Original Article

Spinal sagittal and coronal morphology characteristics in children with short stature

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Background: The characteristics of total sagittal and coronal plane parameters in children with short stature (SS) and the correlations between these parameters are currently unknown. This case-control study sought to retrospectively investigate the characteristics of total sagittal and coronal plane parameters in children with SS and examine the correlations between these parameters.

Methods: The data of children aged 3–15 years with SS and normal heights were collected, and the children were allocated to the observation and control groups, respectively. The following parameters were analyzed: coronal Cobb angle, cervical lordosis (CL) angle, T1 slope (T1S), thoracic kyphosis (TK) angle, lumbar lordosis (LL) angle, sacral inclination angle, pelvic inclination angle, pelvic incidence angle, cervical sagittal axis, spinal sagittal axis, trunk pelvic angle (TPA), and spino-sacral angle (SSA).

Results: In total, 41 children with SS were enrolled in this study, and 80 age- and sex-matched children with normal heights were included as the controls. The CL angle, T1S, and TPA were significantly greater ($P<0.050$) in the children with SS than those with normal heights. The children with SS were further divided into group A with CL (a positive CL angle) and group B without CL (a negative CL angle), while the children with normal heights were further divided into group A' with CL and group B' without CL. The CL angle, T1S, and TK angle were significantly greater ($P<0.05$), but the Cobb angle and spinal sagittal axis were significantly smaller ($P<0.05$) in group A than group B, while the CL angle, T1S, and TK angle were significantly greater ($P<0.05$) in group A than group A'. The Cobb angle was significantly smaller ($P=0.024$), and the spinal sagittal axis and TPA were significantly greater ($P=0.013$ and 0.005, respectively) in group B than group B'. Different correlations were found among the spinal parameters.

Conclusions: SS children have a significantly larger CL angle, T1S, TPA, and TK angle, and a tendency toward a hunchback posture. When scoliosis occurs in the coronal plane in children with SS, the degree of scoliosis is relatively small, and the spine tilts toward the dorsal side.

Keywords: Children; short stature (SS); radiological parameters; sagittal plane balance; spine

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Introduction

Short stature (SS) is a common clinical manifestation in pediatrics, and is defined as individuals of the same race, gender, and age who, under similar living environments, have a height lower than the average height of the normal population by two standard deviations (–2 SD) or below the 3rd percentile (–1.88 SD) (1,2). The causes and treatment methods of SS are complex, and the phenomenon of SS in children and adolescents has attracted great attention from society and parents. The progression of the disease affects children's physical and mental development, and may even lead to psychological disorders, such as inferiority complex and withdrawn personality. Thus, timely diagnosis and early intervention are necessary to ensure the normal development of children with SS (3).

An upright posture enables humans to release their hands, improve their productivity, and maintain a horizontal perspective. Trunk balance is essential for effective upright walking, but the long spine and complex bone and joint composition can cause trunk instability (4). The stability of the overall structure of the human body plays an important role in physical function. In clinical work, it has been noted that the thoracic curvature of the spine in children with SS shows an increasing trend toward kyphosis. This curvature trend changes the overall structure of the body, giving the appearance of shrunken shoulders, back rickets, and collapse, which in turn may affect the overall function of the body, blood circulation, and metabolism, and may also lead to physical retardation and a lack of development in children.

Human gene expression is affected by environmental conditions and daily behaviors, and subsequent changes in the body's representation and associated bad habits may be inherited through and affect future generations (i.e., via epigenetic inheritance). Spinal balance refers to the balance between the spine and the trunk muscle response under external forces to maintain the stability of the body's static and dynamic upright posture under the regulation of the sensory nervous system (5). In recent years, extensive research has been conducted on spinal balance, and radiological parameters of the cervical spine and spine-pelvis have been widely used in the analysis of spinal balance in various populations and the treatment of spinal diseases. For example, research has been conducted on coronal sagittal balance in asymptomatic children, adolescents, adults, and the elderly; degenerative diseases in the elderly (cervical spondylosis, lumbar degenerative diseases, and osteoporotic fractures); spinal deformities (e.g., scoliosis and Humen disease) in adolescents and adults; and spinal balance in immune system diseases involving the spine (rheumatoid and ankylosing spondylitis). Such research can serve as a reference for preoperative evaluation, surgical planning, and the evaluation of surgical effects and postoperative recovery following surgical interventions for spinal diseases (6,7). However, to date, few studies on the sagittal and coronal spinal shape and balance in children with SS have been conducted.

It was hypothesized that the analysis of the sagittal and coronal radiological parameters of the whole spine in children with SS would provide valuable information about the growth and development of children for possible timely critical interventions. Thus, this study sought to investigate the imaging morphological characteristics, and sagittal and coronal radiological parameters of the whole spine in children with SS and normal heights, and to examine the correlation between different parameters to clarify the possible factors affecting the growth and development of children and to better understand the pathogenesis of SS. We present this article in accordance with the STROBE reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-24-992/rc).

Methods

Subjects

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This retrospective single-center study was approved by the Ethics Committee of the Hebei Medical University Third Hospital (No. 2022-001-1), and the requirement of individual consent for this retrospective analysis was waived. All methods were performed in accordance with the relevant guidelines and regulations.

