This is the accepted version of the publication Wu H-D, Chu WC-W, He C-Q, Wong M-S. Assessment of the plane of maximum curvature for patients with adolescent idiopathic scoliosis via computed tomography. Prosthetics and Orthotics (Volume: 44 issue: 5) pp. 298-304. Copyright ©2020 The International Society for Prosthetics and Orthotics. DOI: 10.1177/0309364620941297.

Title

Assessment of the plane of maximum curvature for patients with adolescent idiopathic scoliosis via computed tomography

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All authors contributed equally in the preparation of this manuscript.

Declaration of conflicting interests

The authors declared that there is no conflict of interest.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Abstract

Background: In the assessment of three-dimensional features of adolescent idiopathic scoliosis (AIS), the plane of maximum curvature (PMC) was compared with the coronal Cobb angle.

Objectives: To investigate the intra-rater reliability, variability and difference of the prone PMC measurements taken from CT using the constrained and unconstrained Cobb methods; to assess the difference and correlation between the prone PMC measurements obtained using the constrained and unconstrained Cobb methods; and to examine difference and correlation between the prone PMC Cobb angle and coronal Cobb angle measurements.

Study design: Retrospective study.

Methods: Twenty-nine subjects with AIS aged 15.8±3.5 were enrolled (25 thoracic and 24 thoracolumbar/lumbar curves). An experienced rater measured the PMC using the constrained and unconstrained Cobb methods, and the coronal Cobb angles using the conventional Cobb method on the CT images 3 times each with one-week interval. The intra-class correlation coefficient (ICC [2,1]), Pearson correlation coefficient (r), one-way repeated measures ANOVA and paired t-test were applied for various analyses.

Results: The ICC for all intra-rater reliability assessments were greater than 0.87. The PMC measurements of the two Cobb methods were excellently correlated ($r \geq 0.97$) with no significant difference ($p > 0.05$). The mean PMC Cobb angle was moderately correlated with ($r > 0.72$) but significantly greater ($p < 0.001$) than the mean coronal Cobb angle.

Conclusion: The PMC measurements obtained from CT were found to be reliable while the PMC measurements of the two Cobb methods were comparable. The mean PMC Cobb angle was moderately correlated with but significantly greater than the mean coronal Cobb angle.

(249 words)

Clinical relevance

The PMC measurements taken from CT were found reliable that could be used as a supplement to the coronal Cobb angle in the assessment and management of AIS. With technological advancement, the radiation dose of CT can be further reduced to a safer level for a broader range of cases.

(50 words)

Keywords

Plane of maximum curvature, adolescent idiopathic scoliosis, computed tomography, reliability

Background

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional (3D) spinal deformity characterized by lateral curvature of at least 10º and axial vertebral rotation (AVR).[1] Coronal Cobb angle (coronal-Cobb) measured on the posteroanterior (PA) radiograph is an important parameter for the assessment of AIS, however, it may underestimate the severity of spinal deformity and may not fully reflect curve types.[2-5] The plane of maximum curvature (PMC) may be a promising descriptor for the 3D assessment of AIS,[5] and is increasingly valued in spinal surgery.[6] PMC is a vertical plane located between the sagittal and coronal planes and presents the maximum projected spinal curvature.[1] Parameters include the maximum Cobb angle measured in the PMC (PMC-Cobb) and the orientation of PMC (PMC-orientation, the angle between the PMC and sagittal plane). The PMC (PMC-Cobb & PMC-orientation) may play an important role in the assessment and management of

AIS. As reported in previous studies, the PMC appeared to be more informative in describing the 3D features of the scoliotic spine,[5,7,8] and may be more effective in reflecting the 3D correction of treatment.[9,10] Furthermore, the PMC is superior to the coronal-Cobb in differentiating curve types, as reported by Sangole et al.[4] and Labelle et al.[5] that the coronal-Cobb-based curve type could be further split into different sub-types using the PMC.

