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Assessment of spinal alignment in standing position using Biplanar X-ray images and three-dimensional vertebral models

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Abstract We developed two methods for three-dimensional (3D) evaluation of spinal alignment in standing position by image matching between biplanar x-ray images and 3D vertebral models. One used a Slot-Scanning 3D x-ray Imager (sterEOS) to obtain biplanar x-ray images, and the other used a conventional x-ray system and a rotating table. The 3D vertebral model was constructed from the CT scan data. The spatial position of the vertebral model was determined by minimizing the contour difference between the projected image of the model and the biplanar x-ray images. Verification experiments were conducted using a torso phantom. The relative positions of the upper vertebrae to the lowest vertebrae of the cervical, thoracic, and lumbar vertebrae were evaluated. The mean, standard deviation, and mean square error of the relative position were less than 1° and 1 mm in all cases for sterEOS. The maximum mean squared errors of the conventional x-ray system and the rotating table were 0.7° and 0.4 mm for the cervical spine, 1.0° and 1.2 mm for the thoracic spine, and 1.1° and 1.2 mm for the lumbar spine. Therefore, both methods could be useful for evaluating the spinal alignment in standing position.

Keywords: spine, alignment, Image matching, bi planar x-ray, validation

Introduction

The spine is composed of 24 vertebrae: 7 cervical, 12 thoracic, and 5 lumbar vertebrae, 5 sacral vertebrae which are fused together, and 3 to 5 caudal vertebrae also fused together. The spinal column is the axis of the body and plays an important role in protecting the spinal cord and providing both mobility and stability. The alignment of the spinal column is almost straight in the frontal or back view, but in the lateral (sagittal) view, there are two successive forward and backward curves, with the cervical spine showing anterior curve, the thoracic spine showing posterior, the lumbar spine again showing anterior, and the sacral spine showing posterior (Fig. 1). Functional disorders and diseases of the spine are often accompanied by changes in alignment, such as scoliosis, in which the spine is bent from side to side in frontal or back views, and is also rotated (twisted).[1,2] Therefore, spinal alignment assessment is essential for the diagnosis and prevention of spinal diseases, and is also very important in setting targets for spinal correction surgery.[3]

In clinical practice, two-dimensional assessment of spinal alignment using standing frontal and lateral radiography is common. However, as mentioned above, changes in spinal alignment are three-dimensional and it is necessary to take this into account when performing the evaluation. X-ray CT scan and nuclear magnetic resonance imaging (MRI) can be applied as three-dimensional evaluation methods, but it has been reported that the alignment is different from that under weight-bearing standing because the imaging is performed in the supine position.[4]

In this study, we investigated an image-matching method using standing biplanar x-ray images and individual vertebral bone models as a method for evaluating 3D alignment. The Slot-Scanning 3D x-ray Imager (hereinafter referred to as "sterEOS") has been developed as a dedicated modality for standing biplanar x-ray imaging[5,6] and is used both in Japan and overseas.[4,7-9] The features of sterEOS include the ability to narrow the x-ray field in the form of a slit and the ability to adjust the x-ray dose according to the thickness of the subject. In addition, the system is equipped with a standard vertebral bone model, which enables three-dimensional alignment evaluation by deforming the standard model and superimposing it on the subject's x-ray images. However, there are only a few of these devices installed, and the number of facilities using them is limited.

On the other hand, x-ray CT scanners are widely used in Japan for diagnosis and preoperative planning in the field of spine

