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A Purpose-Design Computational Method for Estimation of Plane of Maximum Curvature in Adolescent Idiopathic Scoliosis

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Abstract
Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional (3D) deformity, and the plane of maximum curvature (PMC) is proposed to reflect these clinical features, which refers to a vertical plane presenting the maximum projected spinal curvature and its parameters include the PMC Cobb and orientation (angle between PMC and sagittal planes). This study aims to develop a computational method (CM) for PMC estimation. Twenty-nine patients with AIS and computed tomography (CT) images were recruited. For CT, PMC was determined by rotating a vertical plane about its vertical axis with 5° increment until the maximum Cobb angle was measured. For CM, PMC was estimated via identifying the eight points (the corner points of superior and inferior endplates of the upper and lower end-vertebrae respectively) in the coronal and lateral CT images. Two experienced raters repeated the PMC estimation three times with one-week interval. The intra-class correlation coefficient (ICC) and Bland-Altman method were used for statistical analysis. Twenty-seven right thoracic curves (RTs) (mean Cobb: 46.1°±12.4°) and 23 left thoracolumbar/lumbar (LTLs/LLs) (mean Cobb: 30.6°±11.1°) were analysed. The intra- and inter-rater ICC values were >0.91 and 0.84 in RTs and LTLs/LLs, respectively. The PMCs obtained from the CM and CT were showed good agreement was also observed between the PMCs obtained from the two methods according to ICC (>0.90) and Bland-Altman method assessments. This purpose-design computational method could provide reliable and valid estimation of PMCs for AIS, which has potential to be used as an alternative for 3D assessment.

Keywords: Adolescent Idiopathic Scoliosis; Three-dimensional Assessment; Computational Method; Plane of Maximum Curvature

Introduction
Adolescent idiopathic scoliosis (AIS) is a complicated three-dimensional (3D) deformity of spine.[1] The Cobb angle measured from the coronal radiograph is the gold standard for the clinical assessment of scoliosis,[2] but it may underestimate the severity of spinal curvature and also cannot fully reflect the pattern of spinal curve.[3,4] The plane of maximum curvature (PMC) was considered as a promising descriptor for the 3D assessment of scoliosis[5] and has been increasingly valuable in orthopedic operation of spine.[6] PMC is defined as a vertical plane that positions between the sagittal and coronal planes, and presents the maximum spinal curvature [1]. Its parameters include the maximum Cobb angle in PMC (PMC-Cobb) and orientation of PMC (PMC-orientation, the angle between the PMC and sagittal plane[7]). PMC could be estimated through

rotating a vertical plane, where a spinal curve is projected onto, until the maximum Cobb angle is found. However, 3D reconstruction model of scoliotic spine was required.[3,8,9] The computed tomography (CT), which are recognized as valid 3D assessment of scoliosis, can also be used to obtain the PMC. However, it was commonly applied to severe cases, not for routine clinical application to mild or moderate cases because of high radiation exposure. Therefore, this study aimed to develop a more user-friendly computational method (CM) to estimate the PMC basing on the coronal and sagittal images, and to verify the results with CT.

Materials & Methods

Subjects Twenty-nine were selected from the database of a local hospital using criteria: diagnosed with AIS; age: 10-24; coronal-Cobb=10°-80°; and with CT images of the whole spine. Those who had prior surgical treatment or other diseases affecting the spinal profile were excluded. Human subject ethical approval was granted from the authors' Institutional Review Board.

PMC estimation using CM The CM was based on the global axis system (x, y, z) of the human body with the origin at the center of the superior endplate of the 1st sacral vertebra [10]. It assessed the spinal curve by calculating the angle (β) formed by the intersection lines of a vertical plane and the superior endplate of the upper-end vertebra and inferior endplate of the lower-end vertebrae of a specific spinal curve (Fig. 1). The Cobb angles (β) in different vertical planes were calculated based on the 3D coordinates of 8 points at the superior endplate of upper end vertebra and inferior endplate of lower end vertebra in the sagittal and coronal planes using the formula as below, and the maximum Cobb angle (β_{max}) could be then determined among the calculated Cobb angles (β).

