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RESEARCH

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Effect of different corrective force directions applied by spinal orthoses on the patients with adolescent idiopathic scoliosis

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Abstract

Background Spinal orthoses are commonly prescribed for adolescent idiopathic scoliosis (AIS), yet their three-dimensional correction was not fully understood. The amount of deformity control largely depends on the corrective forces applied, which remain empirically based due to a lack of consensus on optimal force application. This study investigated the effects of different corrective force directions exerted by spinal orthoses on patients with AIS.

Methods A retrospective analysis was conducted on 78 subjects. The trunk was segmented into four quadrants using coronal and sagittal planes from a top-down perspective. Each left or right posterolateral quadrant (with 90°) was further subdivided into zones 1–4, from the sagittal to coronal planes. Based on the zone where the resultant corrective force direction fell, the subjects were categorized into Group 1 (zone 1), Group 2 (zone 2), Group 3 (zone 3), or Group 4 (zone 4). The direction of the corrective force was estimated using modified models of the subjects' bodies, designed through a computer-aided design and manufacturing system integral to the orthosis fabrication process. The effects of corrective forces in different zones on scoliotic spine were assessed.

Results Among the subjects, 3 were in Group 1, 17 in Group 2, 52 in Group 3, and 6 in Group 4. Due to the limited number of subjects, data from Groups 1 and 4 were not analysed. Groups 2 and 3 showed significant reductions in Cobb angle in the coronal plane and plane of maximum curvature (PMC) following orthosis fitting ($p < 0.05$). Group 2 displayed a significant decrease > 5° in thoracic kyphosis ($p < 0.05$). Both Groups 2 and 3 exhibited significant reductions in lumbar lordosis. PMC orientation remained unchanged over time ($p > 0.05$) but was notably higher in Group 2 after orthosis fitting ($p < 0.05$).

Conclusions Corrective forces applied by spinal orthoses in zones 2 and 3 effectively controlled lateral curve progression. Notably, only forces in zone 3 neither significantly reduced thoracic kyphosis nor exacerbated the deviation of scoliotic spine from the sagittal plane. Further research is needed to validate and expand upon these results.

Keywords Scoliosis, Orthosis, Corrective Force, Clinical Outcome

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Background

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformity of the spine with an unclear cause, affecting 0.47%—5.2% of the population [1, 2]. If left untreated, AIS can progress rapidly during the growth spurt, impacting trunk aesthetics and cardiopulmonary function to varying extents [1]. Spinal orthoses are typically prescribed for AIS cases with a Cobb angle of 20°–40° to manage spinal curvature progression during growth [3]. While orthoses effectively correct coronal plane deformities (lateral curvature) [4–7], they have limited impact on transverse plane deformities (back humps) and generally reduce normal curvatures in the sagittal plane (thoracic kyphosis and lumbar lordosis) [8, 9].

Biomechanical design of spinal orthosis is crucial for effective correction. Three-point pressure system is widely recognized as a key biomechanical principle in orthosis design [10]. This system involves a posterolateral corrective force and two counterforces generated by orthosis on the scoliotic spine. However, there is inconsistent documentation on applying these forces for optimal three-dimensional correction, leading to empirical orthosis design in clinical practice.

To improve biomechanical design of spinal orthoses, Wong MS, et al. studied the correlation between biomechanical parameters (pad pressure and strap tension) and spinal correction, highlighting the importance of proper strap tightness and accurate pad placement and direction [11]. In a more recent study, Lin Y, et al. introduced a smart pressure regulator to dynamically adjust orthosis pad pressure in real-time, ensuring continuous corrective pressure [6]. The results suggested that maintaining appropriate corrective force levels improved patient outcomes. Furthermore, Hassan Beygi B, et al. used an assessment frame where patients were positioned inside, and pressure pads were strategically controlled while the scoliotic spine was evaluated using clinical ultrasound to enhance curvature correction, emphasizing the importance of pad location and force direction [12].

Various studies have employed the finite element method to analyze orthosis biomechanics. Cobetto N, et al. applied this method to simulate and assist in orthosis design, revealing the importance of corrective force level and direction in correcting the spinal deformity [13]. Furthermore, Karimi MT, et al. explored different corrective forces, finding that horizontal force minimally impacted spinal morphology, tensile force reduced curvature in both coronal and sagittal planes, and a combination of horizontal and tensile forces primarily reduced coronal curvature [14]. Additionally, Guy A, et al. personalized orthotic design using the finite element method, highlighting the importance of accurate corrective force levels and directions in controlling spinal deformity [15].

