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Computer-assisted Cobb angle measurement from posteroanterior radiographs by a curve fitting method

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Abstract: Incorrect determination of the top or end vertebrae of a scoliotic curve causes measurement errors when using the Cobb method. Such problems are due to subjectivity. This study was performed to minimize subjectivity by using a curve fitting method. A digitally scanned posteroanterior radiographic image was used for each patient. User-defined midpoints of the curvature, which indicate the midpoints of the vertebrae, were used to fit the polynomial equation. The locations of the top and end vertebrae were calculated using the first derivative of the fitted polynomial equation to obtain the analytical Cobb angle. The interobserver technical error of measurements was calculated as 1.06 degrees with a reliability coefficient of 1.00. The results indicate that 100% of the variations were not related to measurement error. Small angle variations show that subjectivity was minimized.

Key words: Curve fitting, Cobb angle, scoliosis, computer-assisted measurement

1. Introduction

The Cobb method is the most commonly used technique to measure the magnitude of deformity in scoliosis cases [1], wherein the superior and inferior surfaces of the top and bottom (end) vertebrae must be defined by considering the magnitude of the inclination angle to the side of the concavity [2]. According to the Scoliosis Research Society, the Cobb angle is the angle between the lines drawn on the endplates of the end vertebrae. The analytical Cobb angle is the angle between perpendiculars at inflectional points of the projection of the vertebral body line in a specified plane. This study used the analytical Cobb method. Therefore, perpendicular lines were drawn on the radiograph, indicating the slope of the vertebrae considering the vertebral body line. The magnitude of the angle between the intersecting lines gives the analytical Cobb angle.

The identification process for the top and bottom vertebrae and the vertebral pedicles is most prone to measurement mistakes, which are attributed to subjectivity [3,4]. Therefore, subjectivity constitutes a fundamental problem for the precise measurement of the Cobb angle. The difficulties in the selection of the two vertebrae can be summarized below:

- The inclination of certain vertebrae is almost the same; however, a small degree of error causes larger error values when calculating the Cobb angle. This situation can be explained by considering 360 rectangles that are arranged with 1 degree of error. This error value cannot be easily determined with the naked eye. However, because of the accumulation of errors, a circular pattern will obviously be caused at the end of the 360th piece of the rectangles.

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- Lines must be drawn from the superior and inferior surfaces of the top and bottom vertebrae. These lines must have the exact same tilt angle as their relevant vertebrae. However, manually marked lines cause errors.
- The quality of the scanned image is another parameter of selection of the vertebrae. The borderlines of the vertebrae must be seen clearly from the radiographs. However, in many cases these borderlines are not clear and cause difficulties in the selection of vertebrae.
- The position of the patient causes errors during the X-ray process.

Considering the difficulties given above, computerized measurement methods are needed to obtain a precise measurement of the Cobb angle.

Inter- and intraobserver variability of the Cobb method has been reported [3–7]. Under the conditions of the selection of the end vertebrae, interobserver variability has been reported as 6.3 degrees [3]. An interobserver variability of 7.2 degrees has been reported when each examiner is permitted to select the end vertebrae [3]. The highest range of manual Cobb measurements on any film has been reported as 8 degrees [6].

Computer-based methods have been developed for the precise measurement of the Cobb angle [4,8–10]. Although it was not clearly stated whether the classic Cobb measurement method or the analytical Cobb measurement method was used in the mentioned publications, it can be concluded that the classic Cobb method was used in [4,8,9] and the analytical Cobb measurement method was used in [10]. To obtain reliability of digital measurements, digitized radiographs have been used to measure the Cobb angle [8]. Under conditions of preselection, intra- and interobserver variability was reported as $\pm$ 1.3 and 1.26 degrees, respectively. The results promised precise measurements; however, the identification of the end vertebrae was neglected. A computerized method was developed to measure the Cobb angle automatically on spinal posteroanterior (PA) radiographs after the brightness and the contrast of the image were adjusted and the top and bottom of the vertebrae were selected [10]. The mean absolute differences of intra- and interobserver variability were less than 3 and 5 degrees, respectively. Interclass correlation coefficients (ICCs) showed high agreement between automatic and manual measurements (ICCs >0.95). Image processing algorithms provide the best solution. However, this method still requires selecting the end vertebrae and manually adjusting the brightness and contrast of the radiograph before processing. A fast 3D reconstruction method from biplanar X-rays was used to compare scoliotic spines [9]. Satisfactory results were obtained with a 95% confidence interval on a Cobb angle of $\pm$ 3.3 degrees. The reconstruction time for this method was reported as 10 min. The calibration method of biplanar radiography of the spine is important because it minimizes measurement errors. An important method for calibration was published, which uses the focal distance and a small calibration object to obtain the correct scale of 3D reconstructions of the spine [11,12]. Reconstruction time is also important. A novel method was proposed for 3D reconstructions of the spine from biplanar radiographs, which reduces the reconstruction time to 90 s for mild patients and 110 s for severe patients [13,14]. A simple computerized method was presented for measuring and quantifying the magnitude of scoliotic curvatures [4]. A digitally scanned radiograph was used to define the vertebral column as a line that can be subdivided into a number of segments rather than into the exact number of vertebrae. Intra- and interobserver technical error of measurements (TEMs) and reliability coefficients were calculated. TEM is the most commonly used gauge of imprecision and is obtained by carrying out a number of repeated measurements on the same subject [15,16]. Mean intraobserver TEM was estimated to be 0.789 degrees with a mean reliability coefficient of 0.985, which indicates that 98% of the variance is due to factors unrelated to measurement error. Interobserver TEM is estimated as 1.22 degrees with a reliability coefficient of 0.988.

