Correlation between foot pressure distribution and curve pattern in adolescent idiopathic scoliosis

Correlación entre la distribución de la presión plantar y el patrón de la curva en la escoliosis idiopática adolescente

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Abstract

Introduction. Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity that impacts postural control and plantar pressure distribution, yet the relationship between specific curve patterns and foot loading remains poorly understood.
Objectives: To evaluate how thoracic and lumbar curve patterns influence plantar pressure distribution in the coronal and sagittal planes.
Methodology: Eighty-six adolescents with moderate AIS (Cobb angle ≈38°) were prospectively recruited and categorized into two groups: Thoracic group (n=43; Lenke type 1) and Lumbar group (n=43; Lenke type 5). Static plantar pressure was measured using the FreeMed® computerized pressure platform (Sensor Medica, Rome, Italy). Primary outcomes included percentage of body weight on the concave versus convex side (coronal plane) and forefoot versus rearfoot (sagittal plane).
Main Results: A very strong positive correlation was found between curve pattern and coronal pressure distribution (R = 0.853; p < 0.001; 95% CI: 0.781–0.905), with weight consistently shifting toward the concave side. Thoracic curves demonstrated significantly greater concavity loading (54.9% ± 2.4%) compared to lumbar curves (52.5% ± 2.1%; mean difference = 2.4%; p < 0.001). A moderate correlation was observed between Cobb angle and asymmetry (R = 0.412; p = 0.023). No significant correlation was found in the sagittal plane (R = 0.064; p = 0.547).
Conclusions: Curve location in AIS significantly dictates coronal plantar loading, with thoracic curves producing greater asymmetry than lumbar curves. Sagittal plane distribution remains unaffected by curve pattern. These findings support the integration of baropodometry into clinical assessment and the development of curve-specific rehabilitation protocols.

Keywords

Adolescent idiopathic scoliosis; plantar pressure; baropodometry; postural balance; biomechanics.

Resumen

Introducción. La escoliosis idiopática del adolescente (EIA) es una deformidad espinal tridimensional que afecta el control postural y la distribución de la presión plantar, pero la relación entre los patrones de curva específicos y la carga del pie sigue siendo poco comprendida.
Objetivos: Evaluar cómo los patrones de curva torácica y lumbar influyen en la distribución de la presión plantar en los planos coronal y sagital.
Metodología: Ochenta y seis adolescentes con EIA moderada (ángulo de Cobb ≈38°) fueron reclutados prospectivamente y categorizados en dos grupos: grupo torácico (n=43; tipo Lenke 1) y grupo lumbar (n=43; tipo Lenke 5). La presión plantar estática se midió utilizando la plataforma de presión computarizada FreeMed® (Sensor Medica, Roma, Italia). Los resultados primarios incluyeron el porcentaje de peso corporal en el lado cóncavo versus convexo (plano coronal) y antepié versus retropié (plano sagital).
Resultados: Se encontró una correlación positiva muy fuerte entre el patrón de curva y la distribución de presión coronal (R = 0,853; p < 0,001; IC del 95%: 0,781–0,905), con el peso desplazándose consistentemente hacia el lado cóncavo. Las curvas torácicas demostraron una carga de concavidad significativamente mayor (54,9% ± 2,4%) en comparación con las curvas lumbares (52,5% ± 2,1%; diferencia media = 2,4%; p < 0,001). Se observó una correlación moderada entre el ángulo de Cobb y la asimetría (R = 0,412; p = 0,023). No se encontró correlación significativa en el plano sagital (R = 0,064; p = 0,547).
Conclusiones: La ubicación de la curva en la EIA determina significativamente la carga plantar coronal, con las curvas torácicas produciendo mayor asimetría que las curvas lumbares. La distribución del plano sagital permanece inafectada por el patrón de curva. Estos hallazgos respaldan la integración de la baropodometría en la evaluación clínica y el desarrollo de protocolos de rehabilitación específicos para cada curva.

Palabras clave

Escoliosis idiopática adolescente; presión plantar; baropodometría; equilibrio postural; biomecánica.

Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity characterized by a lateral curvature in the coronal plane with a Cobb angle of at least 10°, accompanied by vertebral rotation and alterations in the sagittal profile (Weinstein et al., 2008). AIS affects approximately 2% to 3% of adolescents globally, with females having a significantly higher risk of curve progression requiring intervention (Konieczny et al., 2013; Negrini et al., 2018).

