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Biomechanical changes in adolescent idiopathic scoliosis during walking

A protocol for systematic review and meta-analysis

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Abstract

Background: To clarify the differences in biomechanical characteristics present in adolescent idiopathic scoliosis (AIS) patients during walking.

Methods: Cross-sectional studies related to the biomechanical characteristics of AIS were included by searching 7 major databases and analyzed using RevMan 5.4 software.

Results: There were a total of 15 trials involving 377 AIS patients. The results showed that during walking, AIS had increased pelvic coronal tilt (effect size [ES] = –1.34, 95% confidence intervals [CI] = –2.41 to –0.27, P = .01), knee and ankle sagittal mobility were reduced (ES = –5.22, 95% CI = –7.51 to –2.94, P < .001; ES = –3.58, 95% CI = –5.93 to –1.22, P = .003). The duration of electromyogram activity was prolonged in the gluteus medius (ES = 7.65, 95% CI = 5.33–9.96, P < .001), lumbar square (ES = 10.73, 95% CI = 6.97–14.49, P < .001), and erector spinae (ES = 14.35, 95% CI = 6.94–21.76, P < .001) muscles. The results of subgroup analysis showed that the step length of the concave side of the spine was reduced (ES = –0.36, 95% CI = –0.71 to –0.01, P = .04).

Conclusion: AIS has characteristic biomechanical changes in spatiotemporal, phase kinematics, motor mechanics, and electromyographic signatures. Further comprehensive studies are required in the future to analyze the biomechanical and electromyographic differences among different degrees and types of scoliosis, as well as the differences between the concave and convex sides of scoliosis during walking.

Abbreviations: AIS = adolescent idiopathic scoliosis, CA = concave, CI = confidence intervals, CNKI = China National Knowledge Infrastructure, CX = convex, EMG = electromyogram, ES = effect size, ROM = range of motion, SMD = standard mean difference, WMD = weighted mean difference.

Keywords: adolescent idiopathic scoliosis, biomechanical, meta-analysis, rehabilitation, walking

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional (3D) deformity of the spine that occurs in adolescents for unknown reasons. It involves abnormalities in the coronal, sagittal, and axial positions,[1] where axial plane deformities cannot be determined solely by coronal and sagittal plane deformities.[2] The prevalence of AIS in adolescents (10–17 years old) is approximately 1 to 3%.[3,4] The prevalence varies with gender, with rates between 0.15% and 0.66% for boys and 0.24 to 3.10% for girls.[5] The exact cause of AIS is unclear, but possible explanations include genetic and hormonal factors, connective tissue abnormalities, and central nervous system issues. In the early stages, AIS is difficult to detect as there are no obvious symptoms, but the condition can worsen rapidly during the growth spurt of adolescents. AIS not only leads to spinal deformities, but also cosmetic issues such as trunk deviation, high and low shoulders, funnel chest, razor back, waistline asymmetry, short and long legs, pelvic tilt, flat feet, and psychological problems. In severe cases, it can impair cardiopulmonary function and eventually lead to respiratory failure.[6] Biomechanically, patients with AIS experience complex changes during walking. The severity of scoliosis, the

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The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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number of scoliotic angles, and the extent and location of the affected spinal segments interact with each other.[7–9] These biomechanical characteristics can have a significant impact on the patient's gait. Therefore, it is crucial to systematically evaluate the biomechanical characteristics of AIS patients using multiple pieces of evidence. This will help inform clinicians about possible biomechanical changes and provide an evidence-based foundation for the prevention, assessment, and treatment of AIS. This study critically examines several observational studies that compare patients with AIS to age-matched healthy adolescents. The objective is to identify and analyze the variations in biomechanical and other characteristics observed in patients with AIS during walking.

2. Data and methods

2.1. Literature search strategy

Seven major electronic databases were searched for the study: PubMed, Embase, Cochrane Library, Scopus, Web of Science, China National Knowledge Infrastructure, and Wanfang database, with a search time frame ending March 15, 2023, and with languages limited to English and Chinese. The program under review is registered with PROSPERO (CRD42023410945). Ethical review was not required for this article because the study was evidence-based and not subjected to clinical trials. Searches were conducted using a combination of subject terms and free terms, and references for inclusion in the literature were also traced. English search terms: AIS, gait, motion analysis, kinematics, electromyographies, surface electromyography. For an example of searching PubMed, see Supplementary attachment 1, Supplemental Digital Content, http://links.lww.com/MD/L6.

2.2. Inclusion and exclusion criteria

Inclusion criteria: (1) study subjects with a clinical diagnosis of AIS and aged 10–17 years. (2) Cross-sectional studies. (3) Human biomechanical studies based on walking activities. (4) No restrictions on disease severity, gender, type of spinal curve and location of spinal segments involved. (5) Chinese and English literature.

Exclusion criteria: (1) patients who used orthoses to support walking or patients who had scoliosis correction surgery. (2) Mathematical modeling and finite element analysis were used for validation rather than a comparison of biomechanical characteristics as the main purpose of the study. (3) Duplicate publications. (4) Reviews, conference papers, letters and case reports without original data.

