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Deep Learning-based Automatic Measures of Spinal Curvature in Idiopathic Scoliosis

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ABSTRACT: This study aimed to evaluate the accuracy of a proposed method for measuring scoliosis curvature and its level of agreement with the traditional method of experts' Cobb angle measurements, which serves as the reference standard. This study included 301 whole-spine radiographs of 86 patients with idiopathic scoliosis. The proposed method used a deep-learning model to measure spinal curvatures automatically. In addition, segmentation of the entire spine, extraction of the central line, detection of inflection points, and measurement of the curvature angle were performed. The proposed method was more reliable than the traditional Cobb angle measurement method. The intraclass correlation coefficient for absolute agreement between the two methods was 0.969 (95% confidence interval: 0.957~0.977), indicating excellent agreement. Bland–Altman analysis showed no specific pattern, with a mean difference of -1.29 and 95% limits of agreement ranging from -9.49 to 6.91. The accuracy of the proposed method for detecting scoliosis with a Cobb angle ≥ 40 degrees was 88.4%, with a sensitivity and specificity of 95.9% and 83.2%, respectively. The accuracy of the proposed method for detecting spinal curve progression was 84.9%, with a sensitivity and specificity of 63.6% and 90.5%, respectively. The proposed model for automatic spinal curvature measurement using deep learning showed acceptable accuracy and excellent agreement with the traditional method for Cobb angle measurement. The proposed method may be useful for detecting severe scoliosis and monitoring moderate scoliosis that may progress over time.

KEYWORDS: Biomedical Engineering; Biomedical Imaging; Scoliosis; Cobb Angle Measures; Deep Learning.

Introduction

Scoliosis is a type of spinal deformity that causes lateral curvature of the spine. It can occur in people with conditions such as cerebral palsy and muscular dystrophy; however, most cases are idiopathic, meaning the cause is unknown. Idiopathic scoliosis is usually diagnosed in adolescents during their growth spurt and affects approximately 3% worldwide.[1] It is characterized by a lateral deviation of the spine greater than 10 degrees, measured using the Cobb angle on an X-ray image.[2] Also, scoliosis can cause various complications, such as back pain, respiratory problems, cosmetic issues, and psychological distress.[3] Therefore, accurate diagnosis and scoliosis monitoring are essential for effective treatment planning.

The Cobb angle measurement is the gold standard for evaluating scoliosis in clinical practice.[4] However, this method has several drawbacks that could be improved to maintain its reliability and validity. First, it is subjective and prone to interobserver and intraobserver variability.[5] Second, it is influenced by the patient's position and degree of rotation during X-ray image acquisition.[6] Third, it does not capture the three-dimensional nature of a spinal deformity.[7]

Several computer-assisted methods to measure the Cobb angle more objectively and accurately have been proposed to overcome these limitations. These methods typically involve manual or semiautomatic detection of vertebral landmarks on X-ray images using graphical user interfaces or image processing techniques.[8-10] However, these methods require human intervention and expertise to select appropriate landmarks and curves on the spine. Moreover, these methods are sensitive to image quality and resolution and may need to be revised in complex or atypical cases. In this study, we proposed a model for the automatic measurement of spinal curvature using the U-Net model, which simplifies the process and reduces error by segmenting the entire spine, extracting the central line, detecting inflection points, and measuring the curvature angle.

This study was designed to (a) evaluate the reliability between the traditional experts' Cobb angle measurements and the proposed measurements, (b) investigate the accuracy of the proposed method for detecting severe scoliosis that may require surgery and monitoring moderate scoliosis that may progress over time, using the traditional Cobb angle measurement method as the reference standard, and (c) determine the interobserver reliability of Cobb angle measurements among novices who are not trained in radiology, compared to experts' Cobb angle measurements.

Methods

Data Collection:

Our Institutional Review Board approved this retrospective study (No. 2010-124-1166). A total of 301 whole-spine anteroposterior (AP) radiographs of 86 patients with idiopathic scoliosis obtained from the Department of Orthopedics, Seoul National University Hospital, were used for the study. Inclusion criteria for this study include patients between the ages of ten and nineteen who have been diagnosed with idiopathic scoliosis. Exclusion criteria consist of patients who have undergone spine surgery, those with infantile idiopathic scoliosis,

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and individuals with scoliosis resulting from certain conditions such as cerebral palsy and muscular dystrophy. Whole-spine AP radiographs were taken with patients in the conventional standing posture at a fixed distance of 228 cm from the X-ray source.