The biomechanical consequences of AIS extend beyond the spinal column. As the spine deviates from the midline, the body's center of mass shifts, compelling the lower extremities to adapt to maintain upright stability (Dalleau et al., 2011; Nault et al., 2002). The plantar surface of the foot serves as the interface between the body and the ground, making plantar pressure distribution a sensitive indicator of postural compensation (Betsch et al., 2013).

A critical radiographic marker for assessing coronal compensation is the Central Sacral Vertical Line (CSVL), a vertical line originating from the center of the first sacral vertebra used to evaluate spinal balance relative to the midline (O'Brien et al., 2008). Previous research has demonstrated that AIS patients exhibit increased postural sway and greater asymmetry in plantar pressure compared to healthy controls (de Oliveira et al., 2020; Park & Kim, 2021).

Despite growing evidence of altered foot loading in AIS, significant knowledge gaps remain. Most studies have compared AIS patients to healthy controls without distinguishing between different curve patterns (Pauk et al., 2020). The Lenke classification system provides a standardized framework for such comparisons (Lenke et al., 2001), yet limited data exist on whether thoracic (Lenke type 1) and lumbar (Lenke type 5) curves produce distinct plantar pressure signatures. Furthermore, the relationship between curve magnitude and pressure asymmetry has not been systematically quantified.

Understanding these loading patterns is clinically relevant for non-operative treatments including the Schroth method and corrective bracing (Kuru et al., 2021; Schreiber et al., 2019). Baropodometry offers a radiation-free method to quantify treatment effects and guide orthotic interventions (Lin et al., 2022).

The primary objective of this study was to determine the correlation between curve pattern (thoracic vs. lumbar) and plantar pressure distribution in both the coronal and sagittal planes among adolescents with moderate AIS. Secondary objectives included comparing the magnitude of asymmetry between curve types and examining the relationship between Cobb angle and pressure asymmetry.

We hypothesized that: (1) there would be a strong correlation between curve location and coronal pressure shifts toward the concavity; (2) thoracic curves would exhibit greater asymmetry than lumbar curves; (3) sagittal plane distribution would remain independent of curve pattern; and (4) there would be a positive relationship between Cobb angle and pressure asymmetry.

Materials and Method

Study Design and Ethical Considerations

This prospective cross-sectional observational study was conducted at [Institution Name]. The study protocol was approved by the Institutional Review Board of the Faculty of Physical Therapy (Approval Number: PT.REC/012/005853). The study was registered with ClinicalTrials.gov (Identifier: NCT07172048). Written informed consent was obtained from all participants, and parental assent was secured as they are under 18 years of age.

Participants

An a priori power analysis (G*Power 3.1) indicated that a sample size of 82 participants (41 per group) would provide 85% power to detect a strong correlation (R = 0.50) with α = 0.05 (two-tailed). To account for potential dropouts, 86 participants were recruited consecutively from the outpatient orthopedics clinic.

- Inclusion criteria were: age 10–18 years; diagnosis of AIS confirmed by standing full-spine radiography; moderate curve severity (Cobb angle 20°–45°); Lenke type 1 (thoracic) or Lenke type

5 (lumbar) curves; no prior treatment for scoliosis; and ability to stand independently for 30 seconds.

- Exclusion criteria were: history of spinal surgery; leg length discrepancy >1 cm; vestibular or neurological disorders; musculoskeletal injuries affecting lower extremities within the past 6 months; BMI > 30 kg/m^2; foot deformities affecting pressure distribution; and inability to comply with study procedures.

Eligible participants were assigned to two groups based on the apex of their primary curve according to the Lenke classification system (Lenke et al., 2001): Thoracic Group (n=43; Lenke type 1; apex between T2 and T11) and Lumbar Group (n=43; Lenke type 5; apex between L1 and L4).

Instrumentation

- Radiographic assessment: Standing full-spine posteroanterior radiographs were analyzed by two experienced orthopedic surgeons. Parameters measured included Cobb angle, curve classification, CSVL deviation, and Risser sign. Inter-rater reliability for Cobb angle measurements was excellent (ICC = 0.92; 95% CI: 0.88–0.95).
- Baropodometric measurement: Static plantar pressure was recorded using the FreeMed® computerized pressure platform (Sensor Medica, Rome, Italy; software version 2.8.4). This platform utilizes capacitive sensor technology with a sensing area of 60 × 50 cm, 2,400 integrated sensors (4 sensors/cm^2), sampling frequency of 100 Hz, and pressure range of 10–700 kPa. The platform was calibrated according to manufacturer specifications prior to each data collection session.