2.3. Filtering and data extraction

After removing duplicates using EndNote X20 literature management software, 2 researchers independently conducted the initial screening of titles and abstracts. The literature that met the inclusion criteria was read in full and further screened according to the exclusion criteria. In cases of disagreement, a third researcher was consulted for adjudication. The final included literature underwent information extraction, which was independently performed and cross-checked by 2 researchers. The extracted information included: (1) Basic study information such as first author, year of publication, patient characteristics (age, gender, disease severity, location of spinal involved segments, curve type, etc). (2) Biomechanical comparison results, including spatiotemporal characteristics data, stage kinematic data, mechanical characteristics data, and electromyographic data. Eligibility disagreements were initially resolved through discussion, and if disagreements persisted, a third reviewer made the final decision.

The sample size, mean, and standard deviation were directly extracted from the included studies to calculate the effect size (ES) and 95% confidence intervals (95% CI). When the raw data were presented as median and interquartile spacing, the mean and standard deviation were estimated and derived using the formulae provided by Luo et al[10] and Wan et al.[11] When the raw data were presented as mean and 95% CI, they were obtained from the mean and standard deviation calculator provided in the Cochrane Handbook. If the raw data were presented only as bar charts, the online conversion tool WebPlotDigitizer 4.5 was used to extract the data. If necessary, the authors of the studies were contacted to obtain additional data.

2.4. Literature quality evaluation

Considering that only observational studies were evaluated, a modified version[12] of a quality index for nonrandomized trials[13] was utilized. The modified nonrandomized trial quality index[12] was used to assess the level of quality of the included cross-sectional studies, see Supplementary attachment 2, Supplemental Digital Content, http://links.lww.com/MD/L7 for details. Items related to the assessment of intervention validity were removed from this modified measure (items 4, 8, 9, 13, 14, 17, 19, 23, 24, 26, and 27), resulting in 16 items across 3 dimensions: assessment report (items 1 to 3, 5 to 7, and 10), external validity (items 11 and 12), and internal validity (items 15, 16, 18, 20 to 22, and 25). The total score on the scale was 17 (items 5 was 2, and the remaining items were 1). The quality rating was categorized as follows: <10 points, low; 10–13 points, medium; >13 points, high. The quality evaluation of the literature was conducted independently by 2 researchers, with 1 researcher blinded to the title, journal, author, or author's affiliation of the literature. A final check was performed by both researchers, and any disagreements were resolved through discussion until a consensus was reached.

2.5. Statistical analysis

Data analysis was conducted using RevMan 5.4. Combined ES statistics were calculated using weighted mean difference and 95% CI, provided that the measurement instruments used were consistent across studies and the variables had consistent units. If not, standard mean difference and 95% CI were used instead. The effects were categorized according to Hopkins criteria[14] as follows: small ES (<0.2), small ES (0.2–0.6), medium ES (0.6–1.2), and large ES (>1.2). Interstudy heterogeneity was assessed using the χ^2 and quantitative evaluation was done using I^2 values. I^2 values of 50%, 50 to 75%, and > 75% indicated low, moderate, and high heterogeneity, respectively. A fixed-effects model was applied when heterogeneity was low ($P > .1$, $I^2 < 50\%$). If heterogeneity was high ($P \leq .1$, $I^2 \geq 50\%$), a random-effects model was used and a subgroup analysis was conducted to explore potential factors causing heterogeneity. Only observational studies were included in this study, and Furlan et al[15] provided levels of evidence to account for biomechanical bias associated with AIS disease. These levels of evidence were as follows: strong level of evidence (large ES and low heterogeneity), moderate level of evidence (moderate ES and low heterogeneity), limited level of evidence (small ES and low heterogeneity, or moderate/large ES and moderate heterogeneity), presence of controversy (high heterogeneity), and null evidence (including 0 within 95% CI). Funnel plots were used to assess publication bias when the major outcome indicator appeared in more than 8 publications. Subgroup analysis was conducted by dividing patients with AIS into different subgroups to investigate the effects of factors such as disease severity and lateral bending direction on deviation.

3. Results

3.1. Literature screening results

A total of 2534 papers were collected during the initial examination, following the search strategy. After stratification screening, 15 cross-sectional studies[15–29] were included, involving 377 patients with AIS. Figure 1 displays the findings of the literature screening process.

3.2. Basic characteristics and quality evaluation

The majority of patients with AIS had right thoracic curvature. However, the severity of scoliosis varied slightly among studies. Therefore, subgroup analysis was conducted based on the severity of scoliosis and the concave and convex side of scoliosis in patients. Table 1 presents the key characteristics of the included studies. A total of 15 publications[15–29] were included, with a quality score ranging from 11 to 15 and a mean score of 13.4, indicating moderate to high methodological quality. Please refer to Table 2 for more details.

3.3. Integrated results

3.3.1. Spatial and temporal characteristics indicators. The spatiotemporal characteristic indexes mainly included 4 indexes, including the step speed, step length, step frequency, and duration of the stance phase.