Currently, several techniques allow PMC measurements. Biplanar radiography[7,11] (e.g. EOS imaging system) and 3D ultrasound imaging[12] can be used to assess the PMC. However, the reliability and validity of PMC measurements using these techniques need to be investigated before clinical application. Computed tomography (CT) is a common method for 3D assessment of severe AIS in clinical practice as it allows the assessment of spinal deformity in both the coronal, sagittal and transverse planes with the same image-set.[13] CT has been used to evaluate coronal curvature with a small error of measurement (< 2.7°)[13], and axial vertebral rotation[14,15] with high reliability (intraclass correlation coefficient = 0.95[14]). It has also been used to investigate the asymmetry of vertebral body[16] and pedicles[16,17] as well as anterior-posterior length[18] of the spinal column. However, it has never been used for the PMC measurement. If the CT method can be demonstrated to be reliable in the PMC assessment, it could facilitate clinical application of the PMC measurement so that it may serve as a supplement to coronal-Cobb measurement in the assessment and management of AIS.

Because of the complicated global, regional and local deformity of AIS[1,16-18], it is unknown if the end-vertebrae most tilted in the coronal plane would also be most tilted in any other vertical planes (different from the coronal plane). Thus, constrained and unconstrained Cobb methods were proposed. As shown in Figure 1, the constrained Cobb method measures the Cobb angle in other vertical planes but with the upper and lower end-vertebrae constrained to the upper and lower end-vertebrae pre-selected from the coronal plane;[1,7,19] while the unconstrained Cobb method measures the Cobb angle in other vertical planes with the upper and lower end-vertebrae determined from the instantly measured vertical plane.[7] In the constrained Cobb method, there is no need to select the end-vertebrae in other vertical planes, thus, it would be less time-consuming and appear to be used more frequently for determining the PMC when using the other techniques (e.g. biplanar radiology).[7,11,19] Although possible discrepancy of the PMC measurement between these two methods has been reported in some studies,[7,19] their comparability has not yet been specifically investigated.

It may improve the understanding of 3D features of spinal deformities to analyze the potential difference and correlation of AIS parameters obtained from the images taken in different positions. The dependent relationships between the PMC (PMC-Cobb & PMC-orientation) and coronal/sagittal-Cobb have been assessed in the standing position[4,15,20]. The PMC-Cobb was notably greater than the corresponding coronal-Cobb in the standing position,[2,3,7-10,21] however, the difference and correlation between the PMC-Cobb and coronal-Cobb were not investigated in a recumbent (prone/supine) position.

Thus, the objectives of this study were to (1) investigate the intra-rater reliability, variability and difference of the PMC measurements taken from CT using the constrained and unconstrained Cobb methods in the prone position; (2) assess the difference and correlation between the PMC measurements obtained using the constrained and unconstrained Cobb methods in the prone position; and (3) examine difference and correlation between the PMC-Cobb and coronal-Cobb measurements in the prone position.

[insert Figure 1.]

Methods

Subjects

This study retrospectively reviewed the 3D images of the scoliotic spine taken from CT. Ethical approval for this study has been granted from the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University. Subjects were selected from the database of a local scoliotic clinic according to the following inclusion criteria: (1) diagnosed with AIS; (2) age: ≥ 10 years; and (3) underwent CT of the whole spine. Subjects were excluded if they had received surgical treatment of the spine before CT scan or were diagnosed with other conditions that might affect the spinal morphology.

All subjects were imaged in the prone position with a CT scanner (LightSpeed®16, GE Healthcare, USA with parameters set at 400 mA s, 120 kVp, 0.625 mm thicknesses, and 5 mm gap between slices) between 2015 and 2017 for the purpose of their own clinical examinations.

