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● *Original Contribution*

SPINAL CURVATURE MEASUREMENT BY TRACKED ULTRASOUND SNAPSHOTS

Tamas Ungi,* Franklin King,* Michael Kempston,† Zsuzsanna Keri,* Andras Lasso,* Parvin Mousavi,‡ John Rudan,† Daniel P. Borschneck,† and Gabor Fichtinger*

*Laboratory for Percutaneous Surgery, School of Computing, Queen's University, Kingston, Ontario, Canada; †Department of Surgery, School of Medicine, Queen's University, Kingston, Ontario, Canada; and ‡Medical Informatics Laboratory, School of Computing, Queen's University, Kingston, Ontario, Canada

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Abstract—Monitoring spinal curvature in adolescent kyphoscoliosis requires regular radiographic examinations; however, the applied ionizing radiation increases the risk of cancer. Ultrasound imaging is favored over radiography because it does not emit ionizing radiation. Therefore, we tested an ultrasound system for spinal curvature measurement, with the help of spatial tracking of the ultrasound transducer. Tracked ultrasound was used to localize vertebral transverse processes as landmarks along the spine to measure curvature angles. The method was tested in two scoliotic spine models by localizing the same landmarks using both ultrasound and radiographic imaging and comparing the angles obtained. A close correlation was found between tracked ultrasound and radiographic curvature measurements. Differences between results of the two methods were 1.27 ± 0.84° (average ± SD) in an adult model and 0.96 ± 0.87° in a pediatric model. Our results suggest that tracked ultrasound may become a more tolerable and more accessible alternative to radiographic spine monitoring in adolescent kyphoscoliosis. (E-mail: ungi@cs.queensu.ca)

Key Words: **Adolescent idiopathic kyphoscoliosis, Scoliosis, Kyphosis, Tracked sonography, Tracked ultrasound snapshot.**

INTRODUCTION

Kyphoscoliosis affects approximately 1 in 1000 individuals and causes severe spinal deformity in about 10% of these cases (Goldman et al. 2012). About 90% of cases of this disease are of the idiopathic type. It is discovered in adolescents (10–14 y) and progresses until the spine reaches full development (16–22 y of age). Kyphoscoliosis progression is monitored by quantitative measurement of the spinal curvature (Stokes et al. 1994), and treatment decisions are based on angles measured during monitoring. The curvature is most commonly quantified by the Cobb angle, defined between a line drawn parallel to the end-plates of vertebrae above and below the curvature. Cobb angles below 20° require only monitoring; Cobb angles between 20° and 40° can be treated by bracing to slow progression. Surgical treatment is advised when the Cobb angle exceeds 40° or when respiratory problems occur because of severe chest deformation.

The standard method used to diagnose and monitor progression of kyphoscoliosis is radiographic examination, which exposes the patient to ionizing x-ray radiation. Repeated radiographic examinations are linked to an increased risk of breast cancer development in girls with scoliosis (Doody et al. 2000; Hoffman et al. 1989). A more recent study found that radiographic diagnostics in childhood also contribute significantly to leukemia and prostate cancer (Schmitz-Feuerhake et al. 2011). This risk increases with cumulative radiation dose and is estimated to reach twofold compared with the baseline population risk.

Various technologies have been investigated in the past for radiation-free evaluation of scoliosis. Surface topographic methods estimate spine curvature from scans of the patient's skin obtained with a stereo camera, but they are not sufficiently precise, cannot assess vertebral rotation and cannot visualize the bone architecture (Goldberg et al. 2001). A recent surface topographic study reported differences up to 9° compared with radiographic Cobb angle measurement (Frerich et al. 2012). Special magnetic resonance imaging (MRI) machines offer accurate and tolerable evaluation of spinal curves in a standing

