Assessment of Scoliotic Deformity Using Spinous Processes: Comparison of Different Analysis Methods of an Ultrasonographic System

Terry K. Koo, PhD,[a] Jing-Yi Guo, PhD,[b] Christina Ippolito, DC,[c] and Jamie C. Bedle, DC[d]

Abstract

Objective: The purpose of this study was to evaluate the performance of 5 analysis methods in quantifying scoliotic deformity, using the spatial positions of SP tips acquired by a custom-developed ultrasound-based system, with different curve fitting methods and angle metrics in terms of their correlation with Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae and convexity direction.

Methods: Three spinal column dry bone specimens were randomly configured to 30 different scoliotic deformities. Raw spatial data of the SP tips were processed by the following 3 methods: (1) fifth-order polynomial fitting, (2) locally weighted polynomial regression (LOESS) with smoothing parameter (α) = .25, and (3) LOESS with α = .4. Angle between the 2 tangents along the spinal curve with the most positive and negative slopes (ie, posterior deformity angle) and summation of the angles formed by every 2 lines joining 3 neighboring SPs between the end vertebrae (ie, accumulating angle) were computed to quantify scoliotic deformity. Their performances were compared in terms of their correlation with Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae.

Results: Posterior deformity angle calculated from the spinal curve constructed by LOESS with α = .4 excelled in every aspect of the comparison (ie, Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae and convexity direction), making it the method of choice of those tested for processing the spatial data of the SP tips in this ultrasonography study using dry bone specimens.

Conclusions: The ultrasound-based system and the LOESS (0.4)–posterior deformity angle method developed for this study offer a viable technology for quantifying scoliotic deformity in a reliable and radiation-free manner. However, further validation using scoliosis subjects is needed before they can be used to quantify spinal deformity in the clinical setting. (J Manipulative Physiol Ther 2014;37:667-677)

Key Indexing Terms: *Scoliosis; Instrumentation; Spine; Safety; Ultrasonography*

The Cobb angle is the criterion standard for clinical evaluation and monitoring the progression of scoliotic deformity.[1] It is the angle between 2 lines drawn parallel to the end plates of the most tilted vertebral bodies at the upper and lower ends of a spinal curve on a standing posteroanterior (PA) or anteroposterior (AP) radiographs.[1] However, when the Cobb angle method is used, scoliosis patients are routinely exposed to harmful ionizing radiation regardless of their curve severity.[2] Given that ionizing radiation is dangerous even at low doses and that there are no safe limits,[3] alternative methods that could accurately and reliably quantify scoliotic deformity while minimizing ionizing radiation exposure are highly favorable in clinical settings.

Taking advantage of the superficial and palpable nature of the tips of spinous processes (SPs), several groups have developed radiation-free methods such as photogrammetry-based[4,5], video-based[6], electromagnetic tracking[7,8] and electromechanical[9] digitization to acquire their spatial positions and used them to quantify spinal

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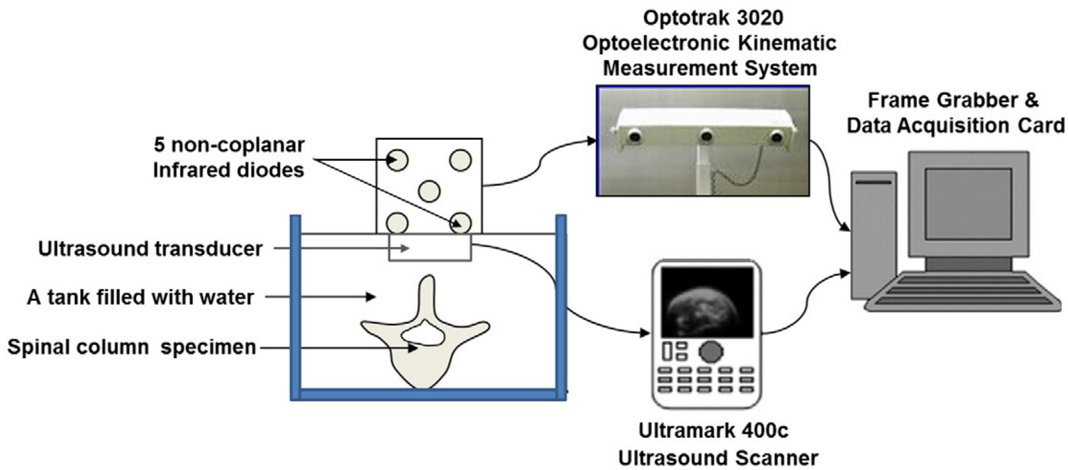

Fig 1. *A schematic diagram illustrating the ultrasound-based system and the experimental setup for the validation experiment. (Color version of figure is available online.)*

deformity. Others used a tracked ultrasound transducer to acquire a stack of ultrasound images along the scoliotic spine and relied on the hyperechoic appearance of the SP tips within these images to determine their spatial locations.[10,11]

No matter which approaches are being used to acquire the spatial positions of the SP tips, these data need to be further processed to construct a spinal curve, and some kind of angle metrics need to be defined and measured from the spinal curve to quantify scoliotic deformity. However, these procedures either were not explicitly described in the literature[6,8] or had inherent limitations.[7,9-11] Li et al [10] appeared to use raw spatial data of the SP tips directly without doing any curve fitting or smoothing and defined an angle metrics called accumulating angle (ACA) (ie, the summation of the angles formed by every 2 lines joining 3 neighboring SPs within a specific spinal region, eg, T1 to L1) to quantify scoliotic deformity. However, their method only quantifies the degree of deformity over a preselected spinal region, not the most affected spinal region. Given that the clinical criterion standard (ie, Cobb angle) indeed quantifies scoliotic deformity at the most affected spinal region, a better metric for scoliosis assessment should possess this characteristic. In addition, if raw spatial data of the SP tips are used directly, ACA would be prone to substantial errors if their coordinates are not properly located. To overcome these problems, some researchers used high-order polynomials to curve fit the SP tips and quantified spinal curvature at a specific spinal region by measuring the angle between the tangents at 2 predefined vertebral levels.[7,9] However, high-order polynomial fittings tend to oscillate severely near the end points of the data ranges. This may lead to extreme error when estimating the derivative near the end points. Another weakness of polynomial fittings is that they are "nonlocal," meaning that the fitted value of y at a given value of x_0 depends strongly on data values with x far from x_0.[12]

