3D analysis of congenital scoliosis due to hemivertebra using biplanar radiography

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Abstract

Introduction This study aims to investigate the use of biplanar radiography for assessing congenital scoliosis due to hemivertebra in 3D.

Materials and methods A reconstruction method was developed to model 3D spines with congenital scoliosis from biplanar radiography. 3D measurements quantifying the global posture, scoliotic deformities and imbalance and describing the shape and pose of the hemivertebra were automatically computed. Five cases of congenital scoliosis were analyzed and the accuracy of the method was evaluated by comparing 3D reconstructions from biplanar radiography with 3D segmentations generated from CT.

Results The mean shape accuracy was 1.8 mm (1.5 mm for the vertebral bodies and pedicles and 2.2 mm for the posterior arches).

Conclusion Biplanar radiography can be considered an interesting tool for clinical follow-up of congenital scoliosis as it overcomes some limitations of the analyses based on CT or anteroposterior X-ray: head to feet acquisition,

low radiation dose and provides a set of automatically computed postural and morphological parameters in 3D.

Keywords Congenital scoliosis · Hemivertebra · 3D reconstruction · Biplanar radiography · Postural analysis

Introduction

Diagnosis and treatment of congenital scoliosis remain a great challenge. The complexity of the three-dimensional (3D) deformations makes the diagnosis and the interpretation of such pathologies difficult. In particular, the evaluation of the deformity progression is fundamental for patient follow-up. Congenital curvatures may indeed be highly progressive and require surgical treatment.

Anteroposterior (AP) X-rays remain the gold standard for congenital scoliosis follow-up [1]. Cobb's angle is commonly used to assess the curve severity on AP radiographs. Lateral X-rays are used to quantify sagittal balance of the trunk by measuring the translation of vertebrae from the S1 or bicoxofemoral plumbline [2]. However, due to the superimposition of anatomical structures, the interpretation of spinal deformities based on conventional X-rays is not a trivial task. Moreover, analyzing congenital scoliosis based on radiographic images results in a two-dimensional interpretation of a pathology that is characterized by 3D patterns of deformity and imbalance.

Computer tomography (CT) provides a detailed visualization of complex bony deformities [3]. A CT-based morphologic evaluation helps to assess vertebral instability, fused segments and could improve the prognosis of the scoliotic curvature progression. In clinical practice, CT is often used for preoperative surgical planning [1]. However,

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CT remains mostly a tool for visualization and qualitative assessment purposes, rarely used for quantifying the bony deformations. Moreover, this imaging modality leads to important radiation doses for the patient [4]. Therefore, CT is rarely used for clinical follow-up of congenital scoliosis [1]. On the other hand, magnetic resonance imaging (MRI) is an interesting modality for studying the neural axis or the cartilage endplates but is less appropriate for assessing bony structures. Finally, both CT scan and MRI acquisitions are usually performed in supine position, which may underestimate spinal curvature and possible dislocations [5].

Alternative methods based on biplanar radiography were recently proposed for the clinical analysis of idiopathic scoliosis [6–10]. Such methods provide a 3D reconstruction of the thoracic and lumbar spine together with quantitative clinical measurements within a processing time between 3 and 10 min [7]. They are particularly adopted in scoliosis follow-up, providing a three-dimensional analysis with the patient in standing position and a low radiation dose [11]. However, the study of congenital scoliosis using biplanar radiography has never been investigated. In fact, congenital malformations such as hemivertebrae present a broad spectrum of complex deformity, which requires the development of specific approaches.

The present study aims to investigate the use of biplanar radiography for assessing congenital scoliosis and hemivertebrae in 3D. Based on a previous work [7], a reconstruction method was developed to model 3D thoracic and lumbar spines with congenital scoliosis. 3D measurements quantifying the global posture, scoliotic deformities and imbalance and describing the shape and pose of the hemivertebra were automatically computed from the 3D reconstructions. Five cases of congenital scoliosis were analyzed. The accuracy of the method was evaluated by comparing 3D reconstructions obtained from biplanar radiography with 3D segmentations generated from CT.