Address correspondence to: Tamas Ungi, School of Computing, Queen's University, 557 Goodwin Hall, Kingston, ON, Canada, K7 L 2 N8. E-mail: ungi@cs.queensu.ca

patient position, but MRI is more expensive and less accessible compared with other modalities (Diefenbach et al. 2013). Furthermore, MRI is not compatible with metallic implants and requires the patient to be motionless for several minutes. Ultrasound imaging provides tolerable visualization of the posterior surface of the spine and is more accessible than MRI or radiography. Portable ultrasound machines would allow spine monitoring, even in areas with no permanent medical imaging devices. A significant linear correlation was discovered between the radiographic Cobb angle and the vertebral rotation measured by ultrasound at the apical vertebra in untreated patients (Suzuki et al. 1989). This is a tolerable and real-time method for estimating spinal curvature (Li et al. 2010), but the correlation is relatively weak, and in patients who have begun treatment, the correlation is not observable anymore. Therefore, vertebral rotation measurement is not suitable for routine scoliosis monitoring. Another application of ultrasound imaging equips the transducer with position tracking. This opens new possibilities in ultrasound diagnostics, because a 3-D volume can be reconstructed from tracked 2-D ultrasound images. The reconstructed volumes reveal vertebral landmarks that enable measurement of spinal deformations (Purnama et al. 2010). *In vitro* experiments confirm that visible laminae could be used as landmarks to estimate the Cobb angle (Chen et al. 2011). Tracked ultrasound images can be used not only to reconstruct 3-D volumes, but to define anatomic landmarks in the 3-D tracking space. The tracked ultrasound snapshot technique uses recorded 2-D ultrasound images with spatial tracking information, and it has been successfully used in spinal interventions (Ungi et al. 2012). Zheng and Cheung (2011) proposed a method equivalent to the tracked ultrasound snapshot technique to localize vertebral landmarks along the spine and measure scoliosis angles from the lines connecting these landmarks. However, their method requires a wide ultrasound transducer to capture both sides of vertebrae in images in axial orientation. None of the ultrasound-based techniques have been translated into clinical practice yet.

We investigated tracked ultrasound snapshots in sagittal orientation for spinal curvature measurement using transverse processes as vertebral landmarks. A commercially available tracked ultrasound system with a standard linear transducer was used with freely available open-source software. We evaluated the accuracy of this method on two scoliotic spine models by comparing measurements with conventional radiographic measurements. Tests were done by three different operators to assess reproducibility.

METHODS

Experiment design

Vertebral angles measured by tracked ultrasound were evaluated by comparison with angles determined on radiographic images, which are considered the clinical standard in spinal curvature monitoring. All vertebral angles were measured relative to a reference line that was defined by averaging the angles of all vertebrae. Measurement of each vertebra relative to this reference line provided 17 samples (12 thoracic and 5 lumbar) in each phantom for our comparative study. The reference line is also not sensitive to errors in individual vertebral angles; therefore, other vertebrae do not contribute to the error in the measured angle of each vertebra.

Each vertebra orientation was measured by the transverse process angle (TxA), defined by a line between the lateral ends of the two transverse processes (Fig. 1) relative to the reference line. The TxA was chosen for our measurements because it can be directly visualized in both ultrasound and radiographic images. The most common radiographic landmarks used in scoliosis measurement are end-plates of vertebrae (Fig. 1), because they are clearly visible in human radiographs. However, end-plates are not visible on ultrasound images because of the acoustic shadowing from posterior anatomic structures. The TxA was clearly visible in radiographs, so the sonographic and radiographic modalities could be reliably compared in this study using the TxA.

Three physicians acted as operators and performed all measurements independently for inter-operator variability analysis. All operators were experienced in radiographic analysis of spine curvatures. Radiographic images for ground truth measurements were acquired using a GE Brivo XR (GE Healthcare, Waukesha, WI, USA) x-ray system.

All operators were asked to identify the two end-plates and to measure the TxA for each vertebra on radiographic images. Then, all operators performed the sonographic measurement protocol on the spine phantoms so that TxA measurements obtained with the two

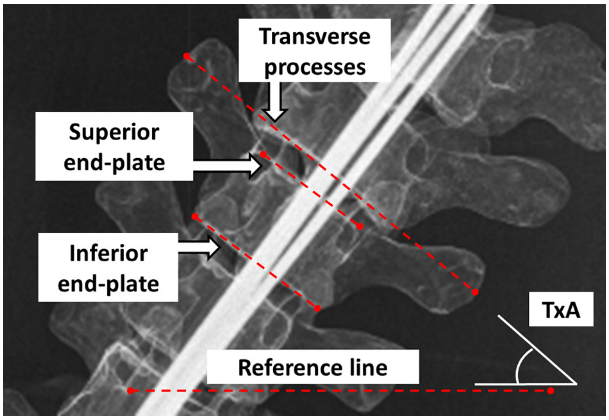

Fig. 1. Radiographic lines used for curvature measurement for a single thoracic vertebra in postero-anterior radiographic projection. TxA = transverse process angle.

modalities could be compared. We evaluated the inter-operator variability of sonographic TxA measurement against that of radiographic end-plate angle measurement, because the end-plate angle is currently considered the clinical standard in spine curvature measurement.