Deep-learning-based Computation of Spinal Curvature: The automatic measurement of the Cobb angle consisted of four steps (Figure 1): segmenting the entire spine, extracting the central line, detecting the inflection points, and measuring the Cobb angle. First, the U-Net model was trained using 200 radiographic images and manually segmented spine masks to automatically segment the entire spine. The 200 radiographs used for spine auto-segmentation were patients who were diagnosed with adolescent idiopathic scoliosis with their x-rays, and they were not used for results analysis. Next, morphological operations were used to produce a skeleton of the spine from the segmented areas, and a seventh-order polynomial curve-fitting method was used to extract the points on the skeleton. After, the first derivative of the spinal curve was computed to detect the inflection points on the skeleton curve. The Cobb angle was then calculated automatically based on the detected inflection points.

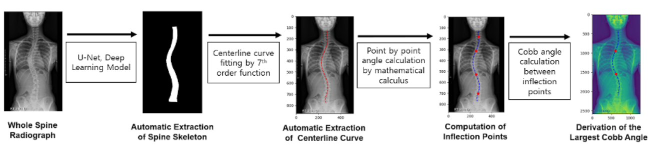

Figure 1: Overview of spinal curvature evaluation. A U-Net model was trained for automatic spine segmentation, followed by morphological operations and curve-fitting techniques to extract the central line, detect inflection points, and automatically measure the Cobb angle.

Cobb Angle Measurement by human readers:

Blinding of the observers was performed. All 301 radiographs were numbered and analyzed in consensus by an experienced orthopedic surgeon and an experienced radiologist using an electrical tool for Cobb angle measurements embedded in the Picture Archiving and Communication System (PACS) (INFINITT PACS; INFINITT Healthcare, Seoul, Korea). Lines were manually drawn through the endplates of the curve's upper and lower end vertebrae on the monitor, and the Cobb angle was automatically generated on the screen. These results were considered the reference standard for Cobb angle measurements. Additionally, four novice observers analyzed the Cobb angles in 30 randomly selected radiographs using the same method They were blinded to the results obtained by the experts or the proposed method. However, they were educated on how to measure the Cobb angles and tested using five radiographs before proceeding with the primary analysis.

Statistical Analysis:

Data were presented as means and standard deviations. A comparison between the proposed method and the traditional experts' Cobb angle measuring method was performed using the paired t-test. Agreement between the two methods in measuring spinal curvature was evaluated using the intraclass correlation coefficient (ICC) two-way mixed model on the absolute agreement and Bland–Altman plots. An ICC less than 0.2 was considered unacceptable; 0.2 to 0.39 questionable; 0.4 to 0.59 good; 0.6 to 0.74 very good; and 0.75 to 1.00 excellent. Using Bland–Altman analysis, the mean difference and 95% confidence limits of agreement were calculated. The accuracy, sensitivity, specificity, negative predictive value, and positive predictive value of the proposed method for detecting scoliosis with an angle of 40 degrees or greater were assessed using the Cobb angles obtained from the traditional method as the reference standard. Likewise, the accuracy, sensitivity, specificity, negative predictive value, and positive predictive value of the proposed method for detecting spinal curve progression were assessed using the traditional Cobb angles obtained by experts as the reference standard. An increase of five degrees or more of the Cobb angle in the follow-up radiograph was defined as progression, and radiographs with an interval of more than six months from the first radiograph were included. Frequencies of Cobb angle of 40 degrees or greater, or the progression in scoliosis in the follow-up, were compared between the measurements by experts and those by the proposed method using the McNemar test. Finally, the mean values of the Cobb angles from the reference standard and those from each novice were compared using the paired t-test, and the interobserver reliability between the measurements from the reference standard and those from each novice was evaluated using the ICC two-way mixed model on the absolute agreement. All statistical analyses were performed using SPSS software (version 25.0; IBM, Armonk, NY, USA). A p-value < 0.05 was considered statistically significant.