To overcome these limitations, we developed new analysis procedures to objectively quantify scoliotic deformity using the locations of SP tips acquired by a custom-developed radiation-free ultrasound-based system. We proposed to use a "local" smoothing technique, namely, locally weighted polynomial regression (LOESS) to curve fit the SP tips projected to the coronal plane, construct a spinal curve, and calculate the angle between 2 tangents along the spinal curve with the most positive and negative slopes (ie, the posterior deformity angle [PDA]). To test this method, the performance of this new analysis procedure needed to be compared with existing analysis methods reported in the literature[7,9,10] in terms of their correlation with Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae. We hypothesized that the new analysis procedure would provide a better estimate of scoliotic deformity. Therefore, the purpose of this study was to evaluate the performance of 5 analysis methods in quantifying scoliotic deformity, using the spatial positions of SP tips acquired by a custom-developed ultrasound-based system, with different curve fitting methods and angle metrics in terms of their correlation with Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae and convexity direction.

Methods

Descriptions of the Ultrasound-Based System

An ultrasound-based system was developed to locate the 3-dimensional (3D) coordinates of each SP tip with respect to a common laboratory coordinate system [L]. The

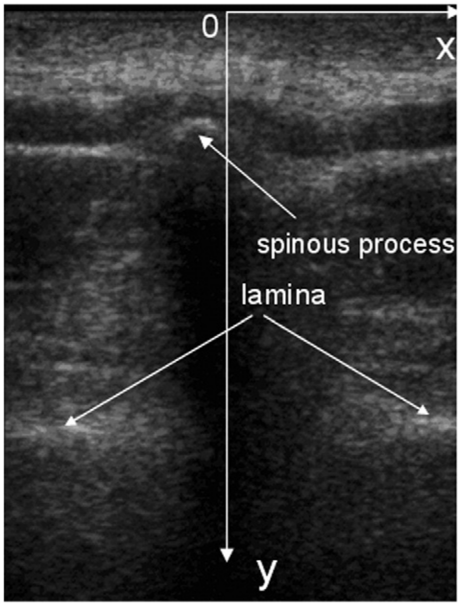

Fig 2. *Ultrasound image of a human vertebra. A local coordinate system was defined with its x-y plane aligned with the ultrasound image and its origin located at the center of the upper border of the image.*

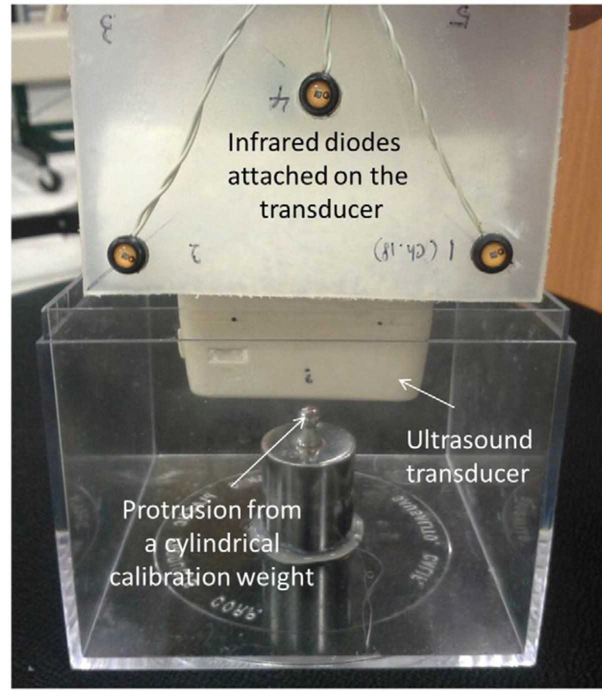

Fig 3. *The experimental setup for validating the ultrasound-based system to digitize spatial positions. (Color version of figure is available online.)*

laboratory coordinate system was defined such that the x-y and y-z planes corresponded to the coronal and sagittal planes, respectively. The ultrasound-based system consists of an ultrasound scanner (Ultramark 400c; ATL Ultrasound Inc, Bothell, WA) with a 6.5 to 10 MHz linear transducer to image the SP, an optoelectronic measurement system (Northern Digital Inc, Waterloo, Canada) with 5 noncoplanar infrared diodes attached on the ultrasound transducer to keep track of the transducer's pose with respect to the laboratory coordinate system and a personal computer with a frame grabber (PCI-1411) and a data acquisition card (PCI 6024E) (National Instruments Corporation, Austin, TX) installed for capturing the ultrasound images and synchronized with the pose data of the ultrasound transducer (Fig 1).

A local coordinate system [*l*] was defined on the ultrasound transducer such that its x-y plane aligned with the ultrasound image captured by the ultrasound scanner and its origin located at the center of the upper border of the ultrasound image. Local coordinates of each SP tip were digitized from its corresponding ultrasound image based on its hyperechoic appearance (Fig 2). Coordinate transformation was then performed at each SP tip to transform its coordinates from the local coordinate system to the common laboratory coordinate system:

$$P_L = {}^{L}T_l \cdot P_l \qquad (1)$$

where, ${}^{L}T_l$ is a transformation matrix[13] tracked by the optoelectronic measurement system, which represents the relative position and orientation of the local coordinate system [*l*] with respect to the laboratory coordinate system [L], and P_l *and* P_L represent the coordinates of the SP tip with respect to the local and laboratory coordinate systems, respectively.