Between January 2021 and February 2022, patients with SS who had undergone X-ray radiographs at the Hebei Medical University Third Hospital were retrospectively enrolled as the observation group, and healthy children with normal heights were enrolled as the control group. To be eligible for inclusion in this study, the children in the observation group had to meet the following inclusion criteria: be aged 3–15 years; have been diagnosed with SS; and have undergone anteroposterior and lateral whole-spine X-ray radiographs. Children were excluded from the study if they met any of the following exclusion criteria: had SS

Table 1 Clinical data of children with short stature

Variables	Classification	Male, n	Female, n	χ^2	P
Etiology	Growth hormone deficiency	4	4	4.601	0.210
	Partial growth hormone deficiency	5	1		
	Idiopathic short stature	20	6		
	Hypothyroidism	0	1		
Body type	Thin	4	5	4.851	0.164
	Normal	22	6		
	Overweight	2	0		
	Obese	1	1		

combined with spinal and spinal cord dysplasia, metabolic bone disease, a history of trauma and surgery in the spine and its surrounding tissues, or spinal tumors and infections; and/or had unclear imaging for data measurement. To be eligible for inclusion in this study, the children in the control group had to meet the following inclusion criteria: be aged 3–15 years; have undergone anteroposterior and lateral whole-spine X-ray radiographs; have no history of spinal diseases or spinal surgery; have no history of spinal and spinal cord dysplasia, or metabolic bone disease; and have no imaging abnormalities before or during the study, such as isthmus lysis, spondylolisthesis, or spinal abnormalities.

Research methods

The observation group comprised 41 children with SS, aged 3–15 years, of whom 29 (70.7%) were male and 12 (29.3%) were female (*Table 1*). The control group comprised 80 children with normal heights, aged 3–15 years, of whom 51 (63.8%) were male and 29 (36.2%) were female. All subjects had anteroposterior and lateral whole-spine X-ray radiographs. In the radiographs, a constant distance between the subject and the X-ray source was maintained, and the subject was instructed to adopt a natural standing position, with both eyes facing straight ahead, and both hips and knees naturally extended. The image clearly displayed the full length of the spine, pelvis, and vertebral bone structure, and the soft tissue layers were visible without splice artifacts. Images were obtained from the hospital's image archiving and communication system, and measurements were performed. Data on the heights of the parents of the children with SS were also collected.

Parameters measured

The maximal Cobb angle of the coronal spinal plane is the angle between the tangent line of the upper endplate of the upper vertebral body and the tangent line of the lower endplate of the lower vertebral body on the maximal curvature of the spinal coronal plane (*Figure 1*). The cervical lordosis (CL) angle (*Figure 1*) was measured using the Jackson physiological stress line method, which involves drawing a tangent line along the posterior edge of the C2 and C7 cervical vertebrae (8,9). The angle formed by the extension of these two lines is the lordosis on the ventral pharyngeal side of the cervical spine, and is negative on the dorsal side of the cervical spine. The T1 slope (T1S) (*Figure 1*) is the angle between the tangent line of the upper endplate of the first thoracic vertebral body and the horizontal line. The thoracic kyphosis (TK) angle (*Figure 1*) is the angle between the tangent line of the upper endplate of the first thoracic vertebral body and the tangent line of the lower endplate of the 12th thoracic vertebral body. Lumbar lordosis (LL) (*Figure 1*) is the angle between the tangent line of the upper endplate of the L1 vertebral body and the tangent line of the upper endplate of the S1 vertebral body. Sacral slope (*Figure 1*) is the angle between the tangent line of the upper endplate of the first sacral vertebral body and the horizontal line. Pelvic incidence (PI) (*Figure 1*) is the angle between the midpoint of the line connecting the centers of the two femoral heads—the line connecting the center of the first sacral body upper endplate and the perpendicular line of the sacral upper endplate. The center of the line connecting the femoral head is located in front of the midpoint of the sacral upper endplate, which is positive. The pelvic tilt (PT) angle (*Figure 1*) is calculated using the formula PT = PI – sacral slope, and is the angle