Results and Discussion

Table 1 shows the basic characteristics of the 86 patients and the distribution of the Cobb angles of the 301 radiographs. Although the mean values of the results from the proposed method were significantly greater than those from the traditional method (39.01 ± 12.85 vs. 37.7 ± 12.42; mean difference, -1.29 ± 4.18 [p < 0.001]), an agreement between the two methods was excellent (ICC, 0.969; 95% confidence interval, 0.957~0.977 [p < 0.001]) (Figure 2). In Figure 3, Bland–Altman plots between Cobb angles and the proposed method show no specific pattern, with a mean difference of -1.29 and 95% limits of agreement ranging from -9.49 to 6.91.

Table 1: Baseline characteristics and distribution of the Cobb angles in 301 radiographs of 86 patients. People with severe scoliosis with an angle of 40 or greater comprised 40.5% of the study population.

Baseline characteristics	
Female (%)	74 (86.1)
Age, years* (range)	14.0 ± 2.6 (5.6~21.3)
No. of follow-up radiographs* (range)	3.5 ± 3.1 (1~16)
Cobb angle	**No. Radiographs (%)**
<20º	23 (7.6)
20~<40º	156 (51.8)
40~<60º	113 (37.5)
≥60º	9 (3.0)

*mean ± standard deviations

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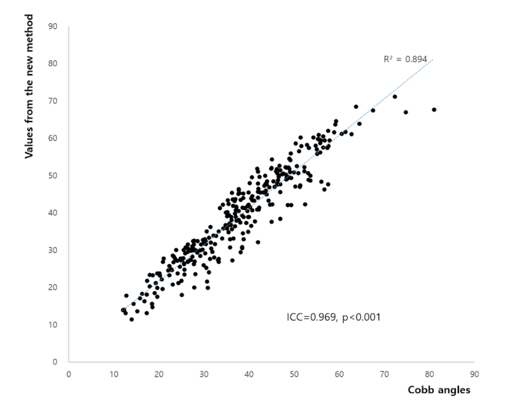

Figure 2: Agreement between measurements using the traditional experts' Cobb angle method and the proposed method. High agreement between the newly proposed measurements and the traditional Cobb angle measurements is shown with an ICC of 0.969.

The performance of the proposed method for the detection of scoliosis with an angle of 40 degrees or greater in the 301 radiographs was acceptable: accuracy, 88.4%; sensitivity, 95.9%; specificity, 83.2%; negative predictive value, 96.7%; and positive predictive value, 79.6% (McNemar test, $p < 0.001$) (Table 2). In terms of performance of the proposed method for detection of progression of more than five degrees in a total of 159 follow-up radiographs of 52 patients, accuracy, sensitivity, specificity, positive predictive value, and negative predictive value were 84.9%, 63.6%, 90.5%, 63.6%, and 90.5%, respectively (McNemar test, $p = 1.0$) (Table 2).

Table 2: Performance of the proposed method for detecting scoliosis with a Cobb angle of 40 degrees or greater (n = 301 radiographs) and for detecting progression in scoliosis (n = 159 radiographs). Accuracies for detecting severe scoliosis and progression are respectively 88.4% and 84.9%.

Accuracy for the detection of scoliosis with 40 degrees or greater			
		Cobb angles by experts	
		40º or more	Less than 40º
The proposed method	40º or more	117	30
	Less than 40º	5	149
Accuracy for the detection of the progression in scoliosis			
		Cobb angles by experts	
		Progression	No progression
The proposed method	Progression	21	12
	No progression	12	114

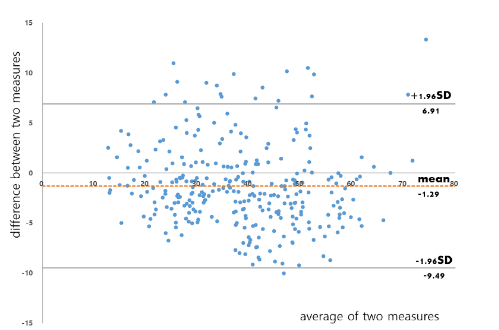

Figure 3: Bland–Altman plots between the Cobb angle measurement by experts and those by the proposed method. The graph shows no specific pattern, with a mean difference of -1.29 and 95% limits of agreement ranging from -9.49 to 6.91.

