Ultrasound Volume Projection Imaging for Assessment of Scoliosis

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***Abstract*—The standing radiograph is used as a gold standard to diagnose spinal deformity including scoliosis, a medical condition defined as lateral spine curvature $>10^{\circ}$. However, the health concern of X-ray and large inter-observer variation of measurements on X-ray images have significantly restricted its application, particularly for scoliosis screening and close follow-up for adolescent patients. In this study, a radiation-free freehand 3-D ultrasound system was developed for scoliosis assessment using a volume projection imaging method. Based on the obtained coronal view images, two measurement methods were proposed using transverse process and spinous profile as landmarks, respectively. As a reliability study, 36 subjects (age: 30.1 ± 14.5; male: 12; female: 24) with different degrees of scoliosis were scanned using the system to test the inter- and intra-observer repeatability. The intra- and inter-observer tests indicated that the new assessment methods were repeatable, with ICC larger than 0.92. Small intra- and inter-observer variations of measuring spine curvature were observed for the two measurement methods (intra-: $1.4 \pm 1.0^{\circ}$ and $1.4 \pm 1.1^{\circ}$; inter-: $2.2 \pm 1.6^{\circ}$ and $2.5 \pm 1.6^{\circ}$). The results also showed that the spinal curvature obtained by the new method had good linear correlations with X-ray Cobb's method ($R^2 = 0.8, p < 0.001$, 29 subjects). These results suggested that the ultrasound volume projection imaging method can be a promising approach for the assessment of scoliosis, and further research should be followed up to demonstrate its potential clinical applications for mass screening and curve progression and treatment outcome monitoring of scoliosis patients.**

***Index Terms*—Cobb angle, coronal view, freehand 3-D ultrasound, nonplanar volume rendering, scoliosis, spine deformity, ultrasound imaging.**

I. Introduction

SCOLIOSIS is a medical condition defined as a 3-D spine deformity with curvature of more than 10° in the coronal plane, which is typically classified as idiopathic scoliosis and nonidiopathic scoliosis. And 65% of scoliosis cases was estimated to be idiopathic [1]. It is particularly concerned with the risk of curve progression for those skeletally immature patients since curve progression is the most probable occurrence among teenagers with adolescent idiopathic scoliosis (AIS), a subset of idiopathic scoliosis with patients aged 10–18 years, during their rapid growth period. Close observation is required for the patients with spine curvature between 10° to 20°. For more severe cases, treatments including bracing and surgery are necessary [2]. It has been suggested that early screening and observation of scoliosis can apparently mitigate the risky surgical intervention.

The standing radiograph has been widely exploited to evaluate the spine deformity and identify the type of scoliosis through Cobb's method [3], which is a gold standard for delineating spine curvature for scoliosis diagnosis. An increase of 5° or more in the spine curvature angle obtained with the Cobb's method indicates a curve progression [4], [5]. And the regular X-ray examination should be conducted to observe curve progression of AIS and evaluate treatment outcome of idiopathic scoliosis [2], [6]. However, the intra-observer and inter-observer variation of measuring spine curvature using Cobb's method can reach 3°–5° and 6°–9°, respectively [5], [7], [8], restricting the application of radiograph in scoliosis examination and evaluation of treatment efficacy. Moreover, frequent X-ray examination would make harmful effects on human body, especially for teenagers. Levy *et al.* [9] reported that considerable amount of X-ray radiation received by those AIS patients over their growth period consequently raised the risk of cancer by 2.4‰. It was also found that 90% of AIS patients with curvature progression received unnecessary intervention with radiograph [10]. Even worse, single radiograph cannot cover the whole spine in some clinics, requiring additional radiograph to assess the whole view of spine [11]. Therefore, new imaging modalities which can provide accurate idiopathic scoliosis assessment and monitoring during mass screening and treatment without the hazard of radiation are clearly necessary.

Radiation-free imaging techniques including ultrasound and magnetic resonance imaging (MRI) can also be used to identify the bony features and serve the measurement of spine curvature. MRI can estimate the spine curvature with 3-D information. However, patients have to undergo the examination in a supine posture. It was reported that the spine curvature angle measured under a standing posture was significantly more accurate than measurements with other postures, such as supine posture [5], [12]. It is also time consuming and expensive for

Manuscript received December 15, 2014; accepted January 06, 2015. Date of publication January 12, 2015; date of current version July 29, 2015. This study was supported in part by the Research Grant Council of Hong Kong (PolyU5332/07E, PolyU152220/14E) and in part by the Hong Kong Innovation and Technology Fund (UIM213). Chung-Wai James Cheung, Guang-Quan Zhou, and Yong-ping Zheng have equal contributions to the study. *Asterisk indicates corresponding author.*

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Digital Object Identifier 10.1109/TMI.2015.2390233

performing MRI examinations. Therefore, MRI is not suitable for fulfilling mass-screening and frequent measurement of scoliosis treatment outcome. By contrast, ultrasound imaging is a low-cost and radiation-free imaging modality. Various measurement approaches for deriving spine curvatures using 2-D B-mode ultrasound imaging techniques and bony features have been reported. Although 2-D ultrasound lacks the ability to view complex 3-D spine structure, the feasibility of using laminae as landmarks in B-mode images to measure spine curvature has been demonstrated *in vitro* experiments [13].