Acquisition of PMC measurements

All CT slices of the whole spine (Dicom format) were visualized three-dimensionally using an open-source image processing software named 3DSlicer (version 4.8.1, 3DSlicer Platform: www.slicer.org). As shown in Figure 2, a vertical plane, upon which the scoliotic spine was projected, was rotated 90° around the z axis of the global axis system.[22] According to the location of each curve type in this axis system, the vertical plane was rotated from 0° to -90° for right thoracic curves (RTs); 0° to +90° for left thoracic curves (LTs); -180° to -270° for left thoracolumbar/lumbar curves (LTLs/LLs) and +180° to +270° for right thoracolumbar/lumbar curves (RTLs/RLs) in increments of 5°. The Cobb angle of a spinal curve was measured in each rotated plane (n=19) separately using the constrained and unconstrained Cobb methods (Figure 1) using image analysis software named Digimizer (version 4.3.5, MedCalc Software bvba, Belgium), and was recorded as an absolute value. The maximum Cobb angle was then determined, and the rotated plane showing the maximum Cobb angle was the PMC. The determined maximum Cobb angle was the PMC-Cobb, and the orientation of that rotated plane was considered the PMC-orientation. Additionally, the coronal-Cobb was measured on the CT coronal images using the conventional Cobb method.[1]

A rater with 3+ years of experience in scoliosis clinical research repeated the PMC (PMC-Cobb & PMC-orientation) measurements 3 times separately using the constrained and unconstrained Cobb methods with one-week interval between each time to reduce recall bias. The coronal-Cobb was measured repeatedly using the same protocol. The average of the repeated measurements, including the PMC (PMC-Cobb & PMC-orientation) and coronal-Cobb, was used for the subsequent analyses.

[insert Figure 2.]

Statistical analyses

Statistical analyses were performed using SPSS (version 21, IBM, Chicago, IL, USA) with the critical alpha set at 0.05. For the 1st objective, the intra-class correlation coefficient (ICC [2,1], two-way random model and absolute agreement) with 95% confidence interval was used. The strength of reliability was evaluated via the criteria proposed by Currier [23]: very reliable (ICC: 0.8-1.0), moderately reliable (ICC: 0.60-0.79) and questionably reliable (ICC<0.60). Besides, the one-way repeated measures ANOVA, mean absolute difference (MAD), standard deviation (SD) and standard error of measurement (SEM) were applied. For the 2nd objective, the paired t-test (2-tailed), MAD, SD, SEM and Pearson correlation coefficient (r) were evaluated. The strength of correlation was categorized using the following criteria: very good to excellent (r: 0.75-1.00), moderate to good (r: 0.50-0.75) and poor correlation (r: 0.25-0.50).[24] For the 3rd objective, the paired t-test (2-tailed), MAD, SD and Pearson correlation coefficient (r) were applied.

Results

Twenty-nine subjects (27 females & 2 males; aged 15.8±3.5 with a range of 12-24 years) were selected from the database for this study. Forty-nine curves from these subjects were analyzed, including 25 RTs (mean prone coronal-Cobb: 45.9°±12.2° with a range of 26.2°-71.1°) and 24 LTLs/LLs (mean prone coronal-Cobb: 31.8°±11.8° with a range of 16.4°-54.2°).

Intra-rater reliability assessment of PMC measurements

As shown in Table 1, for both the RTs and LTL/LLs groups, the PMC (PMC-Cobb & PMC-orientation) measurements of the constrained and unconstrained Cobb methods were very reliable (intra-ICC = 0.92 to 0.98 for the PMC-Cobb, and intra-ICC = 0.87 to 0.94 for the PMC-orientation). Moreover, the intra-rater variability of the PMC measurements of the two methods was small, with MAD=0.3°, SD=1.5°-1.8° and SEM=0.3°-0.4° for the PMC-Cobb, and MAD=0.4°-1.5°, SD=5.4°-7.3° and SEM=1.1°-1.5° for the PMC-orientation. No significant intra-rater difference was found among all the repeated PMC measurements (p>0.05 for the PMC-Cobb, and p>0.05 for the PMC-orientation).

Table 1. Intra-rater reliability of PMC (PMC-Cobb & PMC-orientation) measurements.