3.3.2. Step speed. A systematic review was conducted, including a total of 10 cross-sectional studies,[17,19,21,22,24–29] with a combined sample size of 301 patients diagnosed with AIS. Due to substantial heterogeneity among the studies ($I^2 = 75\%$, $P < .001$), a random-effects model was utilized. The patients with AIS were further categorized into different subgroups based on the range of Cobb angle reported in each study: mild to moderate group (Cobb angle 10 to 40°), moderate to severe group (Cobb angle ≥ 40°), and mild to moderate to severe full range group (Cobb angle ≥ 10°). The control groups consisted of healthy adolescents. The results indicated no statistically significant difference between any of the subgroups and the normal controls (ES = −0.21, 95% CI = −0.57–0.15, $P = .26$). Please refer to Figure 2 for more details.

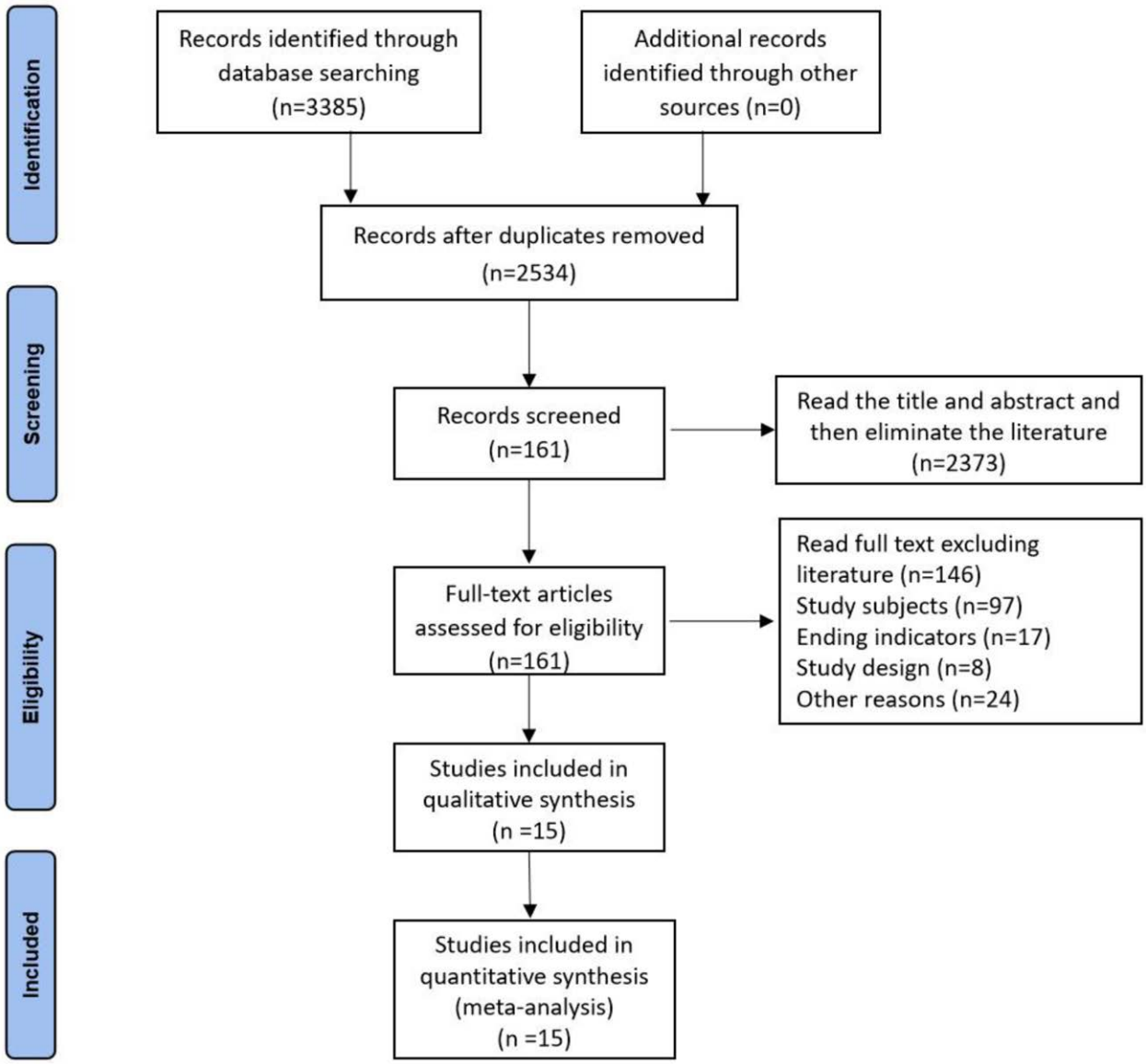

Figure 1. Flow chart of literature screening.

Table 1

Basic characteristics of the included literature.