Methods

The clinical study design received approval of an independent ethic committee and written informed consent was obtained from all the patients. Five patients (2 boys and 3 girls, of 5–18 years of age) with congenital scoliosis due to single or multiple hemivertebrae were included in this study. CT scans were taken for all the patients for clinical follow-up purposes (for the assessment of congenital deformities or surgical planning). Three different CT devices were used: a Sensation 16 (Siemens Medical System, Erlangen, Germany), a Lightspeed 16 (GE Healthcare, Chalfont St. Giles, UK) and a MX8000 IDT 16 (Philips Healthcare, Best, The Netherlands). The mean [range] pixel size of the CT slices was 0.4 mm [0.2–0.5 mm] with a mean [range]

slice spacing of 1.4 mm [1.0–2.0 mm]. Biplanar X-rays were acquired using the EOS imaging device (EOS imaging, Paris, France). This device performs a simultaneous acquisition of two orthogonal X-rays (AP and lateral), head to feet with a reduced radiation dose [11]. The acquisitions were performed in a standardized standing position [12, 13].

3D reconstruction from biplanar radiography

A semi-automatic 3D reconstruction method was used to obtain subject-specific reconstructions of the thoracic and lumbar spine [7]. First, the operator digitizes the spinal curvature (a curve passing through the vertebral bodies), the T1 upper endplate and L5 lower endplate on both X-rays. A statistical model based on transversal and longitudinal inferences is used to provide an estimation of a 3D spinal shape. The model is projected on both X-rays so that the operator can perform fine adjustments of the vertebral models using control points (Fig. 1). As soon as vertebrae are adjusted, the 3D spinal shape itself improves using the statistical model and quickly converges toward the subject-specific reconstruction. In the present study, an additional process was introduced to deal with the congenital malformations and hemivertebrae. Based on the biplanar X-rays interpretation, the operator is asked to choose the anatomical features that constitute the hemivertebra: right and/or left pedicles, transverse processes, lamina or hemi-lamina and spinal process. The anatomical features not selected by the operator are automatically deleted from the generic model of vertebra, resulting in a generic model of the hemivertebra of the patient. Then, the operator identifies the upper and lower endplates of the hemivertebra by four landmarks in each radiograph. An estimation of the subject-specific 3D model of the hemivertebra is computed by deforming the generic model of the hemivertebra onto the selected landmarks [9]. The 3D hemivertebral shape is finally projected on both radiographs and adjusted in real time by the operator using control points (Fig. 1). The whole reconstruction process takes about 30 min.

Clinical measurements

Measurements characterizing the global posture, scoliotic deformities and imbalances were directly computed from the 3D reconstruction: Cobb's angle, kyphosis, lordosis angles, pelvic tilt, pelvic incidence [7] and T1-spinopelvic inclination in 3D [14]. The precision of these parameters was previously reported with a 95 % confidence interval between 1.2° and 5.6° [7]. Measurements of the hemivertebral shape and position were computed:

- Hemivertebral deviation: transversal offset between the hemivertebral body center and a 3D curve passing

Fig. 1 3D reconstruction from biplanar radiography and model projection on the two X-rays (*top*). The 3D models are adjusted using control points (*bottom* hemivertebra T5)

through the centers of the all the vertebral bodies but the one of the hemivertebra

- Hemivertebral wedging: angle between the upper and lower endplates.

Accuracy evaluation in comparison with CT

The method accuracy was evaluated by comparing the 3D subject-specific models obtained from biplanar radiography with 3D CT segmentations. Segmentations of the vertebral shapes were semi-automatically obtained from the CT scans using the software Amira (Mercury Computer

Systems, Chelmsford, MA, USA). Since the field of view of the CT volume was set up on a reduced region of interest around the hemivertebra, the evaluation of the 3D reconstruction accuracy was limited to the hemivertebra and the upper and lower vertebrae. The comparison between the 3D reconstructions obtained from the two imaging modalities is not straightforward. In fact, because the patient was standing while performing the biplanar radiography and lying while acquiring the CT scans, the position of the bony structures was distinct between the two acquisition modalities. To be able to compare the 3D shapes extracted from biplanar radiography with the ones segmented from CT volumes, each vertebral model

Table 1 Mean (2RMS) shape accuracy between the reconstructions from biplanar radiography and the CT segmentations