Parameter	Mean absolute difference ± standard deviation (°)	Standard error of measurement (°)	One-way repeated measures ANOVA		Intraclass correlation coefficients (95% confidence interval)
			F statistics	P value	
Constrained Cobb method					
RTs					
PMC-Cobb	0.3 ± 1.5	0.3	1.128	0.339	0.942 (0.985 - 0.996)
PMC-orientation	1.1 ± 5.4	1.1	1.459	0.243	0.893 (0.803 - 0.948)
LTLs/LLs					
PMC-Cobb	0.3 ± 1.7	0.3	0.670	0.517	0.984 (0.969 - 0.993)
PMC-orientation	0.4 ± 6.4	1.3	0.114	0.892	0.935 (0.878 - 0.969)
Unconstrained Cobb method					
RTs					
PMC-Cobb	0.3 ± 1.6	0.3	1.274	0.289	0.922 (0.984 - 0.996)
PMC-orientation	1.5 ± 5.9	1.2	2.237	0.118	0.874 (0.771 - 0.939)
LTLs/LLs					
PMC-Cobb	0.3 ± 1.8	0.4	0.754	0.433	0.982 (0.964 - 0.992)
PMC-orientation	0.7 ± 7.3	1.5	0.012	0.920	0.902 (0.818 - 0.953)

Comparability assessment of the constrained and unconstrained Cobb methods

In the RTs and LTL/LLs groups (Table 2), the inter-method differences between the PMC measurements obtained using the constrained and unconstrained Cobb methods were small, with MAD=0.0°-0.6°, SD=0.6°-3.0° and SEM=0.1°-0.6° for the PMC-Cobb, and MAD=0.1°-0.6°, SD=1.4°-2.2° and SEM=0.3°-0.4° for the PMC-orientation. All the inter-method differences were not significant ($p>0.05$ for the PMC-Cobb, and $p>0.05$ for the PMC-orientation). Furthermore, excellent correlations were observed between the PMC measurements of these two Cobb methods ($r=0.97$-0.99 for the PMC-Cobb, and $r=0.98$-0.99 for the PMC-orientation).

Table 2. Difference and correlation between the PMC (PMC-Cobb & PMC-orientation) measurements obtained using the CT constrained and unconstrained Cobb methods.

Parameter	Mean absolute difference ± standard deviation (°)	Standard error of measurement (°)	Paired t-test (2-tailed), p value	Correlation coefficient (r)
RTs				
PMC-Cobb	0.0 ± 0.6	0.1	0.762	0.992
PMC-orientation	0.6 ± 2.2	0.4	0.185	0.981
LTLs/LLs				
PMC-Cobb	0.6 ± 3.0	0.6	0.329	0.967
PMC-orientation	0.1 ± 1.4	0.3	0.627	0.994

Difference and correlation assessment of PMC-Cobb and coronal-Cobb measurements

In the RTs and LTL/LLs groups (Table 3), the PMC-Cobb acquired using the two Cobb methods were significantly greater than the corresponding coronal-Cobb (MAD=4.5°-5.4°, SD=4.2°-4.9°, p<0.001). The correlation between the measurements of these two parameters was excellent in the RTs group (r = 0.94), and moderate to good in the LTL/LLs group (r=0.72-0.75).

Table 3. Difference and correlation between the PMC-Cobb and coronal-Cobb measurements.

Curve type	PMC-Cobb[#] *versus* coronal-Cobb			PMC-Cobb* *versus* coronal-Cobb		
	Mean absolute difference ± standard deviation (°)	Sig. *p* (2-tailed)	Correlation coefficient (r)	Mean absolute difference ± standard deviation (°)	Sig. *p* (2-tailed)	Correlation coefficient (r)
RTs	4.5 ± 4.3	< 0.0001	0.941	4.5 ± 4.2	< 0.001	0.942
LTLs/LLs	5.4 ± 4.9	< 0.0001	0.716	4.8 ± 4.5	< 0.001	0.754

[#]: constrained Cobb method.

*: unconstrained Cobb method.

Sig. *p* (2-tailed): significant *p* value of paired t-test (2-tailed).