Literature	Number	Age/year	Height/cm	Mass/kg	Cobb/°	Type
Chen et al[16]	19/15	16.6/16.8	–/–	–/–	22~67	–
Mahaudens et al[17]	12/12	13.2/12.9	156.0/158.0	41.2/46.4	10~30	–
Mahaudens et al[18]	41/13	15.0/16.0	160.9/164.3	49.2/54.7	10~50	Thoracic left lumbar right convexity (Lenke 5/6)
Yang et al[19]	20/20	14.9/14.4	161.6/160.9	59.2/53.3	11~34	–
Mahaudens et al[20]	13/13	14.0/–	157.0/–	48.5/–	15~40	Thoracolumbar left-sided curvature
Haber et al[21]	31/31	–/–	–/–	–/–	>5	–
Park et al[22]	39/30	15.1/14.8	155.2/154.9	45.6/44.7	13~65	Thoracic convexity and thoracolumbar convexity
Liu et al[23]	10/10	14.0/13.0	–/–	–/–	20~25	Right-sided curvature and left-sided curvature
Schmid et al[24]	14/15	15.2/14.1	166.0/162.0	55.6/54.2	9~71	–
Nadi et al[25]	5/5	–/–	158.0/153.0	41.2/35.6	25~37	Left-sided curvature and right-sided curvature
Wu et al[26]	16/16	14.9/14.8	154.7/154.9	41.7/44.7	42~63	Thoracic right-sided curve
Wu et al[27]	16/16	14.0/14.4	154.8/158.4	42.0/48.6	40~70	Thoracic spine right side bend
Zhu et al[28]	64/32	13.3/13.1	165.0/162.0	46.3/48.9	10~53	Thoracic right lumbar left side curvature
Garg et al[29]	20/20	15.25/16.40	148.13/151.60	42.45/44.36	75 ± 10.75	–
Pesenti et al[30]	57/25	15.2/16.1	162/160	51.4/52.4	45~100	Lenke 1/2

3.3.3. Step length. A total of 8 cross-sectional studies were included[16–19,21,24,26,27] with a total of 232 patients with AIS. A random-effects model was employed due to high heterogeneity between studies (I^2 = 82%, P < .001). The step characteristics were categorized into convex and concave spine (Convex, CX), concave spine (Concave, CA), and double scoliosis (i.e., S-shaped scoliosis) based on the convex versus concave side of the spine in AIS patients. The control group consisted of healthy adolescents, with average left and right side step lengths. The findings showed no significant difference in step length between the convex side of the spine group (ES = –0.59, 95% CI = –1.23–0.06, P = .08) and the double scoliosis group (ES = 0.62, 95% CI = –0.63–1.88, P = .33) compared to the normal control group. However, the step length of the concave side of the spine group in AIS patients was smaller than that of the normal control group (ES = –0.36, 95% CI = –0.71 to –0.01, P = .04), although the evidence supporting this was limited. Please refer to Figure 3 for more details.

3.3.4. Step frequency. A total of 11 cross-sectional studies, with a total of 301 patients with AIS, were included.[16–21,24–27,29] A random-effects model was employed due to high heterogeneity between studies (I^2 = 76%, P < .001). Patients with AIS were divided into different subgroups based on the range of Cobb angle mentioned in each study: mild to moderate group (Cobb angle 10° to 40°), moderate to severe group (Cobb angle ≥ 40°), and mild to moderate to severe full range group (Cobb angle ≥ 10°). The control groups consisted of healthy adolescents. The findings showed no significant difference between all subgroups and normal controls (ES = –0.73, 95% CI = –3.03–1.57, P = .53). Please refer to Figure 4 for more details.

3.3.5. Duration of the standing phase. A total of 7 cross-sectional studies were included,[16–20,22,29] comparing patients with AIS to healthy adolescents, with a total of 164 patients with AIS. A random-effects model was used due to high heterogeneity between studies (I^2 = 91%, P < .001). The results showed no significant difference in the standing phase duration profile between the 2 groups (ES = –0.18, 95% CI = –1.23–0.87, P = .74). Please refer to Figure 5 for further details.

3.3.6. Segmental kinematic indicators. The segmental kinematic indexes mainly included 6 indexes of gait pelvic coronal tilt, gait pelvic sagittal tilt, gait pelvic horizontal tilt, gait hip sagittal range of motion (ROM), gait knee sagittal ROM, and gait ankle sagittal ROM.

3.3.7. Gait pelvic coronal plane tilt. A total of 7 cross-sectional studies were included[17–20,22,24,30] that compared patients with AIS with healthy adolescents, resulting in a sample size of 196 patients with AIS. To account for the high heterogeneity between studies (I^2 = 90%, P < .001), a random-effects model was used. The findings showed a controversial, yet statistically significant, smaller pelvic coronal tilt in gait among AIS patients compared to controls (ES = –1.34, 95% CI = –2.41 to –0.27, P = .01). Please refer to Figure 6A for visual representation.

3.3.8. Gait pelvic sagittal tilt. A total of 7 cross-sectional studies were included,[17–20,22,24,30] comparing 196 patients with AIS to healthy adolescents. A random-effects model was used due to high heterogeneity between studies (I^2 = 75%, P < .001). The results showed no significant difference in gait pelvic sagittal tilt between the 2 groups (ES = –0.12, 95% CI = –0.58–0.34, P = .60). Please refer to Figure 6B for more details.

