

Automatic Cobb Angle Determination From Radiographic Images

Tri Arief Sardjono, PhD,* Michael H. F. Wilkinson, PhD,† Albert G. Veldhuizen, PhD,‡
Peter M. A. van Ooijen, PhD,§ Ketut E. Purnama, PhD,¶ and Gijsbertus J. Verkerke, PhD||**

Study Design. Automatic measurement of Cobb angle in patients with scoliosis.

Objective. To test the accuracy of an automatic Cobb angle determination method from frontal radiographical images.

Summary of Background Data. Thirty-six frontal radiographical images of patients with scoliosis.

Methods. A modified charged particle model is used to determine the curvature on radiographical spinal images. Three curve fitting methods, piece-wise linear, splines, and polynomials, each with 3 variants were used and evaluated for the best fit. The Cobb angle was calculated out of these curve fit lines and compared with a manually determined Cobb angle. The best-automated method is determined on the basis of the lowest mean absolute error and standard deviation, and the highest R^2 .

Results. The error of the manual Cobb angle determination among the 3 observers, determined as the mean of the standard deviations of all sets of measurements, was 3.37°. For the automatic method, the best piece-wise linear method is the 3-segments method. The best spline method is the 10-steps method. The best polynomial method is poly 6. Overall, the best automatic methods are the piece-wise linear method using 3 segments and the polynomial method using poly 6, with a mean absolute error of 4.26° and 3.91° a standard deviation of 3.44° and 3.60°, and a R^2 of 0.9124 and 0.9175. The standard measurement error is significantly lower than the upper bound found in the literature (11.8°).

From the *Institut Teknologi Sepuluh Nopember, Surabaya, Jawa Timur, Indonesia; †Johann Bernoulli Institute of Mathematics and Computer Science, University of Groningen, Groningen, The Netherlands; ‡Department of Orthopaedic Surgery, University of Groningen, University Medical center Groningen, Groningen, The Netherlands; §Department of Radiology, University of Groningen, University Medical center Groningen, Groningen, The Netherlands; ¶Department of Electrical Engineering, Institute of Technology Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia; ||Department of Rehabilitation Medicine, University of Groningen, University Medical Center Groningen, Groningen, The Netherlands; and **Department of Biomechanical Engineering, University of Twente, Enschede, The Netherlands.

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Address correspondence and reprints requests to Tri Arief Sardjono, PhD, Institut Teknologi Sepuluh Nopember, Surabaya, Jawa Timur, Indonesia; E-mail: sardjono@elect-eng.its.ac.id

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Conclusion. The automatic Cobb angle method seemed to be better than the manual methods described in the literature. The piece-wise linear method using 3 segments and the polynomial method using poly 6 yield the 2 best results because the mean absolute error, standard deviation, and R^2 are the best of all methods.

Key words: spinal curvature, scoliosis, Cobb angle, curve fitting, deformable model, charged particle model, radiograph.

Level of Evidence: 3

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Scoliosis, a 3-dimensional deformity of the spinal column, is generally characterized by a lateral deviation of the spine, accompanied by an axial rotation of the vertebrae. To monitor scoliosis progression, a posteroanterior and lateral radiograph of the full spine in standing position is acquired. The Cobb angle derived from a posteroanterior radiograph is the standard parameter for determining the severity of the scoliosis.^{1,2}

The variations in Cobb angle measurement in scoliosis have been investigated by several researchers.^{3–8} The interobserver standard measurement error is up to 11.8° and the standard deviation is up to 3.3°; the intraobserver standard measurement error is up to 6° and the standard deviation is 2.0°.