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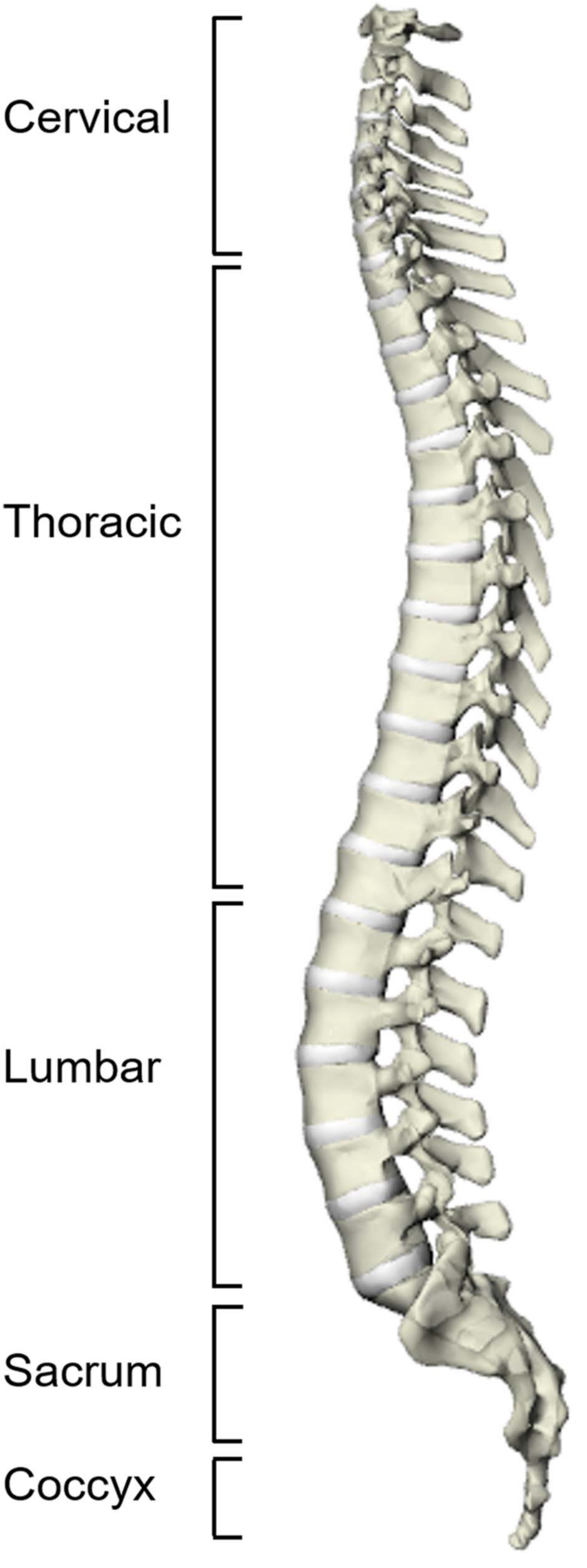

Figure 1. Lateral (sagittal) view of whole spine.

surgery. Therefore, it is possible to construct vertebral bone models for each individual subject from CT scan images and apply a method for three-dimensional evaluation of spinal alignment by image matching with biplaner x-ray images. Therefore, the purpose of this study was to develop and verify two methods for three-dimensional spinal alignment evaluation by image matching using vertebral models constructed from CT scan data and standing biplanar x-ray images from sterEOS or a conventional x-ray system that is widely used in clinical practice. As a first step, the accuracies of the two methods were verified by using a torso phantom.

Materials and methods

Biplanar x-ray imaging using sterEOS

The sterEOS (EOS Imaging, Paris, France) is a dedicated vertical biplanar radiography system which allows simultaneous frontal and lateral images of the whole body.[5,6] In the sterEOS, as shown in Figure 2, two sets of x-ray tubes and x-ray detector units are arranged orthogonally, and move simultaneously along the vertical direction. The x-ray irradiation field is narrowed to a slit, unlike the conventional x-ray system which irradiates a divergent beam. The default speed of the x-ray scanning is 7.6 cm/s. Thus, if the height of the subject is H cm, the time required for acquisition could be H/7.6 seconds. Since the relative positions of the x-ray tube and the detector unit are fixed, the relative positions of the images taken in two directions are also fixed, and the camera calibration described below is unnecessary.