Recently, freehand 3-D ultrasound, combining conventional B-mode ultrasound with position sensor, has been advanced to overcome the limitations of 2-D viewing of 3-D anatomy [14]–[21]. The spine curvature was estimated through manually locating the transverse processes in some ultrasound images with 3-D spatial information. These ultrasound images were manually selected from a pile of 2-D raw B-mode images or captured with accurately locating the target from observations [19]–[21]. However, this approach required the transverse processes to be identified in dozens of ultrasound images, which is time-consuming and subjective. Moreover, the accuracy of the measurement was strongly dependent on the quality of ultrasound B-mode images, especially for *in vivo* experiments. It was found that the performance of *in vivo* measurement was apparently worse than that of phantom experiments [20], and will be further aggravated for subjects with high body mass index (BMI) because the image quality of ultrasound would be severely degraded under a thick subcutaneous fat tissue [22]. Furthermore, although the aforementioned approach utilized 3-D spatial information of images to measure the spine curvature, it did not generate 3-D representation of the spine anatomy, and thus lacked the ability of viewing whole spine anatomy. Alternatively, an emerging approach to measure spine curvature with the visualization of spine anatomy from 3-D volume data can be a potential solution to reveal pathologies obscured in 2-D viewing [23]–[25]. Although some attempts to acquire volume data were made under a supine posture [18], spinal curvature assessment using this method has yet not been reported.

In this study, we proposed an ultrasound volume projection imaging method for the assessment of scoliosis by using a new projection rendering for the volume data acquired with freehand 3-D ultrasound imaging system. Two measurement approaches based on different spine structural features were developed to assess spine curvature on the ultrasound volume projection imaging. The freehand 3-D ultrasound imaging system that we earlier developed [21] was enhanced by including a new frame structure to help subjects maintain a standing posture during scanning. The performance of this new method was evaluated among subjects with different spine curvature angles.

The paper is organized as follows. The overall freehand 3-D ultrasound imaging system, volume projection imaging method, and spine deformity measurement are described in Section II. *In vivo* experiments are presented to demonstrate the performance of new spine imaging modality in Section III and Section IV. Finally, Section V compares and discusses the tested results, and Section VI concludes this work.

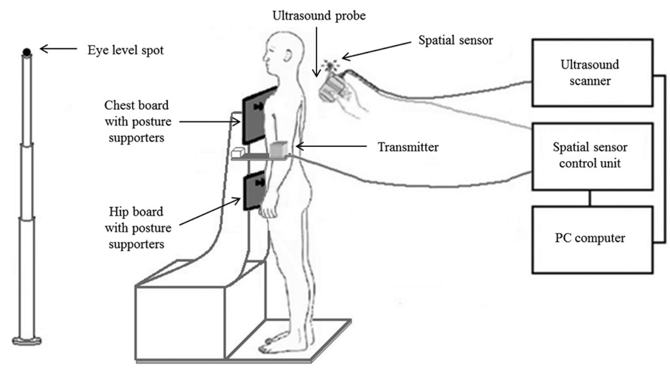

Fig. 1. Diagram of the free-hand 3-D ultrasound system for spine deformity assessment.

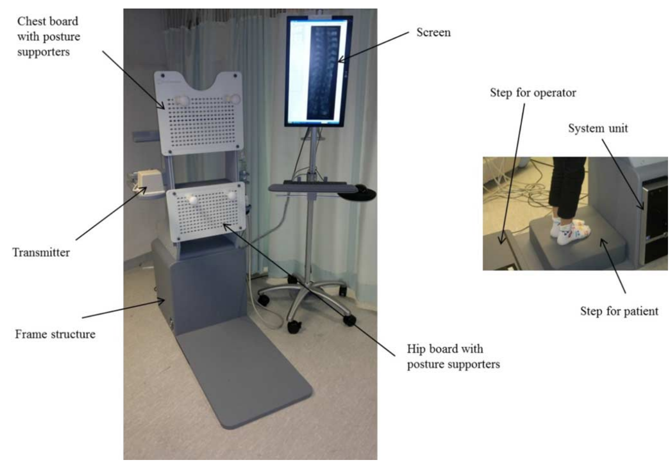

Fig. 2. Frame structure with electromagnetic (EM) transmitter and body supporter used in the free-hand 3-D ultrasound system. Steps for supporting operators and patients with different heights were also developed.

II. Methods

A. Imaging System

A diagram of the proposed ultrasound volume projection imaging system for scoliosis assessment is shown in Fig. 1. The major components of this system were composed of a custom-designed frame structure, an ultrasound scanner EUB-8500 (Hitachi Ltd., Tokyo, Japan), a high performance computer with an Intel Core 2 Q6600 2.4-GHz processor and a video capture card NIIMAQPCI/PXI-1411 (National Instruments Corporation, Austin, TX, USA), and a compact electromagnetic spatial sensing device MiniBird Model 130 (Ascension Technology Corporation, Burlington, VT, USA). And custom-designed software with user-friendly interface programmed by Microsoft Visual Studio 2010 and Visualization Toolkit (VTK) was developed for data acquisition, image processing, visualization, analysis, and spine curvature measurement.

According to the information provided by the manufacturer, the position and orientation resolution of the MiniBird system is better than 0.5 mm and 0.1°, respectively, if the distance between the position sensor and the electromagnetic transmitter is within 46 cm. The resolution may decrease as the increase of the distance and can be significantly influenced by presence of ferromagnetic materials. In this study, the supporting frame structure (Fig. 2) was made of Polyvinyl chloride (PVC) and