Discussion

This is the first study to investigate the intra-rater reliability of the PMC measurements acquired from CT using the constrained and unconstrained Cobb methods, and the comparability of the PMC measurements of the two methods in the prone position. The difference and correlation between the PMC-Cobb and coronal-Cobb measurements were also analyzed. The main findings of this study included: (1) the PMC measurements (PMC-Cobb & PMC-orientation) taken from CT using the two Cobb methods in the prone position were found very reliable; (2) no significant differences but excellent correlations between the PMC measurements of the two Cobb methods in the prone position were observed; (3) the PMC-Cobb measurements were excellently correlated with, and significantly greater than, the corresponding coronal-Cobb measurements in the prone position.

In the RTs and LTL/LLs groups, the PMC measurements of the constrained and unconstrained Cobb methods were very reliable and showed small intra-rater variability (intra-ICC>0.92 and MAD≤0.3° for the PMC-Cobb; and intra-ICC>0.87 and MAD≤1.5° for the PMC-orientation). The intra-rater MAD was much smaller than the clinically acceptable threshold (5°).[25] The intra-rater reliability of PMC-Cobb measurements acquired using the two methods was similar to that obtained using 3D ultrasound (ICC>0.93).[12] These results indicated that the constrained and unconstrained Cobb methods could be used to assess the PMC reliably from CT. Although the CT used in this study were generally taken from the patients with relatively severe AIS (due to radiation exposure concern, patients with mild to moderate AIS were not scanned), it is believed that with technological advancement the radiation dose of CT systems can be further reduced to a safer level. If low-dose CT systems could be widely available, the two Cobb methods might allow the PMC measurement for a broader range of cases. Furthermore, biplanar radiography may be an option for 3D reconstruction of the spine, for which the constrained or unconstrained Cobb method might also be used for the PMC measurement.

The PMC (PMC-Cobb & PMC-orientation) measurements of the constrained and unconstrained Cobb methods were comparable in both the RTs and LTL/LLs groups in the prone position (MAD≤0.6°, p>0.05, r≥0.97). This indicated that the PMC measurements obtained using the constrained Cobb method could reflect the maximum spinal deformity as compared to that acquired using the unconstrained Cobb method. Thus, this study suggested using the constrained Cobb method in assessing PMC since it is less time-consuming and more user-friendly in comparison with the unconstrained Cobb method. Also, this study may provide scientific evidence to support the use of the constrained Cobb method in assessing PMC.

The PMC-Cobb overestimated the curve magnitude as compared to coronal-Cobb (MAD=4.5°-5.4°, p<0.001). Similar results were reported in previous studies.[2,3,7-10,21] In comparison to coronal-Cobb, the PMC could provide information for both the maximum curve magnitude (PMC-Cobb) and the degree of curve segment being rotated towards the coronal plane (PMC-orientation). It has been applied to 3D classification[4,5] of AIS. Sangole, et al. [4] pointed out that two curves with the same coronal-Cobb could present remarkably distinct maximum spinal curvature (PMC-Cobb) and sagittal thoracic kyphosis. Moreover, Labelle, et al. [5] reported that a curve type classified by the Lenke system could be further split into different curve sub-types based on the PMC-orientation. This should be considered when making clinical decisions since different curve sub-types may need different treatment strategies. Thus, it is worthwhile to explore the application of PMC to orthotic decision-making in future studies. Besides, PMC has also been used for evaluating 3D correction provided by orthotic treatments.[9,10] In these two studies, significant correction in the coronal-Cobb and PMC-Cobb was found.[9,10] However, the PMC-orientation was significantly increased instead of being reduced as expected,[9,10] indicating that the curve segment rotated towards the coronal plane even more after wearing the orthosis. In a scoliotic spine, the coronal curve may result from a curve segment (thoracic/thoracolumbar/lumbar segment) rotated from the sagittal plane towards the coronal plane with or without alteration in physiological curvature. The goal of orthotic intervention is to push the rotated curve segment back to the sagittal plane (coronal-Cobb = 0°) while keeping a normal spinal profile in the sagittal plane (physiological curvature). Thus, only emphasizing the coronal-Cobb correction but ignoring the changes of PMC-orientation in evaluating the treatment correction, the physiological curvature of the thoracic/thoracolumbar/lumbar region may not be maintained. This indicates that the coronal-Cobb alone may not be comprehensive enough for evaluating the "true" correction of treatment and reflecting the "real" condition of AIS. Therefore, it would be necessary to employ the corresponding PMC (PMC-Cobb & PMC-orientation) measurements as a method to supplement the coronal-Cobb measurements in the orthotic management of AIS.