A comparison of manual *versus* computer-assisted radiographical measurement of the Cobb angle (performed on digitized images using a computer mouse) was done by Shea *et al*,⁹ in 1998. Using this computerized technique, sources of intrinsic error, for example, the variability introduced by using different manual protractors, the inaccuracy of standard protractors, and the use of wide-diameter radiographical markers, were avoided. However, determining the upper and lower vertebra with the highest angle still has to be done manually and will cause an intrinsic error. Other methods to determine the Cobb angle were studied by Jeifries *et al*¹⁰ and Stokes and Aronson.¹¹ Jeifries used a Graf/Pen sonic digitizer to put a pair of points in each vertebra to determine the center between each pair of points. Lines were drawn parallel to vertebral body to determine the Cobb angle. The maximum standard deviations of manual and computer measurement were 4.6 and 2.5°, respectively. Stokes used manual marking of 4 points for each vertebral body. The stored coordinates were input to a computer algorithm to determine the Cobb angle. The maximum intraobserver and interobserver standard deviations were 2.4 and 2.7°, respectively. Wever *et al*¹²

placed 6 landmarks manually per vertebra on each anteroposterior radiograph. Then, these landmarks were scanned and saved as Cartesian coordinates in a computer file. The mid-point of the vertebral bodies and the lateral tilt of the upper and lower endplates of each vertebra were calculated by a computer algorithm. Michaela *et al*¹³ measured the inter- and intraobserver reliability of the Cobb angle using manual and digital measurement tools. The error caused by the definition of end vertebrae and the overall accuracy does not improve by using digital radiography. Samuvel *et al*¹⁴ have developed a mask-based segmentation algorithm for automatic measurement of the Cobb angle from a radiographical image. The landmark point is put manually in the center of each vertebra. Then, the mask is placed over the landmark point and resized it until it finds the best match.

To further decrease the error in the Cobb angle determination and to speed up the procedure, we propose an automatic Cobb angle determination method by using a numerical procedure based on the charged particle model (CPM), which was introduced by Jalba *et al*.¹⁵ This model contains charged particles that move in an electric field. The particles have a positive charge and are attracted by the dark contour of the spine that is charged negatively. The modified CPM is a deformable model as well. A modification is proposed by using springs between the charged particles to force the particles to follow the curvature. For curvature detection, we have tried several existing deformable methods such as the GVF snake model and the CPM model, but all of them could not be used to measure the Cobb angle of patient with scoliosis automatically.

This article describes the automatic Cobb angle determination from radiographical images using a modified CPM and presents the reduction in error that is achieved.

MATERIALS AND METHODS

Materials

Thirty-six frontal radiographical images of patients with scoliosis were used, both single and double curved. Patient selection was done by using the radiographs of the most recent patients with a diagnosis of scoliosis. Primary or secondary curves were treated similarly. Because of the limited field of view of the x-ray system, multiple radiographical images (typically 2) have to be obtained to cover the whole spine. They were reconstructed (stitched) into a single composite image.

Methods

Manual Cobb Angle Determination

The parameter that influences the accuracy of our method most is the Cobb angle, so all results were depicted as function of the Cobb angle. A manual Cobb angle measurement was done on 36 radiographical images by 3 observers. Two observers are orthopedic surgeons and the other one is the first author guided by an orthopedic surgeon. The manual measurements were done on physical printed radiographical images. On the basis of the shape of the curvature, scoliosis can be characterized by a single (C) or a double curve (S).

Both single and double curves can develop in 2 directions. In case of a double curve, it was treated as 2 single curves. After deciding which 2 vertebrae were tilted most severely toward the concavity of the curve, a line was drawn along the upper endplate of the upper body and along the lower endplate of the lower body. If the endplate could not be seen easily, these lines were drawn along the left or right side of the vertebral body or along the pedicles. Then, the Cobb angle, the angle between these 2 lines, was measured. When these 2 lines intersected outside the film, 2 perpendicular lines to these first 2 lines were drawn that did intersect on the film. The angle between them again is the Cobb angle.

