: 1–6p.
8. Baudoin A, Skalli W, Mitton D, Parametric Subject-specific Model for *in vivo* 3D Reconstruction using Bi-planar X-rays: Application to the Upper Femoral Extremity, *Comput Assist Radiol Surg* 2007; 2: S112–S114.
9. Andre B., Dansereau J., Labelle H., Optimized Vertical Stereo base Radiographic Setup for the Clinical Three-dimensional Reconstruction of the Human Spine, *J Biomech* 1994; 27: 1023–1035p.
10. Kadoury, Cheriet, Laporte, *et al.* A Versatile 3D Reconstruction System of the Spine and Pelvis for Clinical Assessment of Spinal Deformities, *Med Biol Eng Comput* 2007; 45: 591–602p.
11. F Cheriet, J Meunier, Self-calibration of a Biplane X-ray Imaging System for an Optimal Three Dimensional Reconstruction, *Comput Med Imag Grap* 1999; 23(3): 133–141p.
12. Cheriet, Delorme, Dansereau, *et al.* Intraoperative 3D Reconstruction of the Scoliotic Spine from Radiographs, *Annales de Chirurgie* 1999; 53: 808–815p.
13. Cheriet, Dansereau, Petit, *et al.* Towards the Self-calibration of a Multiview Radiographic Imaging System for the 3D Reconstruction of the Human Spine and Rib Cage, *Int J Patt Recogn Artifi Intell* 1999; 13: 761–779p.
14. Kadoury, Cheriet, Dansereau, *et al.* Three-dimensional Reconstruction of the Scoliotic Spine and Pelvis from Uncalibrated Biplanar X-ray Images, *J Spinal Disord Techniq* 2007; 20: 160–167p.

15. Kadoury S., Cheriet F., Labelle H., Self-Calibration of Biplanar Radiographic Images Through Geometric Spine Shape Descriptors, *Biomed Eng IEEE T* July 2010; 57(7): 1663,1675p.
16. Trochu. F, A Contouring Program based on Dual Kiging Interpolation, *Eng Comp* 1993; 9: 160–177p.
17. B. André, J. Dansereau, Allard, Calibration Object Measurements and Three-dimensional Reconstruction Accuracy of the DLT Algorithm, *Proc. 14th Annual Meeting American Society Biomechanics*, 1990, 89–90p.
18. B. Andre, J. Dansereau, H. Labelle, Effect of Radiography Landmark Identification Errors on the Accuracy of Three-dimensional Reconstruction of the Human Spine, *Medial Biol Eng Comput* 1992; 30: 569–575p.
19. Wood G. A., Marshall R. N., The Accuracy of DLT Extrapolation in Three-dimensional Film Analyis, *J Biomech* 1986; 19: 781–785p.
20. Dumas R, Mitton D, Laporte S, *et al.* Explicit Calibration Method and Specific Device Designed for Stereoradiography, *J Biomech* 2003; 36(6): 827–834p.
21. D.Moura, J. Sousa, J. M. Tavares, *et al.* A Flexible Approach for the Calibration of Biplanar Radiography of the Spine on Conventional Radiological Systems, *Comp Model Eng Sci* 2010; 60(2): 115–138p.
22. Cheriet, Laporte, Kadoury, *et al.* A Novel System for the 3-D Reconstruction of the Human Spine and Rib Cage from Biplanar X-ray Images, *IEEE T Biomed Eng* 2007; 54: 1356–1358p.
23. J. Weng, N. Ahuja, T.S. Huang, Optimal Motion and Structure Estimation, *IEEE T Patt Anal Mach Intell* 1993; 15(9): 864–884p.
24. M. Panjabi, D. Chang, J. Dvorak, An Analysis of Errors in Kinematic Parameters Associated with *in vivo* Functional Radiographs, *Spine* Feb. 1992; 17: 200–205p.
25. Sampath Kumar, K Prabhakar Nayak, Hareesh K S. Semiautomatic Method for Segmenting Pedicles in Vertebral Radiographs. *Proceedings of ICCCS'12*, Procedia Technology, Elsevier 2012; 6: 39–48p. DOI: 10.1016/j.protcy.2012.10.006
26. J. Novosad, F. Cheriet, S. Delorme, *et al.* Self-calibration of Biplanar Radiographs for a Retrospective Com-parative Study of the 3-D Correction of Adolescent Idiopathic Scoliosis, *Stud. Health Technol Inf* 2002; 91: 272–275p.
27. Lepetit V, Fua P, Monocular Model-based 3D Tracking of Rigid Objects: A Survey, *Found T Comp Graph Vis* 2005; 1(1): 1–89p.
28. Abdel-Aziz Y, Karara H, Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-range Photo-grammetry, *In Proc. Symposium on Close-Range Photogrammetry*, Urbana, Illinois, 1971, 1–18p.