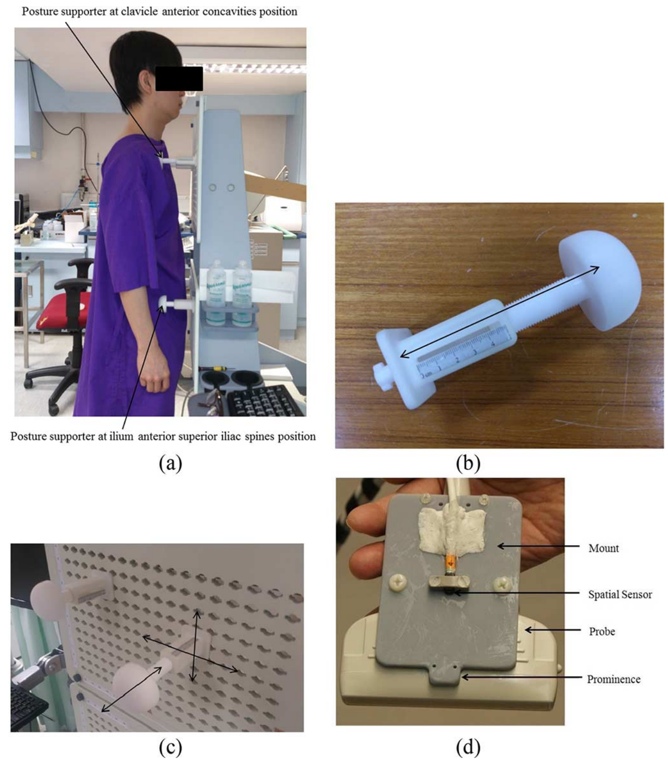

Fig. 3. Posture supporter and spatial sensor fixation: (a) subject using body supporter during scan, (b) body supporter, (c) body supporter fixed on chest board, and (d) ultrasound probe with spatial sensor and fixation mount.

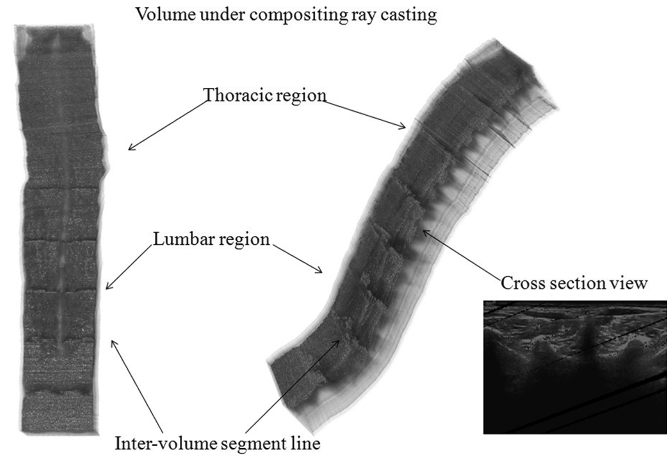

Fig. 4. Visualization of a full spine volume using compositing ray casting in posterior–anterior direction view and 3-D view for a typical scoliotic patient.

acrylic to support subject steadily and to retain the position sensor within the designed working extent during scanning. Two vertically movable boards, chest and hip board, with four adjustable and movable posture supporting pegs, as shown in Fig. 2, were mounted on the frame structure for facilitating subjects to maintain their natural standing posture because the breath of subjects and the pressure exerting from probe might cause body displacement during scanning. The position sensor for collecting position and orientation information of the corresponding B-mode images was fixed onto the ultrasound probe with a custom-made mount (Fig. 3) featured with a prominence to help operators to follow the trend of spine during scanning. Hitachi L53L/10–5 linear ultrasound probe, a 92-mm-wide linear probe with frequency ranging from 5–10 MHz, was chosen because the probe was wide enough to capture all transverse processes from the spine in the view of ultrasound image in a single swap. The pixel resolutions of 2-D ultrasound image were set as 0.15 mm per pixel in both directions, which was kept consistent in the subsequent calibration, data acquisition, reconstruction, visualization, and curvature measurement. And a cross-wire calibration procedure [26] was performed to calculate the spatial and orientation offsets between the 2-D image and the position sensor using Levenberg-Marquardt nonlinear algorithm [27] before data acquisition.

Before scanning, the subjects were requested to remove any metallic items and stand in front of the boards. The positions of four adjustable posture supporting pegs inserted between the subject and the boards were then adjusted to contact with the anterior concave border of clavicle and anterior superior iliac spine for facilitating the subject to maintain a natural standing posture. Adequate amount of ultrasound gel was applied onto the subject to fill all gaps between the probe and subject's skin so as to assure ultrasound image quality. The images of spine were steadily scanned along the spine from the fifth lumbar vertebra (L5) up towards the first thoracic vertebra (T1), which was guided by the spinous process or furrow using the prominence of the custom-made mount, enabling the traverse processes captured in view of ultrasound images. The subject was instructed to stand still and breathe shallowly during scanning. In addition, the subject was also required to stare at the spot located at eye level (Fig. 1) in front of him/her for alleviating effect from head movement which might influence the morphology of the upper spine during scanning. During the data acquisition, ultrasound images were collected at 25 frames/s using the video capture card; while, the MiniBird system recorded the corresponding 3-D position and orientation of the ultrasound images. The time of total scanning for acquiring 2000–2500 images was less than 2 min on average.

B. Ultrasound Volume Projection Imaging

The collected ultrasound images together with corresponding 3-D spatial information were used to generate a 3-D representation of the spine anatomy. Typical volume can be reconstructed from image data ranging from 16 MB to 96 MB in size, depending on the applications [15], [17], [28]. For example, 75 MB images [256 scans $\times$ (640×480 pixels)] were used to reconstruct a finger with the freehand 3-D ultrasound [17]. However, the data size used in spine volume reconstruction was significantly greater than that in typical volume reconstruction, which required more efficient volume reconstruction methods. A segment processing strategy was implemented in this study, in which the acquired images were divided into a number of subsections, with each to form a small volume block representing a portion of spine. For a typical spine scan, the B-mode images were evenly divided into 8 to 10 groups to reconstruct the volume blocks simultaneously using a multi-CPU computer. After generating all individual volume blocks, they were then integrated to form the whole spine volume (Fig. 4).