Validating the Ultrasound-Based System

To validate the ultrasound-based system developed in this study to digitize spatial positions, we digitized the 3D coordinates of the tip of a protrusion from a cylindrical calibration weight (Fig 3) using the ultrasound-based system and compared with its true coordinates. The true coordinates were measured using a digitizing probe (Northern Digital Inc) with an accuracy of ±0.1 mm in x and y axes and ±0.2 mm in z axis, respectively. Three repeated measurements were made by each measurement method, and their mean coordinates were compared. Distance between the mean coordinates digitized by the 2 methods was then used to evaluate the measurement accuracy of the ultrasound-based system. Once confirmed, its validity to quantify scoliotic deformity was further evaluated.

Quantifying Scoliotic Deformity Using SPs

Three dry bone specimens of human spinal columns were systematically configured to 30 different scoliotic deformities (ie, 10 configurations per specimen) by 3 student helpers so that they covered a wide range of deformities in terms of deformity magnitude, convexity direction (ie, left and right), and curve type (ie, single vs double curves). Vertebrae within each specimen were articulated with each other by nylon string, which provides the flexibility to mimic different scoliotic deformities. All specimens were directly purchased from The Bone Room (Berkeley, CA) and used "as is." No information regarding their sex and ethnicity was available. According to the supplier website (https://www.boneroom.com), most bones are from India and China, and most are male. Nonetheless, sex and ethnicity of the specimens should have no effects on the validity of our data. All specimens used in this study are unique because they are real bones from different individuals. The use of dry bone specimens instead of human subjects in this validation experiment facilitated direct digitization of the SP tips, which provided a reference standard to better evaluate the validity of using the ultrasound-based system to quantify scoliotic deformity. It also ensured that all measurements (ie, ultrasound-based digitization, direct digitization, and PA radiograph) were made at the same pose, allowing more direct comparisons between measurement methods. Hence, it represents an essential and logical step of the validation process.

For each deformity configuration, we glued the specimen to the base of a rectangular box using hot melt adhesive and submerged the specimen with water (Fig 1). Hot melt adhesive is a form of thermoplastic adhesive that is commonly supplied in solid cylindrical sticks of various diameters, designed to be melted in an electric hot glue gun. Posterior tubercle of C1 and SP tips from C2 to L5 were then digitized using both the ultrasound-based system and the digitizing probe (ie, reference standard). During the ultrasound-based localization, although the examiner was not blinded to the curve type and magnitude, she was instructed to locate the SP tips based solely on their appearance within the ultrasound images without direct visualization of the specimen through the water.

To quantify scoliotic deformity, the spatial positions of the SP tips were processed by 5 different analysis methods:

(1) LOESS (0.25)–PDA and (2) LOESS (0.4)–PDA

In these methods, we used locally weighted polynomial regression (LOESS) with a smoothing parameter (α) set to .25 and .4, respectively to smooth the SP tips projected on the coronal plane, construct a spinal curve, and calculate a new angle metric called *PDA* to quantify scoliotic deformity. LOESS combines much of the simplicity of linear least squares regression with the flexibility of nonlinear regression. It does this by fitting simple models to localized subsets of the data to build up a function that describes the deterministic part of the variation in the data, point by point.[14] At each SP tip (ie, target SP), the LOESS method fitted a second-order polynomial to a subset of SP tips near the target SP, with coefficients of the local polynomial being estimated by weighted least squares algorithm, giving more weight to SP tips near the target SP and less weight to SP tips further away. The subset of SP tips used for each weighted least squares fit in LOESS comprised $n \cdot \alpha$ points (rounded to the next largest integer) that were closest to the target SP tip. Herein, n denoted the number of SP tips being fitted (ie, n = 24; C1-L5), and α was a smoothing parameter. With α = .25 and .4, these corresponded to the use of 6 (ie, 24 × 0.25) and 10 (ie, 24 × 0.4) closest SP tips respectively to fit a local polynomial to each target SP. Hence, α = .4 would produce a smoother spinal curve that wiggles less in response to fluctuations of the SP tips when compared with α = .25 (Fig 4). The value of the regression function at each SP tip was then obtained by evaluating the corresponding local polynomial. The LOESS fit was complete after the coefficients of the local polynomial had been computed for each SP tip. Once the spinal curve was constructed, PDA at the coronal plane was determined by differentiating the local polynomial at each SP tip, identifying the tangents with the most positive and negative slopes, and calculating the angle between them. The definition of PDA resembled that of the Cobb angle except that the posterior elements (ie, SPs) instead of the anterior elements (ie, vertebral bodies) were being used to quantify the degree of scoliotic deformity. This analysis method also allowed for automatic identification of the end vertebrae of the scoliotic deformity.

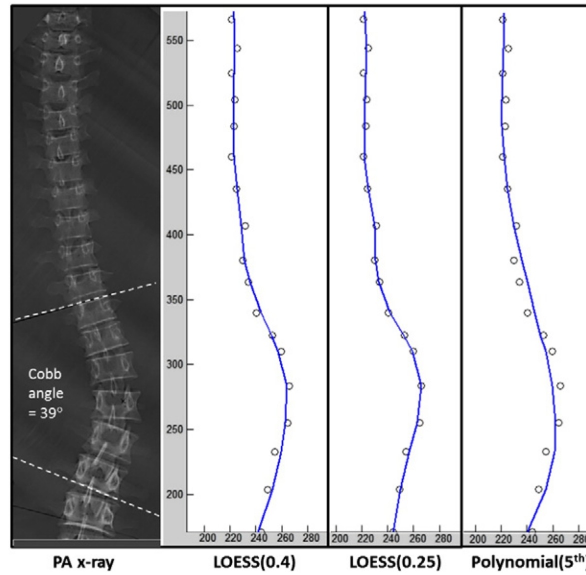

Fig 4. *From left to right, PA radiograph of a deformity configuration and its corresponding spinal curve constructed by LOESS (0.4), LOESS (0.25), and polynomial (fifth), respectively using the spatial positions of the SPs acquired by the ultrasound-based system. Units in millimeter. (Color version of figure is available online.)*

(3) Polynomial (fifth)–PDA

This method curve fitted all SP tips using a fifth-order polynomial (Fig 4) as proposed by Singh et al[7] and calculated the angle between the 2 tangents along the spinal curve with the most positive and negative slopes.