Despite extensive research, consensus on optimal corrective force application remained elusive. This study aimed to explore the effects of different corrective force directions applied by spinal orthoses on patients with AIS. The findings were expected to provide scientific evidence for clinical practice and lay a groundwork for future research in this field.

Methods

Subjects

Eligibility was determined based on the Scoliosis Research Society (SRS) criteria [16]: (1) ages 10–18, (2) diagnosis of AIS with a primary curve of 20°–40°, (3) undergoing full-time treatment with a rigid under-arm spinal orthosis, and (4) possessing bi-planar EOS imaging records of the whole spine from pre-orthosis, immediate in-orthosis, and follow-up off-orthosis assessments. Exclusion criteria encompassed prior surgical interventions or other conditions affecting the spinal profile. This study adhered to the Helsinki Declaration and received approval from the Institutional Review Board (Ref: HSEARS20170807003). Based on these criteria, 78 consecutive subjects (24 males and 54 females, ages 10 to 17) were selected from a local scoliosis center's database (2016–2019). Images were taken with subjects standing shoulders and elbows flexed at 45° flexion, and palms supporting the wall. Coronal and sagittal images were contentiously scanned using the EOS imaging system.

Study procedures

The direction of the corrective force exerted by the spinal orthosis was determined using modified body models of subjects through a computer-aided design and manufacturing (CAD/CAM) system, which is integral to orthoses fabrication (Fig. 1a). As subjects' orthoses were fabricated from these models, the orthoses' pressure pads and these models' pressure areas have the same profiles. The study assumed that the corrective pressure applied by the orthosis's pressure pad on the patient's body is analogous to hydrostatic pressure. In the transverse plane at the middle level of the model's pressure area (Fig. 1b), the direction of the resultant corrective force was estimated to be perpendicular to the axis connecting the extremities of the pressure area according to the principle of hydrostatic pressure. This estimated direction of the resultant corrective force was considered representative of the force exerted by the entire pressure pad of the orthosis.

In the transverse plane (Fig. 1b), the x-axis, oriented posteriorly, represents the sagittal plane (orientation = 0°), while the y-axis, directed rightward, indicates the coronal plane (orientation = 90°). Typically, a corrective force targets the left or right thoracic curve, applied