Vertebral level	Whole vertebra	Vertebral body	Upper endplate	Lower endplate	Vertebral walls	Pedicles	Posterior arch
Patient 1							
T2	1.5 (4.3)	1.0 (2.8)	0.7 (1.7)	–	1.4 (3.8)	1.7 (4.1)	1.8 (5.1)
T3 (Hemi.)	1.7 (4.3)	1.8 (4.8)	–	–	1.8 (4.8)	1.9 (4.6)	1.7 (3.9)
T4	1.4 (3.5)	1.5 (3.7)	–	–	1.5 (3.7)	1.5 (3.6)	1.4 (3.4)
Patient 2							
L1	2.7 (7.5)	1.4 (4.0)	0.8 (1.9)	–	1.7 (4.6)	1.5 (4.0)	3.6 (9.3)
L2 (Hemi.)	1.6 (4.7)	1.7 (4.9)	1.6 (4.7)	1.8 (5.3)	1.7 (4.7)	1.4 (3.5)	–
L3	1.6 (4.2)	2.2 (5.6)	–	2.1 (5.1)	2.3 (5.9)	1.3 (3.4)	1.3 (3.3)
Patient 3							
L1	1.9 (5.1)	1.7 (4.2)	1.7 (4.0)	1.9 (4.7)	1.6 (4.0)	0.8 (1.9)	2.2 (6.0)
L2 (Hemi.)	2.4 (7.6)	1.4 (3.5)	1.3 (3.2)	1.3 (3.3)	1.5 (3.8)	1.1 (2.6)	4.0 (11.2)
L3	1.8 (5.3)	1.5 (3.7)	1.7 (4.1)	1.3 (3.2)	1.4 (3.6)	1.3 (3.4)	2.2 (6.4)
Patient 4							
T11	1.9 (5.1)	1.9 (4.9)	1.7 (4.6)	1.5 (3.9)	2.6 (6.3)	1.7 (4.1)	2.1 (5.5)
T12 (Hemi.)	2.4 (6.3)	1.6 (3.9)	1.5 (3.5)	–	1.8 (4.1)	1.4 (3.4)	3.6 (9.1)
T13	2.0 (5.3)	2.0 (4.9)	–	1.7 (4.2)	2.1 (5.1)	2.2 (5.5)	2.1 (5.5)
Patient 5							
T10	1.2 (3.0)	1.1 (2.9)	1.1 (2.7)	1.0 (2.6)	1.4 (3.5)	1.2 (2.8)	1.3 (3.2)
T11 (Hemi.)	1.2 (3.1)	1.0 (2.5)	1.1 (2.6)	0.9 (2.3)	1.0 (2.5)	1.3 (2.9)	1.6 (4.1)
T12	1.5 (3.9)	1.2 (2.9)	1.3 (3.1)	1.2 (2.9)	1.1 (2.8)	1.8 (4.3)	1.8 (4.6)
Total							
Upper vert. (<i>n</i> = 5)	1.8 (5.2)	1.4 (3.8)	1.2 (3.2)	1.5 (3.9)	1.7 (4.5)	1.4 (3.5)	2.2 (6.1)
Hemi. (<i>n</i> = 5)	1.9 (5.4)	1.5 (4.0)	1.3 (3.6)	1.3 (3.8)	1.6 (4.1)	1.4 (3.4)	2.7 (7.7)
Lower vert. (<i>n</i> = 5)	1.7 (4.5)	1.6 (4.3)	1.5 (3.7)	1.5 (4.0)	1.7 (4.4)	1.6 (4.1)	1.7 (4.8)
All (<i>n</i> = 15)	1.8 (5.1)	1.5 (4.0)	1.3 (3.5)	1.5 (3.9)	1.7 (4.3)	1.5 (3.7)	2.2 (6.3)

2RMS 2 Root mean square errors, providing a 95 % confidence interval for the point-to-surface distances

obtained from biplanar radiography was rigidly registered into the environment of its corresponding CT acquisition. To facilitate the registration process, AP and lateral X-rays were simulated by projecting the voxels of the CT volume. The reconstructed 3D shapes obtained from biplanar radiography were manually registered so that their projected contours match the contours of the simulated X-rays, resulting in reconstructed shapes registered onto their corresponding 3D CT segmentations. Finally, point-to-surface distances between the 3D registered shapes and the 3D segmentations from CT were computed to evaluate the shape accuracy of the reconstruction method.

Results

The 3D reconstruction method was evaluated with a mean shape accuracy of 1.8 mm and 2 Root Mean Square (RMS) errors of 5.2 mm (the 2RMS errors providing a 95 % confidence interval for the point-to-surface distances) (Table 1). Generally, the less accurate reconstruction of the hemivertebrae posterior arch (mean error 2.2 mm, 2RMS 6.3 mm)