Biplanar x-ray imaging using a conventional x-ray system

A conventional x-ray system consists of an x-ray tube and an x-ray detecting part called imaging plate (IP). The distance between the x-ray tube and IP varies depending on the subject. For biplanar imaging using a single x-ray tube, we use a rotating table to turn the subject. As the relative position between the x-ray tube and IP is determined each time, camera calibration is necessary to define the spatial positional relationship between them. In this study, three panels with 18 steel ball markers for each are mounted on a rotating table, and the subject is x-rayed together with these panels. The x-ray tube is placed at a distance of 2 m from the IP (Fig. 3). The subject stands on the rotating table, and a frontal image is taken at 0° of rotation and a lateral image is taken at 90° of rotation (Fig. 4). Then, from the coordinates of the steel ball markers on the biplanar images, the camera constants assuming pinhole projection are determined and the projection matrix is constructed.[10] The world coordinate system was derived from the coordinates of the steel ball markers: the right to left direction in the frontal image was set as the X-axis, the image plane to x-ray tube direction as the Y-axis, and the lower to upper direction as the Z-axis (denoted as X_w, Y_w, and Z_w, respectively).

Reconstruction of vertebral models

A vertebral model was constructed from the CT scan data. The CT scan data of the entire spine were loaded into a three-dimensional modeling software (Mimics Research 23.0; Materialise, Leuven, Belgium), and the binarization process was used to extract bone regions to create three-dimensional models of individual vertebrae. For each vertebra model, a local coordinate system was set by custom-made software. The average coordinate value of the point cloud consisting the vertebral body was set as the origin of the local coordinate system, and the lateral direction was set as the X-axis (the right direction was positive), the anteroposterior direction as the Y-axis (the anterior direction was

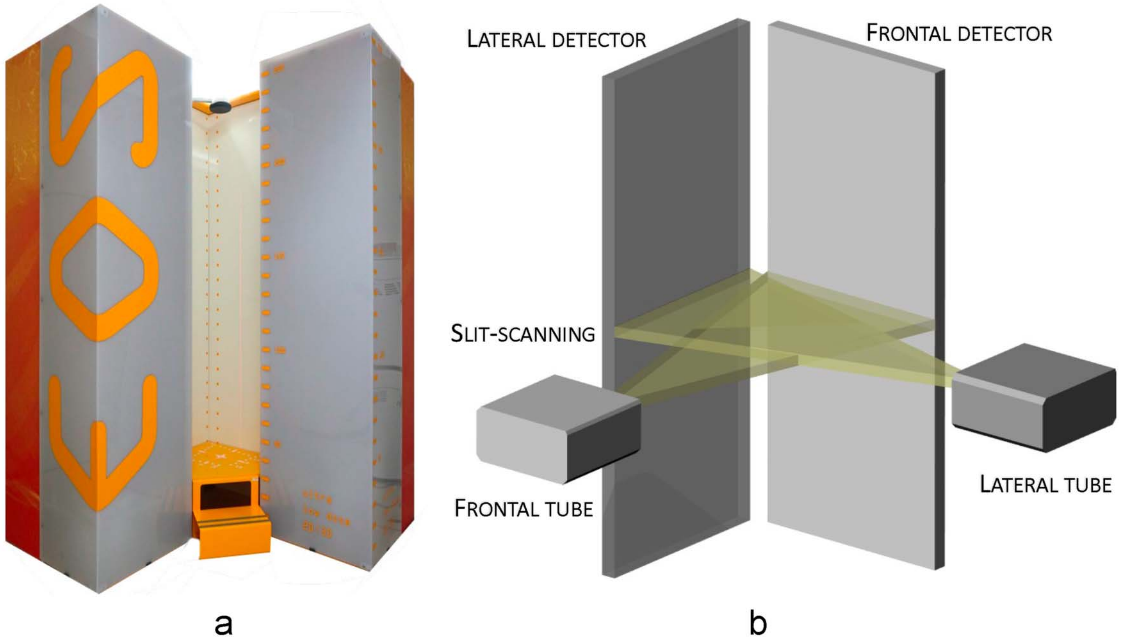

Figure 2. Overview of sterEOS (A) and its configuration of x-ray tubes and detector units (B).

positive), and the craniocaudal direction as the Z-axis (the cranial direction was positive) (Fig. 5).