Automatic Cobb Angle Determination

The automatic Cobb angle measurement was done using a modified CPM, a new approach of a deformable model, which was introduced by Jalba *et al*¹⁵ in 2004. It determines the left and right edges of the individual vertebral bodies as presented on a frontal radiographical image. On the basis of the gray levels in the radiographical image, it is transferred numerically into an electric field. The charge of the electric field is proportional to the edge map or gradient magnitude of the image. The number of positively charged particle is added automatically. The initial particle positions can be defined manually by the user or automatically by an image analysis method. They start moving in the simulated electric field. Because the edges of the vertebrae have a high negative load, the particles move toward these edges, and thereby they define the left and right edges of the individual vertebral bodies. The movement of the particles is restricted without reducing the flexibility of the particles by simulating springs between the particles. Vertical and horizontal springs are introduced. The stiffness of the vertical springs is 3.5 au, and that of the horizontal springs is 0.8 au. After a trial-and-error process, these values were found to give the best results.

Specific software is not needed for this automatic Cobb angle determination method. We have developed this algorithm using Math Lab and an open source program and an executable file can be built. The mathematical description of this modified CPM is presented in Appendix 1 (see Supplemental Digital Content, available at <http://links.lww.com/BRS/A789>).

The procedure for a single and a double scoliotic curve is different. For an S-curve, we divided the spine in vertical direction in 3 parts, all with an equal number of particles. In each part, the most extreme angle was determined. The 2 Cobb angles were determined by the difference between the most extreme angle of the top and middle part and between the middle and bottom part, respectively. For C-curves only 2 parts were defined. The Cobb angle was determined similarly. The Cobb angle is determined by the average of the left and right Cobb angle.

To smoothen the line through the particles, 3 curve fitting methods were applied, piece-wise linear, splines, and polynomials. From every position on the curve, the tangential was determined. Then, the Cobb angle was calculated automatically from these lines by determining the difference

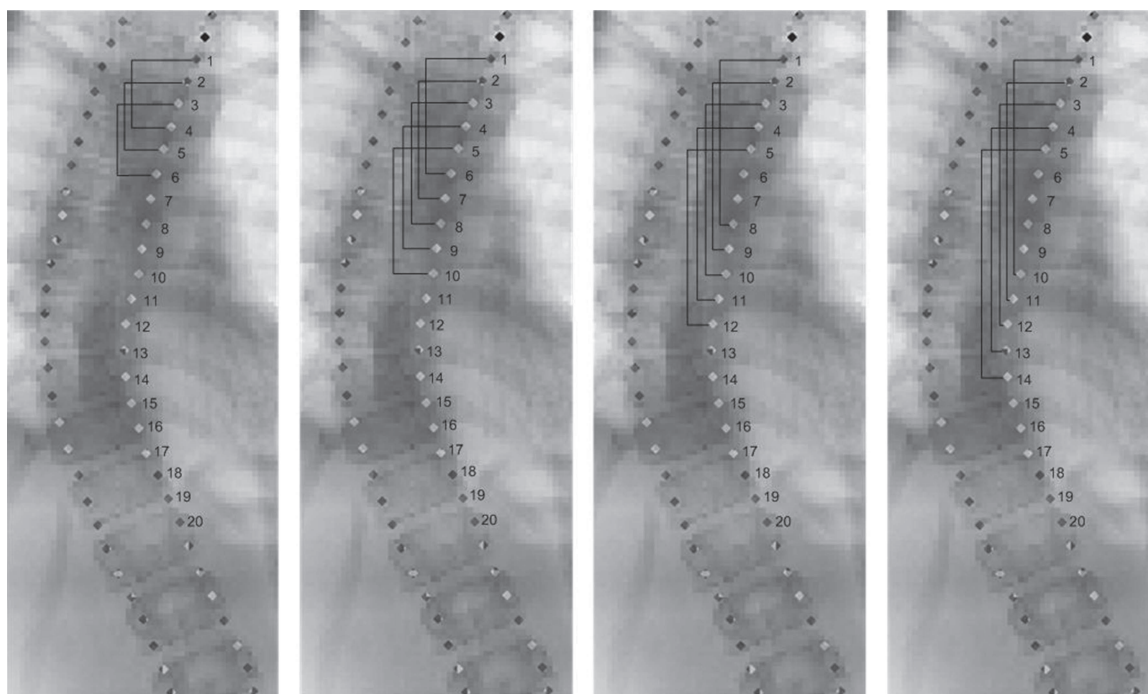


Figure 1. The piece-wise linear method using 3 different segment lengths, (left to right): 3, 5, 7, and 9 particles.

