

Gait spatiotemporal parameters and bilateral asymmetry in mild adolescent idiopathic scoliosis stratified by main curve location

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Abstract

Whether mild adolescent idiopathic scoliosis (AIS) is associated with altered gait remains unclear. This single-centre cross-sectional study compared spatiotemporal gait parameters and bilateral asymmetry in 42 adolescents with mild AIS ($10^\circ \leq$ main curve Cobb angle $< 25^\circ$) and 19 healthy controls, all aged 10–18 years. The AIS group comprised 11 participants with thoracic curves and 31 with thoracolumbar or lumbar curves. Gait was assessed during barefoot treadmill walking at a self-selected, comfortable speed. Bilateral asymmetry was quantified as the absolute left–right difference. Two-group comparisons and three-group omnibus tests were adjusted separately across 17 outcomes using the Benjamini–Hochberg procedure. Exploratory analyses included Dunn–Bonferroni comparisons, Spearman correlations and convex–concave comparisons. No covariates were adjusted for in the analyses. No between-group differences remained significant after correction for multiple comparisons across outcomes. Unadjusted analyses suggested longer stride time, lower cadence and greater rearfoot contact duration asymmetry in AIS. Correlations with temporal gait parameters were not significant, and none of the seven convex–concave comparisons remained significant after Bonferroni correction. These findings provide exploratory observations rather than evidence of a distinct gait pattern associated with mild AIS or with main curve location. Larger studies accounting for confounding and walking speed are needed; nonsignificant findings do not establish equivalence.

Introduction

Adolescent idiopathic scoliosis (AIS) is a common three-dimensional structural deformity of the spine that develops during growth [1, 2]. Reported prevalence estimates range from approximately 0.93% to 12%, with 2–3% reported most commonly [3].

The effects of AIS extend beyond static spinal deformity. Associated trunk asymmetry, altered pelvic alignment and impaired postural control may affect lower-limb biomechanics and walking function [4, 5]. In a population-wide screening study of 2.22 million adolescents in mainland China, Xu et al. reported an overall AIS prevalence of 1.20%, with mild scoliosis accounting for approximately 80% of cases [6]. However, whether adolescents with mild AIS exhibit detectable gait changes remains unclear. Previous studies have reported inconsistent findings regarding spatiotemporal gait parameters, including walking speed and stride length [7]. Zhu et al. found altered foot posture and pressure distribution in moderate and severe AIS, but no significant differences between adolescents with mild AIS and healthy controls [8]. Tekin et al. [9] reported no significant differences in most gait parameters overall, including walking speed and cadence, whereas Haber and Sacco [10] and Mallau et al. [11] reported reduced walking speed in AIS.

Previous AIS gait studies have largely focused on plantar pressure distribution or overall spatiotemporal parameters, such as stride length, step width and walking speed. Average gait parameters may overlook subtle changes in mild AIS, while bilateral asymmetry in lower-limb and plantar loading has received less attention. AIS is characterised by structural differences between the convex and concave sides [12, 13],

whereas walking depends on the coordinated movement of both lower limbs. Assessments limited to overall parameters or aggregate plantar pressure distributions may therefore miss potentially relevant asymmetry. In mild AIS, asymmetry measures may provide information about bilateral differences that are not captured by overall averages. This study examined overall spatiotemporal gait parameters, absolute left–right differences in gait and plantar loading measures, and measurements reclassified according to the convex and concave sides of the main curve. The aim was to provide preliminary evidence to inform further research on the identification and rehabilitation assessment of AIS-related lower-limb biomechanical changes.

Methods

Study design and participants

This single-centre cross-sectional observational study recruited participants at the Third Affiliated Hospital of Zhejiang Chinese Medical University between May and September 2026. Demographic, spinal radiographic, plantar morphology, gait and plantar loading data were collected to compare adolescents with mild AIS and healthy controls, with additional analyses according to main curve location and convex–concave side. The study was approved by the hospital’s Medical Ethics Committee (approval no. ZSLL-KY-2026-033) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from the guardians of all participants.

Eligible participants were aged 10–18 years. Participants in the AIS group had a confirmed diagnosis of AIS and a main curve Cobb angle of 10° to $< 25^{\circ}$ on standing anteroposterior whole-spine radiographs. Healthy controls were confirmed to be free of scoliosis by clinical assessment and had a maximum coronal Cobb angle $< 10^{\circ}$ on standing whole-spine radiographs. All participants underwent standing anteroposterior and lateral whole-spine radiography and plantar pressure and gait assessment during the same assessment period, were able to complete testing with valid measurements, and had complete demographic, radiographic, gait and plantar loading data. Written guardian consent was required.

Exclusion criteria were congenital, neuromuscular, syndromic or other scoliosis with an identifiable cause; nonstructural scoliosis; a documented history of scoliosis before 10 years of age; previous spinal or lower-limb surgery; and lower-limb deformity, neurological disease or any other condition likely to substantially affect gait. A total of 61 participants were included: 42 with mild AIS and 19 healthy controls. In participants with multiple curves, the curve with the largest Cobb angle was designated the main curve. The AIS group was subdivided into thoracic ($n = 11$) and thoracolumbar/lumbar (TL/L; $n = 31$) groups. For supplementary paired analyses, left and right measurements were reclassified as convex-side and concave-side measurements according to the direction of the main curve.

Radiographic assessment

All participants underwent standing anteroposterior and lateral whole-spine radiography. Cobb angles were measured using the standard Cobb method: the most tilted upper and lower end vertebrae were identified, lines were drawn along the superior endplate of the upper vertebra and the inferior endplate of the lower vertebra, and the angle between these lines was recorded. Surgimap software was used to measure Cobb angles and identify curve location and convexity on anteroposterior images (Fig. 1). Scoliosis was defined as a Cobb angle $\geq 10^\circ$. For participants with multiple curves, the angle, location and convexity of the curve with the largest Cobb angle were recorded. Main curve location was classified by the apical vertebral level: curves with a thoracic apex were classified into the thoracic group, and those with a thoracolumbar or lumbar apex were classified into the TL/L group.

Skeletal maturity was assessed using the Risser sign, based on ossification and fusion of the iliac crest apophysis. Risser grades ranged from 0 to 5: grade 0 indicated no visible ossification, grades 1–4 indicated progressive ossification, and grade 5 indicated complete fusion.

To reduce measurement bias, two researchers who had received standardised training independently measured all radiographic parameters. Disagreements were adjudicated by a third physician.

Plantar morphology, plantar pressure and gait assessment

Static plantar morphology was assessed using a plantar scanner. Participants stood barefoot in a relaxed upright position, looking straight ahead with their arms resting naturally at their sides. Bilateral plantar morphology was recorded once a stable standing posture was achieved.