Tracked sonography system

The tracked ultrasound measurement system comprised a conventional ultrasound machine, a position tracker and a data acquisition computer (Fig. 2). A position sensor was rigidly fixed to the ultrasound transducer, and another position sensor (reference sensor) was attached to the patient's back to provide a reference coordinate system for position tracking. The reference sensor was placed in a plastic holder with anatomic direction marks so the system could show the acquired ultrasound images in an anatomic coordinate system for easier analysis of sonographic landmarks. We used an ultrasound machine integrated with an electromagnetic position tracker, the Sonix Tablet with GPS extension (Ultrasonix, Richmond, BC, Canada). This product integrates a Model 180 electromagnetic tracking sensor (Ascension, Milton, VT, USA) in the housing of the ultrasound transducer. According to data provided by the manufacturer, this sensor is tracked within a radius of 580 mm from the electromagnetic field generator with a static orientation error of 0.5°root mean square and position error of 1.4 mm root mean square. The GPS extension also exposes open tracker ports on the tracker system control unit (SCU), allowing us to add the reference sensor to the system. Ultrasound images and tracking data were processed and saved on a separate computer to reduce the computation load of the ultrasound machine.

Data processing software of the tracked sonography system was modularly designed for convenient adaptation to different ultrasound machines and tracker systems (Fig. 3).

A software interface to the hardware components was provided by the Public Software Library for Ultrasound Research (PLUS, www.plustoolkit.org) (Lasso et al. 2012). PLUS provided temporal synchronization between the imaging and tracking data, and provided calibration for accurate ultrasound image tracking. The processed tracked ultrasound data was sent by PLUS through the OpenIGTLink network communication protocol (Tokuda et al. 2009) to the end-user application. The end-user application was implemented as a downloadable extension for the 3-D Slicer application framework (www.slicer.org). It also used modules of the SlicerIGT extension (www.slicerigt.org). 3-D Slicer is a medical image processing, analysis and visualization software that facilitates the development of new prototype applications in the form of extensions (Fedorov et al. 2012). The software that we implemented and used for this study can be installed from the extension manager of the latest version of the 3-D Slicer application. The name of the extension is Scoliosis. All software used in this study is open-source, freely available for research or commercial use without any restrictions.

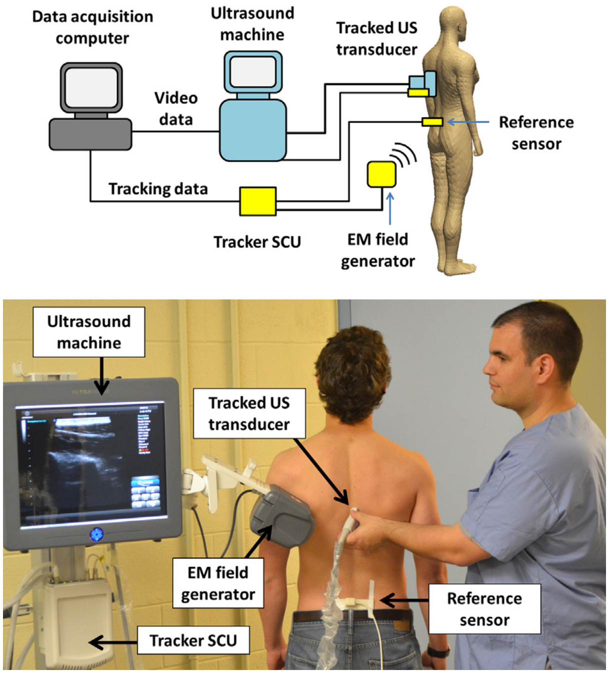

Fig. 2. Top: Schematics of a typical tracked sonography system. The electromagnetic tracker consists of a system control unit (SCU) and an electromagnetic (EM) field generator. The tracking sensors and the field generator are connected to the tracker SCU. Bottom: The tracked sonographic system in use. US = ultrasound.