in the angle between the 2 tangentials, with the most extreme slope from the left and right line. The automatic Cobb angle procedures are summarized in Appendix 2 (see Supplemental Digital Content, available at <http://links.lww.com/BRS/A789>).

Piece-Wise Linear

The piece-wise linear method is one of the curve fitting methods. Particles were clustered in segments with 3 different lengths, containing 3, 5, 7, and 9 particles (Figure 1). For segment length 5, for instance, we then draw a line from the starting particle (particle number 1) to particle number 6. The second line was drawn from particle number 2 to particle number 7 and so on. The slope of each line was calculated as the angle between the line and the horizontal line. These angles were grouped into 2 (for C-curves) or 3 different groups (for S-curves), and in each group the most extreme angle was determined. The Cobb angles were determined as described earlier.

Splines

Splines are smooth curves through a series of points, defined by a mathematical algorithm. The MATLAB (MathWorks Inc., Natick, MA) “cubic spline” function was used with 3 different “spline steps,” 10, 15, and 20 (Figure 2). Then, the slope of each line that is obtained in each spline steps was calculated, and found the most extreme angle with the horizontal line and determined the Cobb angle.

Polynomials

A polynomial curve is defined by a polynomial function. The MATLAB “polyfit” function of 3 different orders, 4, 5, and

6 was used to determine the polynomials (Figure 3). Then, “polyval” function was used to evaluate the polynomial curve. We again calculated the slope of each line, which is obtained in each polynomial order, found the most extreme angles with the horizontal line, and determined the Cobb angle.

Reproducibility of the Automatic Cobb Angle Measurement

The reproducibility of the automatic Cobb angle determination was evaluated on 36 spinal radiographical images. The automatic Cobb angle determination using polynomial 6 was applied 5 times for each radiography, and the standard deviation of each Cobb angle was calculated as a measure of reproducibility.

RESULTS

The accuracy of an automatic procedure that determines the Cobb angle of a patient with scoliosis from frontal radiographical image was evaluated by calculating the mean absolute error, standard deviation, and R^2 . The best performance of the automatic methods is determined on the basis the lowest value of the mean absolute error and standard deviation, and the highest value of R^2 .

Manual Cobb Angle Determination

Figure 4 shows the scatter plots and trend lines of the manual Cobb angle 1 *versus* manual Cobb angles 2 and 3. The mean absolute deviation from the median is 3.20° and the average of the standard deviation is 3.37° . y_1 and y_2 are the trend lines of the scatter plots of manual Cobb angle 2 and 3 *versus* manual Cobb angle 1.