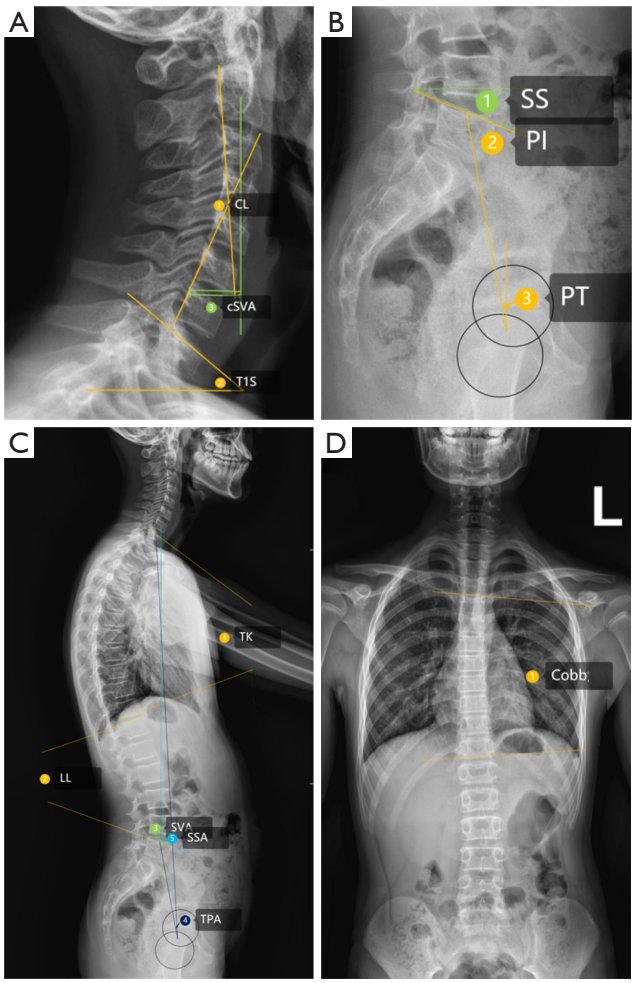

Figure 1 Measurement of parameters. (A) Measurement approaches for CL angle, the cSVA, and the T1S. (B) Measurement of the SS, PI, and PT. (C) Measurement of TK, LL, the SVA, the SSA, and the TPA. (D) The Cobb angle is shown. CL, cervical lordosis; cSVA, cervical sagittal vertical axis; T1S, T1 slope; SS, sacral slope; PI, pelvic incidence; PT, pelvic tilt; TK, thoracic kyphosis; LL, lumbar lordosis; SVA, sagittal vertical axis; SSA, spino-sacral angle; TPA, trunk pelvic angle.

between the midpoint of the line connecting the center of the bilateral femoral head to the center of the upper endplate of the first sacral vertebral body and the vertical line, with positive and negative values like those for PI.

The spinal sagittal balance was evaluated using a number of parameters (10-12). The cervical sagittal vertical axis (cSVA) (*Figure 1*) is the horizontal distance from the posterior upper corner of C7 to the vertical line passing through the center of the C2 vertebral body, and a cSVA >40 mm indicates cervical sagittal imbalance. The sagittal vertical axis (SVA) of the spine (*Figure 1*) is determined by drawing a vertical line through the center of the C7 vertebral body, and its horizontal distance from the posterior upper corner of the S1 vertebral body is the c7-s1 SVA. A c7-s1 SVA >50 mm is defined as sagittal imbalance. When the plumb line is located in front of the upper corner behind S1 (C7), it is a positive value, and negative when not. The trunk pelvic angle (TPA) (*Figure 1*) is the included angle between the line connecting the midpoint of the T1 vertebral body's upper endplate with the midpoint of the femoral head, and the line connecting the midpoint of the sacral upper endplate with the midpoint of the femoral head. If the T1 vertebral body center is located in front of the midpoint of the bilateral femoral head center line, the TPA has a positive value, and if the center is located in the rear, the TPA has a negative value. The spino-sacral angle (SSA) (*Figure 1*) is the angle formed between the line connecting the center of the upper sacral endplate and C7 vertebral body center and the centerline of the upper sacral endplate.

All the parameters were measured by three researchers, and the results were taken as the average. If a disagreement arose, the researchers consulted with one another to reach a conclusion.

Statistical analysis

This study was analyzed using SPSS 25.0 software (IBM, Chicago, IL, USA). The categorical data are presented as the frequency and percentage, and were tested using the Chi-squared test. The Shapiro-Wilk method was used to perform normality tests on various measurement parameters. The measurement data are presented as the mean ± SD for normally distributed data, and the median [interquartile range (IQR)] for the non-normally distributed data. Differences between the different measurement data groups were tested using the independent sample *t*-test for the normally distributed data, and the Mann-Whitney *U* test for the non-normally distributed data. The effect value of the *t*-test-Cohen's d and 95% confidence interval were calculated. A P value <0.05 was considered statistically significant. The correlation analysis between different groups of data was conducted using the Spearman correlation analysis (bilateral) ($|r| < 0.3$: weak correlation; $0.3 \leq |r| < 0.5$: mild correlation; $0.5 \leq |r| < 0.8$: moderate correlation; $|r| \geq 0.8$: severe correlation; $|r| > 0.95$: significant correlation).

Table 2 Measurement parameters of children with short stature and normal heights

Variables	Short stature	Normal heights	*Z*/*t*	P	Cohen's d	95% CI
Cobb angle (°)	6.3±2.8	6.4 (6.3)	−0.435	0.663	–	–
CL (°)	18.1 (30.2)	8.8 (19.3)	−1.993	0.046*	–	–
T1S (°)	23.1±11.3	19.5±8.7	2.026	0.045*	0.37	−0.74 to 8.89
TK (°)	37.0±11.2	34.3±9.7	1.473	0.143	–	–
LL (°)	45.2±9.6	45.6±10.7	−0.181	0.856	–	–
SS (°)	32.7±8.2	33.8±8.5	−0.733	0.464	–	–
PI (°)	39.1 (10.2)	37.4 (15.5)	−0.197	0.843	–	–
PT (°)	6.7±8.0	5.7 (8.5)	−0.301	0.763	–	–
cSVA (mm)	1.5 (0.8)	1.4±0.8	−1.027	0.305	–	–
SVA (mm)	−0.9±3.2	0.0 (4.1)	−1.791	0.073	–	–
TPA (°)	−5.3 (5.8)	−2.9 (4.4)	−3.190	0.001**	–	–
SSA (°)	127.2±8.7	126.1±9.6	0.636	0.525	–	–

Data are presented as the mean ± standard deviation if normally distributed, or as the median (interquartile range) if not normally distributed. *, P<0.05; **, P<0.01. CI, confidence interval; CL, cervical lordosis; T1S, T1 slope; TK, thoracic kyphosis; LL, lumbar lordosis; SS, sacral slope; PI, pelvic incidence; PT, pelvic tilt; cSVA, cervical sagittal vertical axis; SVA, sagittal vertical axis; TPA, trunk pelvic angle; SSA, spino-sacral angle.