Image matching

In sterEOS, the virtual imaging space shown in Figure 6 was constructed from the focal length (1.3 m) and image size. The vertical magnification was set to zero, and the horizontal x-ray focal point was set to the center of the image width. The world coordinate system was set as the left to right direction in the frontal image was the X-axis, the x-ray tube to image plane direction as the Y-axis, and the lower to upper direction as the Z-axis (denoted as X_w, Y_w, and Z_w, respectively). In the case of using a rotating table, the virtual imaging space was constructed using the projection matrix described in the previous section. In both imaging spaces, the x-ray images taken at 0° (front) and 90° (lateral) were placed in the image plane, and then, the 3D vertebral model was loaded to display the contour points of the projected image. For each contour point, the distance to the nearest model contour point is calculated, and the normalized value is summed over all contour points.

$$D_{mean} = D^{0}_{mean} + D^{90}_{mean} = \sum_{i=1}^{N^0} \|\mathrm{OLX}_i^0 - \mathrm{OLV}_i^0\| \Big/ N^0 + \sum_{i=1}^{N^{90}} \|\mathrm{OLX}_i^{90} - \mathrm{OLV}_i^{90}\| \Big/ N^{90} \qquad (1)$$

where OLXi is the i-th contour point of the x-ray image, OLVi is the nearest contour point to OLXi in the virtual projection image, and N is the number of contour points. The superscripts

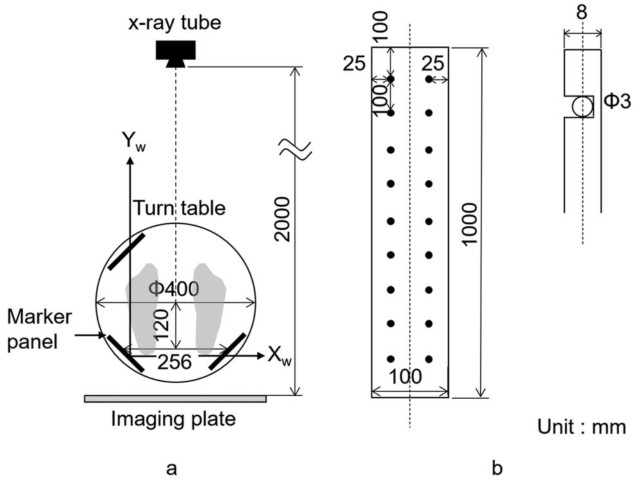

Figure 3. Configurations of conventional x-ray tube and rotation table with 3 marker panels (A) and 18 steel ball markers placed on each panel (B). The marker panels are set 780 mm above the rotating table to cover the torso.

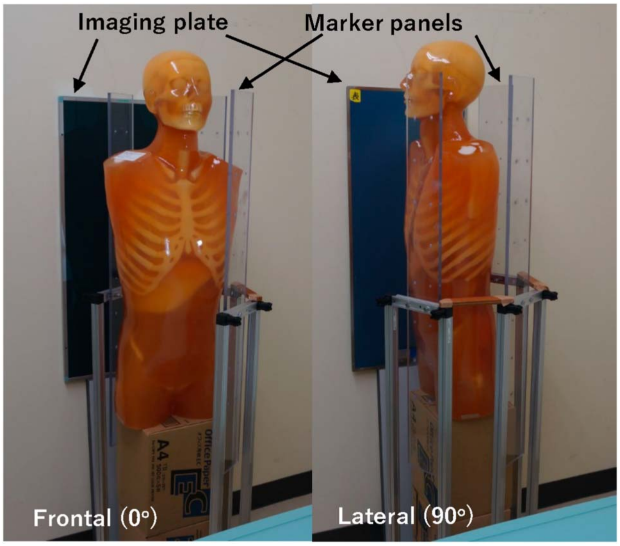

Figure 4. Subject position for biplanar x-ray imaging.