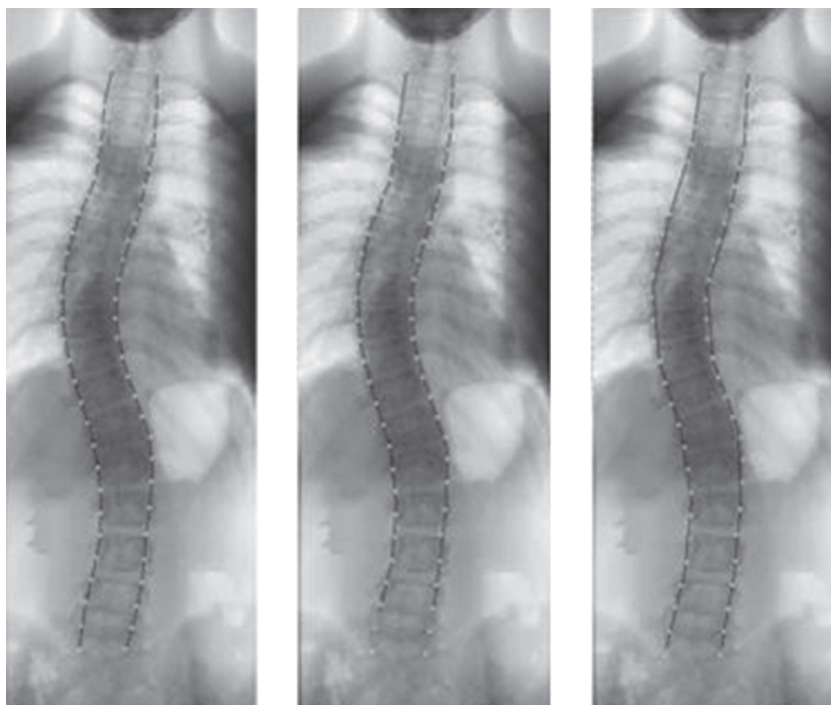


Figure 2. The spline method using 3 different “splinesteps” (left to right): 10, 15, and 20.

Automatic Cobb Angle Determination

Piece-Wise Linear With Segment Length 1

Figure 5 shows the results of the automatic Cobb angle determination using segment length 1 of a representative radiograph. The 2 lines are not so smooth, so smoothing them by the applied curve fitting methods was indeed necessary to avoid errors in the Cobb angle determination.

Piece-Wise Linear, Splines, and Polynomials

Figures 6, 7, and 8 show the best of the piece-wise linear, spline, and polynomial methods that were investigated, all plotted *versus* the average of the manual Cobb angles per point, including linear regression result. Table 1 shows the performance measures of these methods

The bias correction was done by using the equations mentioned in Table 1. These equations were determined by

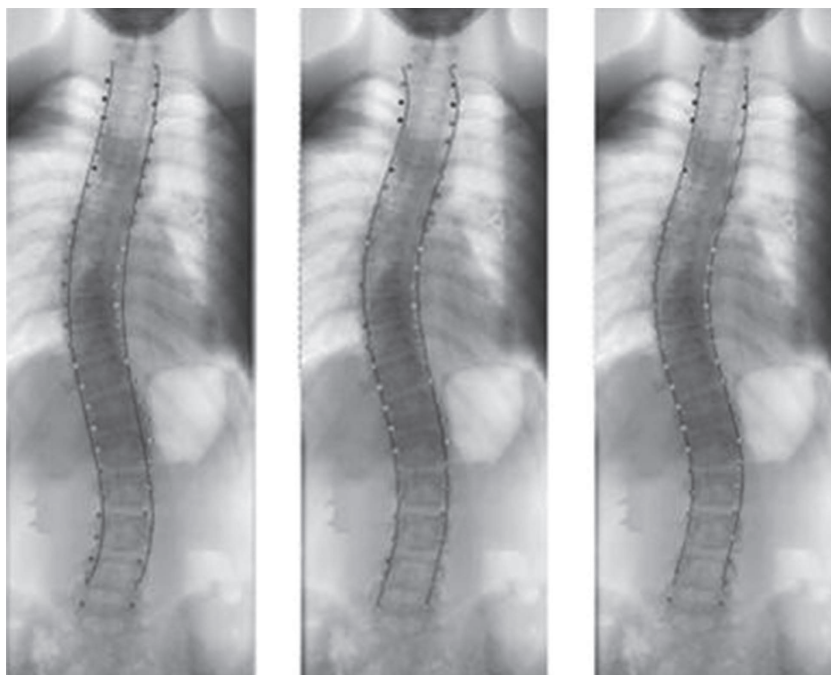


Figure 3. The polynomial curve method using 3 different polynomial degrees (left to right): 4, 5, and 6.