Many 3-D reconstruction methods have been proposed to build volume data from freehand 3-D ultrasound scanning, including distance weighted (DW) interpolation [17], [29]–[31] and nearest neighborhood interpolation [32]–[34]. As the scanning density of freehand 3-D ultrasound is not constant, there is a trade-off in determining the radius R of the neighborhood for interpolation. If the radius R is too small, few pixels may be involved in reconstruction for a voxel, leading to noisy images in the reconstructed volume because of limited smoothing effect. In contrast, if radius R is too large, the slices will be severely blurred. Meairs, *et al.* [31] proposed a Gaussian convolution kernel in DW interpolation to reduce the smoothness with a large radius. However, the computation time would be increased significantly [17]. Huang, *et al.* [17] proposed a squared distance weighted (SDW) interpolation using squared inverse distance W as the weighting factor for voxel calculation to achieve a better trade-off between computation speed and image quality. The relative weight for the kth pixel was determined by

$$W_k = \frac{1}{(d_k + \alpha)^2} \tag{1}$$

where d_k is the Euclidean distance from the kth pixel to the centre of the voxel V_c, and α is a positive parameter for adjusting the effect of the interpolation. The SDW interpolation was applied with the fixed rectangle to achieve a better image quality. To preserve more texture pattern, an α value of 0.1 or less should be set. In contrast, to suppress more speckles, the α value should be 10 or greater. In this study, the SDW method with $\alpha = 0.01$ was used to reconstruct volume data the after evaluating effect of different α values.

Based on the reconstructed volume data about spine, a coronal view visualization, a view similar to the posterior–anterior radiograph, could be derived using conventional reslicing techniques or volume rendering techniques to provide the visualization of spine anatomy. Therefore, the hidden bony features inside the spine volume would be revealed and the spine deformity could be assessed with volume visualization. Conventional reslicing techniques may not be able to reveal necessary information due to the complexity of spine anatomy. As shown in Fig. 5, if the reslicing plane was simply set as a planar coronal plane, regions without spine bony feature could always be observed in a single resliced plane, due to the natural curve of spine. On the other hand, proper volume rendering may be able to provide a better visualization of spine features since it can combine spine bony features located in different sliced planes from the volume data.

With the consideration of the natural curve of spine, a narrow-band nonplanar volume rendering algorithm was developed to better visualize spine anatomy, and it was named as volume projection imaging (VPI). As shown in Fig. 6, the 3-D representation of the spine anatomy obtained through the voxel-based reconstruction was put in the cube form in Cartesian coordinate system. The visualization through the standard planar volume rendering is to generate the 2-D projection image according to a specific planar plane in Cartesian coordinate system (Fig. 6). The natural curve of spine was not taken into account in planar volume rendering, resulting in regions without spine feature. On the other hand, a developable (unrollable) surface can be specified by the user to follow the natural curve of spine, as shown in Fig. 6 [35]. In this system, the spine scanning followed the trend of spine, which was obviously observed from the volume data in the cube form (Fig. 6). The developable surface can therefore be determined with the profile surface of spine volume data, which was the physical surface of the ultrasound probe if the probe closely contacted with the skin or the interface between the skin and gel if the gap between the probe and skin was filled with gel. In this study, this surface (referred as developable surface) was automatically detected from the reconstructed volume data through locating the first nonvoid voxels along the direction from the probe to the spine in Cartesian coordinate system. A predefined threshold T_s was set as 50 to distinguish the surface from void voxels during profile surface detection. The developable surfaces can then be determined by their relative distance to the identified profile surface, and the corresponding

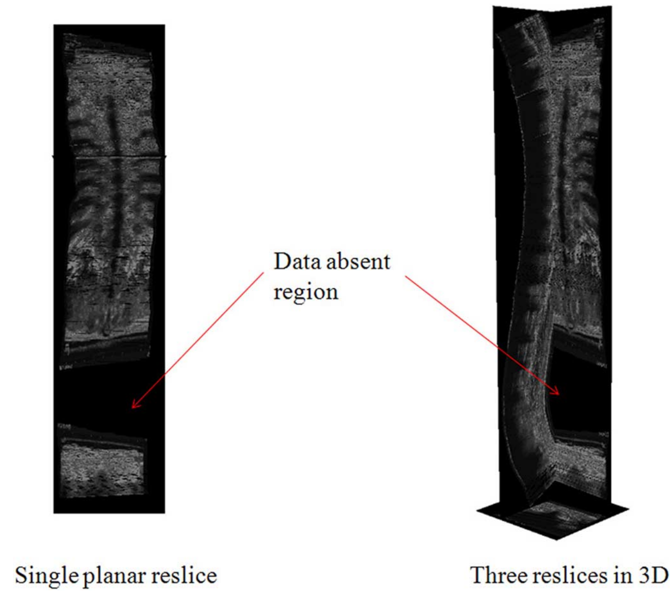

Fig. 5. Reslice of volume along coronal plane in 3-D space for a typical scoliotic patient.

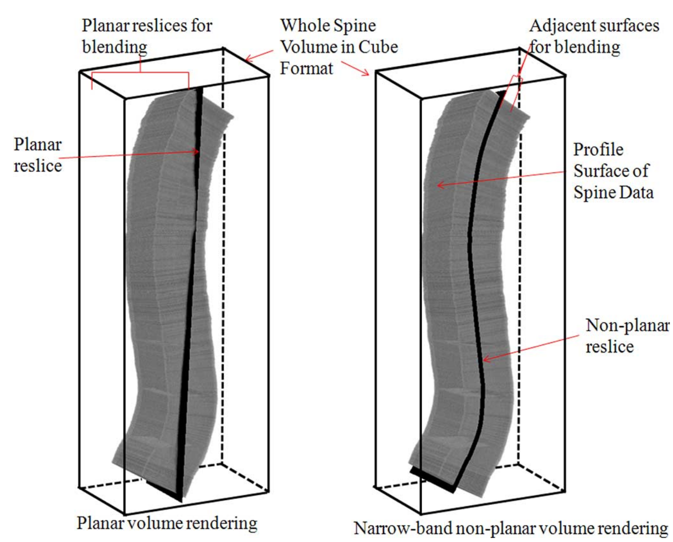

Fig. 6. Illustration of nonplanar volume rendering technique using skin surface as reference.