There are several limitations to this study. As only one rater was involved in the measurement of the PMC, the study lacks inter-rater reliability. It should also be noted that this retrospective study may not allow checking whether all the patients could keep a standardized position in taking CT. The sample size, range of curve magnitude and curve pattern should be increased for better conclusive results.

Conclusion

The PMC measurements (PMC-Cobb & PMC-orientation) taken from the CT were found reliable, and the PMC measurements of the constrained and unconstrained Cobb methods were comparable. The difference and correlation between the PMC-Cobb and coronal-Cobb measurements in the prone position could demonstrate the importance of employing the PMC measurements to supplement the coronal-Cobb measurements in the assessment and management of AIS.

(2485 words)

Captions

Figure 1. Constrained (solid lines) and unconstrained (dashed lines) Cobb methods (the rotated planes (n=19) were generated by rotating a vertical plane 90° around the vertical axis from the sagittal to coronal plane with an increment of 5°; counterclockwise rotation was for a right thoracic curve and recorded as negative (-)).

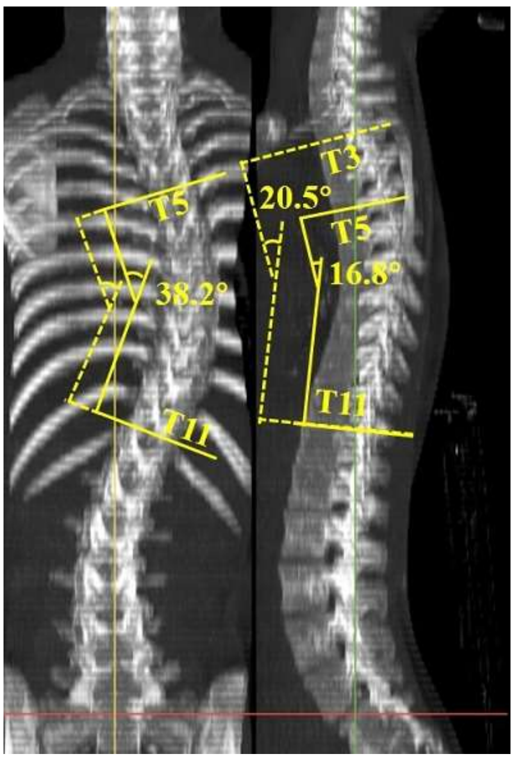


Figure 2. Global axis system in the human body. The x and y axis pointing posteriorly and to the right side represent the sagittal and coronal planes respectively. The orientation of the vertical plane was referred separately as negative (-) for counter-clockwise rotation and positive (+) for clockwise rotation, being at 0°/±180° or ±90°/±270° when overlapping with the sagittal plane or coronal plane, respectively.