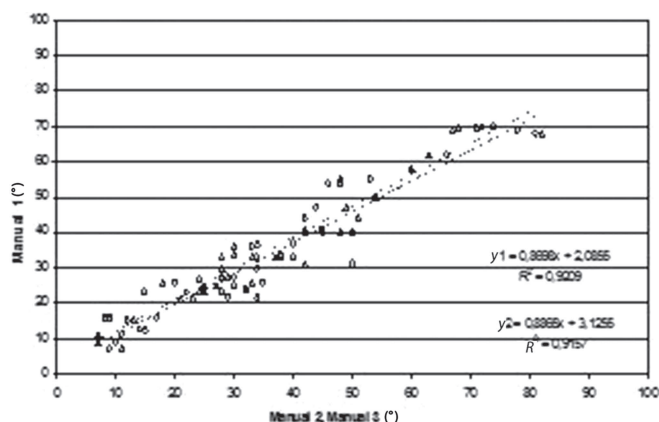


Figure 4. The scattered points of manual Cobb angle 1 versus manual 2 and 3.

scattered points of manual Cobb angle (average) and automatic Cobb angle measurement using linear regression. It should be noted that the standard deviation after bias correction also includes a component of variance introduced by the error in the mean of the 3 manual measurements. Correcting for this contribution is straightforward, by subtracting this variance ($3.78 = \text{square of the standard error in the mean}$) from the square of the standard deviation listed in Table 1, and taking the square root of the result. This yields a standard deviation of 2.84 for the 3-segment piece-wise linear method, 3.03 for the sixth order polynomial method, and 4.68 for the 10-step spline method.

Reproducibility of the Automatic Cobb Angle Determination

The reproducibility of the automatic Cobb angle determination, evaluated on 36 spinal radiographical images resulted in an average of the standard deviation of 2.84° , for the 3-segment piece-wise linear method. Because this is equal to the standard deviation of the earlier mentioned Cobb angle measurement corrected for the contribution to the variance of the manual estimates, this suggests that the residuals of the fit in Table 1 are entirely due to statistical error, and no further higher order trends are present in the data at any significant level.

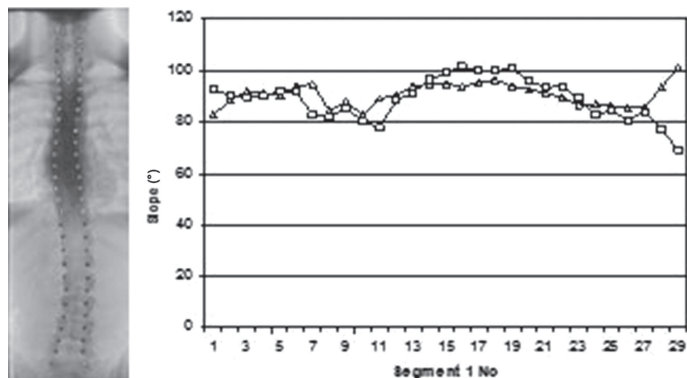


Figure 5. Frontal 1 (left) and the scattered points of the slope (right and left particles) for each segment (1 segment) in frontal 1 (right).

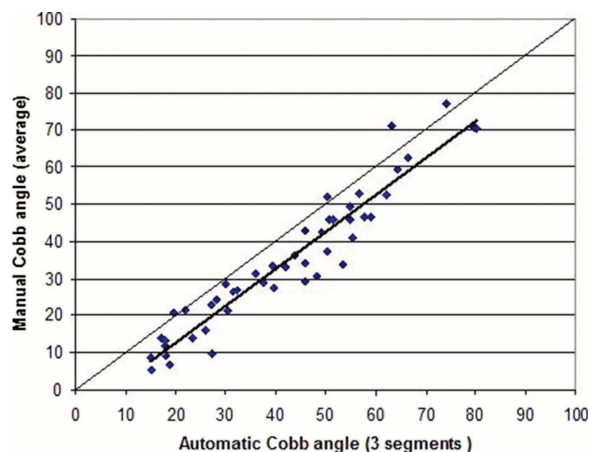


Figure 6. The scattered points of manual Cobb angle (average) and automatic Cobb angle using the segmented particles position method (3 segments).