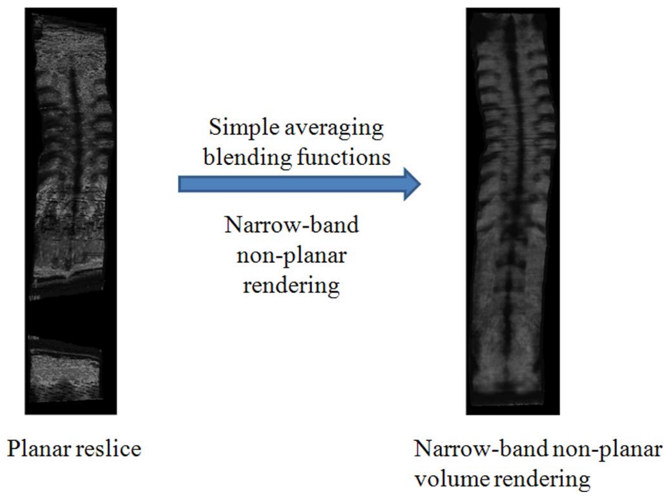

Fig. 7. Typical results obtained with and without narrow-band nonplanar volume rendering with averaging imaging processing technique from a spine volumetric data.

Algorithm 1 Proposed Algorithm for Volume Projection Imaging (VPI)

Initialization: Set the profile surface P_{Pro}; The referred surface in the narrow-band volume rendering P_n; The number of adjacent developable surfaces N_s

Output: The visualization of spine anatomy

clear the volume rendering image I

for each adjacent developable surfaces P_l in the range $l = n$ to $n + N_s$ **do**

    computing the intersection with the 3D ultrasound data using P_{Pro}

    for each pixel in the volume rendering image; **j** = 1 to **N do**

        compounding type is AVERAGE

            $I(j) = P_l(j)/N_s$

    end for

end for

nonplanar reslicing can be obtained through computing the intersection of the developable surfaces with the volumetric ultrasound data. Finally the nonplanar narrow-band volume rendering was applied to compound a series of adjacent developable surfaces to generate the visualization of spine anatomy (Fig. 7). The details of the nonplanar narrow-band volume rendering are summarized in Algorithm 1.

As shown in Fig. 6, both the position of the developable surface P_n and number of adjacent developable surfaces N_s were adaptable to generate the rendering at different viewpoints, resulting in revealing the hidden information of the spine at different depths. The N_s was set to 50 in this study. Different blending functions, such as simple average intensity compounding, maximum intensity compounding and minimum intensity compounding, could be implemented to produce different effects in the final rendering image [23]–[25]. It was found that the nonplanar narrow-band volume rendering with the simple average intensity compounding represented spine anatomy most clearly, as shown in Fig. 7.

C. Spine Deformity Measurement

Two manual measurement methods were proposed for measuring the spine curvature using the spine VPI image. The first method was spinous profile as a reference, named as VPI-SP. It was observed that an ultrasound shadow curve generated by

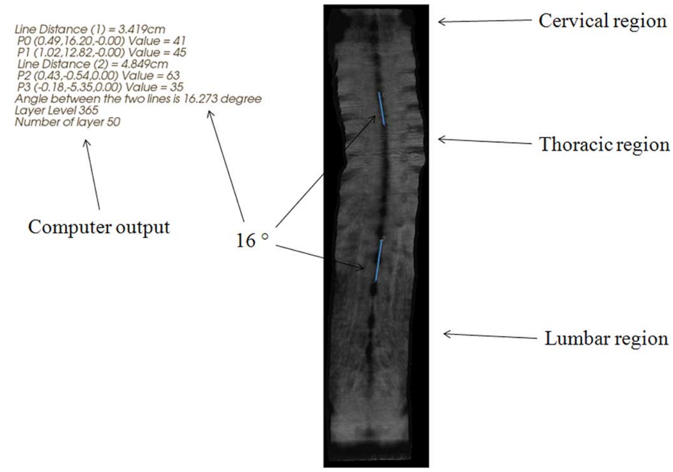

Fig. 8. Spine curvature measurement using the spinous column profile as reference (VPI-SP).

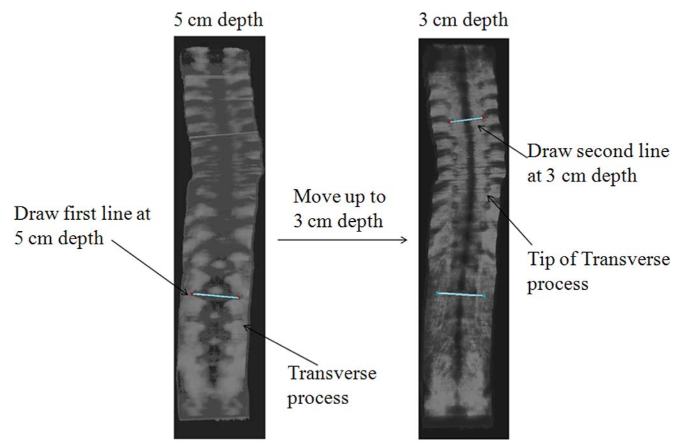

Fig. 9. Spine curvature measurement using transverse processes as reference (VPI-TP).

spinous processes lay nearby the midline of the spine VPI image (Fig. 8). Hence, the portions containing curve inflection point can be treated as the most tilted vertebrae, which could be manually identified for spine curvature measurement. As shown in Fig. 8, two short lines with the limited length covering the corresponding vertebra body were manually drawn in the middle of the shadow curve for denoting the location of the curve inflection point in the rendering image and calculating the angle of spine curvature accordingly.