(4) Raw-ACA

This method used the raw spatial data of the SP tips as suggested by Li et al[10] to calculate the summation of the angles formed by every 2 lines joining 3 neighboring SPs (ie, ACA) between the end vertebrae identified by LOESS (0.4). We opted to identify the end vertebrae using LOESS (0.4) because end vertebrae identified by this method were shown to be most closely resemble with those identified by a radiologist (JB) from the PA radiograph who was blinded to the results of the ultrasound methods (see results).

(5) LOESS (0.4)–ACA

The ACA between the end vertebrae identified by LOESS (0.4) was also calculated from the spatial positions of the SP tips that were smoothed by LOESS (0.4).

All computations including coordinate transformation, smoothing/curve fitting, and angle metric calculation were implemented within a custom-developed program using Matlab and curve fitting toolbox (Mathwork Inc, Natick, MA).

Data Analysis

Two repeated measurements were made by each measurement system (ie, ultrasound-based system and digitizing probe), and the average of the 2 measurements was used for further analyses. For each analysis method, absolute mean difference of the angle metric between the 2 systems was calculated. Paired *t* test was used to test for any significant difference of the angle metric between systems. Such analyses aimed to reveal the potential effects of digitization errors on each angle metric determined by the 5 analysis methods. For each system-method combination, test-retest reliability was determined using intraclass correlation coefficient (ICC) based on a single-rating, absolute-agreement, 2-way mixed effect model (ie, $ICC_{3,1}$).[15]

Upon completion of the validation experiment of the first specimen, we decided to take a step further to evaluate the correlations between the angle metrics determined by the ultrasound-based system and the Cobb angle using Pearson correlation coefficient (*r*). Hence, we also acquired PA radiographic images from each configuration of the second and the third bone specimens (ie, 20 deformity configurations) and had the Cobb angles independently measured by a radiologist (JB). All PA radiographs were taken with the focal-film and object-film distances set to 40 and ½ in, respectively.

Using the end vertebrae identified by the radiologist from the PA radiographs as reference standard, we evaluated the relative accuracy of 3 different identification methods (ie, LOESS [0.25], LOESS [0.4], and polynomial [fifth]) to automatically locate the end vertebrae and convexity direction. For each identification method, we calculated the end vertebra identification score (S_{EV}) for each deformity configuration. We defined S_{EV} as the mean absolute difference in end vertebra level from the reference level. According to the definition, $S_{EV} = 0$ represents perfect agreement from the reference. For instance, if T6 and T7 (it is possible that more than 1 vertebra have similar slopes) and L2 are identified as the cephalad and caudad end vertebrae, respectively by the PA radiograph, and T8 and T12 are the cephalad and caudad end vertebrae identified by an identification method, the absolute difference in cephalad and caudad end vertebra level will be 1 (because T8 is 1 level below the nearest reference cephalad end vertebra) and 2 (because T12 is 2 levels above the reference caudad vertebra), respectively, and hence, S_{EV} will equal 1.5. Nonparametric-related samples Friedman 2-way analysis of variance by ranks tests were used to compare S_{EV} among the 3 identification methods. Separated analyses were conducted for each measurement system. All statistical analyses were conducted using SPSS statistical package version 19 (IBM SPSS, Armonk, NY). For all tests, a *P* value less than .05 was considered significant.

Table 1. *Comparisons of Scoliotic Deformity Measurements Calculated by 5 Different Processing Methods*

Processing Method	PDA_u/ACA_u (Degrees) [a] (Mean ± SD)	PDA_d/ACA_d (Degrees) [b] (Mean ± SD)	Absolute Difference (Degrees) (Mean ± SD)
LOESS (0.25)–PDA	68.2 ± 17.4	68.3 ± 17.1	2.4 ± 2.2
LOESS (0.4)–PDA	62.8 ± 14.6	62.7 ± 14.8	1.0 ± 0.7
Polynomial (fifth)–PDA	63.6 ± 16.1	64.2 ± 16.6	1.6 ± 2.1
Raw-ACA	103.2 ± 34.8	108.2 ± 40.7	14.4 ± 14.2
LOESS (0.4)–ACA	60.9 ± 14.0	60.9 ± 14.3	1.6 ± 1.5

ACA, accumulating angle; *LOESS*, locally weighted polynomial regression; *PDA*, posterior deformity angle.

[a] The PDA_u and ACA_u stand for PDA and ACA, respectively measured by the ultrasound-based system.

[b] The PDA_d and ACA_d stand for PDA and ACA, respectively measured by the digitizing probe. All values reported here were based on the measurements of 30 deformity configurations.

Results

The mean distance (±SD) between the same landmark (ie, the tip of the reference object) digitized by the ultrasound-based system and the digitizing probe was 1.5 ± 0.4 mm, confirming the validity of using the ultrasound-based system to digitize 3D coordinates of the SP tips.