DISCUSSION

The determination of the spinal shape is important to evaluate scoliosis progression. The Cobb angle measurement is derived from the spinal shape and is an important parameter to determine the severity of scoliosis. To decide the proper treatment, an accurate determination of the Cobb angle is required. To improve the present Cobb angle determination methods, a new algorithm was developed, applied on 36 radiographs, and validated with Cobb angles that were determined manually.

The best-automated method is determined on the basis of the lowest mean absolute error and standard deviation, and the highest R^2 . The best segmented particle position method is the 3-segments method with a standard deviation of 3.44° , before correction of the variance due to the manual estimates of Cobb angle, 2.84° afterwards, and R^2 of 0.9124. The best spline method is the 10-steps method. The standard deviation is lower than those of the other 2 spline-based methods and the R^2 is higher. The best polynomial method is poly 6, which has the lowest mean absolute error, higher standard

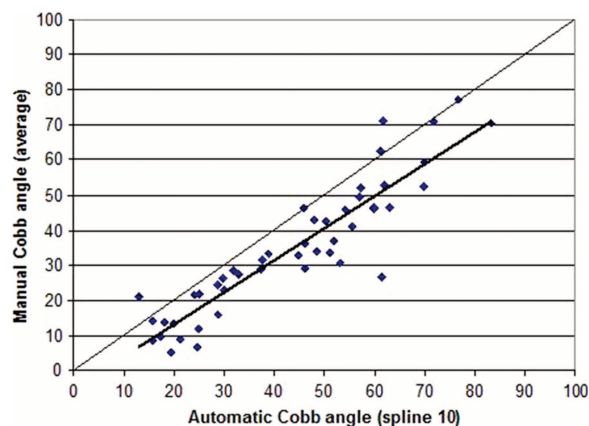


Figure 7. The scattered points of manual Cobb angle (average) and automatic Cobb angle using the spline method (spline step 10).

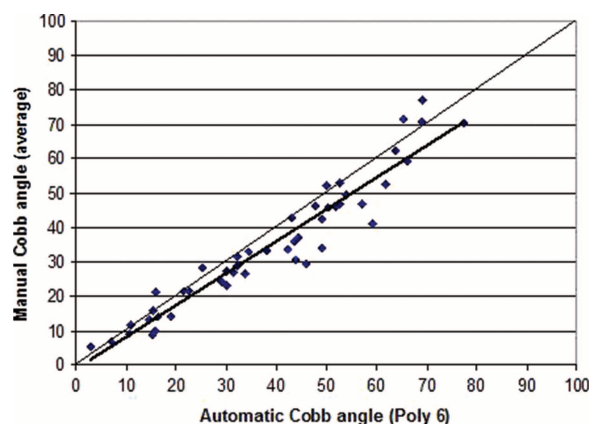


Figure 8. The scattered points of manual Cobb angle (average) and automatic Cobb angle using the polynomial method (sixth polynomial degree).

deviation, and highest R^2 . Poly 4 scores clearly worse, the differences with poly 5 are very small. The piece-wise linear method using 3 segments and the polynomial method using poly 6 yield the 2 best results because the mean absolute error, standard deviation, and R^2 are the 2 best of all methods.

Our test panel that determined the Cobb angle manually was very consistent, because the mean absolute deviation from the median (3.20°) is slightly lower than what is described in literature (3.3°). The mean result was used as the ground truth to evaluate various automatic Cobb angle determination methods.