Results

In total, 41 children with SS aged 3–15 years were enrolled in the study, of whom 29 (70.7%) were male and 12 (29.3%) were female (*Table 1*). According to the disease etiology, growth hormone deficiency was present in 8 (19.5%) patients, partial growth hormone deficiency in 6 (14.6%) patients, idiopathic SS in 26 (63.5%) patients, and hypothyroidism in 1 (2.4%) patient. Based on the body mass index (BMI) SD of children and adolescents, the children with SS were classified into the following body types: thin (n=9, 22.0%), normal (n=28, 68.2%), overweight (n=2, 4.9%), and obese (n=2, 4.9%). The children's fathers had a mean height of 168.3±6.6 cm, of whom 1 had a height of <160 cm and 40 had a height of ≥160 cm, while the children's mothers had a mean height of 154.6±5.3 cm, of whom 4 had a height of <150 cm, and 37 had a height of ≥150 cm. In total, 80 children with normal heights, aged 3–15 years, were included in the control group, of whom 51 (63.8%) were male and 29 (36.2%) were female. There was no statistically significant differences (P>0.05) between the two groups in terms of age and sex.

The CL, T1S, and TPA were significantly greater (P<0.050) in the children with SS than those with normal heights (*Table 2*). The children with SS were further divided into group A with CL (positive CL), which included 18 males and 6 females, aged 9.7±3.7 years, and group B without CL (negative CL), which included 11 males and 6 females, aged 9.0 (IQR: 5) years. The children with normal heights were further classified into group A' with CL, which included 35 males and 12 females, aged 9.0 (IQR: 7) years, and group B' without CL, which included 16 males and 17 females, aged 11.0 (IQR: 5) years.

No significant difference (P>0.05) was found between groups A and B or A' in the terms of age and sex; however, the CL, T1S, and TK angle were significantly greater (P<0.05) while the Cobb angle and SVA were significantly smaller (P<0.05) in group A than group B (*Table 3*). The CL angle, T1S, and TK angle were significantly greater (P<0.05) in group A than group A' (*Table 4*).

In groups B and B' without CL, no significant difference (P>0.05) was found between group B with SS and group B' with normal heights in terms of age and sex. The Cobb angle was significantly smaller (P=0.024) and the SVA and TPA were significantly greater (P=0.013 and 0.005, respectively) in group B than group B' (*Table 5*).

There were 24 cases had CL, of whom 2 patients concurrent with growth hormone deficiency, 4 patients had partial growth hormone deficiency, and 18 patients had idiopathic SS, whereas there were 17 cases had non-

Table 3 Measurement parameters in groups A and B

Variables	Group A	Group B	*Z*/*t*	P	Cohen's d	95% CI
Cobb angle (°)	4.6±1.9	8.8±2.1	–6.743	0.000**	2.11	–6.25 to –1.59
CL (°)	28.2±12.0	–1.7 (2.1)	–5.400	0.000**	–	–
T1S (°)	27.1±10.3	17.4±10.3	2.951	0.005**	0.94	6.42 to 18.45
TK (°)	42.2±10.3	29.7±8.1	4.166	0.000**	0.40	6.22 to 18.43
LL (°)	45.0±9.5	45.5±9.5	–0.181	0.858	–	–
SS (°)	34.2±8.3	30.5±7.7	1.433	0.160	–	–
PI (°)	39.0 (14.9)	39.6±5.8	–0.582	0.560	–	–
PT (°)	5.1±8.5	7.3 (14.6)	–1.045	0.296	–	–
cSVA (mm)	1.6 (0.7)	1.4±0.5	–0.940	0.347	–	–
SVA (mm)	0.3±2.7	–2.7±3.1	3.354	0.002**	1.04	1.12 to 4.94
TPA (°)	–5.2 (6.8)	–6.1±3.4	–1.006	0.314	–	–
SSA (°)	129.1 (9.0)	127.8±8.6	–0.079	0.937	–	–

Data are presented as the mean ± standard deviation if normally distributed, or as the median (interquartile range) if not normally distributed. Group A: children with short stature and cervical lordosis (positive CL); Group B: children with short stature but without cervical lordosis. **, P<0.01. CI, confidence interval; CL, cervical lordosis; T1S, T1 slope; TK, thoracic kyphosis; LL, lumbar lordosis; SS, sacral slope; PI, pelvic incidence; PT, pelvic tilt; cSVA, cervical sagittal vertical axis; SVA, sagittal vertical axis; TPA, trunk pelvic angle; SSA, spino-sacral angle.