3.3.9. Gait pelvis horizontal plane tilt. In this study, a total of 196 patients with AIS were compared to healthy adolescents in 7 cross-sectional studies.[17–20,22,24,30] Due to high heterogeneity between the studies (I^2 = 59%, P = .02), a random-effects model was used. The results showed no significant difference in gait pelvic horizontal plane tilt between the 2 groups (ES = –0.05, 95% CI = –0.72–0.61, P = .88). Refer to Figure 6C for visualization.

3.3.10. Gait hip sagittal ROM. Four cross-sectional studies[18,20,23,25] were included in this analysis, comparing patients with AIS to healthy adolescents. A total of 69 patients with AIS were included. A random-effects model was used due to the high heterogeneity between the studies (I^2 = 91%, P < .001). The results showed no significant difference in gait hip sagittal ROM between the 2 groups (ES = 1.99, 95% CI = –3.35–7.33, P = .47). Please refer to Figure 7A for visual representation.

3.3.11. Gait knee sagittal ROM. A total of 4 cross-sectional studies were included[18,20,23,25] that compared patients with AIS to healthy adolescents, involving a total of 69 AIS patients. Since there was little heterogeneity among the studies (I^2 = 49%, P = .12), a fixed-effects model was used. The findings indicated that the sagittal ROM of the knee joint during gait was significantly smaller in AIS patients compared to controls (ES = –5.22, 95% CI = –7.51 to –2.94, P <. 001), providing strong evidence. Please refer to Figure 7B for visual representation.

3.3.12. Gait ankle sagittal ROM. Four cross-sectional studies were included in this analysis,[18,20,23,25] comparing patients with AIS to healthy adolescents. A total of 69 patients with AIS were included. Since there was minimal heterogeneity across the studies (I^2 = 0, P = .65), a fixed-effects model was used. The results showed that patients with AIS had significantly smaller

Table 2

Quality evaluation of the included literature.

Literature	Assessment report							External validity			Internal validity							Score	Grade
	ITEM 1	ITEM 2	ITEM 3	ITEM 5	ITEM 6	ITEM 7	ITEM 10	ITEM 11	ITEM 12	ITEM 15	ITEM 16	ITEM 18	ITEM 20	ITEM 21	ITEM 22	ITEM 25		
Chen et al[16]	1	1	1	2	1	1	1	1	1	0	1	1	1	0	0	1	14	High
Mahaudens et al[17]	1	1	1	1	1	1	1	0	1	0	1	1	1	0	0	1	12	Medium
Mahaudens et al[18]	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	13	Medium
Yang et al[19]	1	1	1	2	1	1	1	0	1	0	1	1	1	1	1	1	15	High
Mahaudens et al[20]	1	1	1	1	1	1	0	0	1	0	1	1	1	1	0	0	11	Medium
Haber et al[21]	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	14	High
Park et al[22]	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	14	High
Liu et al[23]	1	1	1	1	1	1	1	0	1	0	1	1	1	0	0	1	12	Medium
Schmid et al[24]	1	1	1	1	1	1	1	0	1	0	1	1	1	0	0	1	12	Medium
Nadi et al[25]	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	13	Medium
Wu et al[26]	1	1	1	2	1	1	1	0	1	0	1	1	1	0	1	1	14	High
Wu et al[27]	1	1	1	2	1	1	1	0	1	0	1	1	1	1	0	1	14	High
Zhu et al[28]	1	1	1	2	1	1	1	1	0	0	1	1	1	1	1	1	15	High
Garg et al[29]	1	1	1	2	1	1	1	0	0	0	1	1	1	1	1	1	14	High
Pesenti et al[30]	1	1	1	2	1	1	1	0	0	0	1	1	1	1	1	1	14	High

ankle sagittal ROM in gait compared to controls (ES = −3.58, 95% CI = −5.93 to −1.22, P = .003), indicating strong evidence. Please refer to Figure 7C for a visual representation.

3.3.13. Mechanical characteristics indicators. The force indexes mainly included 2 indexes: knee extension moment and ankle plantarflexion moment in gait.

3.3.14. Hip extension moment in gait. Two cross-sectional studies were included,[25,26] involving a total of 21 patients with AIS. The hip extension moments were categorized into 2 groups based on the convex and concave sides of the spine in AIS patients. The control groups consisted of healthy adolescents, with the left and right hip extension moments averaged. The findings indicated that the hip extension moment on the convex side and the hip extension moment on the concave side of the spine were smaller in AIS patients compared to the normal control group. Due to the limited available literature, a meta-analysis could not be performed.

3.3.15. Plantarflexion moment of the ankle joint in gait. Two cross-sectional studies were included,[25,26] involving a total of 21 patients with AIS. The ankle plantarflexion moments were categorized into convex and concave ankle plantarflexion moments, based on the sides of the spine in AIS patients. The control group consisted of healthy adolescents, with an average of left and right ankle plantarflexion moments. The findings indicated that the ankle plantarflexion moment on the convex side of the spine and the plantarflexion moment on the concave side of the spine were smaller in AIS patients compared to the normal control group. Due to limited available literature, meta-analysis was not conducted.