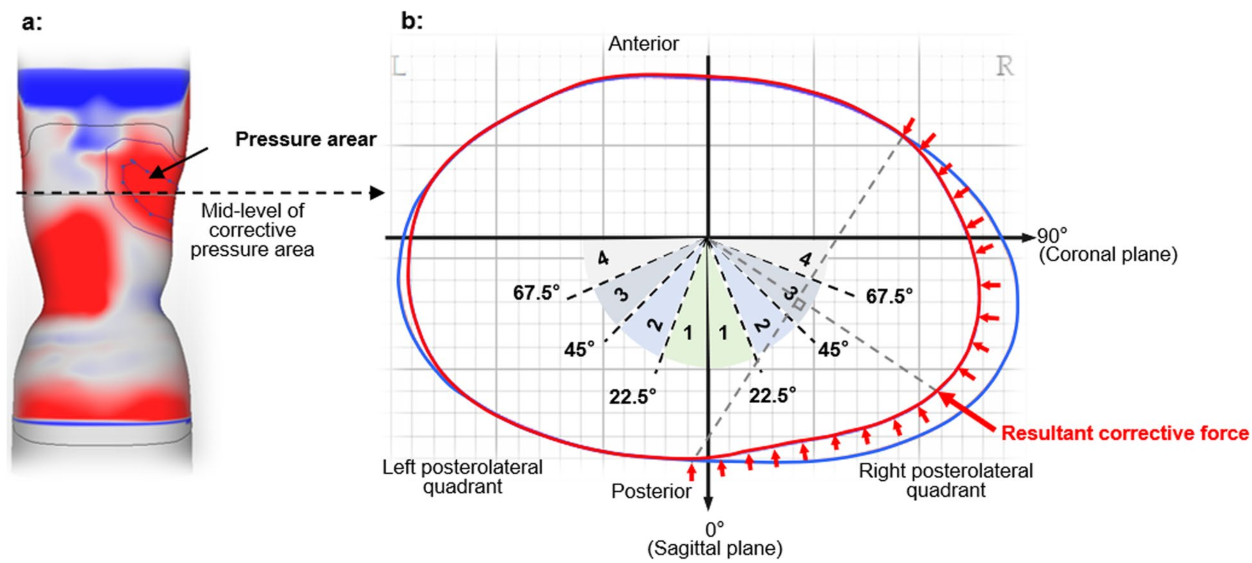

Fig. 1 **a** A modified model utilized for orthosis creation in the CAD/CAM system (Notes: Red areas indicate corrective pressure zones, grey areas indicate pressure-relief zones, and blue areas indicate the original zones). **b** The transverse plane passing through the mid-level of corrective pressure area (Notes: Numbers 1–4 progressing from the sagittal to coronal planes represent the zones 1–4)

in a posterolateral direction ranging from 0° to 90°. The left or right back quadrant (with 90°) was subdivided into 4 zones from the sagittal to coronal planes: zone 1 (0° to 22.5°), zone 2 (22.5° to 45°), zone 3 (45° to 67.5°), and zone 4 (67.5° to 90°). Subjects were categorized into Group 1 (zone 1), Group 2 (zone 2), Group 3 (zone 3), or Group 4 (zone 4) based on the zone of the estimated resultant corrective force direction.

Assessments

Key measure outcomes assessed at pre-orthosis, immediate in-orthosis, and follow-up off-orthosis (6–18 months after initially orthosis fitting) visits included Cobb angle in the coronal plane (coronal-Cobb), thoracic kyphosis (T4-T12), lumbar lordosis (L1-S1), and plane of maximum curvature (PMC). PMC is a vertical plane between the coronal and sagittal planes, where the maximum Cobb angle is measured when a scoliotic spine is projected onto it [17]. PMC-Cobb reflects the maximum curvature of the scoliotic spine, indicating the true magnitude of the spinal curve, while PMC-orientation is the angle between the sagittal plane and PMC, indicating the deviation of a scoliotic spine from the sagittal plane. In a typical spine, the PMC generally aligns with the sagittal plane, with PMC-Cobb equivalent to thoracic kyphosis in thoracic region and lumbar lordosis in lumbar region, and PMC-orientation at 0°. A computational method, developed and validated by our team [18], was employed to estimate PMC-Cobb and PMC-orientation based on the coronal and sagittal images of the scoliotic spine. All measurements were conducted by an experienced assessor, who was blinded to subject group allocation.

Spinal curvature progression was defined using a 5° or 10° threshold of Cobb angle change [19, 20]. According to the consensus statement endorsed by the international Scientific Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) and SRS [3], a 5° threshold is utilized to assess the effectiveness of spinal orthosis in controlling spinal curvature progression. Literature also noted that variations $<10°$ can be contributed by an individual's posture during x-ray imaging and the associated measurement error of Cobb angle measurements [20–22]. Thus, changes $\geq 10°$ are considered clinically significant. Both the 5° and 10° thresholds were employed to analyze the effectiveness of spinal orthosis in this study.

Statistical analyses

Statistical analyses were performed using SPSS statistics 20.0 (IBM Corporation). The Shapiro–Wilk test was employed to assess data normality. Normally distributed data were expressed as mean ± standard deviation (SD). Differences between groups were analyzed using independent sample t-test, while changes within groups over time were assessed using one-way repeated measures ANOVA. A p-value < 0.05 was considered statistically significant.

Results

Subjects

A total of 78 subjects were analyzed: 3 in Group 1, 17 (5 males/12 females) in Group 2, 52 (16 males/36 females) in Group 3, and 6 in Group 4. Due to the limited cases for Groups 1 and 4, the analysis focused on Groups 2 and 3. Demographic data for these two groups are presented in Table 1. The average follow-up duration was 7.5 ± 2.0 months, ranging from 6.0 to 18.0 months. Pre-orthosis assessments showed no significant differences in age, Body Mass Index, Risser sign, coronal-Cobb, thoracic kyphosis, lumbar lordosis, PMC-Cobb, and PMC-orientation between Groups 2 and 3 (p > 0.05).