Moreover, it was also revealed that the bony features such as transverse process could be identified in the obtained spine VPI image (Fig. 9). The second proposed measurement method was based on identifying two pairs of transverse processes from the most tilted vertebras, named as VPI-TP method. As shown in Fig. 9, lines can be drawn according to tips of transverse processes from the most tilted vertebras in the spine VPI image, which is nearby the curve inflection points in the image. However, the transverse processes may not always lie in the same nonplanar volume rendering plane with the preset depth P_n because the transverse processes are located at various depths among different vertebrae. It is necessary to examine the volume rendering image at various depths P_n to ensure that pairs of transverse processes could be visualized in the VPI image correctly (Fig. 9). In the worst case, tips of transverse processes in vertebra could not be identified because of reduction in image quality or tips out of imaging range, particularly in lower lumbar region. The ends of transverse process were then used for calculating the angle of spine curvature in these cases.

III. Experiments

A total of 36 subjects (age: 30.1 ± 14.5; 12 male and 24 female) including eleven teenagers were recruited for evaluating the performance of the spine deformity assessment using the new ultrasound imaging method. Each subject was scanned by the same examiner and volume data was reconstructed for each scan. Among them, 29 subjects had been examined with radiograph, thus were included in the correlation study between X-ray and the new method. This study was approved by the institutional ethical committee and all subjects gave written informed consent prior to participation in the experiment. Statistical analysis software SPSS (version 16; SPSS Inc., Chicago, IL, USA) was used for the data analysis.

All the 36 subjects were included for the evaluation of intra-observer and inter-observer repeatability of spine curvature measurement using the obtained VPI image. Based on the collected volumetric data, VPI images were formed by two observers, who could select depth and layer thickness for volume projection. For each VPI image, the angle of spine curvature was measured twice using both VPI-SP and VPI-TP methods by the corresponding observer. The observers used the vertebrae selected for X-ray Cobb angle measurement as a reference. The mean of the two measurements of each observer was used for the inter-observer repeatability evaluation. Furthermore, one of the observers performed another measurement for the same set of VPI images at a different time to evaluate the intra-observer repeatability. The intra-class correlation coefficient (ICC) was used to test the repeatability of the intra-observer and inter-observer measurements [36]. The absolute difference between the measurements was also calculated to understand the variation of intra-observer and inter-observer measurements.

The results of 29 subjects (age: 30.6 ± 14.7; 9 male and 20 female) with radiographs provided by their clinicians were involved in the correlation test between the VPI and X-ray measurement results. The Cobb angle was derived from the radiographs using Cobb's method by software SDV free edition version 1.3 (Santesoft Ltd, Athens, Greece). For each VPI image, the VPI-SP and VPI-TP methods were performed twice to obtain the angle of spine curvature and the mean value was used for comparing with the Cobb angle. Linear regression analysis was used to describe the relationship between the measurement of the ultrasound VPI and the Cobb angle from the radiographs; Bland and Altman's test of differences [37] was also applied to evaluate the agreement of the measurement results obtained by the two imaging methods. Level of significance was accepted at $p < 0.05$.

IV. Results

For the repeatability of measurement based on the collected volumetric data, the inter-observer repeatability between the two observers for VPI-SP and VPI-TP was high, with ICC values of 0.92 ($p < 0.001$) and 0.96 ($p < 0.001$), respectively. The absolute difference between the measurements by the two observers for VPI-SP and VPI-TP was $2.2 \pm 1.6^\circ$ and $2.5 \pm 1.6^\circ$, respectively. The intra-observer tests of the two measurement methods also showed excellent repeatability, with the ICC being 0.99 ($p < 0.001$) and 0.98 ($p < 0.001$) respectively for the VPI-SP and VPI-TP methods, and the absolute difference between the two measurement methods by the same observer was $1.4 \pm 1.0^\circ$ and $1.4 \pm 1.1^\circ$ accordingly. These results indicated that the proposed VPI measurement methods were observer independent.

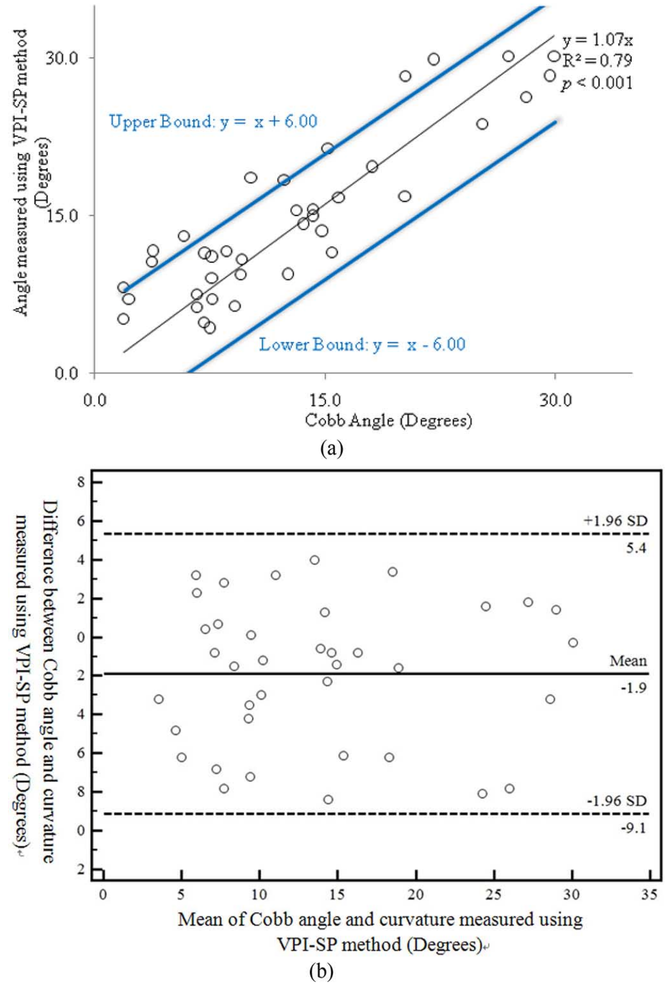

Fig. 10. Comparison between the X-ray Cobb's method and the VPI method with the spine column profile as reference (VPI-SP): (a) Correlation between the Cobb angle and the angle measured by VPI-SP, and (b) Bland-Altman plot between the two sets of measurement results.