Table 4 Measurement parameters of groups A and A'

Variables	Group A	Group A'	*Z*/*t*	P	Cohen's d	95% CI
Cobb angle (°)	4.6±1.9	4.8 (4.1)	–0.699	0.484	–	–
CL (°)	28.2±12.0	16.8±8.0	4.762	0.000**	1.20	6.63 to 15.9
T1S (°)	27.1±10.3	22.5±7.6	–2.225	0.026*	0.53	1.6 to 10.2
TK (°)	42.2±10.3	37.0±8.7	2.228	0.029*	0.56	–0.19 to 9.3
LL (°)	45.0±9.5	46.1±11.5	–0.391	0.697	–	–
SS (°)	34.2±8.3	33.7±8.7	0.219	0.827	–	–
PI (°)	39.0 (14.9)	36.4 (18.3)	–0.109	0.913	–	–
PT (°)	5.1±8.5	5.7 (8.8)	–0.310	0.757	–	–
cSVA (mm)	1.6 (0.7)	1.3±0.9	–1.447	0.148	–	–
SVA (mm)	0.3±2.7	1.5 (4.3)	–1.216	0.224	–	–
TPA (°)	–5.2 (6.8)	–2.8 (5.1)	–1.903	0.057	–	–
SSA (°)	129.1 (9.0)	124.6±9.9	–1.149	0.251	–	–

Data are presented as the mean ± standard deviation if normally distributed, or as the median (interquartile range) if not normally distributed. Group A: children with short stature and cervical lordosis (positive CL); Group A': children with normal heights and cervical lordosis. *, P<0.05; **, P<0.01. CI, confidence interval; CL, cervical lordosis; T1S, T1 slope; TK, thoracic kyphosis; LL, lumbar lordosis; SS, sacral slope; PI, pelvic incidence; PT, pelvic tilt; cSVA, cervical sagittal vertical axis; SVA, sagittal vertical axis; TPA, trunk pelvic angle; SSA, spino-sacral angle.

Table 5 Measurement parameters of groups B and B'

Variables	Group B	Group B'	Z/t	P
Cobb angle (°)	8.8±2.1	10.7 (5.7)	−2.264	0.024*
CL (°)	−1.7 (2.1)	−2.5±2.1	−0.574	0.566
T1S (°)	17.4±10.3	15.0±8.4	0.987	0.329
TK (°)	29.7±8.1	30.2±9.7	−0.100	0.921
LL (°)	45.5±9.5	45.0±9.4	0.235	0.815
SS (°)	30.5±7.7	34.0±8.4	−1.458	0.151
PI (°)	39.6±5.8	38.0 (14.7)	−0.246	0.806
PT (°)	7.3 (14.6)	6.1±6.4	−0.922	0.357
cSVA (mm)	1.4±0.5	1.6±0.7	−0.692	0.492
SVA (mm)	−2.7±3.1	−0.8±2.2	−2.575	0.013*
TPA (°)	−6.1±3.4	−3.5±2.8	−2.916	0.005**
SSA (°)	127.8±8.6	128.2±8.7	−0.148	0.883

Data are presented as the mean ± standard deviation if normally distributed, or as the median (interquartile range) if not normally distributed. Group B: children with short stature but without cervical lordosis; Group B': children with normal heights but without cervical lordosis. *, P<0.05; **, P<0.01. CL, cervical lordosis; T1S, T1 slope; TK, thoracic kyphosis; LL, lumbar lordosis; SS, sacral slope; PI, pelvic incidence; PT, pelvic tilt; cSVA, cervical sagittal vertical axis; SVA, sagittal vertical axis; TPA, trunk pelvic angle; SSA, spino-sacral angle.

Table 6 The number of cases of children with short stature with type A CL and type B CL in relation to etiology

Etiology	Cervical lordosis (type A)	Cervical non-lordosis (type B)
Growth hormone deficiency	2	5
Partial growth hormone deficiency	4	2
Idiopathic short stature	18	9
Hypothyroidism	0	1

CL, cervical lordosis.

lordosis, of whom 5 patients concurrent with growth hormone deficiency, 2 patients had partial growth hormone deficiency, 9 patients had idiopathic SS, and 1 patient had hypothyroidism (*Table 6*). In the group of patients with idiopathic SS, CL (type A) was observed in two times more patients than non-lordosis (type B) (*Table 6*).

No significant correlation was found between any of the parameters, and age, sex, and BMI (P>0.05; *Table 6*). The maximal Cobb angle was found to be significantly mildly or moderately negatively correlated with the CL angle, T1S, TK angle, SVA, and TPA (P<0.05), but significantly mildly positively correlated with the PI (P<0.05) (*Figure 2*). The CL angle was found to be significantly mildly or moderately positively correlated with the T1S, TK angle, SVA, and sacral slope (P<0.05), while the T1S was significantly moderately positively correlated with the TK angle and SVA (P<0.05), but significantly mildly negatively correlated with the SSA (P<0.05). A significant (P<0.05) mild positive correlation was found between the TK angle and SVA, between the PI and PT, and between the SVA and TPA. A significant moderate correlation was found between LL and the sacral slope and SSA (positive) or the PT (negative), and the sacral slope and the PT (negative) or SSA (positive) (P<0.05). A significant negative correlation was found between the PT and the TPA or SSA (P<0.05).

Discussion

After investigating the characteristics and correlation among coronal sagittal plane parameters in children with SS, we found that the SS children had a significantly larger CL angle, T1S, TPA, and TK angle, with a tendency toward a hunchback posture. When scoliosis occurs in the coronal plane in children with SS, the degree of scoliosis is relatively small, and the spine tilts toward the dorsal side. The anatomical structure of the spine is complex, and involves a large number of joints and special mechanical positions. Its coronal sagittal balance is a prerequisite for maintaining basic functions, such as human activity and load-bearing capacity (13).

