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ORIGINAL ARTICLE

Freehand three-dimensional ultrasound system for assessment of scoliosis

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Summary *Background/Objective:* Standing radiograph with Cobb's method is routinely used to diagnose scoliosis, a medical condition defined as a lateral spine curvature $> 10°$ with concordant vertebral rotation. However, radiation hazard and two-dimensional (2-D) viewing of 3-D anatomy restrict the application of radiograph in scoliosis examination.
Methods: In this study, a freehand 3-D ultrasound system was developed for the radiation-free assessment of scoliosis. Bony landmarks of the spine were manually extracted from a series of ultrasound images with their spatial information recorded to form a 3-D spine model for measuring its curvature. To validate its feasibility, *in vivo* measurements were conducted in 28 volunteers (age: 28.0 ± 13.0 years, 9 males and 19 females). A significant linear correlation ($R^2 = 0.86$; $p < 0.001$) was found between the spine curvatures as measured by Cobb's method and the 3-D ultrasound imaging with transverse process and superior articular process as landmarks. The intra- and interobserver tests indicated that the proposed method is repeatable.
Results: The 3-D ultrasound method using bony landmarks tended to underestimate the deformity, and a proper scaling is required. Nevertheless, this study demonstrated the feasibility of the freehand 3-D ultrasound system to assess scoliosis in the standing posture with the proposed methods and 3-D spine profile.
Conclusion: Further studies are required to understand the variations that exist between the ultrasound and radiograph results with a larger number of volunteers, and to demonstrate its potential clinical applications for monitoring of scoliosis patients. Through further clinical trials and development, the reported 3-D ultrasound imaging system can potentially be used for scoliosis mass screening and frequent monitoring of progress and treatment outcome because of its radiation-free and easy accessibility feature.

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Introduction

Scoliosis is a three-dimensional (3-D) spine deformation, characterised by a lateral spine curvature $> 10^{\circ}$ [1], frequently accompanied with vertebral rotation [2]. Sixty-five percent of cases are estimated to be idiopathic [3]. Treatments for scoliosis including bracing and surgery are essential when the spine curvatures exceed 20° for skeleton immature patients [4]. This is particularly true with the risk of curve progression for teenage patients as significant curve progressions are often observed among children during their rapid growth period. It has been suggested that the prevalence of scoliosis in the population after puberty is higher than that in the population prior to puberty [5—7]. Therefore, early screening and frequent monitoring of scoliosis can apparently mitigate the curve progression and treatments intervention.

The standing radiograph has been widely exploited to evaluate the spine deformity and identify the type of scoliosis through Cobb's method [8], which is currently considered the gold standard in scoliosis diagnosis. The degree of spine curvature obtained with Cobb's method is named the Cobb angle, which provides vital information for delineating spine curvature and developing treatment plans for curve progression. Patients with scoliosis should regularly undergo X-ray examination of the spine to monitor curve progression and treatment outcome [4,9]. However, the measurement accuracy of the Cobb angle is influenced by the awareness and practice of the observer, the position of the patient, and the position of the radiography tube [10]. The intra- and interobserver variation of measuring Cobb angle can be 3—5° and 6—9°, respectively [10—12]. Moreover, frequent X-ray diagnosis gradually builds up harmful effects in the human body, especially for children. Levy et al [13] reported that the considerable amount of X-ray radiation received by growing children with adolescent idiopathic scoliosis raised the risk of cancer by 2.4/1000. Furthermore, vertebral rotation of the spine is one of the essential parameters for assessing scoliosis as a 3-D deformity, predicting the curvature prognosis, and monitoring the progression [14—16]. However, vertebra rotation information in the traverse plane could not be directly obtained on standing posterior—anterior radiographs [15], resulting in failure to obtain an accurate degree of rotation on the radiograph. Apparently, a radiation-free system that can assess spine deformity on coronal, sagittal, and traverse planes is necessary for the mass screening, diagnosis, and follow-up observation for scoliosis.

Various nonradiation systems based on the skin surface contour of trunk have been developed for assessing scoliosis. Most of them are based on surface topography or optical techniques. Quantec spinal image system (Quantec Image Processing, Warrington, Cheshire, UK) applies Moire topography [17] to obtain surface topography of the patient with fringe pattern projection, in which a *Q* angle is used as a quantitative parameter for measuring the degree of asymmetry in the coronal plane. However, there is a considerable difference between the *Q* angle and the Cobb angle, with the maximum difference between *Q* and Cobb angles of 6° when the Cobb angle is $< 21^{\circ}$ [18]. Recently, the electromagnetic topographical technique was developed for scoliosis screening. Using this principle, the Ortelius 800 system (Orthoscan Technologies, Inc., Sherborn, MA, USA) records the position of the tip of the spinous process by palpating the patient's back with a position sensor attached on the examiner finger and builds a spine representative model for examining spinal deformities. However, the assessment is slightly subjective (ascribed to manual palpation) and vulnerable to spinous process deviation and traumatic damage. It was reported that the Orthoscan did not accurately measure the scoliosis curve [19]. Similarly, measurements using optical techniques are also inaccurate, which is ascribed to the indirect assessment of the spine deformity from trunk asymmetry indices, although the optical systems used for scoliosis examination provide noninvasive and noncontact measurements [9]. These radiation-free systems are less accurate than radiographs because they assess spine deformity indirectly from the body surface.

Radiation-free imaging modalities including ultrasound and magnetic resonance imaging (MRI) can also be used to measure spine curvature. MRI can provide adequate 3-D information for assessing the spine curvature. However, examination is routinely conducted with the patient placed in a supine position. It was revealed that the Cobb angle obtained in the standing posture is more accurate than the measurements performed in the supine posture [15]. MRI in the upright position has recently become commercially available, but it has yet to gain widespread acceptance. In addition, MRI examination is time consuming and expensive. Therefore, it is not feasible to use MRI in mass screening and longitudinal observation for scoliosis. By contrast, ultrasound imaging is a low-cost, widely available, and radiation-free imaging modality. It has been reported that the vertebra rotation can be derived with ultrasound imaging [20]. The feasibility of using landmarks in cross-sectional B-mode ultrasound images acquired with continuous scanning approach, including laminae and transverse process (TP) as the landmarks, to assess spine curvature has been demonstrated in *in vitro* experiments [21—23]. A number of 3-D ultrasound systems have been advanced to overcome the limitations of 2-D viewing of 3-D anatomy [22—31]. Purnama et al [29] showed that imaging of the human spine using freehand 3-D ultrasound was feasible, but no measurement of spine curvature angle was conducted. Ungi et al [30] reported about using ultrasound images collected along the sagittal direction with position information for spine curvature measurement. The TPs in ultrasound images acquired using the single snap approach were manually marked to devise the spatial information and calculate the TP angle for measuring vertebra orientation. Cheung et al [22,28] reported a method to form a 3-D spine profile by using spinous processes and TPs detected in 3-D ultrasound images of spine phantoms. Koo et al [23] compared different methods for measuring spinal curvature of spine phantoms using data collected with 3-D ultrasound imaging. The performance and accuracy of the aforementioned methods with freehand 3-D ultrasound have not been evaluated *in vivo*, and the effect of the patient posture was not taken into account in above studies. It has been reported that the muscle balance and standing stability can be significantly influenced by body postures [32,33]. Chen et al [34] reported a preliminary study with four scoliosis patients to demonstrate the feasibility of measuring spine curvature based on a coronal view image