Dynamic plantar pressure and spatiotemporal gait parameters were recorded using a Zebris plantar pressure and gait analysis system (FDM-TR40-3i; Zebris Medical GmbH, Germany). Participants first completed at least 3 min of barefoot treadmill familiarisation, during which a self-selected, comfortable walking speed was established. Familiarisation was not included in the formal recording period. Treadmill speed was then held constant at the selected speed. Participants looked straight ahead, breathed normally and allowed their arms to swing freely. Three 90-s recordings were obtained, with adequate rest between recordings. The system automatically collected valid footprints and generated dynamic plantar pressure and spatiotemporal gait parameters during each recording.

The software's three-region analysis divided each foot's maximum pressure map geometrically into the forefoot (40%), midfoot (30%) and heel (30%; termed the rearfoot throughout this article). Maximum pressure and contact duration measures were extracted for each region. These regions followed the software's geometric rules rather than individual bony anatomical landmarks.

Figure 2 illustrates the assessment workflow and representative gait cycle parameters. Barefoot static plantar scans were acquired during the same assessment period to characterise bilateral plantar morphology; these data were not included in the present analyses. Dynamic assessment captured plantar pressure changes and spatiotemporal parameters during walking. Using foot contact events, the

system automatically identified and calculated stride time, step time, stance phase, swing phase, double support and cadence.

Data collection and variable definitions

Age, sex, height, weight and body mass index (BMI) were recorded. BMI was calculated as weight in kilograms divided by height in metres squared (kg/m^2). Radiographic variables included thoracic and lumbar Cobb angles, main curve location and Risser grade, assessed as described under “Radiographic assessment”. The curve with the largest Cobb angle was defined as the main curve; its location was used for stratified comparisons and its Cobb angle was used to describe curve severity.

Overall spatiotemporal gait outcomes were stride length, step width, double support proportion, stride time, cadence, walking speed, mean stance phase proportion and mean swing phase proportion. Stride length was the forward distance between consecutive initial contacts of the same foot; step length was the forward distance between successive initial contacts of opposite feet. Stride time was the interval between consecutive initial contacts of the same foot, and step time was the interval from initial contact of one foot to the next initial contact of the opposite foot. Gait phase proportions were expressed as percentages of the gait cycle.

Bilateral asymmetry was quantified as the absolute left–right difference (AD), calculated as $AD = |X_L - X_R|$, where X_L and X_R represent the corresponding left- and right-side measurements for the same participant. Side-specific results were summarised across the repeated recordings before AD was calculated. The nine asymmetry outcomes were ADs in foot rotation angle, step length, heel-to-forefoot transition time and its percentage, maximum forefoot, midfoot and rearfoot pressures, and forefoot and rearfoot contact duration proportions. AD retained the unit of the underlying measurement; ADs in percentage measures were expressed in percentage points. Larger values indicated greater bilateral differences without indicating their direction. Forefoot and rearfoot contact duration proportions were expressed relative to the stance phase of the corresponding foot.

The same sign convention was applied to both foot rotation angles: internal rotation was negative and external rotation was positive. AD was calculated from the signed left–right difference. Because rotation angles could be negative or close to zero, AD was not normalised to the bilateral mean.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 27.0, with the individual participant as the unit of analysis. Continuous variables and Risser grades are presented as medians (25th, 75th percentiles), and categorical variables as counts and percentages. Two-group and three-group comparisons used the Mann–Whitney U and Kruskal–Wallis H tests, respectively, with tie correction and asymptotic P values. Main curve Cobb angles were compared only between the two AIS subgroups. Sex

distributions were compared using Fisher's exact test for two groups and the Fisher–Freeman–Halton exact test for three groups.

The 17 two-group gait comparisons and the corresponding 17 three-group omnibus tests formed two separate families. Within each family, the Benjamini–Hochberg (BH) procedure controlled the false discovery rate using unrounded P values. Baseline characteristics were excluded from these families. Outcomes with an unadjusted omnibus $P < 0.05$ underwent exploratory Dunn pairwise comparisons, with Bonferroni correction for the three comparisons within each outcome. When the omnibus test did not remain significant after BH correction, post hoc results were treated as exploratory.

Within the AIS group, Spearman rank correlations assessed the associations between rearfoot contact duration proportion AD and stride time and cadence. We report r , 95% confidence intervals (CIs) from 10,000 participant-level bootstrap resamples, and unadjusted two-sided P values. Convex–concave comparisons used Wilcoxon signed-rank tests, excluding zero differences, with Bonferroni correction across seven outcomes. Effect sizes were the rank-biserial correlation (r_{rb}) for independent groups, the paired rank-biserial correlation for paired comparisons, and rank epsilon squared for three-group omnibus tests [$\epsilon^2 = H/(N - 1)$]. These effect sizes and their 95% CIs were calculated using SPSS MATRIX syntax and 10,000 percentile bootstrap resamples, with a fixed random seed of 20260927. Independent groups were resampled separately within each group, and paired data were resampled as intact participant pairs. Values were rounded to eight decimal places before calculating rank-based effect sizes and their CIs to prevent floating-point discrepancies from affecting tied ranks.

All tests were two-sided, with a significance level of 0.05. Where multiple testing corrections were applied, significance was assessed using the corresponding adjusted P values. All CIs were unadjusted for multiple comparisons and did not replace significance decisions based on adjusted P values. No analyses were adjusted for covariates.

Results

Participant characteristics

The study included 61 adolescents: 42 with mild AIS and 19 healthy controls. The AIS group comprised 11 participants with thoracic main curves and 31 with TL/L main curves.

Age, height, weight, BMI and Risser grade did not differ significantly between the AIS and control groups (all $P > 0.05$). The male/female counts were 8/34 and 9/10, respectively, corresponding to female proportions of 81.0% and 52.6%. Sex distributions differed significantly ($P = 0.032$). The predominance of female participants in the AIS group was consistent with the established epidemiological pattern of AIS being more common in females.

After stratification by main curve location, age, height, weight, BMI and Risser grade did not differ significantly among controls, the thoracic group and the TL/L group (all $P > 0.05$). Male/female counts

were 9/10, 4/7 and 4/27, respectively, corresponding to female proportions of 52.6%, 63.6% and 87.1%. Sex distributions differed significantly across the three groups ($P = 0.027$). Main curve Cobb angles did not differ significantly between the thoracic and TL/L groups ($P = 0.252$). Details are provided in Supplementary Tables S1 and S2.