Even without considering the variance introduced by the errors in the mean of the manual measurements, the standard deviation (3.44°) of the automatic method is only slightly higher than the manual method, after correction, and we have a standard deviation of 2.84° , purely due to statistical errors in the automated method. Not only is it better than the error in manual measurements obtained here (3.37°), but also significantly better than values found in the literature. The standard measurement error is 5.68° , estimated as twice the standard deviation (2.84°) is significantly lower than the upper bound found in the literature (11.8°).⁸

The average standard deviation of reproducibility of automatic Cobb angle determination was evaluated using different manual initial particle positions, and resulted in 2.84° , which is considered acceptable and comparable with other methods.³⁻⁷ The different manual initial particle positions were used to simulate different observers and to determine if position differences between observers have an impact. The experiments show that the results in terms of final particle position are similar.

The manual Cobb angle was measured on the basis of the orientation of the endplates of the 2 most tilted vertebral bodies. The automatic Cobb angle was calculated on the basis of the left and right side of the vertebral bodies. This explains partly the difference between the 2 methods. The automatic procedure seems to be more related to the principle of the Cobb angle, characterizing the severity of the curvature.

The modified CPM is applicable on single and double curves, because double curves are treated as 2 single curves. Already, a single motion segment is sufficient to apply the method.

TABLE 1. Performance Measures

Method	Before Bias Correction		After Bias Correction			
	Mean Absolute Error	Standard Deviation	Mean Absolute Error	Standard Deviation	R^2	Best Fit Line
Segmented particle position						
3 segments	7.96	4.58	4.26	3.44	0.9124	$y = 0.9932x - 7.0678$
5 segments	4.91	5.01	4.28	5.18	0.8686	$y = 1.0583x - 3.8761$
7 segments	5.31	7.98	5.46	7.05	0.7688	$y = 1.0473x + 1.9214$
9 segments	9.34	11.30	7.40	9.01	0.6048	$y = 0.9916x + 9.0485$
Spline method						
10 steps	9.64	6.54	5.44	5.07	0.8388	$y = 0.9154x - 5.1375$
15 steps	7.96	10.76	7.45	8.15	0.6454	$y = 0.7074x + 7.0977$
20 steps	6.94	7.93	7.10	7.22	0.7014	$y = 0.8562x + 6.0365$
Polynomial method						
Poly 4	6.18	5.04	5.61	4.50	0.8489	$y = 0.898x + 0.9976$
Poly 5	4.79	4.26	3.93	3.86	0.9116	$y = 0.9214x + 0.05$
Poly 6	5.21	4.32	3.91	3.60	0.9175	$y = 0.9312x - 1.3046$

All values in degrees, except R^2 .

The selected automatic detection method can determine the Cobb angle with an error that is much lower than the error of a manual Cobb angle determination. Also, the automatic method can be combined with the presently available software that is used to reconstruct a radiograph and thus can determine the Cobb angle much faster than manual measurement and with a more constant quality. The automatic method takes only 1 to 2 minutes, and the manual one takes 10 to 15 minutes.

FUTURE WORK

Further investigations will focus on feature extraction to get much more information contained in the radiographical spinal image of a patient with scoliosis, especially to determine the shape of the spine and to estimate the degree of rotation of the vertebra by considering the relation of the pedicles to the midline.

➤ Key Points

- ❑ A manual Cobb angle measurement was done on 36 radiographical images by 3 observers, 2 observers are orthopedic surgeons and the other one is the first author guided by an orthopedic surgeon.
- ❑ To further decrease the error in the Cobb angle determination and to speed up the procedure, we propose an automatic Cobb angle determination by using a numerical procedure based on the CPM.
- ❑ To smoothen the line through the particles, 3 curve fitting methods were applied, piece-wise linear, splines, and polynomials
- ❑ Our test panel that determined the Cobb angle manually was very consistent, because the mean absolute deviation from the median (3.20°) is slightly lower than what is described in literature (3.3°).

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