Intra-group comparisons of each outcome measure

Outcome measures at pre-orthosis, immediate in-orthosis, and follow-up off-orthosis visits are summarized in Table 2. and illustrated in Fig. 2a-e. In Groups 2 and 3, coronal-Cobb significantly decreased at the immediate in-orthosis visit (4.8°, p < 0.01; 4.5°, p < 0.001) but returned to levels similar to those at the pre-orthosis visit during the follow-up off-orthosis visit. Furthermore, thoracic kyphosis in Group 2 significantly decreased after orthosis fitting (p < 0.05), with a reduction of > 5° (6.1°) at the follow-up off-orthosis visit. Lumbar lordosis in Group 2 showed a significant reduction of > 10° at both the immediate in-orthosis and follow-up off-orthosis visits (11.8° and 12.9°, respectively, p < 0.01), while in Group 3, it exceeded the 5° threshold only at the immediate in-orthosis visit (5.1°, p < 0.001). Additionally, PMC-Cobb significantly decreased in both groups at the immediate in-orthosis visit, with reductions of > 5° only in Group 2 (6.4°, p < 0.01). PMC-orientation remained stable in Group 3 (p > 0.05) but showed a slight increase in Group 2 after orthosis fitting (p > 0.05).

Table 1 Demographic data

	Group 2	Group 3	p
Gender, male/female	5/12	16/36	
Age, mean ± SD (years)	14.0 ± 1.7	13.5 ± 1.6	0.221
BMI	17.8 ± 1.8	17.5 ± 1.7	0.208
Risser sign	2.4 ± 1.5	1.7 ± 1.4	0.088
Coronal-Cobb, mean ± SD (degrees)	24.7 ± 7.1	21.7 ± 6.3	0.094
Thoracic kyphosis, mean ± SD (degrees)	23.1 ± 12.6	22.7 ± 11.5	0.907
Lumbar lordosis, mean ± SD (degrees)	57.0 ± 9.1	52.9 ± 9.9	0.131
PMC-Cobb, mean ± SD (degrees)	32.5 ± 11.0	32.9 ± 11.4	0.894
PMC-orientation, mean ± SD (degrees)	57.5 ± 21.5	47.8 ± 20.6	0.098

BMI body mass index, *SD* standard deviation

Inter-group comparisons of each outcome measure

Inter-group comparisons are shown in Fig. 3. At the follow-up off-orthosis visit, coronal-Cobb was significantly higher in Group 2 compared to Group 3, with a difference of > 5°(5.6°, p < 0.05). Additionally, PMC-orientation was significantly greater in Group 2 than in Group 3 at the immediate in-orthosis and follow-up off-orthosis visits, with differences of 12.1° and 12.2°, respectively (p < 0.05).

Discussion

The application of corrective forces by spinal orthoses is crucial for managing scoliotic deformities, yet achieving optimal three-dimensional correction remains challenging. This underscores the need to explore the effects of different corrective force directions in patients with AIS. The main findings of this

Table 2 Comparisons of each outcome measure in two groups over time

		Pre-orthosis Mean ± SD (°)	Immediate in-orthosis Mean ± SD (°)	Follow-up off-orthosis Mean ± SD (°)
Group 2	Coronal-Cobb	24.7±7.1	19.9±7.6	25.4±11.3
	Thoracic kyphosis	23.1±12.6	18.9±11.1	17.0±8.8
	Lumbar lordosis	57.0±9.1	45.2±9.4	44.1±12.6
	PMC-Cobb	32.5±11.0	25.9±10.0	29.7±11.6
	PMC-orientation	57.5±21.5	58.1±19.6	60.9±16.2
Group 3	Coronal-Cobb	22.5±5.7	18.0±7.2	19.8±8.9
	Thoracic kyphosis	21.9±9.9	22.3±9.2	22.1±10.0
	Lumbar lordosis	52.5±8.8	47.4±7.3	47.9±10.1
	PMC-Cobb	32.8±10.8	28.2±10.1	30.4±11.1
	PMC-orientation	49.5±19.8	46.0±22.0	48.7±23.7

SD standard deviation, *Coronal-Cobb* Cobb angle in the coronal plane, *PMC-Cobb* Cobb angle in the plane of maximum curvature, *PMC-orientation* the angle between the sagittal plane and plane of maximum curvature