Overall spatiotemporal gait parameters

Median stride time was longer in the AIS group than in controls [1.24 (1.14, 1.37) vs 1.14 (1.11, 1.27) s; $U = 246.5$, unadjusted $P = 0.0175$], and median cadence was lower [97.00 (87.75, 105.25) vs 103.00 (95.00, 108.00) steps/min; $U = 252.5$, unadjusted $P = 0.0224$]. Neither difference remained significant after BH correction (both adjusted $P = 0.1498$). Median walking speed was also lower in the AIS group [2.55 (2.48, 2.80) vs 2.70 (2.60, 3.00) km/h; $U = 274.5$, unadjusted $P = 0.0497$], but this difference was not significant after correction (BH-adjusted $P = 0.1936$). Unadjusted P values for all other overall spatiotemporal parameters exceeded 0.05, and all BH-adjusted P values exceeded 0.05 (Table 1).

Table 1
Overall spatiotemporal gait parameters in healthy controls and adolescents with mild AIS.

Measure	Controls (n = 19)	Mild AIS (n = 42)	U	Z	Unadjusted P	BH- adjusted P	r_{rb} (95% CI)
Stride length (cm)	89.00 (82.00, 94.00)	90.50 (80.00, 101.00)	382.5	-0.257	0.797	0.968	0.041 (-0.256, 0.341)
Step width (cm)	12.00 (10.00, 14.00)	11.00 (9.00, 12.25)	278.0	-1.901	0.057	0.194	-0.303 (-0.594, 0.014)
Double support (% gait cycle)	26.00 (23.70, 29.00)	26.05 (24.45, 28.55)	397.5	-0.023	0.981	0.981	0.004 (-0.303, 0.318)
Stride time (s)	1.14 (1.11, 1.27)	1.24 (1.14, 1.37)	246.5	-2.377	0.017	0.150	0.382 (0.095, 0.640)
Cadence (steps/min)	103.00 (95.00, 108.00)	97.00 (87.75, 105.25)	252.5	-2.284	0.022	0.150	-0.367 (-0.629, -0.078)
Walking speed (km/h)	2.70 (2.60, 3.00)	2.55 (2.48, 2.80)	274.5	-1.962	0.050	0.194	-0.312 (-0.584, -0.034)
Mean stance phase (% gait cycle)	63.00 (62.00, 64.40)	63.13 (62.15, 64.16)	395.0	-0.062	0.950	0.981	0.010 (-0.294, 0.325)
Mean swing phase (% gait cycle)	37.00 (35.60, 38.00)	36.90 (35.84, 37.85)	395.0	-0.062	0.950	0.981	-0.010 (-0.325, 0.294)
Values are medians (25th, 75th percentiles). Mann–Whitney U tests report U, standardised Z, and two-sided asymptotic unadjusted P values. The eight outcomes in this table and the nine asymmetry outcomes in Table 3 formed one family of 17 tests, with BH correction applied to unrounded P values. r_{rb} denotes the rank-biserial correlation: positive values indicate generally higher measurements in AIS, and negative values indicate generally higher measurements in controls. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. Significance within the family was defined as BH-adjusted $P < 0.05$. CIs were not adjusted for multiple comparisons. AIS, adolescent idiopathic scoliosis; BH, Benjamini–Hochberg; CI, confidence interval.							

In the analysis stratified by main curve location, the omnibus tests for stride time [$H(2) = 7.177$, unadjusted $P = 0.0276$] and cadence [$H(2) = 6.812$, unadjusted $P = 0.0332$] had unadjusted P values < 0.05 . Neither remained significant after BH correction (both adjusted $P = 0.1880$). All other overall spatiotemporal parameters had unadjusted omnibus P values > 0.05 , and all BH-adjusted P values exceeded 0.05.

Exploratory Dunn comparisons following the unadjusted omnibus tests indicated longer median stride time and lower median cadence in the TL/L group than in controls. After Bonferroni correction for three pairwise comparisons per outcome, the corresponding P values were 0.024 and 0.031. Comparisons of controls with the thoracic group and of the thoracic group with the TL/L group had Bonferroni-adjusted P values > 0.05 for both outcomes. These findings were exploratory and did not remain significant after correction across outcomes (Table 2 and its continuation).

Table 2

Overall spatiotemporal gait parameters in healthy controls and AIS subgroups by main curve location.

Measure	Controls (n = 19)	Thoracic (n = 11)	TL/L (n = 31)	H	Unadjusted P	BH- adjusted P	ϵ^2 (95% CI)
Stride length (cm)	89.00 (82.00, 94.00)	86.00 (79.00, 98.00)	91.00 (81.00, 101.00)	0.475	0.789	0.874	0.008 (0.001, 0.149)
Step width (cm)	12.00 (10.00, 14.00)	11.00 (9.00, 13.00)	11.00 (9.00, 12.00)	3.801	0.149	0.424	0.063 (0.005, 0.254)
Double support (% gait cycle)	26.00 (23.70, 29.00)	26.10 (22.20, 28.40)	26.00 (24.50, 29.00)	0.294	0.863	0.874	0.005 (0.001, 0.146)
Stride time (s)	1.14 (1.11, 1.27)	1.21 (1.13, 1.28)	1.27 (1.15, 1.41)	7.177	0.028	0.188	0.120 (0.018, 0.338)
Cadence (steps/min)	103.00 (95.00, 108.00)	99.00 (94.00, 106.00)	96.00 (87.00, 104.00)	6.812	0.033	0.188	0.114 (0.015, 0.331)
Walking speed (km/h)	2.70 (2.60, 3.00)	2.60 (2.50, 2.70)	2.50 (2.40, 2.80)	4.495	0.106	0.359	0.075 (0.008, 0.277)
Mean stance phase (% gait cycle)	63.00 (62.00, 64.40)	63.10 (60.70, 64.10)	63.15 (62.20, 64.35)	0.290	0.865	0.874	0.005 (0.001, 0.146)
Mean swing phase (% gait cycle)	37.00 (35.60, 38.00)	36.90 (35.90, 39.30)	36.90 (35.65, 37.80)	0.269	0.874	0.874	0.004 (0.001, 0.145)

Values are medians (25th, 75th percentiles). Tie-corrected Kruskal–Wallis tests report H and asymptotic unadjusted P values, with 2 degrees of freedom. The eight omnibus tests in this table and the nine in Table 4 formed one family of 17 tests. BH correction used unrounded P values, with adjusted $P < 0.05$ defining significance. Rank epsilon squared was calculated as $\epsilon^2 = H/(N - 1)$, with $N = 61$; parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. CIs were not adjusted for multiple comparisons. Stride time and cadence underwent exploratory Dunn comparisons because their unadjusted omnibus P values were < 0.05; the results appear in the continuation of Table 2. AIS, adolescent idiopathic scoliosis; BH, Benjamini–Hochberg; CI, confidence interval; TL/L, thoracolumbar/lumbar.