Experimental phantom models

Scoliotic phantom models were used for evaluation of sonographic spine curvature measurement compared with conventional radiographic measurement. All tests were done on two phantom models, an adult spine (Item 1323-21, Sawbones, Vashon, WA, USA) and a pediatric spine (Item 1323-30, Sawbones). The spine models were treated with x-ray contrast material on the surface by the manufacturer for radiographic imaging. We placed them in agar/gelatin gel to enable ultrasound imaging (Madsen et al. 2005). Cellulose (2 g/L) provided acoustic speckle in the gel and made the gel optically opaque, so the spine was not visible in the phantom models. Photos of the phantoms were taken before placement in acoustic gel. The photos and corresponding radiographs are provided in Figure 4.

Sonography protocol

Tracked ultrasound data were collected using an Ultrasonix L14-5 GPS transducer (Ultrasonix), at a

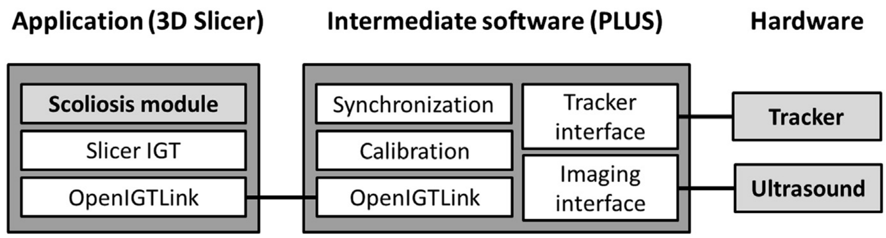

Fig. 3. Software architecture overview of the scoliosis evaluation application.

frequency of 5 MHz and imaging depth of 60 mm. The imaging focus was set at 40 mm as a typical distance of transverse processes from the skin. Gain and dynamic range were adjusted by each operator to create clear visual contrast between bone surface reflections and background soft tissue. All other imaging parameters were set to the manufacturer's default values for musculoskeletal imaging of the ultrasound machine. No filtering algorithms were applied to the images captured directly from the ultrasound machine. Standard water-based ultrasound gel was used for acoustic connection between the phantom and the transducer surface. Transverse processes in the spine were visible at similar imaging settings in both humans and phantom models (Fig. 5).

Angle measurement protocol

Transverse process angles of vertebrae were defined between midpoints of transverse processes as seen on cross sections in ultrasound images parallel to the spine (Fig. 6). The lateral ends of the processes were scanned for consistent measurements. After finding the vertebra, the operator scanned from the side toward the midline until the transverse process was clearly visible. Tracked ultrasound snapshots were taken in these positions on both sides for each vertebra for measurement of the TxA. The transverse process midpoints were manually selected on these ultrasound snapshots where the operator estimated the middle of the acoustic shadow of the transverse process at the bone surface level.

To conveniently find the optimal transducer positions on the skin for TxAs, the midline of the spine was marked on the gel surface along spinous processes. The marked midline significantly reduced scanning time for curvature measurement, which may become an important factor because young patients may not be able to maintain a straight posture for an extended time. The total scanning time was <2 min in all experiments.

Measurements of TxAs were performed after sonographic data acquisition, using the *ruler* annotation tool and the *Scoliosis* module of the 3-D Slicer application. Figure 7 illustrates sonographic TxA measurements in the measurement software. Recorded sonographic snapshots can be individually hidden from the visualization scene, so only the two snapshots of one vertebra are