3.3.16. Electromyographic indicators. The electromyographic indices included 7 different indices to measure the duration of electromyographic activity in various muscles during gait. These muscles include the gluteus medius, lumbar square, erector spinae, rectus abdominis, anterior tibialis, gastrocnemius, and semitendinosus. A total of 3 cross-sectional studies were included in the analysis,[17,18,20] involving 66 patients with AIS. The heterogeneity between the studies was small for the duration of electromyographic activity in the gluteus medius and square lumbar muscles, so a fixed-effect model was used. However, there was larger heterogeneity for the duration of electromyographic activity in the erector spinae muscles (I^2 = 57%, P = .1), so a random-effect model was applied. The findings indicated that the duration of EMG activity in the gluteus medius (ES = 7.65, 95% CI = 5.33–9.96, P < .001) and lumbar square (ES = 10.73, 95% CI = 6.97–14.49, P < .001) was significantly greater in patients with AIS compared to normal controls, with strong evidence. Similarly, the duration of EMG activity in the erector spinae muscle (ES = 14.35, 95% CI = 6.94–21.76, P < .001) was also greater in patients with AIS, but with limited evidence. Figure 8A–C provide visual representations of these findings. Additionally, 2 cross-sectional studies[18,20] were included for indicators of the duration of electromyographic activity in the rectus abdominis, anterior tibialis, gastrocnemius, and semitendinosus muscles. These studies, involving 54 patients with AIS, showed that the duration of electromyographic activity in these muscles was significantly greater in patients with AIS compared to normal controls. Due to the limited available literature, a meta-analysis was not conducted.

3.3.17. Publish offset. Among the included studies, funnel plots and system analyses were performed for some of the index studies with a literature number ≥ 8. Figure 9A–C shows the funnel plots of the speed, step length, and step frequency. It can be observed that the majority of the studies investigating

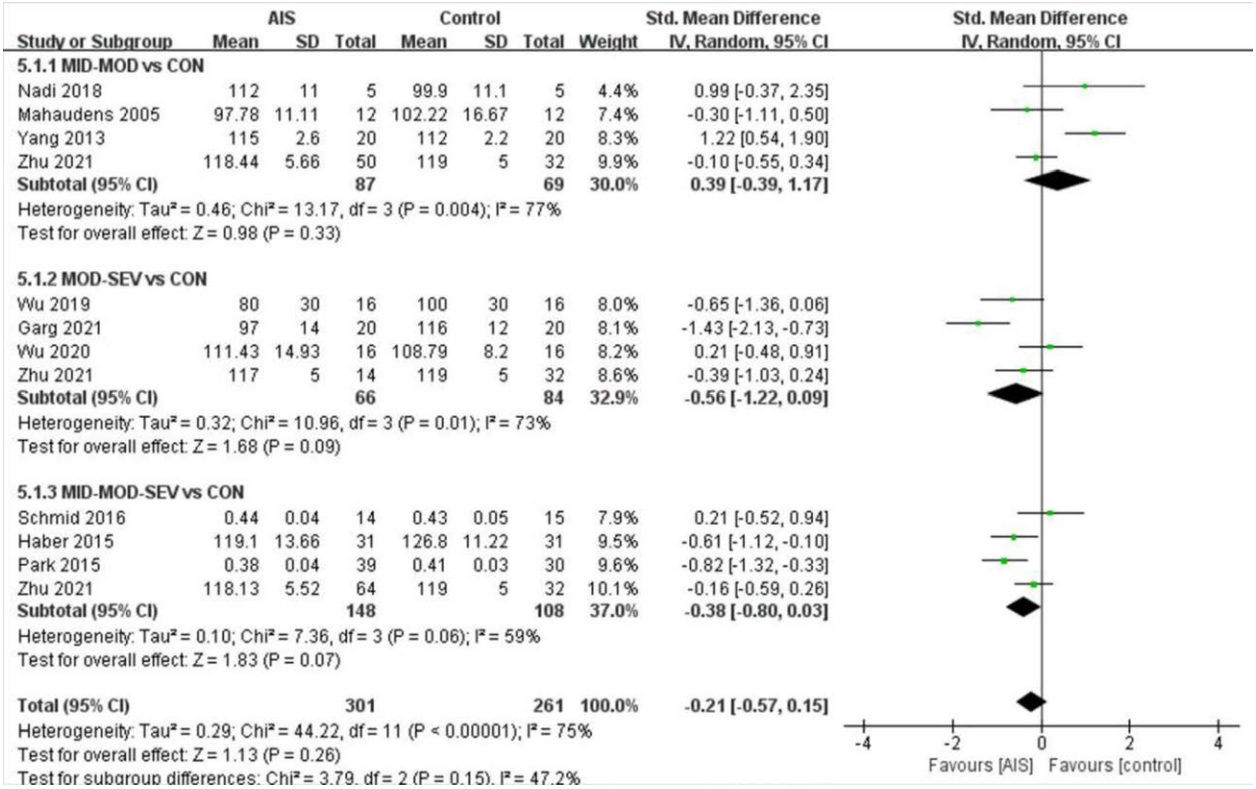

Figure 2. Step speed comparison.