Table 2
(continued). Exploratory Dunn pairwise comparisons with Bonferroni correction.

Measure	Comparison	Z	Unadjusted P	Bonferroni-adjusted P	r_{rb} (95% CI)
Stride time (s)	Controls vs thoracic	0.890	0.373	1.000	0.249 (-0.158, 0.636)
Stride time (s)	Controls vs TL/L	2.645	0.008	0.024	0.430 (0.138, 0.699)
Stride time (s)	Thoracic vs TL/L	1.235	0.217	0.650	0.284 (-0.050, 0.595)
Cadence (steps/min)	Controls vs thoracic	0.802	0.422	1.000	-0.244 (-0.636, 0.163)
Cadence (steps/min)	Controls vs TL/L	2.566	0.010	0.031	-0.411 (-0.684, -0.117)
Cadence (steps/min)	Thoracic vs TL/L	1.264	0.206	0.619	-0.299 (-0.610, 0.035)
Two-sided Dunn tests used pooled ranks across all three groups; Z denotes the absolute standardised test statistic. Bonferroni correction was applied to the three comparisons within each outcome: adjusted $P = \min(3 \times \text{unrounded } P, 1)$. r_{rb} was calculated separately from the data for each pair of groups, rather than from the Dunn Z statistic. Positive values indicate generally higher measurements in the second-listed group; negative values indicate generally higher measurements in the first-listed group. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. CIs were not adjusted for multiple comparisons. Comparisons were prompted by unadjusted omnibus $P < 0.05$; because no corresponding omnibus test survived BH correction across outcomes, these are supplementary exploratory findings. TL/L, thoracolumbar/lumbar; CI, confidence interval.					

Bilateral asymmetry measures

Median rearfoot contact duration proportion AD was greater in the AIS group than in controls [4.80 (1.95, 7.23) vs 1.70 (1.00, 4.80) percentage points; $U = 256.5$, unadjusted $P = 0.0264$]. This difference was not significant after BH correction (adjusted $P = 0.1498$). Unadjusted P values for foot rotation AD and all other asymmetry measures exceeded 0.05, and all BH-adjusted P values exceeded 0.05 (Table 3).

Table 3
Bilateral asymmetry measures in healthy controls and adolescents with mild AIS.

Measure	Controls (n = 19)	Mild AIS (n = 42)	U	Z	Unadjusted P	BH- adjusted P	r_{rb} (95% CI)
Foot rotation AD (°)	2.90 (0.60, 4.50)	4.05 (2.53, 7.73)	282.0	-1.823	0.068	0.194	0.293 (-0.013, 0.575)
Step length AD (cm)	2.00 (1.00, 3.00)	2.00 (1.00, 4.00)	331.0	-1.075	0.282	0.686	0.170 (-0.115, 0.445)
Heel-to- forefoot transition time AD (s)	0.020 (0.010, 0.060)	0.030 (0.010, 0.063)	347.0	-0.818	0.414	0.734	0.130 (-0.193, 0.435)
Heel-to- forefoot transition proportion AD (pp)	2.90 (1.30, 7.90)	3.70 (1.88, 8.15)	357.5	-0.646	0.518	0.734	0.104 (-0.208, 0.407)
Maximum forefoot pressure AD (N/cm ²)	2.20 (1.00, 3.00)	1.55 (0.80, 3.03)	341.0	-0.904	0.366	0.734	-0.145 (-0.441, 0.157)
Maximum midfoot pressure AD (N/cm ²)	1.30 (0.50, 2.30)	1.30 (0.50, 2.03)	377.5	-0.335	0.737	0.964	-0.054 (-0.382, 0.274)
Maximum rearfoot pressure AD (N/cm ²)	2.00 (0.90, 3.80)	2.10 (1.38, 4.25)	356.0	-0.670	0.503	0.734	0.108 (-0.238, 0.444)
Forefoot contact duration proportion AD (pp)	1.90 (0.80, 2.30)	1.50 (0.60, 2.55)	352.5	-0.725	0.469	0.734	-0.117 (-0.406, 0.175)

Values are medians (25th, 75th percentiles). AD = $|X_L - X_R|$, where X_L and X_R are the corresponding left- and right-side measurements. A larger AD indicates greater asymmetry without indicating its direction. Percentage measures are reported in percentage points (pp); forefoot and rearfoot contact duration proportions use the stance phase of the corresponding foot as the denominator. Mann–Whitney U tests report U, Z, and two-sided asymptotic unadjusted P values. Positive r_{rb} indicates generally greater AD in AIS; negative values indicate greater AD in controls. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. The nine outcomes here and the eight in Table 1 formed one family of 17 tests. BH correction used unrounded P values; adjusted $P < 0.05$ defined significance. CIs were not adjusted for multiple comparisons. AIS, adolescent idiopathic scoliosis; AD, absolute left–right difference; BH, Benjamini–Hochberg; CI, confidence interval; r_{rb} , rank-biserial correlation.

Measure	Controls (n = 19)	Mild AIS (n = 42)	U	Z	Unadjusted P	BH- adjusted P	r_{rb} (95% CI)
Rearfoot contact duration proportion AD (pp)	1.70 (1.00, 4.80)	4.80 (1.95, 7.23)	256.5	-2.220	0.026	0.150	0.357 (0.054, 0.647)
Values are medians (25th, 75th percentiles). AD = $X_L - X_R$, where X_L and X_R are the corresponding left- and right-side measurements. A larger AD indicates greater asymmetry without indicating its direction. Percentage measures are reported in percentage points (pp); forefoot and rearfoot contact duration proportions use the stance phase of the corresponding foot as the denominator. Mann–Whitney U tests report U, Z, and two-sided asymptotic unadjusted P values. Positive r_{rb} indicates generally greater AD in AIS; negative values indicate greater AD in controls. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. The nine outcomes here and the eight in Table 1 formed one family of 17 tests. BH correction used unrounded P values; adjusted P < 0.05 defined significance. CIs were not adjusted for multiple comparisons. AIS, adolescent idiopathic scoliosis; AD, absolute left–right difference; BH, Benjamini–Hochberg; CI, confidence interval; r_{rb}, rank-biserial correlation.							