resulted in a decrease of the whole reconstruction accuracy, whereas the vertebral body and pedicles regions were accurately reconstructed (mean error 1.5 mm, 2RMS 4.0 mm for the vertebral bodies and 3.7 mm for the pedicles). A visual comparison between 3D CT segmentations and 3D reconstructions from biplanar radiography is presented Fig. 2. The CT segmentations of Patients 1, 2 and 4 presented several fusions between the bony structures in the hemivertebral region of interest, which was not modeled by the 3D reconstruction method from biplanar radiography. Therefore, the shape accuracy of fused vertebral endplates was not evaluated (Table 1). Bony fusions between the hemivertebra and the upper and lower vertebrae were observed in Patient 1 CT volume. Although not modeled by the 3D reconstruction method from biplanar radiography, the reconstruction was quite accurate (whole vertebrae mean accuracy between 1.4 and 1.7 mm). Bony fusions were also observed between the upper and lower vertebrae in Patient 2 CT volumes. The lower accuracy of the upper vertebra (L1) can be explained by a rough reconstruction of the posterior arch (mean accuracy of 3.6 mm). The vertebral body reconstruction of the lower vertebra (L3), whose important deformations can be

Fig. 2 For each patient, comparison between 3D reconstructions from biplanar radiography (*left*) and 3D CT-scan reconstructions (*right*)

seen in the CT segmentations (Fig. 2), was also slightly lower. The 3D reconstruction of Patient 5 was the most accurate (whole vertebrae mean accuracy between 1.2 and 1.5 mm), although the posterior arches of the hemi-vertebra and the lower vertebra were not appropriately modeled (Fig. 2, rear view). In fact, the posterior arch of the hemi-vertebra was modeled with a hemi-lamina, whereas the CT segmentation showed that this hemi-lamina was connected to the lower vertebra and the hemivertebra lamina to the lower adjacent vertebra.

The automatic computation of clinical parameters is illustrated for two patients in Fig. 3 (Patient 5 and Patient 2) and allows for a comparison of the congenital deformation patterns (Table 2). The hemivertebrae of Patients 1 and 2 were located in the upper thoracic spine (T3 and T2, Table 2). Their deviation was lower than the one of the

other patients (9 mm and 7 mm). Despite a similar deviation, the scoliotic curvature and the hemivertebra wedging were higher for Patient 1 than for Patient 2 (65° and 47° for the scoliotic curvature and 36° and 16° for the hemivertebra wedging, respectively). The kyphosis of these two patients was the lowest (6° and 10°), and much lower than the normality values ($40^{\circ} \pm 10^{\circ}$, as computed from 300 asymptomatic volunteers, from Vialle et al. [15]).

Patient 2 presented also a second hemivertebra, located in the lumbar region (L2, Table 2), which can be compared with the hemivertebra of Patient 3. These two L2 hemivertebrae had quite similar deviations (17 and 19 mm) and wedging (21° and 20°). However, the Cobb's angle associated to Patient 2 (78°) was much higher than that of Patient 3 (32°). The lordoses of these two patients were the lowest (in absolute value, 20° and 9°), and much lower than

Fig. 3 3D spinal reconstructions for Patient 5 (*top* single hemivertebra T11) and Patient 2 (*bottom* double hemivertebra T2 and L2). From *left to right* frontal view, sagittal view, frontal view with focus on the hemivertebra, *top* view with all the vertebrae above the

hemivertebra removed. The hemivertebral deviation d is transversal offset between the hemivertebral body center and a 3D curve passing through the centers of the all the vertebral bodies but the one of the hemivertebra

the normality values ($43^\circ \pm 11^\circ$) [15]. Finally, Patients 4 and 5 presented hemivertebrae located in the lower thoracic region T11 and T12 (Table 2). Their deviation was the same (15°) while the Cobb's angle associated to Patient 5 (37°) was higher than that of Patient 4 (21°).

Discussion

This study aimed to investigate the use of biplanar radiography for assessing congenital scoliosis due to hemivertebra in 3D.

Table 2 Clinical measurements automatically computed from the biplanar radiography 3D

	Hemivertebra level	Hemi. deviation (mm)	Hemi. wedging (°)	Cobb's angle (°)	Kyphosis T4–T12 (°)	Lordosis L1–L5 (°)	Pelvic incidence (°)	Pelvic tilt (°)	3D T1-SPI ^a (°)
Patient 1	T3	9	36	65	6	−42	54	0	14
Patient 2	T2	7	16	47	10	−20	65	27	10
	L2	17	21	78					
Patient 3	L2	19	20	32	21	−9	47	6	8
Patient 4	T12	15	31	21	30	−50	55	4	13
Patient 5	T11	15	24	37	35	−41	62	10	14
Normality values ^b	–	–	–	–	41 ± 10	−43 ± 11	55 ± 11	13 ± 6	−1.4 ± 2.7