Table 1 summarized the mean (±SD) of the angle metrics (ie, PDA or ACA depending on the analysis method) calculated by (1) LOESS (0.25)–PDA, (2) LOESS (0.4)–PDA, (3) polynomial (fifth)–PDA, (4) raw-ACA, and (5) LOESS (0.4)–ACA using the spatial data acquired by the ultrasound-based system and digitizing probe (ie, the reference standard), respectively as well as their mean absolute differences. As expected, analysis methods do affect the calculation of both PDA and ACA. Paired *t* tests

Table 2. *Comparisons of the Test-Retest Reliability Among the 5 Analysis Methods*

Processing Method	ICC Ultrasound-Based Measurement	ICC Digitizing Probe Measurement
LOESS (0.25)–PDA	0.987	0.991
LOESS (0.4)–PDA	0.993	0.996
Polynomial (fifth)–PDA	0.983	0.994
Raw-ACA	0.648	0.833
LOESS (0.4)–ACA	0.965	0.995

ACA, accumulating angle; *ICC*, intraclass correlation coefficient; *LOESS*, locally weighted polynomial regression; *PDA*, posterior deformity angle.

revealed no significant difference in angle metric calculation between measurement systems for LOESS (0.25)–PDA ($P = .928$), LOESS (0.4)–PDA ($P = .709$), polynomial (fifth)–PDA ($P = .214$), and LOESS (0.4)–ACA ($P = .949$). However, ACA calculated from the raw spatial data was significantly different between measurement systems ($P < .001$), indicating that raw-ACA is highly sensitive to digitization artifacts of the SP tips. Descriptively, LOESS (0.4)–PDA had the smallest mean absolute difference among all analysis methods.

Except raw-ACA, test-retest reliability of all analysis methods was excellent with LOESS (0.4)–PDA being the best (Table 2). As expected, test-retest reliability of the digitizing probe was consistently better than the ultrasound-based system, no matter which analysis methods were used. However, this benefit was minimal if some kind of curve fitting or smoothing techniques were incorporated to process the spatial data of the SP tips.

The mean Cobb angle of the 20 deformity configurations was 49.0° (SD, 11.8°; range, 25°-74°) with one-half convex to the right and another half convex to the left. The correlations between Cobb angle and angle metric of each analysis method are plotted in Figure 5. Among the analysis methods, LOESS (0.4)–PDA ($r = 0.918$ for PDA_u and $r = 0.909$ for PDA_d) and LOESS (0.4)–ACA ($r = 0.900$ for ACA_u and $r = 0.915$ for ACA_d) appeared to have the best correlations with the Cobb angle, followed by LOESS (0.25)–PDA ($r = 0.863$ for PDA_u and $r = 0.838$ for PDA_d), then polynomial (fifth)–PDA ($r = 0.793$ for PDA_u and $r = 0.760$ for PDA_d), and raw-ACA was the worst ($r = 0.170$ for ACA_u and $r = 0.006$ for ACA_d); where, the subscripts u and d stand for the measurements made by the ultrasound-based system and the digitizing probe, respectively. In addition, regression analysis revealed that only LOESS (0.4)–PDA and LOESS (0.4)–ACA had their y intercepts in close proximity to zero (Fig 5). Taking together, LOESS (0.4)–PDA and LOESS (0.4)–ACA appear to be the best measures of scoliotic deformity among all tested analysis methods.

The mean (±SD) S_{EV} of LOESS (0.4), LOESS (0.25), and polynomial (fifth) methods were 0.71 ± 0.81, 0.99 ± 1.56, and 3.06 ± 4.72, respectively for the ultrasound-based system and 0.79 ± 0.81, 0.93 ± 0.94, and 3.56 ± 5.23, respectively for the digitizer probe. Friedman 2-way analysis of variance by ranks revealed that S_{EV} of the LOESS (0.4) method was significantly smaller than that of the polynomial (fifth) method ($P = .017$ for both the ultrasound-based system and the digitizing probe). Although no significant difference between LOESS (0.4) and LOESS (0.25) was revealed ($P = .912$ and $P = 1.00$ for the ultrasound-based system and digitizing probe, respectively), LOESS (0.4) appears to have the best relative accuracy among the 3 identification methods. On the other hand, convexity direction of all deformity configurations was successfully identified by both LOESS (0.4) and LOESS (0.25), but polynomial (fifth) only correctly identified 80% of the cases.

Discussion

We successfully developed an ultrasound-based system to accurately digitize the spatial positions of the SP tips in dry bone specimens. We believed that the use of ultrasound-based methods to digitize the SP tips may be better than surface-based methods[6-9] because measurement artifacts related to palpating and locating the SP tips through the overlying skin and soft tissue during in vivo application can be eliminated. This is especially true for obese subjects. It has been reported that a majority of the patients with large measurement errors were those with high body mass index.[8]

The current study developed new analysis methods (ie, LOESS [0.4]–PDA, LOESS [0.25]–PDA, and LOESS [0.4]–ACA) to objectively quantify scoliotic deformity and compared their performances with other analysis methods (ie, polynomial[fifth]–PDA and raw-ACA) reported in the literature. To the author's knowledge, this is the first study that systematically compared different analysis methods of scoliosis assessment under the same experimental settings for systems that involve the use of spatial positions of the SP tips to quantify scoliotic deformity.

If raw spatial data were used without any smoothing, deformity measurements became unreliable (Table 2), poorly correlated with Cobb angle (Fig 5), and highly sensitive to digitization errors (Table 1). When using the ultrasound-based system to locate the SP tips, digitization errors can arise from the imaging process. Depending on the position and orientation of the ultrasound transducer with respect to an SP, different parts of the SP may show up and be regarded as the SP tip. Because of the close proximity of the adjacent SPs, a small digitization error could substantially change the angle between lines joining adjacent SPs. However, smoothing the spatial data with LOESS (0.4) could tremendously improve the deformity measurements (compare raw-ACA and LOESS [0.4]–ACA on Table 1, Table 2, and Fig 5). Therefore, it is imperative to smooth/curve fit the spatial data before they can be used to quantify scoliotic deformity.