After stratification by main curve location, the omnibus test for step length AD had an unadjusted $P < 0.05$ [$H(2) = 8.047$, $P = 0.0179$], but was not significant after BH correction (adjusted $P = 0.1880$). Exploratory Dunn comparisons indicated a greater median step length AD in the TL/L group than in the thoracic group [3.00 (1.00, 5.00) vs 1.00 (0.00, 2.00) cm; Bonferroni-adjusted $P = 0.026$]. Adjusted P values were 0.937 for controls versus the thoracic group and 0.194 for controls versus the TL/L group. These findings were exploratory and did not remain significant after correction across outcomes. All other asymmetry measures had unadjusted omnibus P values > 0.05, and all BH-adjusted P values exceeded 0.05 (Table 4 and its continuation).

Table 4

Bilateral asymmetry measures in healthy controls and AIS subgroups by main curve location.

Measure	Controls (n = 19)	Thoracic (n = 11)	TL/L (n = 31)	H	Unadjusted P	BH- adjusted P	ϵ^2 (95% CI)
Foot rotation AD (°)	2.90 (0.60, 4.50)	3.90 (2.20, 10.00)	4.20 (2.60, 6.80)	3.326	0.190	0.460	0.055 (0.005, 0.244)
Step length AD (cm)	2.00 (1.00, 3.00)	1.00 (0.00, 2.00)	3.00 (1.00, 5.00)	8.047	0.018	0.188	0.134 (0.025, 0.356)
Heel-to- forefoot transition time AD (s)	0.020 (0.010, 0.060)	0.050 (0.010, 0.080)	0.030 (0.010, 0.060)	0.989	0.610	0.874	0.016 (0.001, 0.180)
Heel-to- forefoot transition proportion AD (pp)	2.90 (1.30, 7.90)	5.00 (1.90, 9.10)	3.60 (1.70, 7.00)	1.440	0.487	0.870	0.024 (0.002, 0.173)
Maximum forefoot pressure AD (N/cm ²)	2.20 (1.00, 3.00)	1.80 (0.60, 3.70)	1.50 (0.90, 3.00)	0.824	0.662	0.874	0.014 (0.001, 0.169)
Maximum midfoot pressure AD (N/cm ²)	1.30 (0.50, 2.30)	0.90 (0.40, 2.00)	1.40 (0.50, 2.10)	0.300	0.861	0.874	0.005 (0.001, 0.142)
Maximum rearfoot pressure AD (N/cm ²)	2.00 (0.90, 3.80)	3.20 (1.50, 6.00)	2.00 (1.30, 2.80)	1.340	0.512	0.870	0.022 (0.002, 0.195)
Forefoot contact duration proportion AD (pp)	1.90 (0.80, 2.30)	1.10 (0.60, 1.60)	1.50 (0.50, 2.90)	1.458	0.482	0.870	0.024 (0.003, 0.150)

Values are medians (25th, 75th percentiles). AD = $|X_L - X_R|$ quantifies asymmetry without indicating its direction. Percentage measures are reported in percentage points (pp); forefoot and rearfoot contact duration proportions use the stance phase of the corresponding foot as the denominator. Tie-corrected Kruskal–Wallis tests report H and asymptotic unadjusted P values, with 2 degrees of freedom. Rank epsilon squared was calculated as $\epsilon^2 = H/(N - 1)$, with $N = 61$; parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. The nine omnibus tests here and the eight in Table 2 formed one family of 17 tests. BH correction used unrounded P values; adjusted $P < 0.05$ defined significance. CIs were not adjusted for multiple comparisons. Step length AD underwent exploratory Dunn comparisons because its unadjusted omnibus P was < 0.05 (Table 4, continued). AIS, adolescent idiopathic scoliosis; AD, absolute left–right difference; BH, Benjamini–Hochberg; CI, confidence interval; TL/L, thoracolumbar/lumbar.

Measure	Controls (n = 19)	Thoracic (n = 11)	TL/L (n = 31)	H	Unadjusted P	BH- adjusted P	ϵ^2 (95% CI)
Rearfoot contact duration proportion AD (pp)	1.70 (1.00, 4.80)	4.00 (1.50, 6.10)	4.90 (2.00, 7.30)	5.149	0.076	0.324	0.086 (0.010, 0.295)
Values are medians (25th, 75th percentiles). AD = $X_L - X_R$ quantifies asymmetry without indicating its direction. Percentage measures are reported in percentage points (pp); forefoot and rearfoot contact duration proportions use the stance phase of the corresponding foot as the denominator. Tie-corrected Kruskal–Wallis tests report H and asymptotic unadjusted P values, with 2 degrees of freedom. Rank epsilon squared was calculated as $\epsilon^2 = H/(N - 1)$, with N = 61; parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. The nine omnibus tests here and the eight in Table 2 formed one family of 17 tests. BH correction used unrounded P values; adjusted P < 0.05 defined significance. CIs were not adjusted for multiple comparisons. Step length AD underwent exploratory Dunn comparisons because its unadjusted omnibus P was < 0.05 (Table 4, continued). AIS, adolescent idiopathic scoliosis; AD, absolute left–right difference; BH, Benjamini–Hochberg; CI, confidence interval; TL/L, thoracolumbar/lumbar.							

Table 4
(continued). Exploratory Dunn comparisons of step length AD with Bonferroni correction.

Comparison	Z	Unadjusted P	Bonferroni-adjusted P	r_{rb} (95% CI)
Controls vs thoracic	1.010	0.312	0.937	-0.282 (-0.694, 0.177)
Controls vs TL/L	1.848	0.065	0.194	0.331 (0.031, 0.616)
Thoracic vs TL/L	2.625	0.009	0.026	0.490 (0.161, 0.768)
Two-sided Dunn tests used pooled ranks across all three groups; Z denotes the absolute standardised test statistic. Bonferroni correction was applied to the three pairwise comparisons: adjusted P = $\min(3 \times \text{unrounded P}, 1)$. r_{rb} was calculated separately from the data for each pair of groups, rather than from the Dunn Z statistic. Positive values indicate generally greater step length AD in the second-listed group; negative values indicate greater AD in the first-listed group. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples drawn separately within groups. CIs were not adjusted for multiple comparisons. These comparisons were prompted by unadjusted omnibus P < 0.05; because the omnibus test did not survive BH correction across outcomes, they are supplementary exploratory findings. AD, absolute left–right difference; CI, confidence interval; r_{rb}, rank-biserial correlation; TL/L, thoracolumbar/lumbar.				

Associations between rearfoot contact duration asymmetry and temporal gait parameters

Within the mild AIS group (n = 42), Spearman correlations between rearfoot contact duration proportion AD and stride time ($r_s = -0.164$, P = 0.300) and cadence ($r_s = 0.177$, P = 0.262) were not significant.

These results did not provide sufficient evidence for monotonic associations between rearfoot contact duration asymmetry and temporal gait parameters (Table 5).

Table 5

Correlations between rearfoot contact duration asymmetry and temporal gait parameters in mild AIS.