This study focused on obtaining the polynomial equation of the scoliosis curvature by using a curve fitting method. A digitally scanned PA radiographic image was used for each patient. Five images from different patients were used for reliability experiments. User-defined midpoints of the curvature, which indicate the midpoints of the vertebrae, were used to fit the polynomial equation. Maximum tilting lines and tilting angles of the vertebrae were automatically calculated and selected with the developed software, using the first derivative of the obtained polynomial. Intra- and interobserver TEMs and reliability coefficients were calculated from 5 radiographic images with the help of 5 observers. The software calculates the widest Cobb angle considering the surgical decision-making process. Therefore, if double major or triple major scoliotic curves exist, each curve must be calculated separately with the software.

Hypothesis: It is possible to measure the analytical Cobb angle from a fitted curve on the PA view of the spinal curve. The maximum and minimum points of the fitted curve can be calculated from the first derivative of the obtained polynomial equation. The analytical Cobb angle can be calculated as the angle between the perpendicular lines to these tangent lines.

2. Methods

If the equation of any curve is known, the slope values for all the points on the curve can be precisely determined from the first derivative of the equation. To obtain the polynomial equation of a scoliotic curvature, a curve fitting method was used. Java-based software was developed for the curve fitting process and for the calculation of the Cobb angle of the scoliotic curvature. The curve fitting method needs a sample dataset to produce the polynomial equation. A digitally scanned radiograph was used to collect this dataset. The digital image must be aligned vertically. The user has to draw reference lines to calculate the midpoints of curvature (Figures a and b). Reference lines must be drawn on the superior surfaces of the top vertebrae and the inferior surfaces of the end vertebrae, considering the Cobb criteria. Each vertebra should be marked with a reference line from the beginning to the end of the curvature. The midpoints of these reference lines are the reference dataset for the curve fitting method.

The polynomial equation of a curve can be represented as:

$$f\left(x\right)=y=a_0+a_1x+a_2x^2+a_3x^3+\cdots+a_jx^j=a_0+\sum_{k=1}^{j}a_kx^k \tag{1}$$

where a and x represent the coefficient and variable of the equation, respectively. j represents the order of the polynomial. Finite sets of known x and $f(x)$ values can be obtained from the datasets. Pixel coordinates of the selected midpoints represent the x and y values of the equation. Only the coefficients of the polynomial remain unknown. These unknown coefficients can be calculated with the least squares approach to minimize the error. An equation system can be obtained with the least squares approach and could be represented in matrix form by Eq. (2), where n and i represent the total number of data points and the order of the data point, respectively.