Among the curve fitting/smoothing methods evaluated in this study (ie, LOESS [0.25], LOESS [0.4], and polynomial [fifth]), LOESS (0.4) appears to excel in every aspects of the comparisons (ie, correlation with Cobb angle [Fig 5], test-

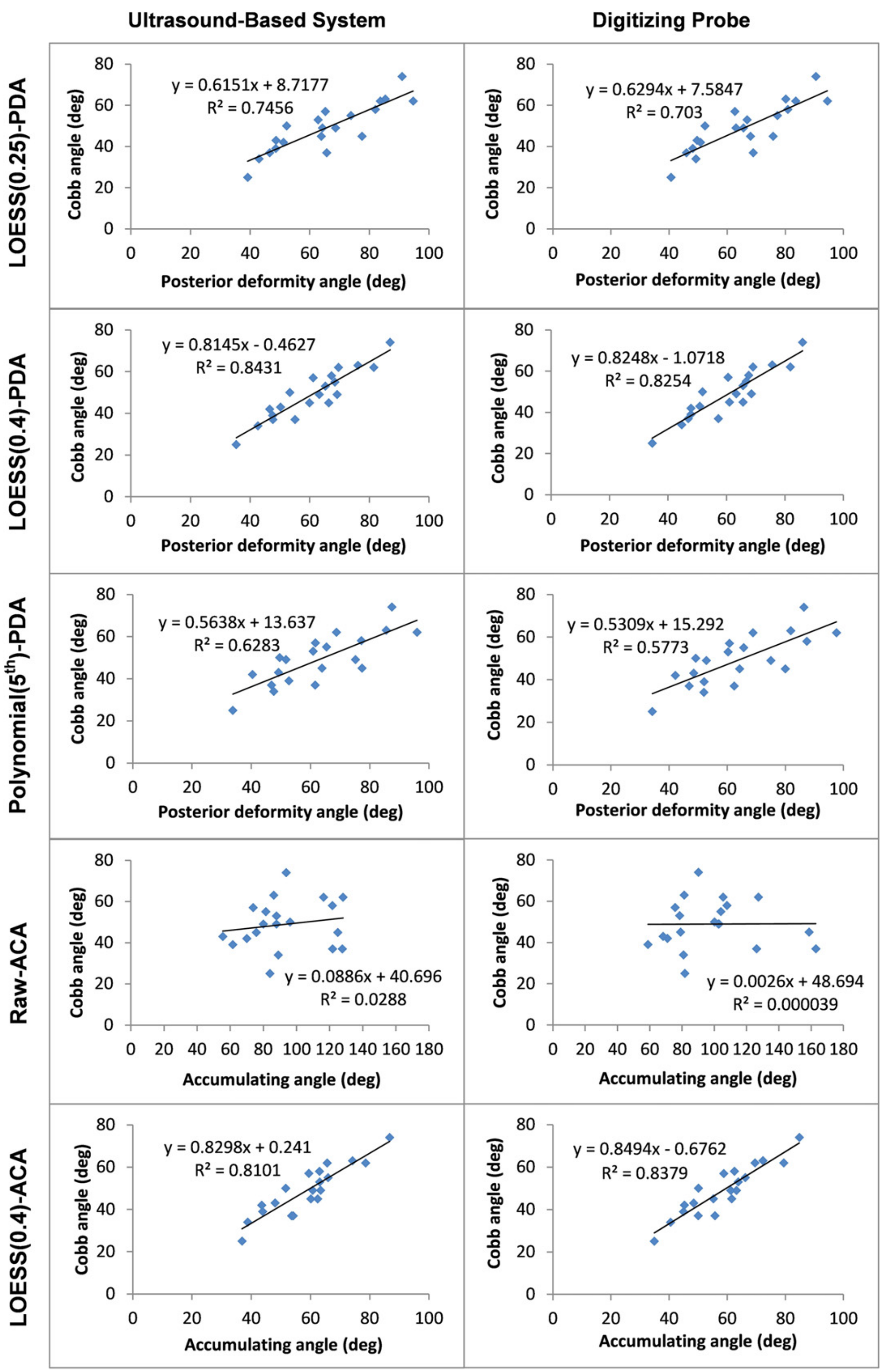

Fig 5. *Correlations between the Cobb angle measured from the PA radiograph and the angle metrics calculated by the 5 analysis methods. Each row represents the results of an analysis method (first row, LOESS [0.25]–PDA; second row, LOESS [0.4]–PDA; third row, polynomial [fifth]–PDA; fourth row, raw-ACA; and fifth row, LOESS [0.4]–ACA). Each column represents the source of the spatial data (left, the ultrasound-based system; right, the digitizing probe). LOESS, locally weighted polynomial regression.*