The interobserver reliability of the four novices, using the Cobb angle measurements obtained by the experts as the reference standard, is shown in Table 3. Again, all novice results differed significantly from the experts, with the mean difference ranging from 2.26 to 9.98.

Table 3: Interobserver reliability of four novices, using the Cobb angle measurements obtained by experts as the reference standard. The Cobb angle measurements obtained by four inexperienced individuals differed significantly from those obtained by the expert.

	Expert	Observer 1	Observer 2	Observer 3	Observer 4
Cobb angles*	38.39±15.29	36.13±16.02	32.96±15.62	35.52±14.22	28.41±13.58
Difference* (range)†	NA	2.26±4.13 (0.55~14.05)	5.43±7.73 (0.35~22.24)	2.87±3.33 (0.14~9.99)	9.98±5.45 (0.53~26.18)
P value†	NA	0.006	0.001	<0.001	<0.001
ICC (95% CIs)	NA	0.978 (0.938~0.991)	0.905 (0.678~0.963)	0.978 (0.873~0.993)	0.858 (-0.14~0.965)
P value‡	NA	<0.001	<0.001	<0.001	<0.001

*mean ± standard deviations (SD)
†Difference between expert's and each novice's Cobb angles
The parenthesis range indicates the absolute difference between the expert's and each novice's Cobb angles.
†Paired t-test between the expert's and each observer's measures
‡P value for ICC between the expert's and each observer's measures
CI, confidence interval
NA, non-applicable

The principal findings of the present study can be summarized as (a) the proposed method for the automatic quantification of the spinal curvature showed excellent agreement (ICC, 0.969) with the traditional method for Cobb angle measurement by experts, (b) the accuracy of the proposed method for detecting scoliosis with a Cobb angle of 40 degrees or greater was good (88.4%), with a sensitivity of 95.9% and a specificity of 83.2%, (c) the accuracy of the proposed method for monitoring spinal curve progression was modest (84.9%), with a sensitivity of 63.6% and a specificity of 90.5%, and (d) interobserver reliability of the four novices showed different ICC values ranging from 0.858 to 0.978, with a comprehensive 95% confidence interval of -0.14 to 0.991. In contrast, the proposed method always provides consistent results.

In our proposed model, segmentation of the entire spine using deep-learning technology was implemented, eliminating the requirement for the manual detection of the anatomical landmarks, which was present in previous computational methods.[11] Previous models implemented partial division of each spinal column because of the complexity of the spine and the number of calculations required. Calculating the curvature is more complex and prone to errors from segmenting individual vertebrae. Instead of manually connecting the midpoints, this deep-learning model automatically draws the midline and converts it into a seventh-order function, which becomes the basis for measuring the spinal curvature, thereby minimizing the impact of segmentation errors on the Cobb angle measurement. In addition, this model resolves the problem of interobserver variability because a machine automatically conducts the measurement. The simplicity of the proposed model saves time and resources and offers convenience by using a functional graph to calculate the spinal curvature. The severity of the curvature can also be observed from the shape of the automatic line, which makes the detection process more accessible.

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This study had some limitations. First, although the proposed method is simple, fully automated, and generates consistent measurements of spinal curvatures, the accuracy levels for detecting severe scoliosis and monitoring progression must be sufficiently high to replace the traditional Cobb angle measurement method. Thus, additional modifications are required to enhance the accuracy of the proposed method. Second, this was a single-center study. Therefore, external validation is necessary to ascertain whether similar results can be replicated in other institutions. Lastly, it's important to note that our model was primarily trained to measure adolescent idiopathic scoliosis, and we lack the data necessary to confirm its accuracy in detecting degenerative changes in the spine that typically occur after the 30s-40s. Therefore, our model may not be optimal for diagnosing degenerative scoliosis, as it was specifically designed to measure adolescent idiopathic scoliosis patients who generally have more severe conditions.

Conclusion

The proposed method for automatic spinal curvature measurement using the U-Net model showed acceptable accuracy and excellent agreement with the traditional method for Cobb angle measurement by experts. The proposed method may be useful for detecting severe scoliosis and monitoring moderate scoliosis that may progress over time.