Asymmetry measure	Temporal gait parameter	n	Spearman r_{S}	95% CI	P
Rearfoot contact duration proportion AD (pp)	Stride time (s)	42	-0.164	-0.448 to 0.136	0.300
Rearfoot contact duration proportion AD (pp)	Cadence (steps/min)	42	0.177	-0.124 to 0.458	0.262
Analyses included the 42 participants with mild AIS. Spearman correlations are reported as r_{S} , 95% CIs, and unadjusted two-sided P values. CIs were estimated from 10,000 participant-level bootstrap resamples, retaining the correspondence between variables within each participant. Rearfoot contact duration proportion AD is the absolute difference between left and right rearfoot contact durations expressed as percentages of the corresponding stance phases, reported in percentage points (pp). These analyses were supplementary and exploratory. AIS, adolescent idiopathic scoliosis; AD, absolute left–right difference; CI, confidence interval.					

Convex–concave comparisons

After reclassifying measurements according to main curve direction, all seven outcomes had 42 complete convex–concave pairs. The Wilcoxon signed-rank test indicated a higher rearfoot contact duration proportion on the concave side than on the convex side [median (25th, 75th percentiles): 65.85% (57.90%, 69.93%) vs 62.70% (58.18%, 66.40%); $Z = -2.220$, unadjusted $P = 0.0265$]. This difference was not significant after Bonferroni correction (adjusted $P = 0.1852$). The other six outcomes had unadjusted P values > 0.05 , and all seven adjusted P values exceeded 0.05 (Table 6). These findings did not provide sufficient evidence for differences between the sides defined by the main curve, but they do not establish equivalence.

Table 6

Gait and plantar loading parameters on the convex and concave sides of the main curve in mild AIS.

Measure	n	Convex side	Concave side	Z	Unadjusted P	Bonferroni-adjusted P	Paired r_{rb} (95% CI)
Foot rotation (°)	42	1.35 (-2.35, 6.30)	3.10 (-1.83, 7.65)	-0.950	0.342	1.000	0.168 (-0.190, 0.493)
Step length (cm)	42	45.00 (39.75, 51.25)	45.00 (40.75, 52.00)	-1.698	0.089	0.626	0.333 (-0.046, 0.661)
Maximum forefoot pressure (N/cm ²)	42	23.50 (20.35, 25.90)	23.40 (19.65, 25.30)	-1.444	0.149	1.000	-0.256 (-0.576, 0.086)
Maximum midfoot pressure (N/cm ²)	42	8.50 (7.00, 11.00)	9.20 (7.85, 11.63)	-1.264	0.206	1.000	0.226 (-0.137, 0.544)
Maximum rearfoot pressure (N/cm ²)	42	22.80 (18.08, 28.48)	23.65 (19.20, 27.83)	-0.441	0.659	1.000	0.079 (-0.281, 0.424)
Forefoot contact duration (% stance phase)	42	89.85 (87.68, 92.13)	89.95 (87.33, 92.93)	-0.206	0.837	1.000	-0.037 (-0.381, 0.312)
Rearfoot contact duration (% stance phase)	42	62.70 (58.18, 66.40)	65.85 (57.90, 69.93)	-2.220	0.026	0.185	0.393 (0.073, 0.688)

Values are medians (25th, 75th percentiles). Left and right measurements were reclassified according to main curve convexity. Two-sided Wilcoxon signed-rank tests excluded zero differences from ranking; n denotes complete pairs. The numbers of nonzero pairs were 34 for step length, 41 each for maximum midfoot and rearfoot pressure, and 42 for the remaining outcomes. Bonferroni correction covered all seven tests: adjusted P = min(7 × unrounded P, 1). Paired $r_{rb} = (W^+ - W^-)/(W^+ + W^-)$, where W^+ and W^- are the rank sums of positive and negative concave-minus-convex differences. Positive values favour larger measurements on the concave side; negative values favour the convex side. Parentheses contain 95% CIs from 10,000 percentile bootstrap resamples of intact participant pairs. CIs were not adjusted for multiple comparisons. Forefoot and rearfoot contact duration proportions are percentages of the corresponding stance phase. AIS, adolescent idiopathic scoliosis; CI, confidence interval; r_{rb} , rank-biserial correlation.

Discussion

This study compared overall spatiotemporal gait parameters and bilateral asymmetry between adolescents with mild AIS and healthy controls, with further stratification by main curve location. Neither the two-group comparisons nor the three-group omnibus tests remained significant after BH correction across outcomes. The present sample therefore did not provide evidence of between-group differences after accounting for multiple testing. Unadjusted analyses suggested temporal gait differences, including longer stride time and lower cadence, whereas spatial parameters such as stride length and step width did not differ significantly. Exploratory comparisons indicated longer stride time and lower cadence in the TL/L group than in controls after Bonferroni correction within each outcome. However, direct comparisons between the thoracic and TL/L groups were not significant for either parameter, so the results do not establish more pronounced temporal changes in TL/L curves. These observations may guide further research but do not demonstrate a specific gait abnormality in mild AIS or an association with main curve location. This is broadly consistent with reports of no significant differences in most gait parameters between adolescents with mild AIS and controls [8, 9]. Conversely, nonsignificant adjusted results do not show that the groups have identical gait characteristics or exclude differences that this sample could not estimate precisely.

Whereas Zhu et al. [8] and Tekin et al. [9] reported no marked gait changes in mild AIS, Haber and Sacco [10], Mallau et al. [11] and Sklenský et al. [14] reported changes in selected gait measures in AIS. A meta-analysis by Kim et al. [15] identified differences in stance phase and frontal-plane pelvic motion, but not in walking speed, step length or cadence. The systematic review and meta-analysis by Khorramroo et al. [16] further highlighted heterogeneity in gait findings across studies of spinal deformity. Differences in curve severity, participant characteristics, testing conditions and outcome definitions limit direct comparison with mild AIS assessed at a self-selected treadmill speed. The present BH-adjusted results did not provide additional clear evidence of group differences and underline the need to account for multiple testing when interpreting numerous gait outcomes.

The longer stride time and lower cadence observed in unadjusted analyses are closely related kinematically and should not be regarded as two independent indications of abnormality. Because testing used a self-selected comfortable speed, these numerical differences may reflect speed selection; whether they persist at comparable walking speeds remains unknown. Research on multifidus muscle fatty infiltration in AIS provides structural context [17], but does not establish a mechanism for the temporal gait observations in this mild AIS sample. The current findings are therefore insufficient to interpret temporal differences as compensatory strategies for maintaining stability or to infer that temporal changes precede spatial abnormalities.