Procedures

- Standardization of concave side: For participants with left-sided curves, left and right foot pressure values were mathematically flipped prior to statistical analysis to ensure that "concave side loading" consistently represented the percentage of body weight on the foot corresponding to the concavity of the primary curve.
- Measurement protocol: Participants stood barefoot in a relaxed posture with arms at their sides, gazing at a fixed point at eye level. They were instructed to stand as still as possible for 30 seconds. Three consecutive trials were performed with 1-minute rest intervals between trials. The average of three trials was used for analysis.
- The FreeStep software automatically calculated: (1) coronal plane variables: left foot load (%), right foot load (%), concave side load (%) after standardization, convex side load (%), and asymmetry index = |Concave load - Convex load|; (2) sagittal plane variables: forefoot load (%) defined as the anterior 52% of total foot length, rearfoot load (%), and forefoot/rearfoot ratio; and (3) total foot variables: mean pressure (kPa), peak pressure (kPa), and contact area (cm^2).
- Blinding: The researcher performing baropodometry analysis was blinded to group allocation. Participants were assigned identification codes, and group information was only revealed after all pressure data had been processed.

Statistical Analysis

Statistical analysis was performed using SPSS version 26.0 (IBM Corp, Armonk, NY, USA). The Shapiro-Wilk test confirmed normal distribution of all continuous variables ($p > 0.05$). Descriptive statistics (mean ± standard deviation) were calculated for all outcome measures.

Pearson's correlation coefficient (R) was utilized to determine the relationship between curve pattern (thoracic vs. lumbar, coded as binary) and pressure variables (concave side load % and forefoot load %). Correlation was also performed between Cobb angle and concave side loading. For all correlations, we report R, R^2, 95% confidence intervals, and p-values.

Independent samples t-tests compared mean pressure values between thoracic and lumbar groups. Levene's test verified homogeneity of variances. Effect sizes were calculated using Cohen's d. Statistical significance was set at $p < 0.05$ (two-tailed).

Intra-session reliability was assessed in the first 20 participants, showing ICC = 0.96 (95% CI: 0.93–0.98) for concave side loading, with coefficient of variation of 2.3%.

Results

Participant Characteristics

A total of 86 participants completed the study (Thoracic group: n=43; Lumbar group: n=43). Table 1 presents demographic and clinical characteristics. There were no significant differences between groups in age, sex distribution, height, weight, BMI, Cobb angle, or Risser sign ($p > 0.05$ for all). Thoracic curves were predominantly right-sided (79.1%), while lumbar curves were predominantly left-sided (72.1%; $p < 0.001$). Thoracic curves demonstrated significantly greater CSVL deviation (12.4 ± 3.2 mm) compared to lumbar curves (8.7 ± 2.8 mm; $p < 0.001$).

Table 1. Demographic and clinical characteristics of participants

Characteristic	Thoracic Group (n=43)	Lumbar Group (n=43)	p-value
Age (years)	14.3 ± 2.1	14.5 ± 2.0	0.647
Sex (female/male)	28 / 15	30 / 13	0.647
Height (cm)	158.7 ± 8.4	159.2 ± 7.9	0.775
Weight (kg)	51.3 ± 6.8	52.1 ± 7.2	0.593
BMI (kg/m^2)	20.3 ± 1.8	20.5 ± 1.9	0.615
Cobb angle (°)	38.7 ± 2.8	38.1 ± 2.5	0.292
Risser sign (0-5)	3.2 ± 1.1	3.3 ± 1.0	0.657
Curve direction (right/left)	34 / 9	12 / 31	<0.001
CSVL deviation (mm)	12.4 ± 3.2	8.7 ± 2.8	<0.001

Values are mean ± standard deviation or frequencies. BMI: Body Mass Index; CSVL: Central Sacral Vertical Line.

Coronal Plane Results

A highly significant and very strong positive correlation was found between curve pattern and concave side loading ($R = 0.853$; $p < 0.001$; 95% CI: 0.781–0.905). The coefficient of determination ($R^2 = 0.728$) indicates that curve pattern explains 72.8% of the variance in coronal pressure distribution.