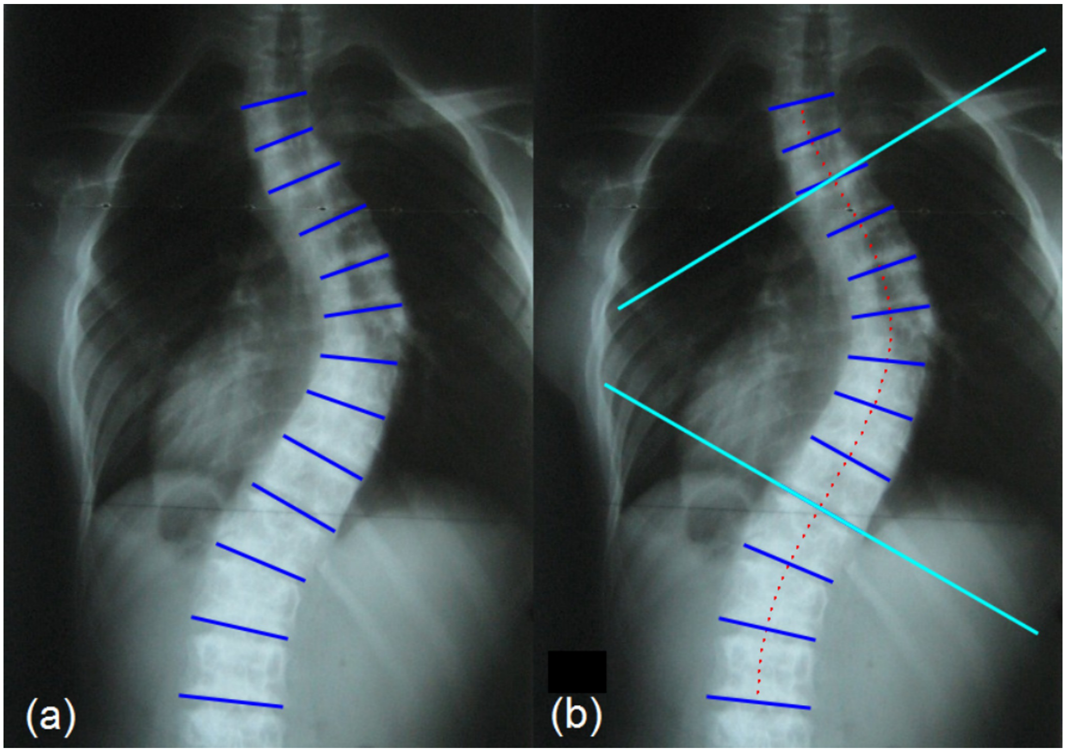

Figure. a) Reference lines drawn by the user, b) fitted curve (dashed line) and inclination lines (long lines) computed and drawn by the computer.

$$\underbrace{\begin{bmatrix} n & \sum x_i & \sum x_i^2 & \cdots & \sum x_i^j \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \cdots & \sum x_i^{j+1} \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \cdots & \sum x_i^{j+2} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \sum x_i^j & \sum x_i^{j+1} & \sum x_i^{j+2} & \cdots & \sum x_i^{j+j} \end{bmatrix}}_{\mathbf{X}} \underbrace{\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_j \end{bmatrix}}_{A} = \underbrace{\begin{bmatrix} \sum y_i \\ \sum x_i y_i \\ \sum x_i^2 y_i \\ \vdots \\ \sum x_i^j y_i \end{bmatrix}}_{B} \tag{2}$$

Coefficient vector **A** can be calculated by multiplying both sides of Eq. (2) by the inverse of **X**.

$$\mathbf{A}{=}\mathbf{X}^{-1}\mathbf{B} \tag{3}$$

All unknown coefficients can be obtained from Eq. (3). The first derivative of Eq. (1) gives the equation of the slopes on the curve of Eq. (4). The slope values of the user-defined midpoints can be calculated by substituting the x values of the midpoints into Eq. (4). The developed software can automatically compare the obtained angle values, considering the sign of the maximum values. These extreme points represent the top and bottom vertebrae according to the analytical Cobb method. Finally, the Cobb angle can be calculated from the tilt angles of the top and bottom vertebrae. The software draws two lines (Figure) considering the slope values of Eq. (4).

$$dy/dx{=}a_1{+}a_2x{+}a_3x^2{+}\cdots{+}a_{j+1}x^{j-1} \tag{4}$$

The Cobb angles were calculated from five digital scoliotic radiograph images by five inexperienced observers to test the reliability of the method. One experienced researcher also measured the Cobb angles manually for a better comparison. All measurements were repeated twice. Intra- and interobserver TEMs and reliability coefficients were calculated using the same methods as in the literature [4,16]. Intraobserver TEMs were calculated with the equation given below:

$$TEM=\sqrt{\sum (D^2)/2N} \tag{5}$$

where D is the difference between measurements and N is the number of subjects. Interobserver TEM was calculated using Eq. (6), where N is the number of subjects (number of X-ray images), M is the mean values of the measurements that are measured from same image, and K is the number of observers.

$$TEM=\sqrt{\frac{\sum_1^N\left(\left(\sum_1^K M^2\right)-\frac{\left(\left(\sum_1^K M\right)^2\right)}{K}\right)}{N\,(K-1)}} \tag{6}$$

The reliability coefficient can be calculated by Eq. (7), where SD is the total intersubject variance, including the measurement error.

$$R= 1-\left(TEM^2/SD^2\right) \tag{7}$$

3. Results

The mean angle values and standard deviations for the manually measured Cobb angles of the subjects are presented in Table 1. Intraobserver TEMs for manually measured Cobb angles were calculated as 2.05 degrees with a reliability coefficient of 0.916. Therefore, the manual measurement results are within the limits of previously reported studies.