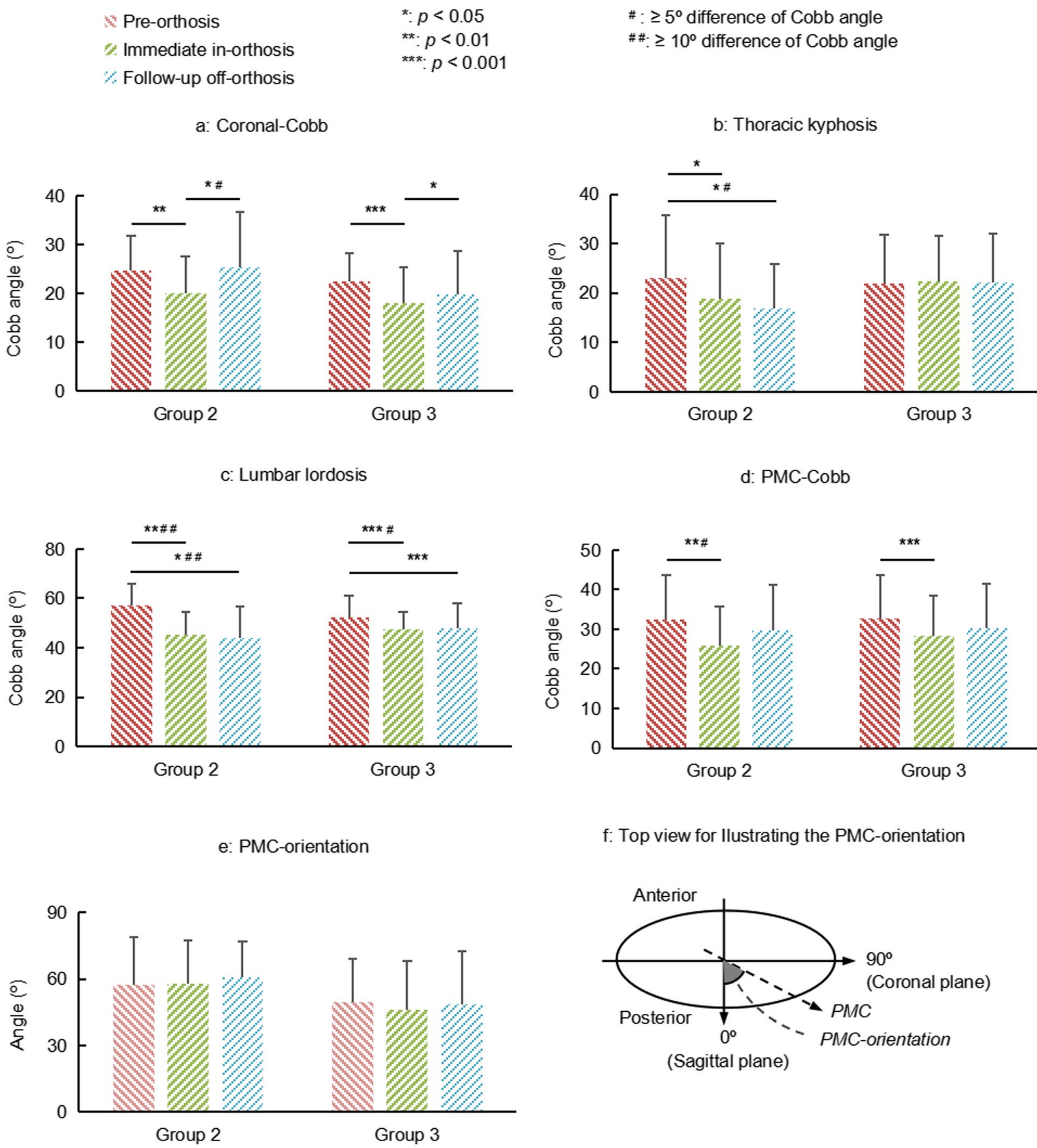

Fig. 2 Comparisons of coronal-Cobb, thoracic kyphosis, lumbar lordosis, PMC-Cobb, and PMC-orientation over time in Groups 2 and 3 (Notes: Pre-orthosis indicates an outcome measure assessed at pre-orthosis visit; immediate indicates an outcome measure assessed at immediate in-orthosis visit; follow-up indicates an outcome measure assessed at follow-up off-orthosis visit)

study are as follows: (1) Coronal-Cobb were effectively controlled in Groups 2 and 3 after orthosis fitting; (2) A significant reduction in thoracic kyphosis was observed only in Group 2, while lumbar lordosis decreased significantly in both groups; (3) PMC-Cobb significantly decreased immediately in both groups, whereas PMC-orientation did not show significant changes; (4) At the follow-up visit, Group 3 exhibited significantly smaller Coronal Cobb angles compared to Group 2, and