Based on the particularity of the spinal structure and previous studies, we put forward the "biomechanical pathogenic theory of asymmetric stress on symmetrical structures" (14). The skeletal structure of the human body is similar to a mortise-and-tenon design with both stability and flexibility (balance and stability are the premise of flexibility). Symmetry is the mechanical basis for the stability of mortise-and-tenon structures. When asymmetric stress is applied to the skeleton structure of the human body, it changes posture and muscle tension through a series of regulatory mechanisms for adaptive compensatory regulation. Differences in the development of anatomical structures, such as the spine and pelvis, may lead to individual differences in spinal alignment, pelvic morphology, and overall balance.

At present, there has been some progress in the study

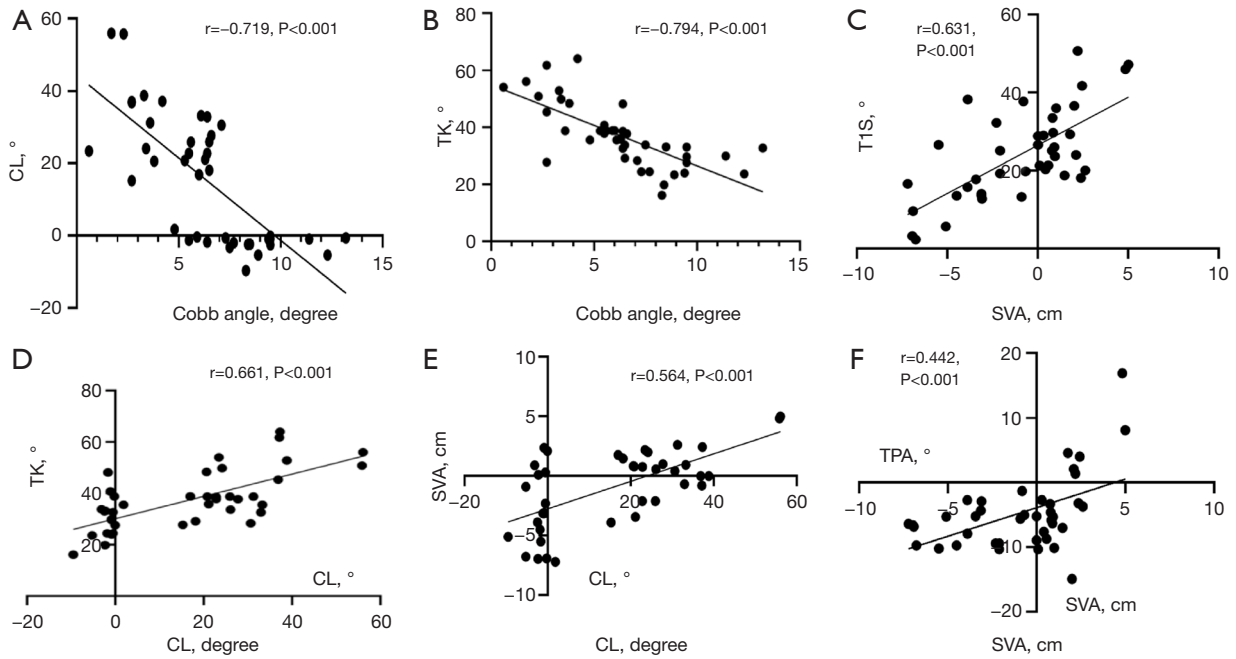

Figure 2 Correlation analysis with scatter plots between some of the spinal parameters. (A) The Cobb angle was found to be significantly negatively correlated with CL. (B) The Cobb angle was found to be significantly negatively correlated with TK. (C) The SVA was found to be significantly positively correlated with the T1S. (D) The CL was found to be significantly positively correlated with the TK. (E) The CL was found to be significantly positively correlated with the SVA. (F) The SVA was found to be significantly positively correlated with the TPA. CL, cervical lordosis; TK, thoracic kyphosis; T1S, T1 slope; SVA, sagittal vertical axis; TPA, trunk pelvic angle.

of spinal coronal sagittal balance in normal children and adults, which provides important reference values for the evaluation and treatment of diseases (7,15,16). However, further research is needed on spinal balance of patients with different pathological conditions. Spinal stability can be affected by pathological conditions, such as ankylosing spondylitis, and adolescent idiopathic scoliosis (17,18), which may lead to varying degrees of spinal imbalance. When the spine is unbalanced, the body strengthens the structural stability through the "locking" mechanism between the joints to maintain the balance, and induces the tension of the muscle fascia to make up for the lack of structural stability. As a result, energy consumption increases, and the body is in a sub-health state and easily fatigued. This long-term pathological adjustment will further damage the symmetry of the symmetrical structure and start the vicious cycle of destabilization-compensation-damage.

The causes of SS are diverse; approximately 1–2% of SS cases are caused by hormonal disorders, 15% by certain chronic systemic diseases, 1% by certain genetic syndromes or bone dysplasia, and 80% by idiopathic SS of unknown etiology (19). Among the children with SS included in this study, most had idiopathic SS (63.8%), followed by SS of endocrine causes, of which growth hormone deficiency was the most common (35.1%). Most of the children with SS in this study had a normal body size (68.2%), followed by a thin body size, and then an overweight and obese body size. Boys or male adolescents accounted for the largest proportion of subjects in our study, which may be related to the small sample size of the study and social factors (e.g., parents may pay more attention to the height of their male children than their female children). Parents' height is a risk factor for SS in children (20). The occurrence of SS is also affected by genetic factors, and a family history of SS significantly increases the incidence of childhood SS (21). Appropriate sports interventions have a certain effect on improving children's height.