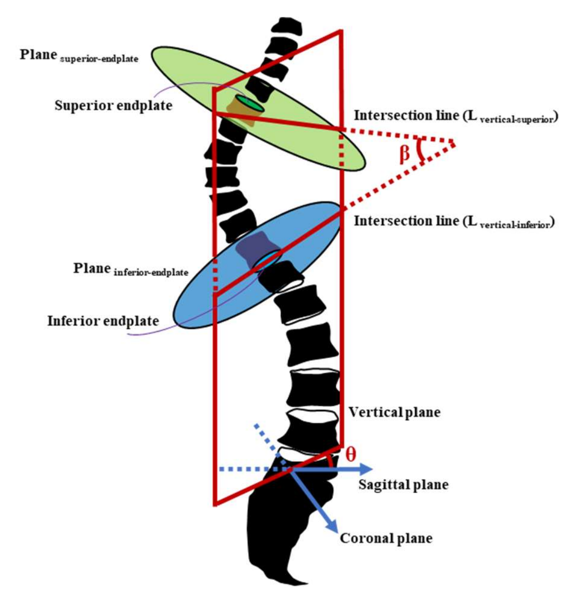

Fig.1 The superior endplate of the upper-end vertebra and inferior endplate of the lower-end vertebra of a specific spinal curve are assumed to be on the planes that can be extended outward named $Plane_{superior\text{-}endplate}$ and $Plane_{inferior\text{-}endplate}$, respectively, to ensure the intersections bettwen the 3 planes. A vertical plane intersects with $Plane_{superior\text{-}endplate}$ and $Plane_{inferior\text{-}endplate}$ at $L_{vertical\text{-}superior}$ and $L_{vertical\text{-}inferior}$, respectively; and the angle (β) formed by the intersection lines is the Cobb angle of the spinal curve in that vertical plane. The orientation of that vertical

$$\beta = arccos\frac{(2aceg + adeh + bcfg) + (adeh - bcfg)cos2\theta + (adgf + bceh)sin2\theta}{\sqrt{(2a^2c^2 + a^2d^2 + b^2c^2) + (a^2d^2 - b^2c^2)cos2\theta + 2adbcsin2\theta}\sqrt{(2e^2g^2 + e^2h^2 + f^2g^2) + (e^2h^2 - f^2g^2)cos2\theta + 2ehgfsin2\theta}}$$

PMC estimation using CT With all the CT images visualized three-dimensionally using an open-source image processing software named 3DSlicer (version 4.8.1, 3DSlicer Platform: www.slicer.org), a plane, where the spine was projected onto, was rotated 90° axially from the sagittal plane to the coronal plane with 5° increments.) the Cobb angle in each rotated plane was measured. The maximum Cobb angle could be then identified, and the rotated plane presenting the maximum Cobb angle was recorded as the PMC.

Data collection Two experienced raters participated in data collection. Based on the same set of the coronal and sagittal CT images of the spine, each rater used the CM to estimate the PMC 3 times with one-week interval. One of the raters measured the PMC 3 times using the CT constrained and unconstrained Cobb methods based on the same set of rotated CT images using the same protocol.

Statistical analysis Statistical analyses were performed in SPSS (version 21, IBM, USA) with a significant level of 0.05. The intra-class correlation coefficient (ICC) with 95% confidence interval was used for the reliability analysis of CM. The strength of reliability was evaluated using the criteria: very reliable (ICC=0.8-1.0), moderately reliable (ICC=0.60-0.79) and questionably reliable (ICC<0.60).[11] The validity of the PMC acquired using the CM was analysed using the ICC, Pearson correlation coefficient (r), and Bland-Altman method. The linear regression analysis was also performed with the correlation coefficient: 0.75-1.00 indicating very good to excellent, 0.50-0.75 indicating moderate to good and 0.25-0.50 indicating poor correlation.[12]

Results and Discussion

A total of 50 curves were eligible for this study, including 27 RTs (mean coronal-Cobb: 46.1°±12.4° with a range of 26.2°-71.1°) and 23 LLs (mean coronal-Cobb: 30.6°±11.1° with a range of 16.4°-54.2°).

Reliability of the CM in the PMC estimation As shown in Table 1&2, the intra- and inter-rater ICC values were from 0.91- 0.98 and 0.84-0.91, respectively, being similar to those for coronal-Cobb reported previously.[13,14] This demonstrated very good reliability of CM in PMC estimation for the RTs and LLs.

Table 2. Inter-rater reliability of the CM between the two raters in PMC estimation for different curve types

PMC parameter	ICC
<u>RTs</u>	
PMC-Cobb	0.905

PMC-orientation	0.912
LLs	
PMC-Cobb	0.877
PMC-orientation	0.839

Table 1. Intra-rater reliability of the CM in PMC estimation for different curve types

PMC Parameter	ICC Rater 1	ICC Rater 2
RTs		
PMC-Cobb	0.952	0.983
PMC-orientation	0.912	0.949
LLs		
PMC-Cobb	0.965	0.977
PMC-orientation	0.958	0.982

Validity of the CM in PMC estimation

TABLE 3. The comparison of PMC estimation using CM and CT for different curve types.