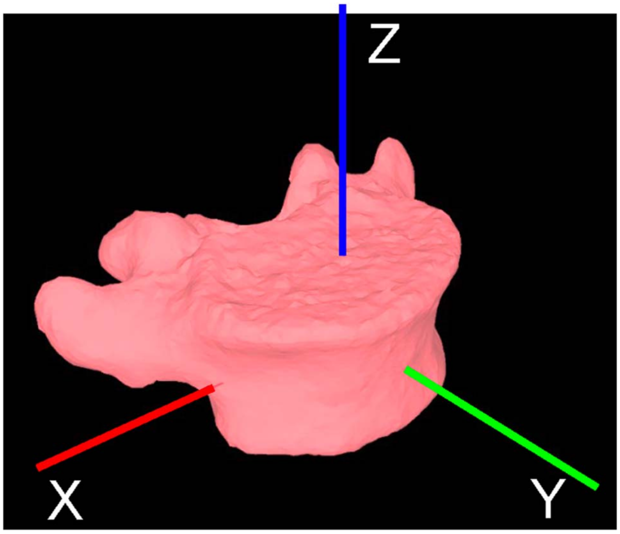

Figure 5. Local coordinate system for vertebral model.

0 and 90 indicate that the values relate to x-ray images of 0° and 90°, respectively. The D_{mean} is a function of the six-degree-of-freedom (6-DOF) parameters representing the position and orientation of the 3D vertebral model: three translation parameters (tx, ty, tz) and three rotation parameters (rx, ry, rz). The initial orientation of the model was parallel to the world coordinate system, i.e., rx = 0, ry = 0, and rz = 0. To determine the initial position, the center of the vertebral body was visually determined in the two images and the origin of the 3D model was translated there. Then, the values of the 6-DOF parameters are automatically determined by minimizing them, using the simplex method.[11,12] The above calculations were performed by a custom-made software running on a Window 10 workstation (XEON processors, 8 cores, 2.1 GHz, 128 GB RAM).

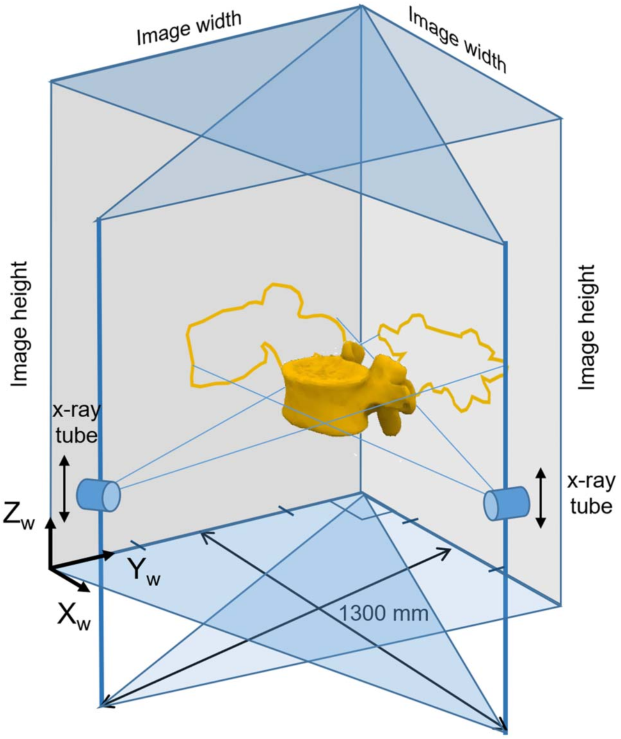

Figure 6. Virtual imaging space of sterEOS for image matching.

Verification using a torso phantom

To verify the accuracy of 3D position and orientation estimation by image matching, we conducted a verification experiment using a torso phantom (CTU-4, Kyoto Kagaku Co., Ltd, Japan, Fig. 4). This phantom is made of soft tissue equivalent and bone equivalent materials, which have the same x-ray absorption characteristics as those of the human body, resulting in the same organ contrast and artifacts as in the human body. Following the method described in the previous section, three-dimensional models of 24 vertebrae comprising the cervical, thoracic, and lumbar vertebrae were constructed from the CT scan data obtained under the following imaging conditions: slice thickness of 1.0 mm, resolution of 1.7 pixel/mm, and pixel size of 0.586 × 0.586 mm^2. A local coordinate system was constructed for individual vertebrae. Frontal and lateral x-ray images were taken by sterEOS under the following conditions: resolution of 5.6 pixel/mm, distance between x-ray tube and detector of 1,300 mm, and image size of 340 × 970 mm^2.