The Jackson physiological stress line method was used as the measurement method for CL angle in this study. As this method is simple and easy to employ, and has the best repeatability, it is one of the most commonly used methods for measuring cervical curvature in clinical practice. Research has found a close relationship between

the cervical curvature and the spinal sequence and balance in the coronal and sagittal plane (22). The T1S is a very important morphological parameter that describes the position of the thoracic spine. It is significantly correlated with cervical curvature, cSVA, and thoracolumbar pelvic arrangement, and can affect the curvature of the cervical spine (23). The cSVA is a cervical sagittal plane balance parameter used to evaluate the overall sagittal displacement of the cervical spine in the sagittal balance, and reduces errors caused by thoracic and lumbar spine displacement during the measurement process. Therefore, the cSVA is frequently used to represent the displacement of the entire spine.

The TK and LL represent the curvature and direction of TK and LL, respectively. The sacral slope is a local parameter of the pelvic sagittal plane, and represents the angle of inclination of the upper sacral endplate, which directly affects the direction of the L5 vertebral body and the entire spine (24). The PI is the main angle used to describe the relationship between the upper endplate of the first sacral vertebral body and the acetabulum, and can be used to represent the morphology of the sacrum and pelvis. The PT represents the position of the pelvis around the femoral head. The SVA is the most widely used distance parameter for spinal sagittal balance, and 5 cm has been identified as the critical value for spinal sagittal balance (25). However, due to the susceptibility of imaging measurements to errors, and the influence of posture (26), this study included some angle parameters for evaluating the spinal sagittal balance. The TPA reflects both the spinal tilt and pelvic posterior tilt (11). The SSA reflects the overall posterior inclination of the spine except for the cervical spine (27). The maximal Cobb angle of the coronal plane is the most commonly used parameter for evaluating scoliosis on X-ray films.

Previous research has reported that the local and overall balance of the spinal sagittal plane in asymptomatic children changes to varying degrees with age, and has also reported differences between different races and genders (28). We found no correlation between the spinal parameters, and age, gender, and BMI in the children with SS, whose growth and development differed to that of the children with normal heights. This suggests that the sagittal morphology of the spine in children with SS does not show a change trend related to age or gender. We found that the shape and balance of the spinal sagittal and coronal planes in the children with SS mostly exhibited two trends, which are described as type I and type II, respectively.

The type I morphology was characterized by the CL angle, T1S, and TK angle, which were statistically higher in the children with SS than the control group, and resulted in a tendency for the children with SS to have a hunchback posture. The greater the curvature of TK, the greater the T1S. To maintain a flat-view state, the CL angle must increase. Therefore, the larger the T1S value, the greater the CL angle. Cervical curvature is influenced by the T1S and TK angle (29), which are sequentially correlated with the LL angle and sacral kyphosis angle. We found no statistically significant correlation between the LL angle and TK angle, and the difference in the lumbar curvature between the SS group and the normal height group was not significant. The reason for this may be that an increase in thoracic curvature compensates for the lumbar curvature.

In the type II morphology, when scoliosis occurs in the coronal plane, the degree of scoliosis is relatively small, and the spine tilts toward the dorsal side. The Cobb angle on the coronal plane of the type II spine is larger than that of the type I spine, while the anterior convex angle of the sagittal cervical spine and the posterior convex angle of the thoracic spine are smaller. When scoliosis occurs, children with normal heights have a larger Cobb angle than children with SS, and children with SS have an increase in spinal kyphosis. However, there was no significant imbalance between the two groups in this study.

Previous studies have found that coronal scoliosis can affect the sagittal parameters of the entire spine, including local and global parameters of the spine and pelvis (30). The anterior convex angle of the cervical spine and the posterior convex angle of the thoracic spine decrease as the coronal Cobb angle increases, and a greater degree of scoliosis will result in a smaller TK angle but a faster progression rate of scoliosis (31). The sagittal axis of the spine was found to be slightly positively correlated with the TPA ($P<0.01$), indicating a certain degree of consistency in evaluating the spinal balance between the two. The correlation between the TPA and PT indicated that the TPA reflected the posterior tilt of the pelvis. The SVA represents the parameter of spinal sagittal plane balance; usually, a $|SVA| >5$ cm indicates spinal sagittal plane imbalance (25). Our study found a statistically significant difference in the SVA between the children with SS and those with normal heights ($P<0.05$). The spine of the SS group showed a tendency to tilt backward, but the cSVA of the two groups showed no backward displacement, indicating that the spine showed a tendency to protrude forward to maintain balance. Further expansion can cause the readjustment of the thoracic spine

to compensate for kyphosis.

Due to the complex composition of the spinal bones and muscles, the formation of many joints between various vertebral bodies, and the influence of the spinal compensation mechanism, the spine may present with varied shapes and differences in the force line and balance (32). In our study, three children with SS had a lateral curvature of the coronal spine (but the Cobb angle was <10°), a small thoracic curvature, but a significant convex cervical curvature. Thus, in these three children with SS, the cervical curvature did not decrease as the Cobb angle increased, which does not reflect the positive correlation found between the thoracic curvature and cervical curvature. Research has shown that cervical curvature decreases as Cobb angles increase in adolescent scoliosis patients, while patients with a Cobb angle >45° present with a "normalized" appearance of protrusion or straightening rather than a pronounced CK (8). This is because when scoliosis occurs, the spine compensates for coronal curvature, while the thoracic curvature decreases when the spine is tilted backward. The spine maintains a balance between the head and cervical spine in the sagittal plane, and the patient adopts a compensatory posture by raising their head and chin to maintain the line of sight, resulting in an increase in the CL angle.