As shown in Table III, the measured X-ray Cobb angle ranged from 1.9° to 29.9°, while the angle range of spine curvature obtained based on VPI with the VPI-SP and VPI-TP methods was 4.3° to 30.2° and 3.9° to 31.8°, respectively. The result obtained using the VPI-SP method had a significant correlation with the X-ray Cobb angle [$R^2 = 0.79; p < 0.001$; Fig. 10(a)]. As shown in Fig. 10(b), the Bland-Altman plot between the measurements with the VPI-SP method and Cobb's method indicated a low mean difference ($d = -1.9^\circ$) and the symmetrically distributed differences around mean difference were within the limits (± 1.96 SD $= 7.3^\circ$). This result suggested that there

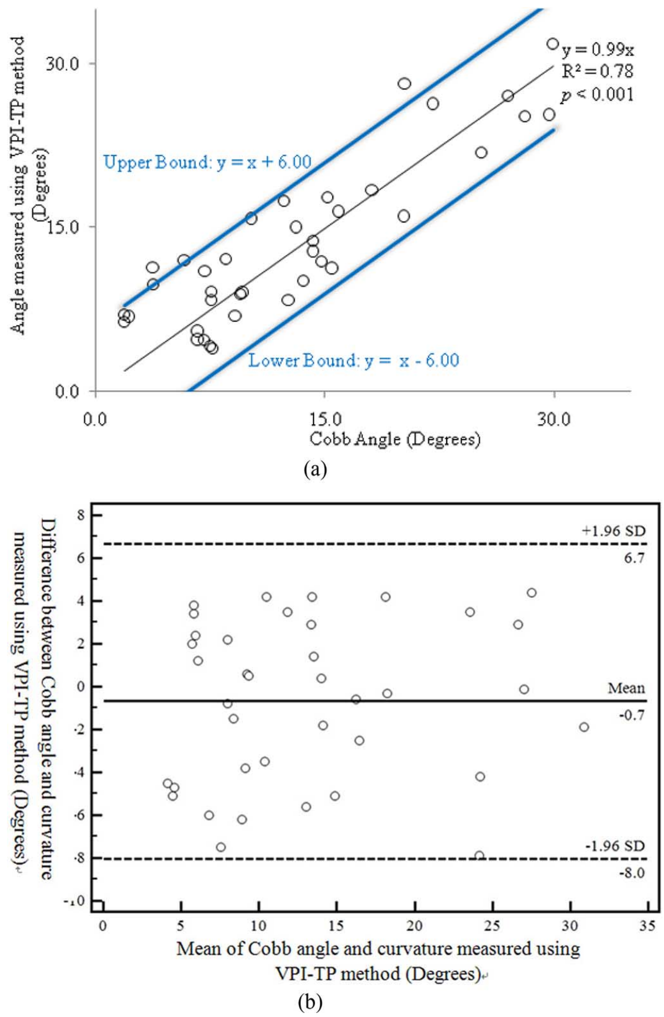

Fig. 11. Comparison between the X-ray Cobb's method and the VPI method with transverse processes as reference (VPI-TP): (a) Correlation between the Cobb angle and the angle measured by VPI-TP, and (b) Bland-Altman plot between the two sets of measurement.

was a good agreement between the results obtained by the two methods. Fig. 11(a) also showed a significant correlation between the measurements with the VPI-TP method and Cobb's method ($R^2 = 0.78; p < 0.001$). Moreover, the result of the Bland-Altman plot [Fig. 11(b)] supported that there was a good agreement between the results obtained by the two methods.

V. Discussion

A new spine imaging modality for the assessment of scoliosis was successfully developed based on a freehand 3-D ultrasound system and volume projection imaging method in this study. The procedure of measurement of spine curvature on VPI images was as simple as the measurement on radiographs. Two measurement methods based on the features of spinous profile and transverse process in VPI images were proposed. The intra- and inter-observer repeatability tests indicated the measurement was highly repeatable. The feasibility of the new method was also demonstrated by the high correlation ($R^2 = 0.8$) between its results and X-ray Cobb angle for 29 subjects with different levels of scoliosis. The results demonstrated that the new measurement method could provide reliable spine curvature measurement with performance comparable to that by X-ray Cobb's method. Unlike the previous method using landmarks observed in separate ultrasound B-mode images [13], [19]–[21], the proposed measurement method was to measure the spine curvature with the visualization of whole spine, reducing the measurement error and eliminating the searching of US B-mode images with corresponding bony features.