Biplanar imaging using a conventional x-ray system (X'sy Pro EFX version, Shimadzu, Kyoto, Japan) was carried out under the resolution of 5.0 pixel/mm, distance between x-ray tube and detector of 2,000 mm, and image size of 524 × 846 mm^2. The images were processed with the enhance-local-contrast algorithm implemented in open-source software Fiji[13] to improve clarity. The 6-DOF parameters of each vertebra were determined by image matching as described in the previous section. For each of the frontal and lateral images about 20 points were selected manually to surround the outer edge of a single vertebral bone. The relative positions of the upper vertebrae to the lowest vertebrae of the cervical, thoracic, and lumbar vertebrae were calculated. That is, for the cervical spine, 4 relative positions of C6 to C3 in reference to C7 were determined. For the thoracic spine, 11 relative positions of T11 to T1 in reference to T12 and for the lumbar spine, four relative positions of L4 to L1 in reference to L5 were determined. The target value (ground truth) for accuracy verification was the relative positions calculated from the CT scan data. The computational time of image matching was about 15 seconds for each vertebra bone.

Results

Figure 7 shows the lumbar vertebral model (L4) fitted to biplanar images. The mean, standard deviation, and root mean squared error (RMSE) of the relative position error of the upper vertebrae to the lowest vertebrae determined by sterEOS or the conventional x-ray, and the rotating table radiographs for the cervical, thoracic, and lumbar spine are presented in Table 1. The mean, standard deviation, and RMSE of the relative position error were less than 1° and 1 mm in all cases. On the other hand, the maximum RMSE for the conventional x-ray and the rotating table were 0.7° and 0.4 mm for the cervical spine, 1.0° and 1.2 mm for the thoracic spine, and 1.1° and 1.2 mm for the lumbar spine.

Discussion

In this study, a method to determine the 3D position of the vertebrae by image matching with a 3D model of the vertebrae to the standing frontal and lateral images taken by sterEOS, or a

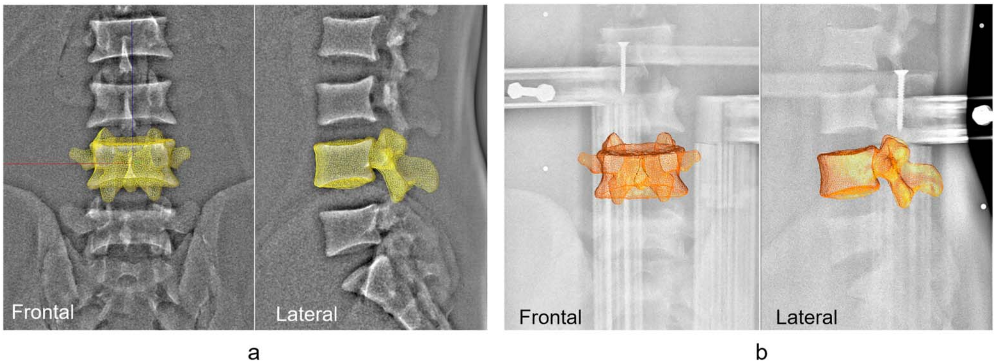

Figure 7. Results of image matching of lumbar vertebra (L4) using sterEOS (A) and conventional x-ray system (B).

conventional x-ray system with a rotation table was presented. The accuracy of the method was verified using a torso phantom.

Glaser et al.[14] verified the accuracy of 3D vertebral shape reconstruction and 3D spinal alignment evaluation using sterEOS for the thoracolumbar spine (L5 to T1). They reported that the accuracy of vertebral shape reconstruction was 1.1 ± 0.2 mm, and the accuracy of alignment evaluation was 1.2 mm and 1.9°, respectively, when compared with CT scan data.