^a 3D T1-Spinopelvic inclination, from Schwab et al. [14]

^b Mean and standard deviation computed on 300 sagittal radiographs of asymptomatic volunteers, from Vialle et al. [15]

Congenital scoliosis due to hemivertebra is often associated with high scoliotic curvatures and complex morphological deformities, which complicates the reconstruction process from biplanar radiography. The anatomical landmarks of the 3D models (Fig. 1) were sometimes difficult to identify on AP and lateral X-rays. This mainly explains the differences that were observed between the 3D reconstructions from biplanar radiography and CT (Fig. 2). These differences are also due to the fact that the patients were not in the same position (supine for the CT acquisition, standing in the biplanar radiography device), which modifies the relative position of the vertebrae. Finally, several dissimilarities are also due to the fact that bony fusions (Patients 1, 2 and 4, Fig. 2) were observed in the CT volumes but not taken into account by the 3D reconstruction method from biplanar radiography. However, these bony fusions are apparent on AP or lateral X-rays and could, therefore, be considered to improve the 3D models used in the reconstruction process.

To evaluate the accuracy of the reconstructed shapes, a method was used to manually register the 3D models obtained from biplanar X-rays in the CT environment. Similar approaches [7, 9, 16, 17] have been previously used to evaluate the accuracy of 3D reconstruction methods from biplanar X-rays for patients with idiopathic scoliosis. These studies reported mean shape reconstruction accuracies between 1.0 and 1.4 mm (2RMS errors between 2.7 and 4.0 mm) for the whole vertebra region, and between 0.9 and 1.2 mm (2RMS errors between 2.2 and 3.0 mm) for the vertebral body and pedicles regions [7, 9]. The reconstruction accuracy evaluated in the present study was found to be slightly lower [with a mean (2RMS) accuracy of 1.8 mm (5.1 mm) for the whole vertebra region and a mean (2RMS) accuracy of 1.5 mm (4.0 mm) for the vertebral body region]. However, such results are promising, considering the complex morphological deformities that make the reconstruction process of congenital scoliosis

much more challenging than reconstructing idiopathic scoliosis from biplanar X-rays, where the deformation patterns are smoother and present less discontinuity.

The evaluation of the method accuracy was also limited by the number of patient included in the study ($n = 5$), although the number of vertebrae from which the method accuracy was computed ($n = 15$) was appropriate. A more extensive study including other congenital deformation patterns would provide a deeper analysis of the versatility of the method. However, due to the rarity and disparity of congenital scoliosis, the gathering of additional patients with both CT and biplanar radiographic analyses was not possible in the present study.

CT remains a more accurate technique for the morphological assessment of the hemivertebra region of interest, for example, when surgical intervention requires a detailed pre-operative planning. However, for routine clinical follow-up, the radiation dose is an important issue and the lying position is not appropriate for quantifying the global posture, scoliotic deformities and imbalances of the patient. Moreover, the lying position can underestimate the severity of the curve and deviation of the hemivertebra, which are important parameters in the decision-making process for the treatment of congenital scoliosis [1].

Therefore, low dose biplanar radiography could provide an interesting tool for clinical follow-up of congenital scoliosis, overcoming some limitations of CT-based analyses: head to feet acquisition in standardized standing position, low radiation dose and a set of automatically computed parameters quantifying the global posture, scoliotic deformities and imbalance and describing the shape and pose of the hemivertebra. In clinical routine, biplanar radiography could also be used together with CT as complementary approaches, in order to take advantage of both imaging modalities: CT for a local analysis of the morphology of the hemivertebra region and biplanar radiography for a global and postural analysis of the whole

spine. Our future work aims at performing a more extensive clinical study, including patients with clinical follow-up, to evaluate the added-value of the method in a clinical routine context.

To conclude, this study proposed a method for assessing congenital scoliosis and hemivertebrae in 3D using biplanar radiography, providing 3D reconstructions of the vertebral shape of the whole thoracic and lumbar spine and automatically computed parameters quantifying the scoliotic deformity and imbalances and the hemivertebra morphology. The method was evaluated against CT on five patients (15 vertebrae) with a mean shape accuracy of 1.8 mm. Future work aims at confirming the potential interest of the method for clinical routine use.

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Conflict of interest None.