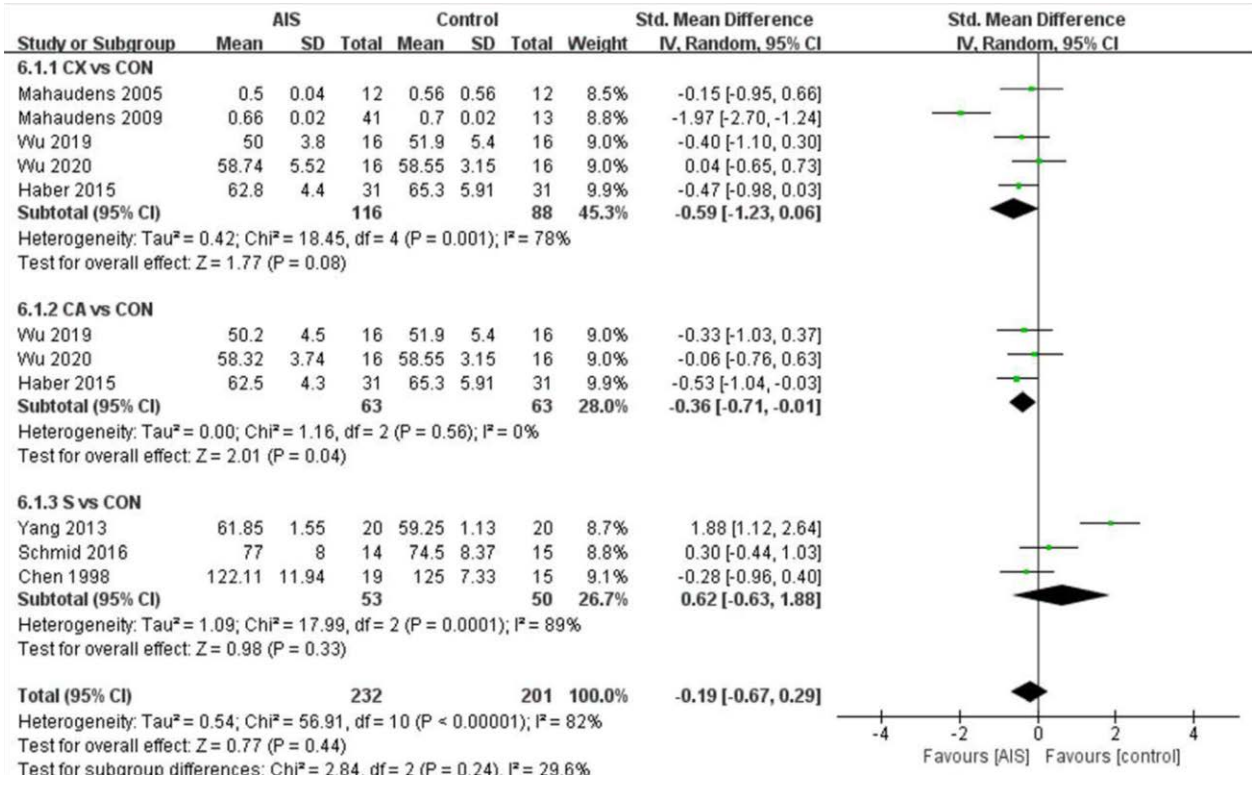

Figure 3. Step lengths comparison.

these indices were distributed within the 95% CI of the funnel plot. These results suggest that the distributions are essentially vertically symmetric, indicating an acceptable level of publication bias.

4. Discussion

Considering the potential causes of idiopathic scoliosis, such as brain asymmetry[31,32] or abnormalities in the development of