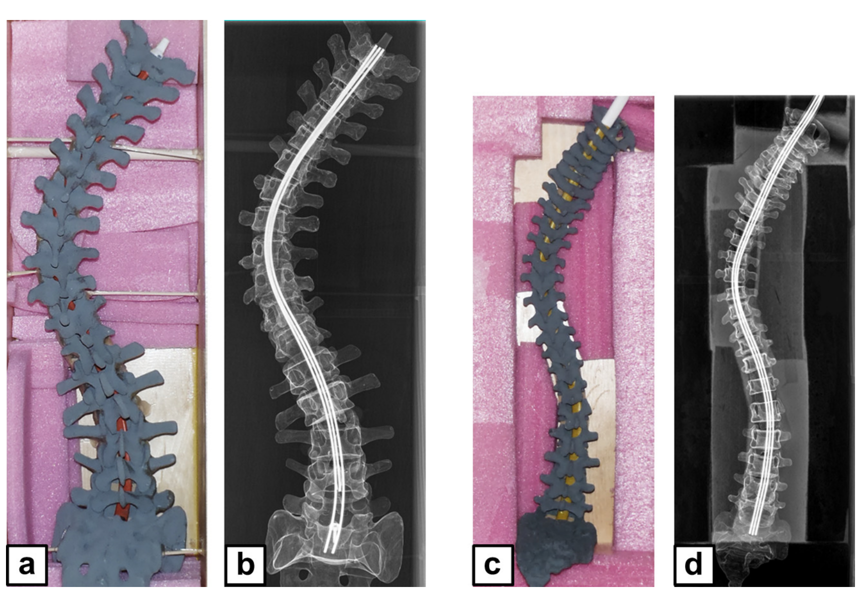

Fig. 4. Experimental phantom models of adult (a) and pediatric (c) scoliotic spines before placement in acoustic gel. (b, d) Corresponding radiographic images.

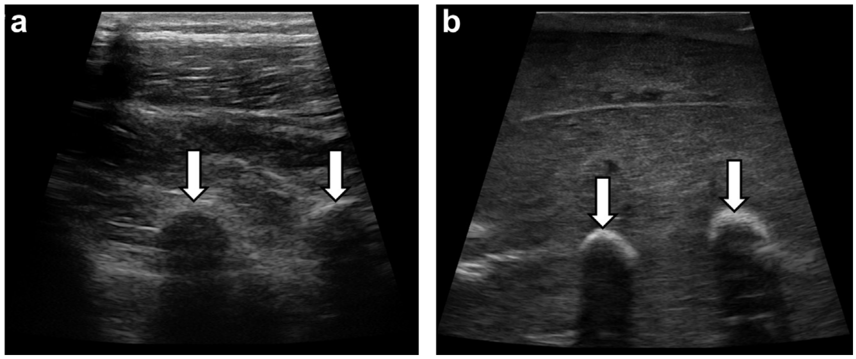

Fig. 5. Paramedian ultrasound images of a human spine (a) and a phantom spine model (b). Arrows point to spinal transverse processes. Both images were acquired at 60-dB dynamic range and 50% gain.

displayed during measurement to avoid obstruction by other segments when defining individual TxA lines.

Radiographic measurements were done on postero-anterior radiographic images, by manually placing lines at the superior and inferior end-plates of each vertebra and along the transverse processes (Fig. 1).

Statistical analysis

Inter-operator differences were computed as pairwise absolute differences between the three operators and are expressed as the average ± standard deviation of differences. To compare inter-operator differences between radiographic end-plate measurement and sonographic TxA measurement, we used the one-tailed independent sample *t*-test with Bonferroni correction for repeated experiments (adult and pediatric). Sonographically and TxA and radiographically determined TxAs were compared using linear correlation. Absolute differences between corresponding measurements from the two modalities were also expressed as the average ± standard deviation.

RESULTS

Average inter-operator differences are summarized in Figure 8. The inter-operator difference was

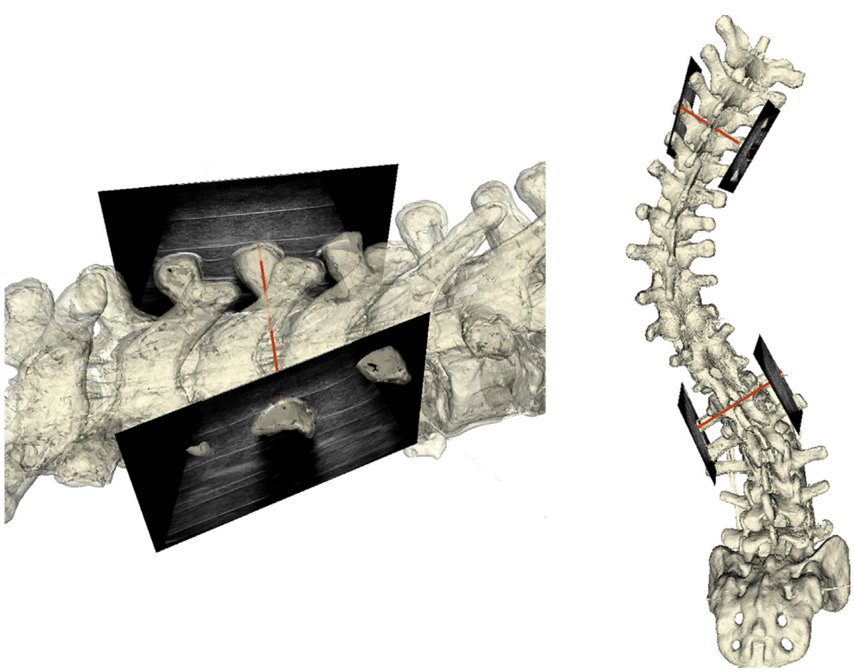

Fig. 6. Transverse process angle (TxA) measurement. Left: Ultrasound snapshots taken on both sides of a vertebra, and the sonographic landmarks connected for definition of TxA. Right: Two TxA lines for the major curvature of this spine model. Surface models for this illustration were generated from a computed tomography scan and are not present in the actual measurement software.