PMC parameter	PMC (mean±standard deviation) (°) CM	CT	ICC between CM and CT
RTs			
PMC-Cobb	48.0±11.4	50.8±12.7	0.968
PMC-orientation	-74.8±9.1	-72.7±8.9	0.909
LLs			
PMC-Cobb	39.8±9.9	44.6±9.4	0.948
PMC-orientation	-234.8±16.1	-232.4±17.1	0.958

As shown in Table 3, high ICC values (0.91 to 0.97 with mean: 0.94±0.02) were found between PMCs (PMC-Cobb, PMC-orientation) obtained from the CM and CT constrained and unconstrained Cobb methods for the both RTs and LLs. Moreover, according to the Bland-Altman method assessment (Fig. 5), all the PMCs (PMC-Cobb, PMC-orientation) almost distributed around the central lines and the mean differences were within (2.9°, 3.1°) for RTs, and (5.1°, 4.3°) for LLs, being smaller or close to the clinical accepted error (5°).[15] These results suggested good agreements between the PMCs obtained from the CM and CT.

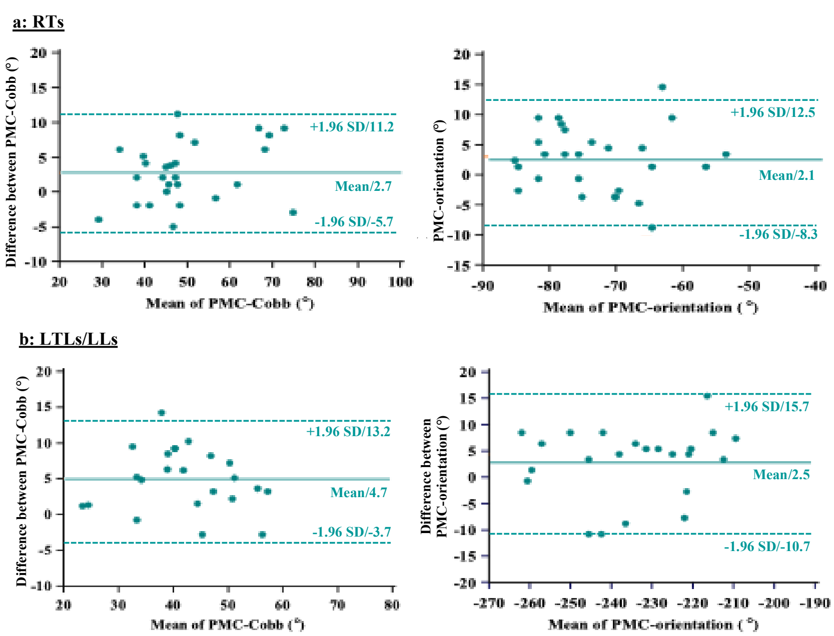

Fig.5 Bland-Altman plot assessing the agreement of PMCs obtained from the CM and CT constrained and unconstrained Cobb methods for the RTs and LLs (Mean =(CT+CM)/2;

The PMC has been used in the 3D assessment[8,16] and 3D classification[17] of scoliosis as well as in 3D correction evaluation of surgical[18] and orthotic[19] treatment. Since providing information about both the actual magnitude of a curve and the degree of a curve being shift towards the coronal plane, the PMC would be superior to other clinical indices, such as the coronal Cobb and apical vertebral rotation, in the description of 3D deformities. As pointed out by Labelle, et al. [20], a curve type proposed by a conventional method (Lenke classification system) could be further split into different curve sub-types based on the PMC (the best fit plane / the plane passing through the end-apical-end vertebrae). Different curve sub-types may require different surgical strategies or different orthosis designs; thus, it should be considered when making surgical strategy or designing spinal orthosis. These reveal the importance of PMC in the clinical assessment and management of scoliosis.

Conclusion

This study developed a computational method for PMC estimation from the coronal and sagittal images with further validation by CT. The results found that the PMC measurements (PMC-Cobb, PMC-orientation) obtained from the computational method were very reliable and had a good agreement in comparison with the CT constrained and unconstrained Cobb methods. These results suggested that the computational method would have the potential to be applied as a useful tool for the 3D assessment of AIS and enhancement of AIS management.

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