There is a biomechanical rationale for examining main curve location. The spine, pelvis and lower limbs form a linked system whose alignment and movement contribute to posture and walking. Radiographic findings in other orthopaedic populations suggest relationships among these segments [18], although this provides only indirect context. Studies of gait determinants, pelvic rotation and step length formation indicate that the pelvis contributes to walking through several components of motion and their coordination [19–21]. Park et al. [7] examined thoracic–pelvic coordination in AIS, and Liu et al. [5]

investigated spinopelvic parameters, balance and gait in Lenke V curves, providing complementary perspectives on function across curve patterns. In the present study, differences in temporal parameters between the TL/L group and controls, and in step length AD between the TL/L and thoracic groups, arose only in exploratory post hoc analyses; the corresponding omnibus tests did not survive BH correction. The small thoracic subgroup also limited precision. Without simultaneous pelvic and lower-limb kinematic measurements, an independent effect of main curve location cannot be established, nor can TL/L curves be inferred to affect lower-limb movement more strongly than thoracic curves. Whether gait characteristics are associated with curve location, and whether any association varies with severity, requires further study. Combining spinal, pelvic and lower-limb imaging with three-dimensional gait analysis across curve locations and severities may clarify the relationships among structural alignment, segmental coordination and spatiotemporal gait parameters.

Rearfoot contact duration proportion AD showed a nominally significant two-group difference, but the evidence was insufficient after BH correction. Previous studies have assessed AIS-related asymmetry through plantar pressure, gait cycle measures, segmental motion, ground reaction forces and centre-of-pressure trajectories [8, 22–25]. These studies provide context, but their differences in curve severity, methods and asymmetry definitions prevent direct equivalence with the rearfoot contact duration asymmetry examined here. Our measure describes the bilateral difference in rearfoot contact duration relative to each foot's stance phase; it does not directly measure load magnitude, joint motion or postural control. The present findings therefore do not establish that mild AIS abnormalities are concentrated in rearfoot contact timing or that general plantar loading asymmetry is present. Whether this measure adds information beyond overall averages requires assessment of repeated-measure reliability and validation in independent samples.

Correlation analyses did not identify significant monotonic associations between rearfoot contact duration proportion AD and either stride time or cadence. Overall temporal parameters describe walking rhythm, whereas rearfoot contact duration proportion AD describes bilateral differences in the relative duration of local foot contact. These measures therefore represent different aspects of gait. In addition, stride time and cadence are closely related, so separate correlations with these variables do not provide independent replication. Given the limited sample size and restriction to mild AIS, more precise effect estimates and further studies are needed to assess possible associations.

After measurements were reclassified as convex-side and concave-side values, none of the seven outcomes remained significant after Bonferroni correction. This sample thus did not provide consistent evidence of differences associated with main curve laterality. Nevertheless, such reclassification has methodological value. AIS involves coronal curvature, altered sagittal alignment and axial rotation, and previous studies have documented convex–concave differences in tissue morphology and motor function [17, 26–29]. Mahaudens et al. [30] observed some gait changes in AIS without significant left–right asymmetry in the kinematic and electromyographic measures assessed. Although those outcomes differ from ours, the findings suggest that overall gait changes and side-specific differences should be evaluated separately. AD quantifies the magnitude of a bilateral difference, whereas convex–concave

comparisons assess whether the direction of that difference is consistently related to main curve convexity. A nonsignificant side comparison does not establish equivalence [31]. Conventional left–right comparisons do not determine whether bilateral differences are associated with curve direction. Some biomechanical studies restrict recruitment to particular curve patterns or directions to reduce heterogeneity. For example, de Reuver et al. [12] included patients with right thoracic main curves and excluded those with left thoracic or lumbar main curves, illustrating the importance of curve-specific applicability when interpreting structural asymmetry. Reclassification according to the convexity of the largest Cobb angle provides a description linked to spinal laterality, but does not fully capture secondary curves, spinal rotation or pelvic alignment. Studies with more detailed curve characterisation, three-dimensional kinematics and centre-of-pressure trajectories could test whether this approach identifies reproducible side-specific features.

Limitations

This study has several limitations. It was a single-centre cross-sectional observational study with prospective recruitment and data collection, a limited sample, and unequal thoracic and TL/L subgroup sizes (11 and 31 participants). These features limited the precision of stratified comparisons and correlation estimates. The cross-sectional design cannot establish the temporal or causal relationship between spinal morphology and gait; it cannot determine whether temporal changes precede spatial abnormalities or represent compensation. Stratification was based on main curve location, and thoracolumbar and lumbar curves were combined without further distinction among single, double or other curve patterns. Reclassification by main curve convexity helps explore direction-related differences but cannot fully represent the combined effects of secondary curves, spinal rotation and pelvic alignment. Pelvic and lower-limb three-dimensional kinematics, electromyographic activity and trunk control were not recorded, so explanations involving the spine–pelvis–lower-limb system remain hypotheses. Finally, the findings concern mild AIS and cannot be directly generalised to moderate or severe scoliosis. Larger multicentre studies with more detailed stratification, better control of confounding, multimodal movement assessment and longitudinal follow-up are needed to evaluate reproducibility and clinical relevance.

Conclusions

Neither the comparisons of mild AIS with healthy controls nor the analyses stratified by main curve location identified significant differences in overall spatiotemporal gait parameters or bilateral asymmetry after BH correction across outcomes. Unadjusted analyses suggested longer stride time, lower cadence and greater rearfoot contact duration proportion AD in mild AIS; exploratory post hoc comparisons suggested greater step length AD in the TL/L group than in the thoracic group. These observations do not establish gait characteristics specific to mild AIS or a particular main curve location. Rearfoot contact duration asymmetry was not significantly correlated with stride time or cadence, and convex–concave comparisons were not significant after Bonferroni correction. Given the limited sample and lack of adjustment for potential confounders, these findings should guide further exploratory

research. Nonsignificant differences do not establish equivalence, and larger studies accounting for confounding and walking speed are required.

Declarations

Ethics approval and consent to participate

The study was approved by the Medical Ethics Committee of the Third Affiliated Hospital of Zhejiang Chinese Medical University (approval no. ZSLL-KY-2026-033). Written informed consent was obtained from the guardians of all participants. The study was conducted in accordance with the Declaration of Helsinki.

Consent to publication

Not applicable.

Author Contribution

Conceptualization: X.m.Y.,X.Y.; methodology: X.m.Y.,X.Y.; formal analysis and investigation: J. M., J.Y.,Y.Y., S.C.; writing—original draft preparation: J. M., J.Y.;writing—review and editing:S.C.,H.N.T.,F.Q.;graph making:Y. C.,J. M.;resources: X.m. Y.,X. Y.; supervision: X.m. Y.,X.Y. All authors read and approved the final manuscript.