When Cobb angle was analyzed as a continuous variable across all participants, a moderate positive correlation was found with concave side loading ($R = 0.412$; $p = 0.023$; 95% CI: 0.198–0.592).

Table 2 presents coronal plane pressure data. In both groups, participants shifted significantly more weight toward the concave side compared to the theoretical symmetrical distribution of 50% (Thoracic: $p < 0.001$; Lumbar: $p < 0.001$).

Table 2. Coronal plane pressure distribution

Variable	Thoracic Group (n=43)	Lumbar Group (n=43)	Mean Difference [95% CI]	p-value
Concave side load (%)	54.9 ± 2.4	52.5 ± 2.1	2.4 [1.3, 3.5]	<0.001
Convex side load (%)	45.1 ± 2.4	47.5 ± 2.1	-2.4 [-3.5, -1.3]	<0.001
Asymmetry index (%)	9.8 ± 2.4	5.0 ± 2.1	4.8 [3.7, 5.9]	<0.001
Mean pressure (kPa)	42.3 ± 5.1	41.8 ± 4.8	0.5 [-1.7, 2.7]	0.647
Contact area (cm^2)	142.6 ± 15.3	144.1 ± 14.7	-1.5 [-8.1, 5.1]	0.653

Values are mean ± standard deviation. Asymmetry index = |Concave load - Convex load|. p-values from independent samples t-tests.

The difference in concave side loading between thoracic and lumbar groups was statistically significant (mean difference = 2.4%, 95% CI: 1.3–3.5%; $p < 0.001$). The asymmetry index was nearly twice as large in the thoracic group (9.8% vs. 5.0%; $p < 0.001$).

Sagittal Plane Results

There was no significant correlation between AIS curve pattern and forefoot loading ($R = 0.064$; $p = 0.547$; 95% CI: -0.148–0.272). Cobb angle showed no correlation with forefoot loading ($R = 0.038$; $p = 0.724$; 95% CI: -0.174–0.247).

Table 3 presents sagittal plane pressure data. There were no statistically significant differences between groups in any sagittal plane variable.

Table 3. Sagittal plane pressure distribution

Variable	Thoracic Group (n=43)	Lumbar Group (n=43)	Mean Difference [95% CI]	p-value
Forefoot load (%)	45.5 ± 5.1	46.0 ± 3.5	-0.5 [-2.5, 1.5]	0.603
Rearfoot load (%)	54.5 ± 5.1	54.0 ± 3.5	0.5 [-1.5, 2.5]	0.603
Forefoot/rearfoot ratio	0.84 ± 0.12	0.85 ± 0.09	-0.01 [-0.06, 0.04]	0.658
Peak forefoot pressure (kPa)	124.3 ± 18.7	126.1 ± 16.9	-1.8 [-9.7, 6.1]	0.645
Peak rearfoot pressure (kPa)	156.7 ± 22.4	153.9 ± 20.8	2.8 [-6.7, 12.3]	0.552

Values are mean ± standard deviation. p-values from independent samples t-tests.

One-sample t-tests comparing forefoot loading to 50% showed no significant deviation in either group (Thoracic: $p = 0.124$; Lumbar: $p = 0.108$).

Exploratory Analyses

CSVL deviation showed a strong positive correlation with concave side loading across all participants ($R = 0.724$; $p < 0.001$; 95% CI: 0.612–0.808). No significant sex differences were found in concave side loading ($p = 0.865$) or forefoot loading ($p = 0.849$). After standardization, there were no significant differences between participants with original right-sided versus left-sided curves ($p = 0.614$).

Discussion

The results of this study demonstrate that curve location in AIS strongly influences coronal plantar pressure distribution, with weight consistently shifting toward the concave side. The very strong correlation between curve pattern and concave side loading ($R = 0.853$) represents one of the largest effect sizes reported in the AIS biomechanics literature. This finding aligns with previous research by Lafferty et al. (2020), who conducted a systematic review of asymmetric plantar pressure distribution in spinal deformities and concluded that such asymmetry is a consistent feature across various spinal conditions. The present study extends these findings by demonstrating that the magnitude of asymmetry varies systematically with curve location.