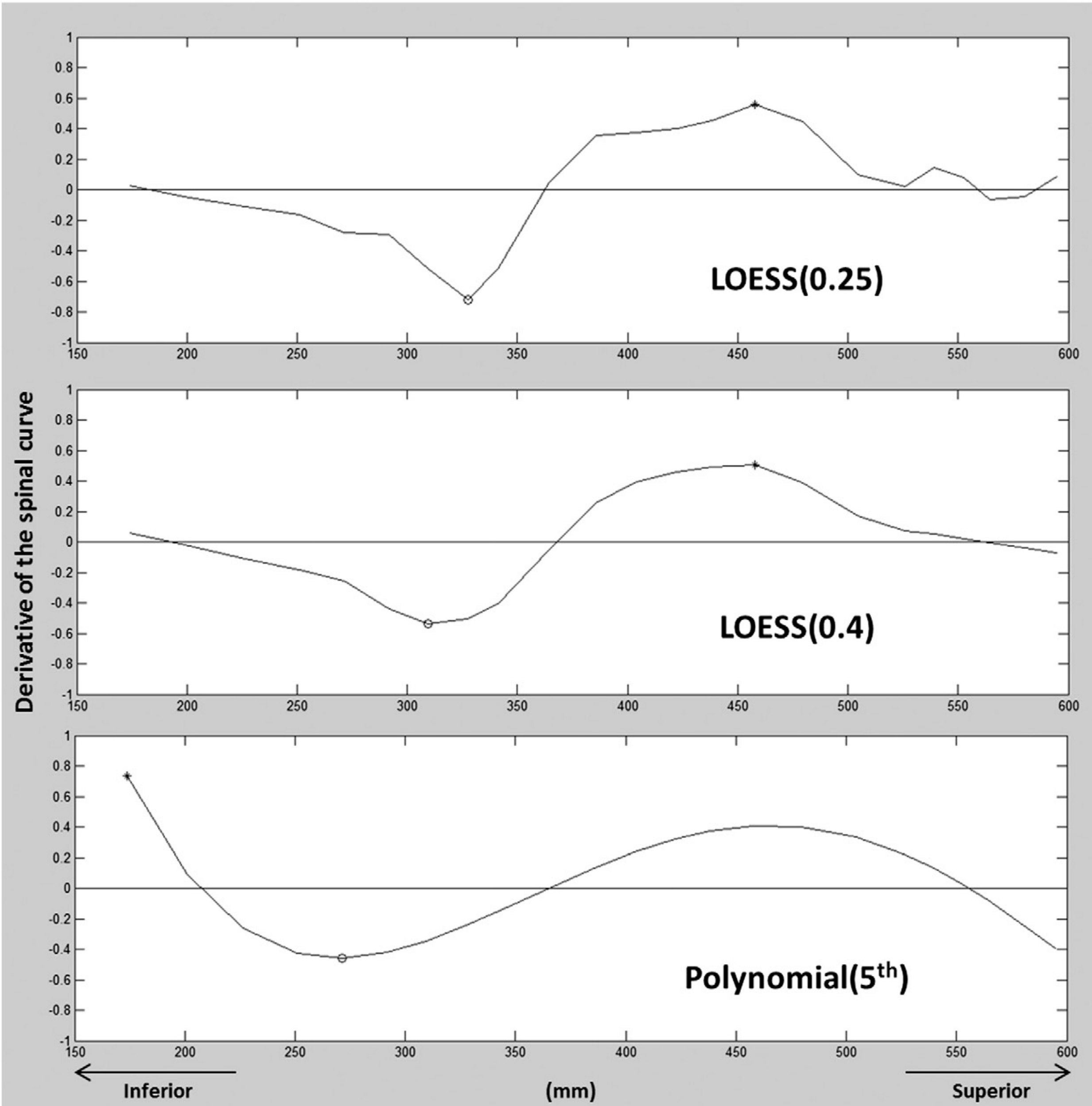

Fig 6. *From top to bottom, derivative plots of the spinal curves along the superior-inferior direction for a tested deformity configuration constructed by LOESS (0.25), LOESS (0.4), and polynomial (fifth), respectively. * and o denote the segmental level with the most positive and negative slope, respectively. As revealed here, the derivative plot of LOESS (0.4) is smoother than that of LOESS (0.25). In addition, polynomial (fifth) results in extreme errors of the derivatives at the end points. LOESS, locally weighted polynomial regression.*

retest reliability [Table 2], vulnerability to digitization errors [Table 1], accuracy of identifying end vertebrae, and accuracy of identifying convexity direction), making it the method of choice for processing the spatial data of the SP tips. Given that a spinal curvature is formed by smooth transition in segmental fashion, the superior performance of LOESS (0.4) over LOESS (0.25) was most likely attributed to its capability to adequately smooth out the wiggling noise along the spinal curve (Fig 4). This benefit is further illustrated by plotting the derivatives of the spinal curve along its superior-inferior direction (Fig 6). The data also confirmed our concerns of using polynomial (fifth) to curve fit the SP tips. We observed severe derivative artifacts at the end points in some deformity configurations (Fig 6), which made identification of end vertebrae, convexity direction as well as quantification of scoliotic deformity problematic. In addition, although the polynomial (fifth) method could generate a highly smoothed spinal curve (Fig 6), it did not appear to fit the SP tips well (Fig 4). This could be attributed to the "nonlocal" nature of the polynomial fitting. Results of the current study clearly demonstrated that a localized form of classic polynomial regression such as LOESS is more appropriate for constructing the spinal curve.

We directly compared the performance of 2 angle metrics (ie, PDA and ACA) to quantify scoliotic deformity by processing the spatial data with the same smoothing method (ie, LOESS [0.4]). Our data revealed that both have excellent correlation with Cobb angle (Fig 5), nearly zero y intercept within the regression equation (Fig 5), excellent reliability (Table 2), and excellent protection from digitization errors (Table 1). It appears that if the spatial data are properly processed beforehand, both PDA and ACA are valid metrics for quantifying scoliotic deformity. Nonetheless, PDA appears to be slightly better than ACA in terms of reliability (Table 2) and vulnerability to digitization errors (Table 1), most likely because the definition of ACA is more sensitive to wiggling noise.