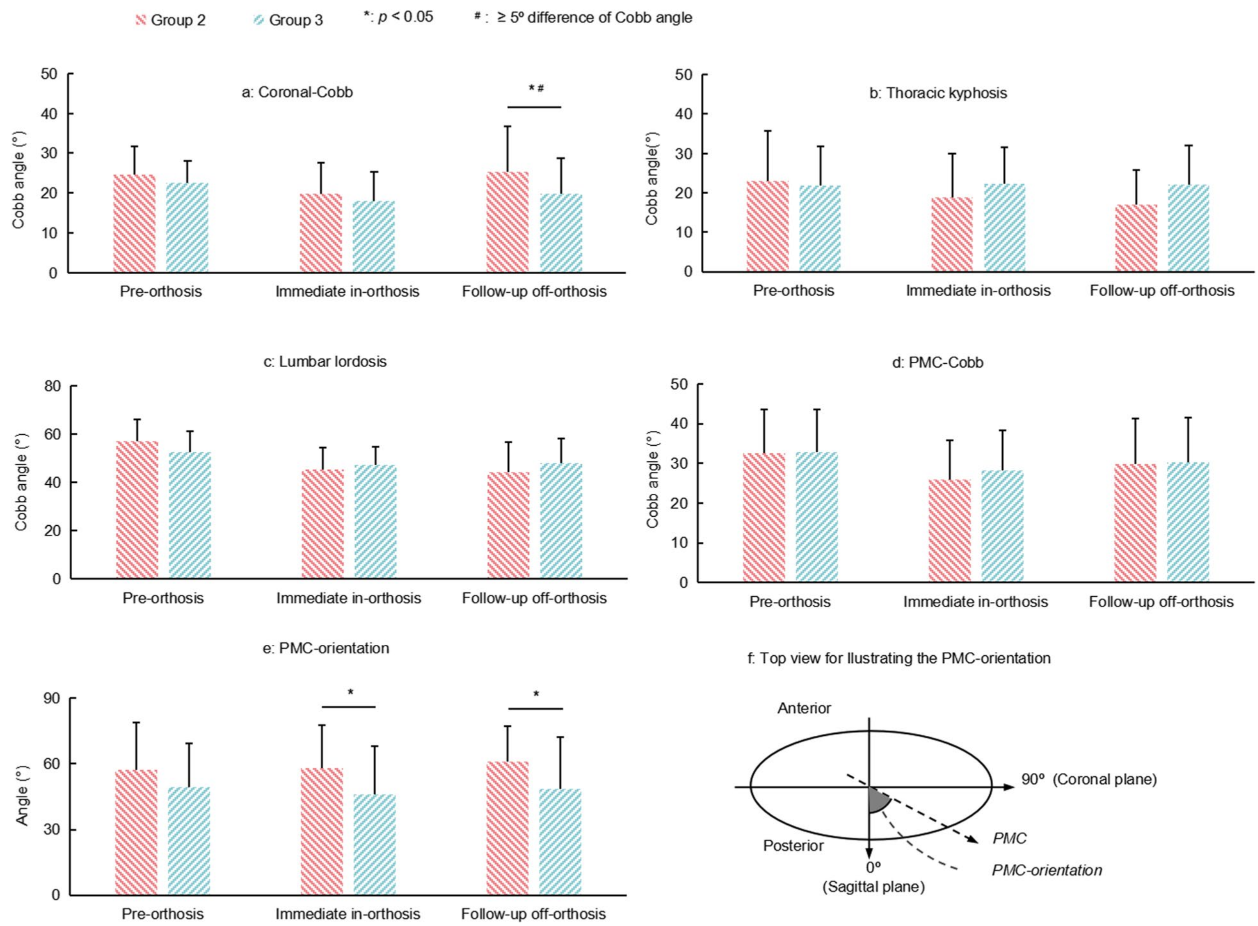

Fig. 3 Comparisons of coronal-Cobb, thoracic kyphosis, lumbar lordosis, PMC-Cobb, and PMC-orientation between Groups 2 and 3 at the pre-orthosis, immediate in-orthosis, and follow-up off-orthosis visits (Notes: Immediate: immediate in-orthosis; Follow-up: follow-up off-orthosis; Coronal-Cobb: Cobb angle in the coronal plane; PMC-Cobb: Cobb angle in the plane of maximum curvature; PMC-orientation: the angle between the sagittal plane and plane of maximum curvature)

PMC-orientation was consistently smaller in Group 3 at both immediate and follow-up visits. Further details of these findings are discussed below.