Acknowledgments

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References

1. Weinstein, S. L.; Dolan, L. A.; Cheng, J. C.; Danielsson, A.; Morcuende, J. A. Adolescent Idiopathic Scoliosis. The Lan cet 2008, 371 (9623), 1527–1537. DOI:10.1016/s0140-67 36(08)60658-3.
2. Cobb JR. Outline for the study of scoliosis. Instr Course L ect. 1948;5:261-75.
3. Negrini, S.; Donzelli, S.; Aulisa, A. G.; Czaprowski, D.; Sc hreiber, S.; de Mauroy, J. C.; Diers, H.; Grivas, T. B.; Knott, P.; Kotwicki, T.; Lebel, A.; Marti, C.; Maruyama, T.; O'Brie n, J.; Price, N.; Parent, E.; Rigo, M.; Romano, M.; Stikeleat her, L.; Wynne, J.; Zaina, F. 2016 SOSORT Guidelines: O rthopaedic and Rehabilitation Treatment of Idiopathic Sco liosis during Growth. *Scoliosis and Spinal Disorders* **2018**, *13* (1). DOI:10.1186/s13013-017-0145-8.
4. Konieczny, M. R.; Senyurt, H.; Krauspe, R. Epidemiology of Adolescent Idiopathic Scoliosis. *Journal of Children's Ort hopaedics* **2013**, *7* (1), 3–9. DOI:10.1007/s11832-012-0457 -4.
5. Vrtovec, T.; Pernuš, F.; Likar, B. A Review of Methods for Quantitative Evaluation of Spinal Curvature. *European Spi ne Journal* **2009**, *18* (5), 593–607. DOI:10.1007/s00586-00 9-0913-0.
6. La Maida, G. A.; Zottarelli, L.; Mineo, G. V.; Misaggi, B. S agittal Balance in Adolescent Idiopathic Scoliosis: Radiogr aphic Study of Spino-Pelvic Compensation after Surgery. *European Spine Journal* **2013**, *22* (S6), 859–867. DOI: 10.10 07/s00586-013-3018-8.
7. Ilharreborde, B.; Even, J.; Lefevre, Y.; Fitoussi, F.; Presedo, A.; Souchet, P.; Penneçot, G.-F.; Mazda, K. How to Deter mine the Upper Level of Instrumentation in Lenke Types 1 and 2 Adolescent Idiopathic Scoliosis. *Journal of Pediatri c Orthopaedics* **2008**, *28* (7), 733–739. DOI:10.1097/bpo.0b 013e318185a36b.
8. Chockalingam, N.; Dangerfield, P. H.; Giakas, G.; Cochra ne, T.; Dorgan, J. C. Computer-Assisted Cobb Measureme nt of Scoliosis. *European Spine Journal* **2002**, *11* (4), 353-35 7. DOI:10.1007/s00586-002-0386-x.
9. Zhang, J.; Lou, E.; Le, L. H.; Hill, D. Computer-Assisted Cobb Angle Measurement on Posteroanterior Radiographs . *Studies in Health Technology and Informatics* **2008**, *140*, 151 –156. DOI:10.3233/978-1-58603-888-5-151.
10. Papaliodis, D. N.; Bonanni, P. G.; Roberts, T. T.; Hesham, K.; Richardson, N.; Cheney, R. A.; Lawrence, J. P.; Carl, A. L.; Lavelle, W. F. Computer Assisted Cobb Angle Measure ments: A Novel Algorithm. *International Journal of Spine S urgery* **2017**, *11* (3), 21. DOI:10.14444/4021.
11. Chi, W.-M.; Cheng, C.-W.; Yeh, W.-C.; Chuang, S.-C.;C hang, T.-S.; Chen, J.-H. Vertebral Axial Rotation Measure ment Method. *Computer Methods and Programs in Biomedic ine* **2006**, *81* (1), 8–17. DOI:10.1016/ j.cmpb.2005.10.004.

Authors

Yubeen Lee, Seoyoung Park, and Seunghoon Han are high schoolers at Saint Paul Preparatory Seoul who participated in this research as members of the Scoliosis Research club with deep interests in biology, statistics, and computer science.