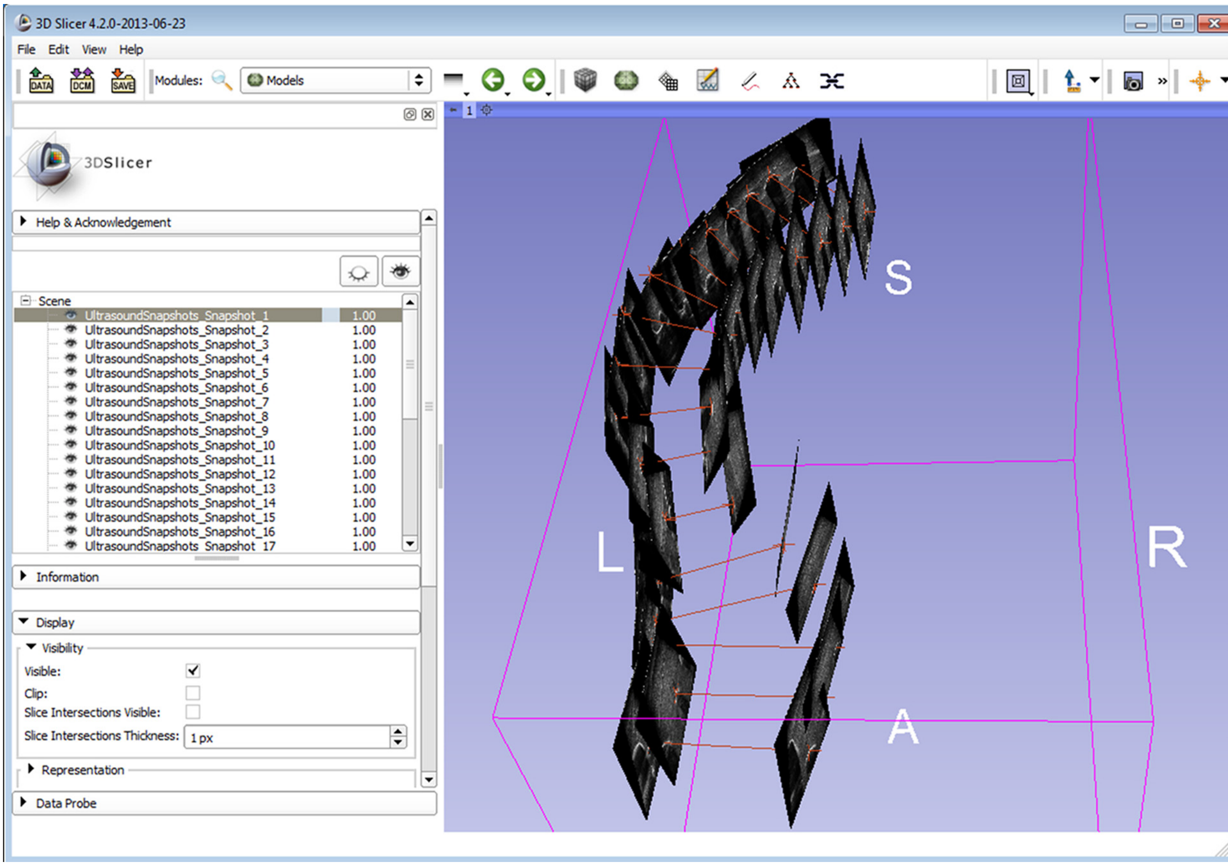

Fig. 7. Left: User interface of application for spinal curvature measurement. Right: Transverse process angle lines and ultrasound snapshots for all segments of the adult spine model.

significantly lower with sonographic measurement than with radiographic end-plate angle measurement, which is the current clinical standard in spinal curvature assessment.