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Data Availability

The de-identified participant-level data supporting the findings of this study, together with variable definitions, are available from the corresponding authors upon reasonable request.

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Figures

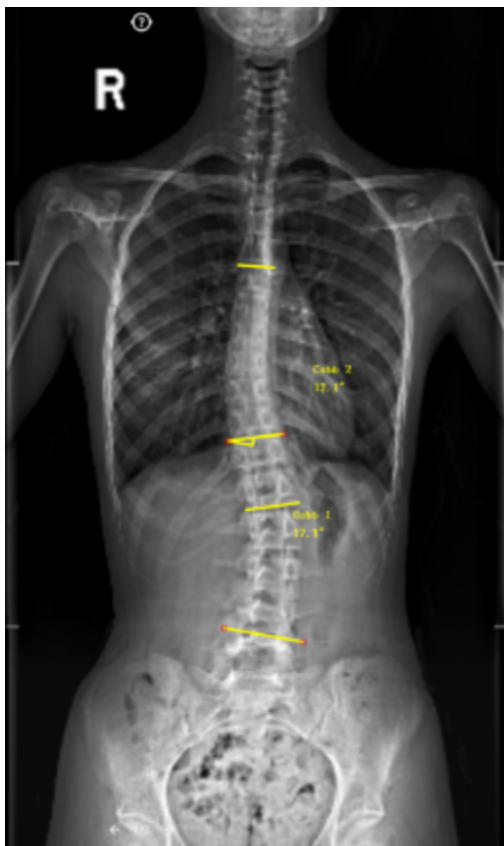


Figure 1

Example of Cobb angle measurement using Surgimap. Yellow lines indicate the endplate measurement lines for the selected end vertebrae. The two displayed Cobb angles are 12.1° and 17.1°. According to the rule defining the main curve as the curve with the largest Cobb angle, the main curve angle in this example is 17.1°. R indicates the participant's right side.

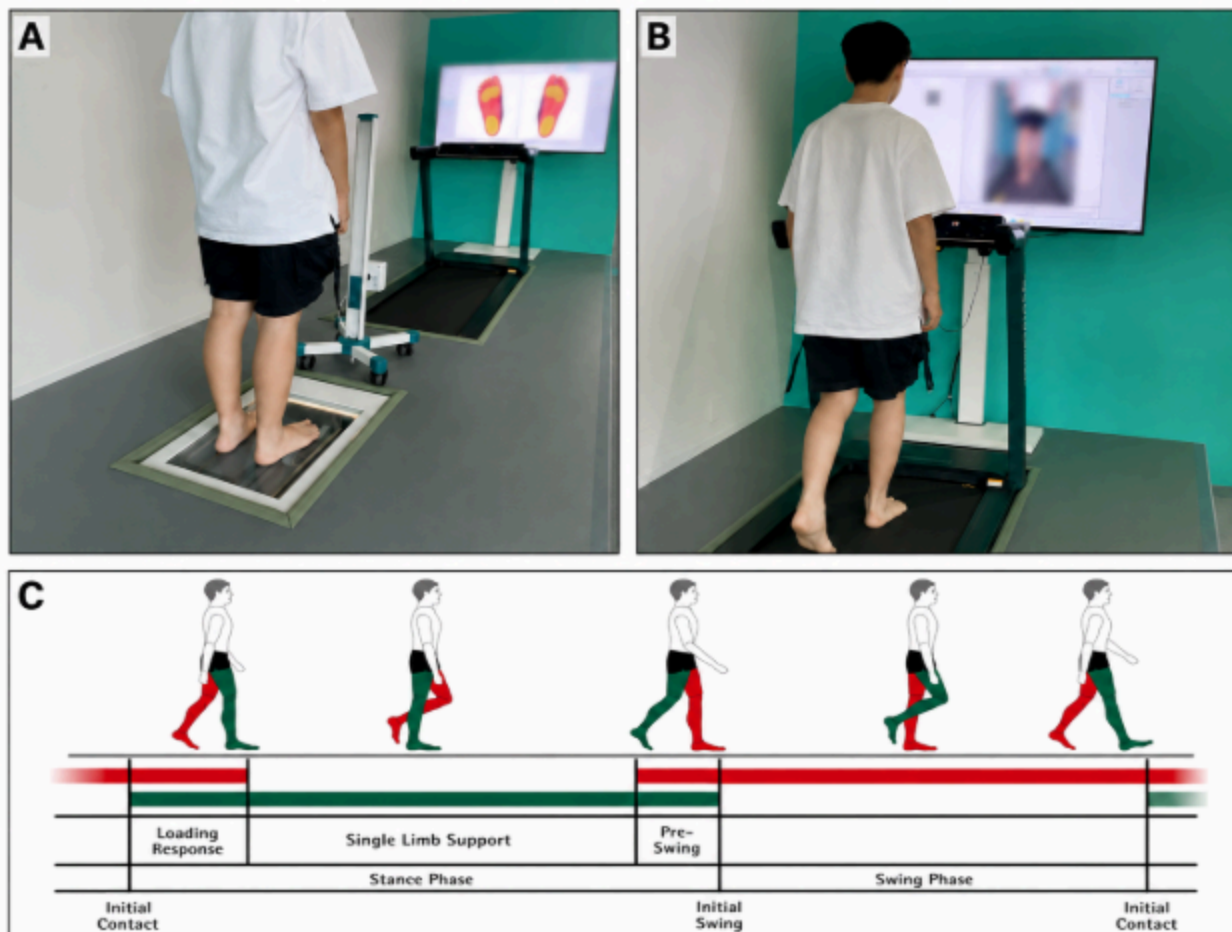


Figure 2

Assessment of plantar morphology, plantar pressure, and gait, with representative gait cycle parameters.

(A) Static plantar morphology assessment. Participants stood barefoot on a plantar scanner in a relaxed upright position, looking straight ahead with their arms at their sides. Bilateral plantar morphology was recorded after a stable standing posture was achieved. These data were not included in the present analyses.

(B) Dynamic plantar pressure and gait assessment. Participants walked barefoot on the Zebris FDM-TR40-3i treadmill system at a self-selected, comfortable speed, looking straight ahead, breathing normally and allowing their arms to swing freely. Dynamic plantar pressure distribution and spatiotemporal gait parameters were recorded simultaneously.

(C) Schematic of a gait cycle and selected spatiotemporal parameters. A complete gait cycle extends from initial contact of one foot to the next initial contact of the same foot and comprises stance and swing phases. The main parameters extracted in this study included stride time, stance phase, swing phase, double support, cadence and walking speed.

Supplementary Files

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