It was found that the results obtained using the VPI-TP method matched slightly better with the Cobb angle in comparison with the VPI-SP method. This could probably be explained by the difference of the spine features used in the two measurement methods. The feature used by the VPI-TP method was closer to that of the Cobb's method, as the endplates of vertebral body used in the Cobb's method were along the same direction of the line correcting the pair of transverse process. On the other hand, the VPI-SP method used the spinous column profile to measure the spine curvature, which was along a different direction to the endplates as used in the Cobb's method. To further demonstrate which spine feature in VPI images is better for the scoliosis assessment, more subjects should be tested in future studies. When interpreting the correlation between the X-ray Cobb's angle and the angle measured by the VPI methods, cautions should be taken for a number of factors. Firstly, the difference of examination time between the ultrasound scanning and radiograph taking might influence the comparison. Secondly, the radiograph examinations were conducted at different clinics. This might also cause variations in the correlation results, as it has been reported that the posture of subject and position of radiographic tube could affect the Cobb angle in radiographs [5]. Thirdly, the patients recruited in the current study had Cobb's angle smaller than 30° and covered a large age range, and it was unknown whether the correlation may change or not for patients with larger Cobb's angles as well as with different ages. Fourthly, the Cobb's method has a large inter-observer variation [5], [7], [8], and this indicates that Cobb's angle may not be the best reference for the new measurement. These issues should be further investigated in future studies with more patients and a better control of X-ray imaging protocol, Cobb's angle measurement, patient age group, and severity of scoliosis.

Being a radiation-free imaging modality, the reported system will be particularly suitable for the screening of scoliosis in teenagers. Scoliosis screening through visually examining the rib hump has been conducted to identify the patients with AIS as early as possible and reduce the case number of surgery for more than two decades in many countries. This screening can provide important knowledge about prevalence, aetiology and natural history of idiopathic scoliosis [38]. However, the sensitivity and specificity of scoliosis screening depends on the experiences of the examiner. Therefore, the effectiveness of scoliosis screening is still under dispute [38]–[42]. Moreover, the screening could increase exposure to radiographs because the radiography is required to officially diagnose scoliosis for positive findings of a rib hump [42]. The new spine imaging method can help to address the issues of the screening through examining the spine anatomy directly using the ultrasound volume projection imaging. Further studies are required to demonstrate the sensitivity and specificity of the scoliosis screening using the proposed 3-D ultrasound imaging method.

It has been demonstrated that the measurement using the new 3-D ultrasound imaging method has lower intra- and inter-observer variations ($1.4 \pm 1.0^\circ$ and $2.2 \pm 1.6^\circ$, respectively, for the VPI-SP method) in comparison with X-ray Cobb's method (3°–5° and 6°–9°, respectively [5], [7], [8]). The results implied that the measurement based on the VPI images were more sensitive to the curve progression. It has been widely reported that it is difficult to reliably observe any change less than 10° using Cobb's method [5], [43], though a 5° of increase or more in the Cobb angle is treated as a curve progression [4], [5]. Therefore, this new radiation-free ultrasound volume projection imaging method can be a good longitude follow-up approach for observing the curve progression and monitoring the treatment outcome of scoliosis.

Scoliosis is recognized as a 3-D spine deformity problem since the spine is a 3-D complex structure [44]. For example, vertebral rotation of spine is regarded as an essential parameter for assessing scoliosis 3-D deformity, predicting curvature prognosis and monitoring its progression [45]. It has been reported that there was a strong linear relationship between the Cobb angle and vertebra rotation [46]. Therefore, the scoliosis should be evaluated on coronal, sagittal, and traverse plane together [12]. However, it was almost impossible to determine the accurate vertebral rotation degree in standing radiograph because it is a 2-D viewing of 3-D anatomy and is incapable to directly provide vertebra rotation information on traverse plane [12]. Computed tomography (CT) and magnetic resonance imaging (MRI) are usually utilized for assessing the vertebra rotation in the supine posture, which is still disputable because of using supine posture in scanning. It is also time consuming and expensive for conducting spine scan with MRI and CT. Recently, CT and MRI for standing posture have become available. However, they are not widely available yet for spine examination. On one side, the vertebral rotation of spine may affect the VPI measurement developed in this study, just as the rotation would be counted towards the curvature when measured along a 2-D plane. This influence has been commonly known to the X-ray Cobb's method. On the other hand, the proposed 3-D ultrasound imaging method could provide different approaches to form a spine model for assessing spine deformity in 3-D in standing posture. Some preliminary works have been reported earlier [19], and this feature makes it possible to evaluate other forms of spine deformation such as kyphosis and vertebra rotation. Further studies are being conducted to demonstrate the feasibility of the 3-D ultrasound imaging for the assessment of kyphosis and vertebra rotation.

There were still a few factors contributing to errors in the proposed ultrasound VPI method for scoliosis assessment. The MiniBird spatial sensor was susceptible to metal because of its electromagnetic based sensing. Precaution was made to avoid using metal parts in the supporting frame. However, the metallic parts and structure inside ultrasound probe and attached wires probably created a distortion in electromagnetic field leading to a system offset or transient jitter in the spatial and orientation data. Moreover, traverse processes of lumber vertebras were often hidden beneath the thick muscle like paraspinal muscle, which made it difficult to use the VPI-TP method to measure curvature on VPI images. The situation for obese subjects was even worse. Thus, ultrasound probes with good penetration should be selected. Further studies should be conducted on how to maintain image quality under different situations. In this study, the scanning was conducted by a single operator, and we demonstrated the repeatability of the measurement based on the same set of volume data. Further studies are required to compare the results obtained by the volumetric data collected by different operators to demonstrate scanning repeatability.

VI. Conclusion

In summary, a new spine imaging modality with freehand 3-D ultrasound has been successfully developed and the feasibility of the proposed method was demonstrated for measuring the angle of spine curvature along the coronal plane. It used a nonplanar narrow-band volume rendering approach, named as volume projection imaging (VPI), to form coronal images from ultrasound volumetric data. Similar performances were demonstrated for the measurement methods using spinous profile and pair of transverse processes in the VPI images. Since the new method is radiation-free, it is particularly suitable for mass screening of idiopathic scoliosis and monitoring the curve progression and treatment outcome. Further studies are required to demonstrate its clinical values with a larger subject number, to improve the system for assessing obese subjects, and to investigate the potential of vertebral rotation measurement.

Acknowledgment

The authors would like to thank M. S. Wong for his generous supported for subject recruitments, and S. Ding for her editing of the manuscript.

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