In studies of three-dimensional evaluation using biplanar conventional x-ray images in standing position, the method of searching for corresponding points (anatomical feature points) on two radiographic images and constructing a three-dimensional structure[15-17] has been reported so far. However, the disadvantage of this method is that there is ambiguity in the selection of corresponding points. Methods of 3D measurement by image registration without camera calibration using digitally reconstructed x-ray images generated from single or biplanar x-ray images and CT images[18-20] have been reported. These methods are similar to our method in that the 3D position is determined by image matching without the need to select the corresponding points. Although the method was verified by computer simulation between two lumbar vertebrae (L5 and L4), the relative position estimation error was reported to be within 1° and 1 mm.

The accuracy of the method using sterEOS is higher than that of Glaser et al.[14] because we use an individual bone model constructed from CT scan data. In addition, the relative position between the upper and lower intervertebral joints can be evaluated without deforming the posterior elements of the vertebrae, which have complex structures such as intervertebral joints and vertebral arches, from the standard shape model. CT scans have already been performed for diagnosis and preoperative planning, and no additional radiation exposure will be needed by this method. Thus, this method could be effective for clinical practice.

The accuracy of the method using the conventional radiography was comparable with those of the previous methods.[18-20] Although these previous methods have the advantage of being free from camera calibration, it cannot be simply compared with the proposed methods because the accuracy was verified only by computer simulation on a single spinal unit (L4-L5). Compared with our method using sterEOS, the accuracy was slightly lower. This is due to the difference in image contrast as shown in Figure 7. However, since the accuracy of the proposed method is higher or similar to those of the previous methods, we believe that this method is also effective to evaluate the spinal alignment.

One of the limitations to this study is that the accuracy of the proposed method was verified on a spine phantom. When the proposed methods are applied to patient images, degenerative deformations of vertebrae could cause difficulties in reconstructing bone models and image matching. In addition, the contour of the vertebrae may be obscured by the surrounding tissue of the spine, and the motion of the subject during biplanar imaging may affect the accuracy.

Table 1

Mean, SD, and RMSE for estimating 6-DOF parameters of relative positions.

		Rotation			Translation		
		x (°)	y (°)	z (°)	x (mm)	y (mm)	z (mm)
Cervical							
sterEOS	Mean	0.0	0.5	−0.6	−0.8	0.1	0.0
	SD	0.3	0.3	0.4	0.2	0.3	0.2
	RMSE	0.3	0.5	0.7	0.9	0.3	0.2
Conv*	Mean	0.1	−0.2	0.6	0.4	−0.1	0.0
	SD	0.4	0.4	0.3	0.1	0.3	0.1
	RMSE	0.4	0.4	0.7	0.4	0.3	0.1
Thoracic							
sterEOS	Mean	0.1	−0.4	−0.2	0.7	−0.1	0.0
	SD	0.4	0.5	0.4	0.5	0.3	0.2
	RMSE	0.4	0.6	0.4	0.9	0.3	0.2
Conv*	Mean	−0.5	0.2	−0.4	−0.5	−1.1	0.1
	SD	0.4	0.6	1.0	0.5	0.5	0.1
	RMSE	0.6	0.6	1.0	0.7	1.2	0.2
Lumbar							
sterEOS	Mean	−0.6	0.2	−0.1	−0.2	−0.6	0.0
	SD	0.3	0.5	0.4	0.4	0.4	0.2
	RMSE	0.6	0.5	0.4	0.4	0.7	0.2
Conv*	Mean	−0.4	0.0	−0.4	−0.1	−1.1	0.1
	SD	0.8	0.4	1.2	0.6	0.5	0.2
	RMSE	0.8	0.3	1.1	0.5	1.2	0.2

*Conv indicates conventional X-ray system and rotating table.

Conclusions

To evaluate the alignment of the standing spine, we presented two methods to determine the three-dimensional position of the vertebrae by image matching the three-dimensional model of the vertebrae to the upright frontal and lateral images of the spine taken by sterEOS or the conventional x-ray system and the rotating table. The accuracies of these methods were verified using a torse phantom. The mean, standard deviation, and RMSE of the relative position error were less than 1° and 1 mm in all cases for sterEOS. The maximum mean squared errors for the conventional x-ray system and the rotating table were 0.7° and

0.4 mm for the cervical spine, 1.0° and 1.2 mm for the thoracic spine, and 1.1° and 1.2 mm for the lumbar spine.

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