Table 1. Manual Cobb measurements.

Radiograph no.	Trial 1	Trial 2	Mean	SD
1	46.00	47.00	46.50	0.71
2	58.00	56.00	57.00	1.41
3	44.00	38.00	41.00	4.24
4	41.00	40.00	40.50	0.71
5	39.00	39.00	39.00	0.00

Table 2 shows the mean angle estimations and standard deviations for computer-assisted measurement of the Cobb angles with the support of the curve fitting method. Measurements were applied twice by each observer, and mean angle values were used. Intraobserver TEMs and the reliability coefficients of each observer were calculated and are presented in Table 2. Mean intraobserver TEMs were calculated as 1.22 degrees with a mean reliability coefficient of 0.938. All intraobserver TEM values (including the mean intraobserver TEM value) are smaller than the manually measured TEM value, which means that the curve fitting method allows for more precise results than the conventional Cobb method. The mean reliability coefficient of 0.938 means that 93.8% of the variance is due to factors unrelated to the measurement error. Therefore, measurements were 93.8% error-free. Interobserver TEM was calculated as 1.06 degrees with a reliability coefficient of 1.00. This means that the measurement error was less than the TEM value of both the manual measurement and the intraobserver TEM, considering the overall observer measurements.

Table 2. Computer-assisted measurement of the Cobb angles with the support of the curve fitting method.

Radiograph no.	Observer 1		Observer 2		Observer 3		Observer 4		Observer 5	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	46.00	0.00	48.00	2.83	45.50	0.71	46.50	2.12	47.50	0.71
2	61.50	0.71	63.00	1.41	61.00	1.41	61.00	0.00	61.00	0.00
3	39.50	0.71	40.00	0.00	39.00	0.00	38.50	0.71	38.50	2.12
4	44.00	1.41	45.50	0.71	45.00	1.41	44.00	1.41	44.00	1.41
5	50.50	0.71	50.50	2.12	47.00	0.00	48.00	1.41	47.50	0.71
Intraobserver TEM	0.84		1.73		0.95		1.34		1.22	
Reliability coefficient (R)	0.944		0.94		0.928		0.943		0.938	

4. Discussion

Subjectivity constitutes a fundamental problem of manual Cobb measurements. Computer-aided measurements promise more precise results. Therefore, a curve fitting method was proposed to reduce subjectivity. Java-based software was developed for both the curve fitting process and the automatic calculation of the Cobb angle from the obtained equation. Satisfactory results were obtained considering similar methods. Variations of manual measurements are reported as being up to 8 degrees [3,6]. In the current study, the maximum TEM was 1.73 degrees, which is smaller than that of the reported computerized methods [9,10]. According to another similar method [4], the interobserver TEM is estimated as 1.22 degrees with a reliability coefficient of 0.988. The curve fitting method estimated the interobserver TEM as 1.06 degrees with a reliability coefficient of 1.00. Therefore, the presented method has successfully reduced the subjectivity-based measurement errors. User-based inputs of reference lines, which generate sample datasets for the curve fitting process, caused variability in measurements. The interobserver reliability coefficient proved that 100% of the variance is due to factors unrelated to measurement error.

The duration of a single measurement was approximately 2 min from loading the image file to obtaining the Cobb angle. Measurement time can be reduced as observers gain experience. The digitalization process was not included in the duration, because almost all clinics and hospitals use digitalized or scanned images of radiographs. The advantages of the developed method can be listed as follows:

- The curve fitting method is more precise than the classical method due to its analytical solution.
- The curve fitting method is easy to apply. Therefore, it minimizes the loss of time during the computation of deformity.
- The curve fitting method does not need any preprocessing steps except for the digitization of the radiograph.
- The basic structure of the spine was used while marking the reference line. Hence, the quality of the radiograph is not very important for this method.
- Some scoliosis cases involve particular deformations of the vertebrae. This deformation of the vertebrae causes confusion in the selection of the top or bottom vertebra in the classical Cobb method. Because the curve fitting method uses overall points on the curve, the aforementioned problem will not cause an error.
- The developed software uses user inputs; therefore, any spinal deformation, such as lordosis and kyphosis, can also be measured.
- Because the developed program is Java-based and fast, it can be used with any smart mobile device.

The new method has many advantages; however, it still needs user input for the calculation process. Adaptive pattern recognition algorithms can overcome this problem, to be considered in further studies.

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