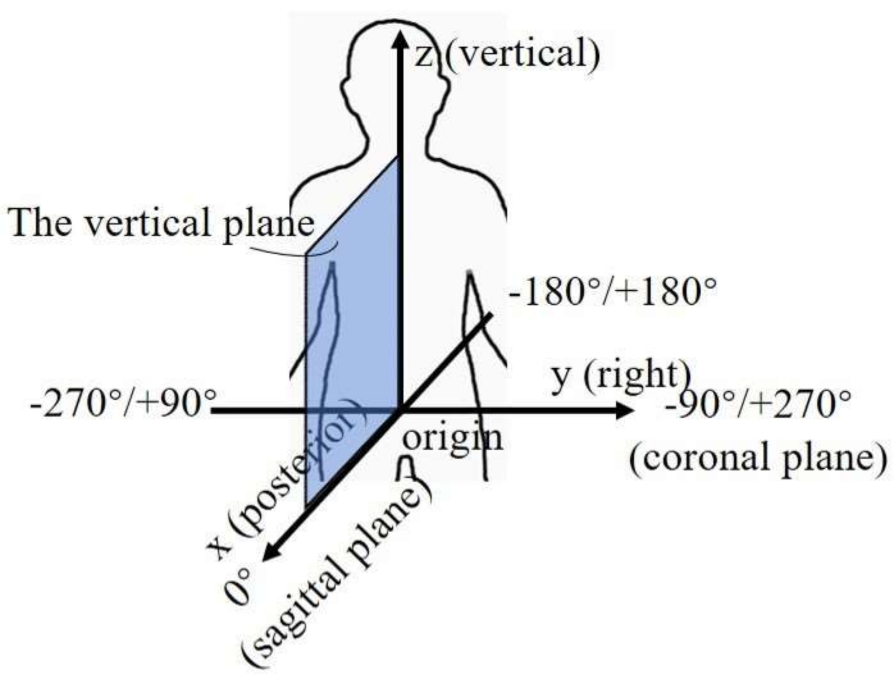
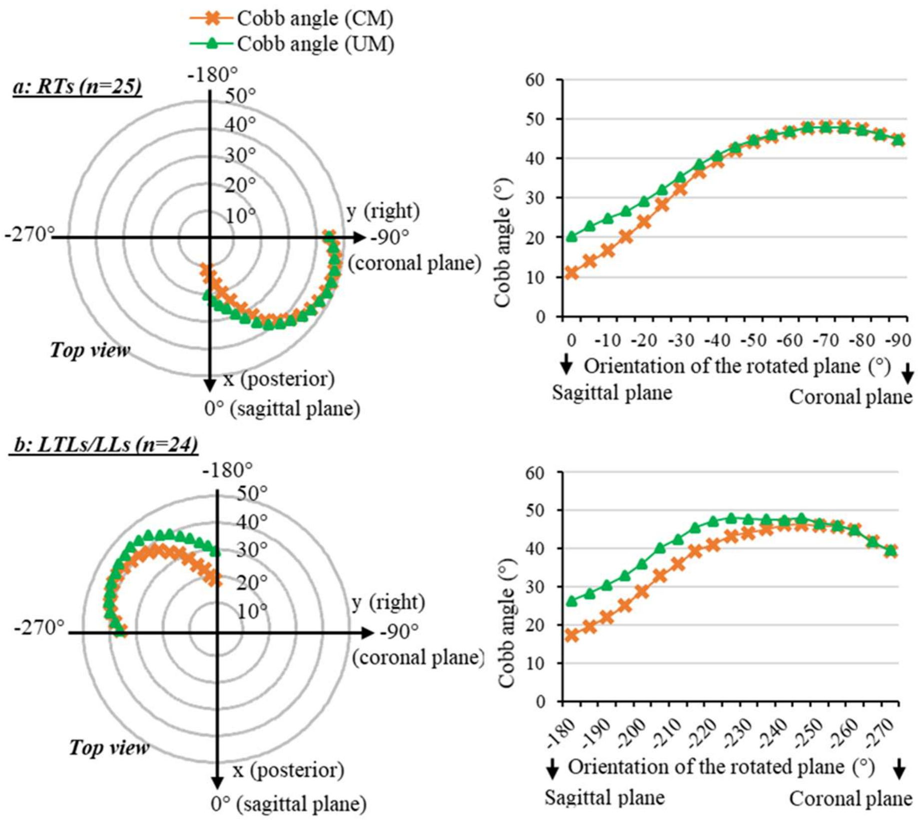


Figure 3. Mean trend of Cobb angle obtained from CM (CT constrained Cobb method) and UM (CT unconstrained Cobb method) in each rotated plane. In the top view (radar plots), the x axis pointing to posterior represents the sagittal plane, and the y axis pointing to right side represents the coronal plane. In the line charts, the vertical and horizontal axis separately represent the magnitude of Cobb angle and orientation of the rotated plane.



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