Comparisons of each outcome measure

The coronal-Cobb angle significantly decreased immediately but returned to pre-orthosis levels in both groups, confirming the orthosis's role in controlling spinal curve progression, as previously documented [4–7]. In the sagittal plane, only Group 2 demonstrated a significant reduction of > 5° in thoracic kyphosis at follow-up visit. The corrective force in zone 2 has greater postero-anterior component, potentially leading to a more substantial reduction in thoracic kyphosis compared to zone 3. This suggests that zone 3 forces may be more suitable for patients with normal or hypo-kyphosis, while zone 2 forces may be better for those with hyper-kyphosis. Regarding lumbar lordosis, both Groups 2 and 3 showed significant reductions after orthosis fitting, with Group 2 exhibiting more pronounced reductions. Theoretically, corrective force in zone 2 would typically lead to a more prominent increase in lumbar lordosis compared to zone 3, which contradicts our findings. This discrepancy may be explained by the intra-abdominal pressure induced by the orthosis's abdominal pressure pad, suggesting that intra-abdominal pressure might have a more significant impact on controlling lumbar lordosis than postero-lateral pressure.

In terms of PMC, both groups exhibited significant reductions in PMC-Cobb, aligning with earlier findings [23]. PMC-orientation did not significantly change over time, consistent with previous studies [9, 23]. However, it was significantly greater in Group 2 after orthosis fitting compared to Group 3. A greater PMC-orientation suggests the scoliotic spine was twisted closer to the coronal plane, resulting in a larger coronal-Cobb, as shown in Fig. 3a. This indicates that corrective forces in zone 2 may increase the deviation of the scoliotic spine from the sagittal pane, whereas forces in zone 3 did not exacerbate this deviation. This could be due to more pronounced postero-anterior components of corrective forces in zone 2, potentially pushing the scoliotic spine further from the sagittal plane. Therefore, unless hyper-kyphosis is present, it is advisable to prioritize corrective forces in zone 3 during orthosis design.

Limitations

The results of this study should be interpreted with several limitations. Due to its retrospective design, factors such as spinal flexibility, patient compliance, and corrective force level were not analyzed, potentially affecting spinal correction outcomes. Additionally, the direction of the corrective force applied by the orthosis was estimated based on the transverse plane at the middle level of the pressure area. This approximation may not fully reflect the true direction of forces across the entire pressure area. Currently, there is no established method to precisely measure the direction of corrective force exerted by an orthosis on patient's trunk, making this estimation a necessary but imperfect substitute. This highlights the imperative for developing more precise measurement techniques. Nevertheless, the findings provide a foundational basis for future prospective, high-quality research in this area.

Conclusions

The application of corrective forces in zones 2 and 3 via spinal orthoses effectively controlled lateral curve progression. Notably, only forces in zone 3 neither reduced the thoracic kyphosis nor exacerbated the scoliotic spine's deviation from the sagittal plane. Thus, for patients without thoracic hyper-kyphosis, it is advisable to prioritize corrective forces in zone 3 during orthoses design. Further research is needed to validate and expand upon these results.

Abbreviations

AIS	Adolescent idiopathic scoliosis
PMC	Plane of maximum curvature
SD	Standard deviation
SOSORT	International Scientific Society on Scoliosis Orthopaedic and Rehabilitation Treatment
SRS	Scoliosis Research Society
CAD/CAM	Computer-aided design and manufacturing

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Authors' contributions

Hui-Dong Wu and Chang-Liang Luo contributed to Conceptualization, Methodology, Data curation, Formal analysis, Writing—original draft, review & editing; Chen He, Lu Li,, and Winnie Chiu-Wing Chu contributed to Data curation, Formal analysis, Writing—review & editing; Wei Liu and Man-Sang Wong contributed to Conceptualization, Methodology, Project administration, Writing—review & editing.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by Human Subjects Ethics Sub-Committee – The Hong Kong Polytechnic University (Ref: HSEARS20170807003). Signed consent forms were not obtained because of the nature of a retrospective study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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