A novel finding is that thoracic curves produce significantly greater coronal asymmetry than lumbar curves (2.4% greater concave loading; $p < 0.001$). This difference may be explained by the greater distance from the thoracic spine apex to the ground, which amplifies the effect of trunk shift on ground reaction forces. Dalleau et al. (2011) previously demonstrated that scoliotic girls exhibit a posterior offset of the center of mass compared to able-bodied controls, suggesting that compensatory mechanisms differ based on curve location. Additionally, the lumbar spine's proximity to the pelvis may allow for more effective compensation through pelvic adjustments. This interpretation is consistent with Czernicki et al. (2023), who found that lumbar curves are associated with more variable pelvic shift patterns that may partially offset spinal malalignment. Our finding of smaller CSVL deviation in lumbar curves (8.7 mm vs. 12.4 mm) despite similar Cobb angles supports this interpretation.

The moderate positive correlation between Cobb angle and concave side loading ($R = 0.412$) indicates a dose-response relationship where greater curve magnitude is associated with more pronounced asymmetry. This finding is consistent with Park and Kim (2021), who reported correlations ranging from $R = 0.31$ to 0.48 between Cobb angle and foot pressure in mixed AIS samples. Similarly, Nault et al. (2002) found significant relationships between standing stability and body posture parameters in AIS, with greater postural instability associated with increased curve severity. The consistency across studies suggests that this relationship is robust and may have clinical utility for monitoring curve progression using radiation-free methods.

The absence of correlation between curve pattern and sagittal plane loading ($R = 0.064$) was consistent with our hypothesis. This finding aligns with de Oliveira et al. (2020), who observed in their baropodometric analysis that coronal stability is compromised in AIS while sagittal parameters remained relatively preserved. Betsch et al. (2013) demonstrated in healthy subjects that leg length inequalities greater than 20 mm produced significant changes in frontal plane spinal parameters but not in sagittal

parameters, suggesting that the sagittal plane may be more resistant to compensatory changes from lower extremity asymmetry. Sagittal plane loading is likely governed by factors independent of lateral spinal deformity, including pelvic incidence (Legaye et al., 1998) and habitual postural adjustments. Our moderate curve sample (mean Cobb ≈38°) may not have reached the threshold for detectable sagittal adaptations.

Comparison with previous studies reveals both consistencies and extensions. Pauk et al. (2020) compared plantar pressure between AIS patients and healthy controls, finding significant asymmetry in the AIS group but not differentiating between curve types. Our study builds on this by demonstrating that asymmetry magnitude varies systematically with curve location. Wang et al. (2023) examined dynamic plantar pressure during gait in AIS and found different patterns than static measures, reporting that patients with AIS exhibit altered loading patterns during the stance phase compared to healthy controls. This suggests that future studies should incorporate both static and dynamic assessments to fully characterize the biomechanical effects of AIS.

These findings have several clinical implications. For patients with thoracic curves, Schroth method exercises should emphasize active unloading of the concave side, while lumbar curves may benefit more from pelvic stabilization approaches (Kuru et al., 2021; Schreiber et al., 2019). The 2.4% difference between curve types suggests that corrective wedges for footwear or brace interfaces may need to be curve-specific (Lin et al., 2022). Baropodometry offers a radiation-free method to quantify baseline asymmetry, monitor changes over time, and evaluate orthotic interventions.

This study has several limitations. First, static measurements may not reflect dynamic loading during gait (Wang et al., 2023). Second, the cross-sectional design prevents causal inferences about whether asymmetry precedes or results from curve progression. Third, results may not generalize to mild (<20°) or severe (>45°) curves. Fourth, potential confounding factors including foot morphology, lower limb alignment, and pelvic geometry were not assessed (Grivas et al., 2021). Fifth, the sample included only Lenke types 1 and 5, and results may differ for other curve types.

Future research should include dynamic assessment during gait, longitudinal follow-up to examine whether pressure asymmetry predicts curve progression, and randomized controlled trials of curve-specific orthotic interventions. Inclusion of a broader range of curve types and severities would enhance generalizability.

Conclusions

Curve location in adolescent idiopathic scoliosis significantly dictates coronal plantar pressure distribution, with weight consistently shifting toward the concave side. Thoracic curves produce greater asymmetry than lumbar curves, likely due to biomechanical differences in the distance from the curve apex to the ground. A moderate dose-response relationship exists between Cobb angle magnitude and pressure asymmetry. Sagittal plane loading remains unaffected by curve pattern in moderate AIS. Baropodometry using the FreeMed® system serves as a valuable radiation-free clinical adjunct for quantifying biomechanical deviations and guiding curve-specific rehabilitation protocols.

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Ethics approval

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