Correlation of sonographic and radiographic angles is illustrated in Figure 9. The coefficient of correlation between all sonographic TxAs and radiographic TxAs by all operators is $R = 0.998$ in the adult phantom and $R = 0.997$ in the pediatric phantom. The difference between sonographically and radiographically determined TxAs is $1.27 \pm 0.84°$ in the adult model and $0.96 \pm 0.87°$ in the pediatric model. The maximum difference between the two methods is 3.4°.

DISCUSSION

There were smaller inter-operator differences in sonographic TxA measurement than in radiographic measurements. This suggests that sonographic TxA measurement is a repeatable method for measuring spinal curvature. In our comparison between sonographic and radiographic TxA measurements, we found a very strong correlation between the two modalities. This indicates that sonographic spinal curvature measurement may be as reliable as the conventional radiographic method.

The main limitation of our experiment was that the phantom models were rigid, unlike patients who may move and change the curvature of their spine during ultrasound imaging. After gaining experience in sonographic

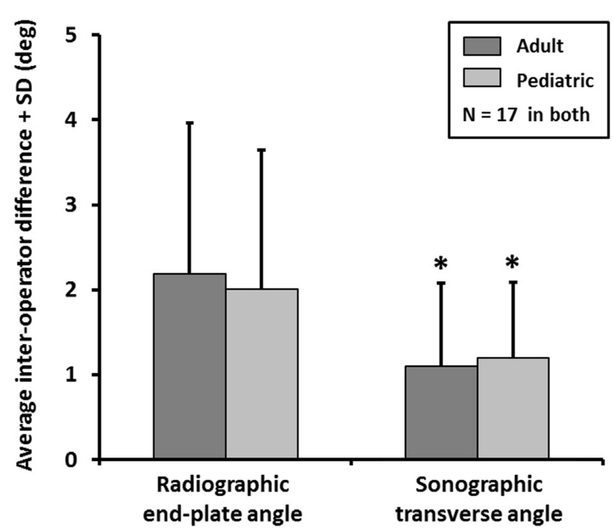

Fig. 8. Average inter-operator differences in radiographic and sonographic transverse process angle measurements. $*p < 0.05$ versus radiographic measurement.