In terms of the correlation with Cobb angle, our ultrasound-based LOESS (0.4)–PDA method ($r = 0.92$) appears to compare favorably with other radiation-free assessment methods reported in the literature. Thometz et al[16] correlated the Q angle, a coronal plane measurement generated by the Quantec Spinal Imaging System with Cobb angle and reported that the r value of the Quantec Spinal Imaging System were 0.65, 0.63, and 0.70, respectively for thoracic, lumbar, and thoracolumbar deformities. Based on surface palpation of SPs using an electromagnetic tracked fingertip, the Ortelius 800 system (Yokneam, Israel) had been reported to have the r values ranging between 0.65 and 0.87 for thoracic curvature and between 0.13 and 0.84 for lumbar curvature.[8,17] More recently, Cheung et al[18] developed an ultrasound-based system to locate the transverse processes and superior articular processes and used these landmarks to quantify scoliotic deformity. The r value of their method was 0.87. Although the r values cannot be directly compared among studies (because of the differences in sample sizes, sample types [human vs spine phantom], and deformity ranges within the samples), our results demonstrated that the system and method developed in this study are a promising radiation-free alternative for quantifying scoliotic deformity.

Taking together, this study provided insights about the more appropriate smoothing technique and angle metric to be used for systems that involve the use of spatial positions of the SP tips to quantify scoliotic deformity. When using the spatial positions of SP tips acquired by the ultrasound-based system developed in this study, we highly recommend the use of LOESS (0.4)–PDA to quantify scoliotic deformity. We believe that this recommendation can be extended to other surface-based assessment methods that rely on the spatial positions of the SP to quantify spinal deformity.[7-10] Nonetheless, a separate study needs to be conducted to confirm this argument.

Just like any methods that use the SP to assess scoliosis, the PDA measured by our ultrasound-based system would not only reflect the lateral deformity of the spine but also be affected by the coupled axial rotation that occurs with scoliosis. Hence, PDA is not the same as the Cobb angle measured from PA radiographs. Given that Cobb angle and PDA are highly correlated and established guidelines have been available for clinicians and spine surgeons to determine the need for bracing or surgery based on the Cobb angle[19], one may contemplate to calculate Cobb angle from PDA. This may be achieved by conducting a large-scale clinical study on scoliotic patients that measures both the PDA using the ultrasound-based system developed in this study and the Cobb angle using PA radiograph and comes up with a linear regression equation that calculates the Cobb angle from PDA. This would be a topic of future study.

In this study, we used an optoelectronic measurement system to acquire the pose data of the ultrasound transducer. It may be replaced by an electromagnetic tracking device to make the system more mobile,[10,11,18,20] allowing for routine use in small clinical settings and/or scoliosis screening in schools. Given that technical accuracies of optoelectronic and electromagnetic tracking systems are nearly the same,[21] replacing optoelectronic tracking by electromagnetic tracking should have minimal effect on the performance of our ultrasound-based system. A separate study is needed to confirm this assumption.

Limitations and Future Studies

Although excellent performance of our ultrasound-based system and LOESS (0.4)–PDA method has been demonstrated, our results did not consider the potential effects of movement artifacts on the measurements because we only tested our system and method using dry bone specimens, not live human subjects. Like other radiation-free systems that rely on identifying the SP to quantify scoliotic deformity, subjects are required to stand still for a few minutes to complete the measurement. During the measurement period, any movements would result in digitization errors of the SP tips, which might in turn affect the deformity measurements. This potential problem can be minimized by stabilizing the trunk with some kind of supporting aid.[9,10] Additional infrared diodes markers may also be attached to the trunk to monitor body motion during the measurement, and criterion can be setup so that when the body motion exceeds certain thresholds, the system will signal the clinician to repeat the measurement. In addition, every effort should be made to speed up the measurement process. The use of a wide-footprint ultrasound transducer to increase the field of view[18] and a silicon sleeve to ensure a good contact surface between the patient's back and the ultrasound probe[10] may greatly reduce the time needed to complete the measurement. These refinements need to be considered when the system is being applied to scoliosis patients.

Although our ultrasound-based system is radiation free, it only provides a single-angle metric to assess scoliosis, which may not be adequate for scoliosis surgical planning.

That limitation may be complemented by the use of the EOS low-dose x-ray system (EOS imaging Inc, Cambridge, MA). EOS could substantially reduce the radiation dose of a PA spine radiograph to one-fifth of the modern traditional x-ray techniques.[22] It not only provides direct measurement of Cobb angle but also detects additional skeletal deformities in 3Ds and measures leg length, which are important information for spine surgeons.

Lastly, because our system and method rely heavily on SPs identification, they may not be applicable to subjects with degenerative changes, calcification of supraspinous or interspinous ligaments, nuchal bones, spinal dysraphism, absent or hypoplastic SP, and block vertebrae, etc.

With the spatial data processed by LOESS (0.4)–PDA, this is a promising approach for quantifying scoliotic deformity in a radiation-free manner. Nonetheless, before our system and method could be used in clinical settings to monitor curve progression and evaluate treatment effectiveness, they must be validated using scoliosis patients.

Conclusions

This study showed that the LOESS (0.4)–PDA method consistently excelled in every aspect of the comparisons in this study using dry bone specimens. We conclude that spatial positions of the SP tips can be accurately acquired by the ultrasound-based system developed in this study.

Practical Applications

- We successfully developed an ultrasound-based system to digitize 3D coordinates of SP tips and used these data to quantify scoliotic deformity.
- This study compared 5 different analysis methods in terms of their correlation with Cobb angle, test-retest reliability, vulnerability to digitization errors, and accuracy of identifying end vertebrae.
- The data revealed that the LOESS (0.4)–PDA method excelled in every aspect of the comparison, making it the method of choice for processing the spatial data of the SP tips.

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Contributorship Information

Concept development (provided idea for the research): T.K.

Design (planned the methods to generate the results): T.K.

Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): T.K.

Data collection/processing (responsible for experiments, patient management, organization, or reporting data): J.G., C.I., J.B.

Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): T.K., J.G., C.I., J.B.

Literature search (performed the literature search): T.K., J.G.

Writing (responsible for writing a substantive part of the manuscript): T.K., J.G.

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