In addition, two patients were found to have anterior displacement of the 7th cervical vertebral body. Anterior cervical spondylolisthesis is associated with increased cervical curvature, and research has shown that the T1S value of patients with cervical spondylolisthesis is significantly higher than that of control subjects (33). Patients with a higher T1S have a greater curvature of CL, and the sliding force generated by the forward movement of the gravity axis makes the upper vertebral body have a tendency to move forward relative to the lower vertebral body. This sliding force can simultaneously cause pathological changes in the intervertebral disc like atrophy and degeneration, and multiple biomechanical mechanisms triggered by the same factor promote cervical spondylolisthesis in patients with a higher T1S. The mechanical changes of the cervical spine after cervical spondylolisthesis cause changes in the curvature of the thoracolumbar spine and even the degree of PT.

In this study, we found a certain degree of scoliosis of the spine in the coronal plane in both the SS and normal-height groups, and the incidence and degree of scoliosis in the SS group were lower than those in the normal-height group. When the TK angle of children with SS increases, a tendency toward a hunchback posture appears, and the degree of scoliosis is lighter. TK angle enlargement has the effect of reducing the total longitudinal length of the spine. We observed that in some children with SS, the anterior edge of the thoracic vertebral body was shorter than the posterior edge, and a decrease in the vertebral height or total spinal length alleviated scoliosis. Excessive curvature of the spine can increase the pressure on its longitudinal growth, which has the potential to prevent or hinder the longitudinal growth of the spine (34). With increases of the spinal curvature on the sagittal plane, the growing space becomes smaller and crowded, the spine is tightened like a bowstring, leading to spinal pressure increase and imbalance. To maintain the spinal stability, the "locking" mechanism is activated, which is in line with the "biomechanical pathogenic theory of asymmetric force on the symmetrical structure of the human body" (14).

In epiphyseal-plate-block surgery to correct genu varus or genu valgus in children, the method is to place a blocking nail on the epiphyseal plate to treat the growth imbalance of the inner and outer sides of the knee joint during the growth period (35). In other words, being subjected to a tensile force (i.e., tensile stress) will facilitate the growth of the epiphyseal plate in the direction of traction, while being subjected to compressive stress may hinder the growth. This may also be a possible mechanism by which sports such as basketball playing and swimming can help increase the body height (36,37). Therefore, by increasing the length of the sagittal curvature of the spine, the longitudinal arrangement space of the vertebral body can be increased, so that crowding does not occur as the vertebral body grows. The probability of scoliosis is also reduced.

Conversely, scoliosis compensation occurs to alleviate the insufficient space for longitudinal growth. The sagittal curvature of the spine in people with scoliosis decreases, which can easily lead to insufficient growth space for the longitudinal vertebral body. The small sagittal curvature may also be a factor that is prone to scoliosis and exacerbation, which may also be a possible reason why the current correction treatment for scoliosis, which mainly focuses on coronal position, is not ideal. Due to the three-dimensional spatial relationship of the vertebral arrangement which manifests as rotational compensation in the transverse plane, correcting the sagittal curvature of the spine is a possible direction for rehabilitation treatment in individuals with SS and scoliosis. Although SS reduces the probability and degree of scoliosis, it can lead to insufficient

growth, and physical and psychological problems. However, a normal curve structure and balanced growth can lead to normal mental and physical development and health.

Throughout life, bone continuously forms, absorbs, shapes, and reshapes, and genetics, mechanics, nutrition, and endocrine factors have important effects on the activity of bone cells. Adopting appropriate exercise methods and intensity can improve bone strength, flexibility, balance, and reaction times. Therefore, bones are more likely to be shaped in children in the growth and development stage, and physical exercise to improve bone metabolism and the overall strength line can also improve bone shape, affecting the shape of the bones and increasing the height of SS children. In addition to definitive endocrine factors, an increasing number of genetic factors have been identified for SS (38). Further epigenetics research should be conducted to change the morphology of the spine, and improve the overall or local stress, and explore whether epigenetic modifications can affect the regulatory effect and thus affect children's growth and development. Changes in mechanics can be conducted by intervening in children's lifestyle habits and physical exercise.

This study had some limitations, including its retrospective and one-center study design, small sample size of patients, and lack of randomization, which might have produced some publication bias and might limit the generalizability of the findings. The assessment of physical activity has high uncertainty and subjectivity, making it difficult to quantify. Therefore, physical activity was not examined in this study but could be further analyzed and discussed in future research. Future prospective, multi-center, randomized, controlled studies with a large sample of patients should be conducted in the future.

Conclusions

The spinal morphology of SS has certain characteristic manifestations, and the balance of the entire spine and changes in local curvature of the spine interact with each other. SS children have a significantly larger CL angle, T1S, TPA and TK angle, and a tendency toward a hunchback posture. When scoliosis occurs in the coronal plane in children with SS, the degree of scoliosis is relatively small, and the spine tilts toward the dorsal side.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This retrospective single-center study was approved by the Ethics Committee of Hebei Medical University Third Hospital (ID 2022-001-1), and the requirement of individual consent for this retrospective analysis was waived.

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