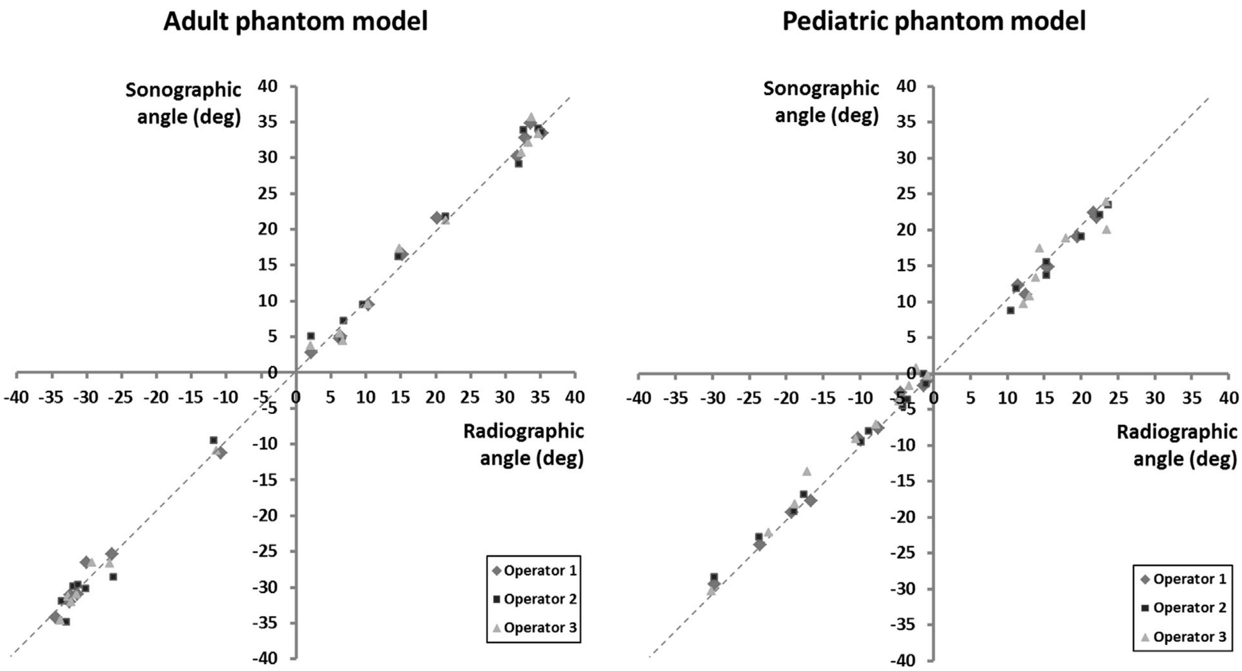

Fig. 9. Scatterplot of sonographic transvers process angle (vertical axis) versus radiographic transverse process angle (horizontal axis) in adult and pediatric models. Measurements by different operators are marked by different glyphs. Ideal correlation is represented by the *dashed line* on both diagrams.

TxA measurement, our operators completed the full scanning process within 2 min. Most adolescents can maintain a straight standing posture for this period. If additional support is needed for younger patients, an assistant may hold the patients' shoulders from the sides during imaging without interfering with their postures. Final proof of practical usability, however, can be achieved only by a future clinical study. Additionally, our phantoms exhibited higher contrast between bone and soft tissue compared with clinical images (Fig. 5). This higher contrast may positively affect the accuracy of measurements. Therefore, accuracy should also be investigated in a future patient study.

Another important technical limitation reported by our operators is that sonographic landmarks of the transverse processes should be defined manually at each spinal segment. Landmarking occurs off-line after the scan. If all vertebral segments are analyzed, it may take up to 6 min for one patient. This time could be reduced in follow-up cases when the segments characterizing the main curvatures of the spine are already identified and other segments may be omitted. Future image processing development may also enable automatic vertebra recognition, completely eliminating the need for manual landmark definitions.

Magnetic resonance imaging has revealed that a significant proportion of vertebra rotation in scoliosis is due to the plastic deformation within the vertebrae themselves, not only the deformation of the discs (Birchall et al. 2005). This suggests that the Cobb angle thresholds defined in current clinical protocols by the angle of end-plates may not be directly applicable to TxA values, because the end-plates may deform relative to the transverse processes. If TxA measurement is to be introduced into clinical practice, therapeutic recommendations may be established only after patient follow-up studies. Therefore, TxA cannot immediately replace conventional Cobb angle measurement in the near future.

Tracked ultrasound measurement has a number of potential advantages compared with conventional radiography. The increased risk of cancer development in children monitored by x-ray imaging may be lowered to the baseline population level. The cost of installation and the footprint of tracked ultrasound systems are only a fraction of that for radiography systems. This may facilitate wider accessibility and lower the cost of patient follow-up in adolescent kyphoscoliosis. Finally, tracked sonographic measurement provides vertebra landmark points in 3-D space; therefore it allows vertebra rotation angle measurement besides scoliotic curvature measurement. This additional information on spinal deformity may prove to be useful in risk assessment and therapeutic decision making in the future.

Our experiments were done using an electromagnetic position tracker. Although the tracking field is sufficiently large for scanning an adult spine, the signal-to-noise ratio decreases as the tracking sensor moves away from the field generator. Therefore, optical position tracking of the ultrasound transducer may seem to be a more suitable alternative, especially when electromagnetic noise can be present in the examination room. However, in our experiments, TxA accuracy compared with radiographic ground truth did not depend on distance from the field generator, which suggests that the currently available commercial tracked ultrasound systems using electromagnetic tracking are also suitable for sonographic scoliosis monitoring.

Although many different metrics were developed and studied in past decades, computerized automatic measurement of spinal deformities remains a challenging task (Vrtovec et al. 2009). Our sonographic method is still dependent on the operator's selection of landmarks for TxA definition. However, the number of user interactions in tracked sonographic curvature measurement is comparable to that in radiographic methods. The low inter-operator variability found in our study also suggests that tracked ultrasound could become a reliable diagnostic and monitoring tool in scoliosis. In comparison, radiographic methods also have significant limitations (Kim et al. 2010). The variability in radiographic Cobb angle measurement is reported to be 2°–7° (Malfair et al. 2010; Sardjono et al. 2013). The angle measurement of the same curve is reported to increase by 5° in the afternoon compared with measurement in the morning (Beauchamp et al. 1993).

CONCLUSIONS

We conclude that tracked sonographic transverse process angle measurement is a promising method in kyphoscoliosis monitoring. If future human subject studies support our results, it may become the recommended modality over radiography because of its tolerability, reproducibility, portability and low cost.

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