References

1. Batra S, Ahuja S (2008) Congenital scoliosis: management and future directions. *Acta Orthop Belg* 74(2):147–160
2. Sangole A, Aubin CE, Labelle H, Lenke L, Jackson R, Newton P, Stokes IA (2010) The central hip vertical axis: a reference axis for the scoliosis research society three-dimensional classification of idiopathic scoliosis. *Spine (Phila Pa 1976)* 35(12):E530–E534. doi:[10.1097/BRS.0b013e3181da38b8](https://doi.org/10.1097/BRS.0b013e3181da38b8)
3. Newton PO, Hahn GW, Fricka KB, Wenger (2002) Utility of three-dimensional and multiplanar reformatted computed tomography for evaluation of pediatric congenital spine abnormalities. *Spine (Phila Pa 1976)* 27(8):844–850
4. Levy AR, Goldberg MS, Mayo NE, Hanley JA, Poitras B (1996) Reducing the lifetime risk of cancer from spinal radiographs among people with adolescent idiopathic scoliosis. *Spine* 21(13):1540–1547 (discussion 1548)
5. Yazici M, Acaroglu ER, Alanay A, Deviren V, Cila A, Surat A (2001) Measurement of vertebral rotation in standing versus supine position in adolescent idiopathic scoliosis. *J Pediatr Orthop* 21(2):252–256
6. Dumas R, Blanchard B, Carlier R, de Loubresse CG, Le Huec JC, Marty C, Moinard M, Vital JM (2008) A semi-automated method using interpolation and optimisation for the 3D reconstruction of the spine from bi-planar radiography: a precision and accuracy study. *Med Biol Eng Comput* 46(1):85–92
7. Humbert L, De Guise JA, Aubert B, Godbout B, Skalli W (2009) 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences. *Med Eng Phys* 31(6):681–687. doi:[10.1016/j.medengphy.2009.01.003](https://doi.org/10.1016/j.medengphy.2009.01.003)
8. Mitulescu A, Semaan I, De Guise JA, Leborgne P, Adamsbaum C, Skalli W (2001) Validation of the non-stereo corresponding points stereoradiographic 3D reconstruction technique. *Med Biol Eng Comput* 39(2):152–158
9. Pomero V, Mitton D, Laporte S, de Guise JA, Skalli W (2004) Fast accurate stereoradiographic 3D-reconstruction of the spine using a combined geometric and statistic model. *Clin Biomech* 19(3):240–247
10. Illes T, Tunyogi-Csapo M, Somoskeoy S (2011) Breakthrough in three-dimensional scoliosis diagnosis: significance of horizontal plane view and vertebra vectors. *Eur Spine J* 20(1):135–143. doi:[10.1007/s00586-010-1566-8](https://doi.org/10.1007/s00586-010-1566-8)
11. Dubousset J, Charpak G, Dorion I, Skalli W, Lavaste F, De Guise JA, Kalifa G, Ferey S (2005) 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(2):287–297 (discussion 297–300)
12. Faro FD, Marks MC, Pawelek J, Newton PO (2004) Evaluation of a functional position for lateral radiograph acquisition in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)* 29(20):2284–2289 [pii]:00007632-200410150-00017
13. Horton WC, Kraiwattanapong C, Akamaru T, Minamide A, Park JS, Park, Hutton WC (2005) The role of the sternum, costosternal articulations, intervertebral disc, and facets in thoracic sagittal plane biomechanics: a comparison of three different sequences of surgical release. *Spine (Phila Pa 1976)* 18:2014–2023 [pii]:00007632-200509150-00004
14. Schwab F, Lafage V, Patel A, Farcy JP (2009) Sagittal plane considerations and the pelvis in the adult patient. *Spine (Phila Pa 1976)* 34(17):1828–1833. doi:[10.1097/BRS.0b013e3181a13c08](https://doi.org/10.1097/BRS.0b013e3181a13c08)
15. Vialle R, Levassor N, Rillardon L, Templier A, Skalli W, Guigui P (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. *J Bone Joint Surg Am* 87(2):260–267. doi:[10.2106/JBJS.D.02043](https://doi.org/10.2106/JBJS.D.02043)
16. Benameur S, Mignotte M, Labelle H, De Guise JA (2005) A hierarchical statistical modeling approach for the unsupervised 3-D biplanar reconstruction of the scoliotic spine. *IEEE Trans Biomed Eng* 52(12):2041–2057
17. Kadoury S, Cheriet F, Labelle H (2009) Personalized X-ray 3-D reconstruction of the scoliotic spine from hybrid statistical and image-based models. *IEEE Trans Med Imaging* 28(9):1422–1435. doi:[10.1109/TMI.2009.2016756](https://doi.org/10.1109/TMI.2009.2016756)