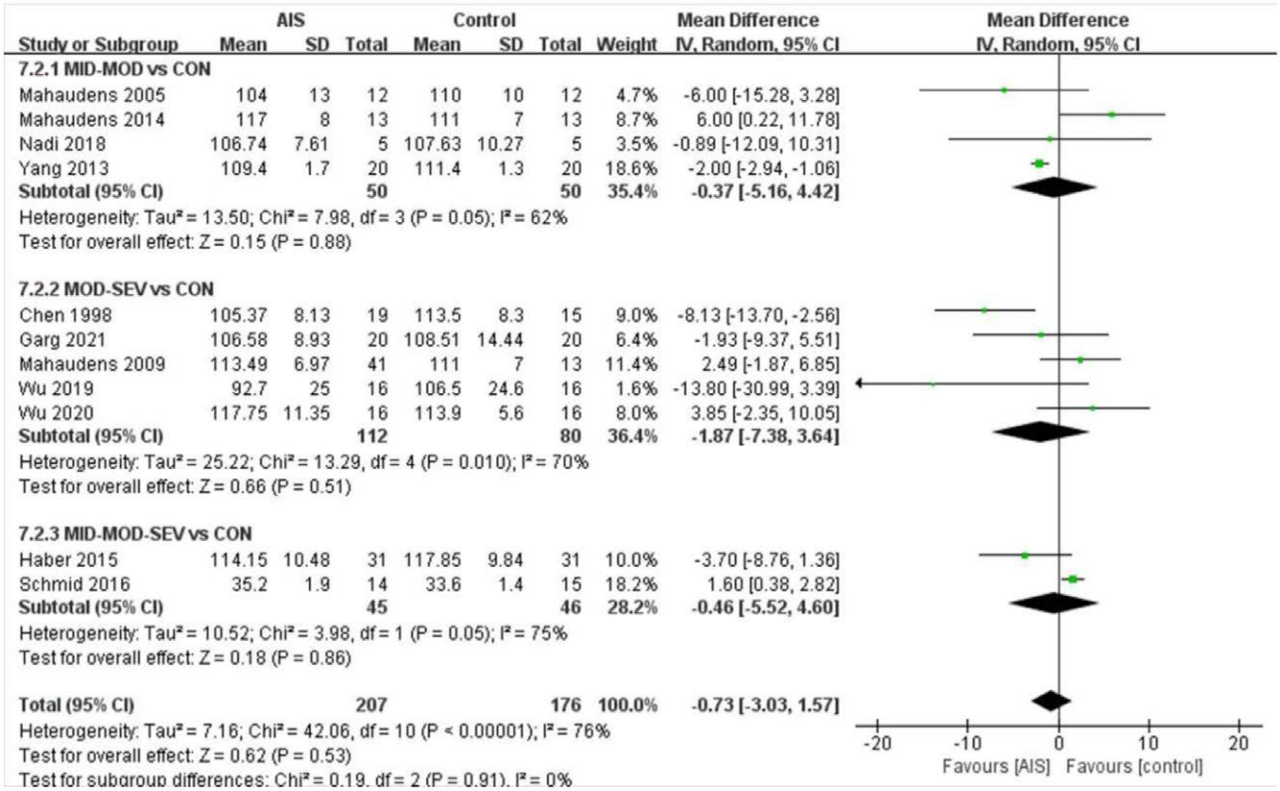

Figure 4. Step frequency comparison.

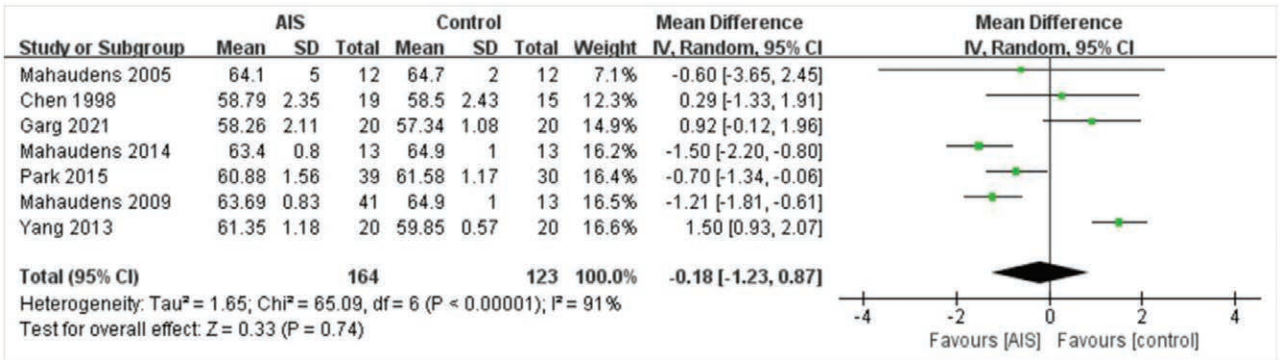

Figure 5. Comparison of the duration of the standing phase.

the central nervous system,[33] it is reasonable to assume that these factors may affect the locomotor system and alter stance. Scoliosis alters the connective structure of the spine, impacting mobility and balance, and potentially leading to an abnormal walking pattern. Biomechanical analysis is crucial for understanding the underlying causes and progression of idiopathic scoliosis.[34,35] Abnormal biomechanical changes in the spine and lower extremities during walking, particularly in adolescents experiencing rapid growth, are believed to be significant factors in triggering and accelerating the progression of AIS.[36] Numerous studies have examined gait characteristics in AIS patients, but the results have been inconsistent due to various factors, including the severity and type of scoliosis curve, gender, and other variables. The impact of scoliosis on spatiotemporal and kinematic parameters lacks robust evidence.[37] A total of 15 papers were included in this meta-analysis study, following the recommendations by Furlan et al[15] for rating the quality level of evidence. The study findings demonstrated that patients with AIS exhibited biomechanical differences during walking compared to normal controls, which were observed in 4 aspects: spatiotemporal characteristics, segmental kinematics, kinematic characteristics, and electromyographic signal characteristics. The quality of evidence for the relevant indicators ranged from controversial to strong.

Gait assessment is a valuable tool for evaluating a patient's dynamic balance response. It plays a crucial role in diagnosing gait disorders, developing treatment plans, and monitoring disease progression.[38] Gait analysis can be categorized into qualitative and quantitative analyses. Qualitative analysis involves subjective human observation and questioning, and is commonly used for patients with abnormal gait patterns, such as stroke patients with hemiplegia. However, the results of qualitative analysis often lack objectivity. On the other hand, quantitative analysis relies on advanced techniques such as 3D gait analysis, which includes the use of marker points, camera equipment, force plates, body surface electromyography, and data analysis systems. These techniques offer the advantages of objectivity and reproducibility.[39] The chosen gait analysis technique for

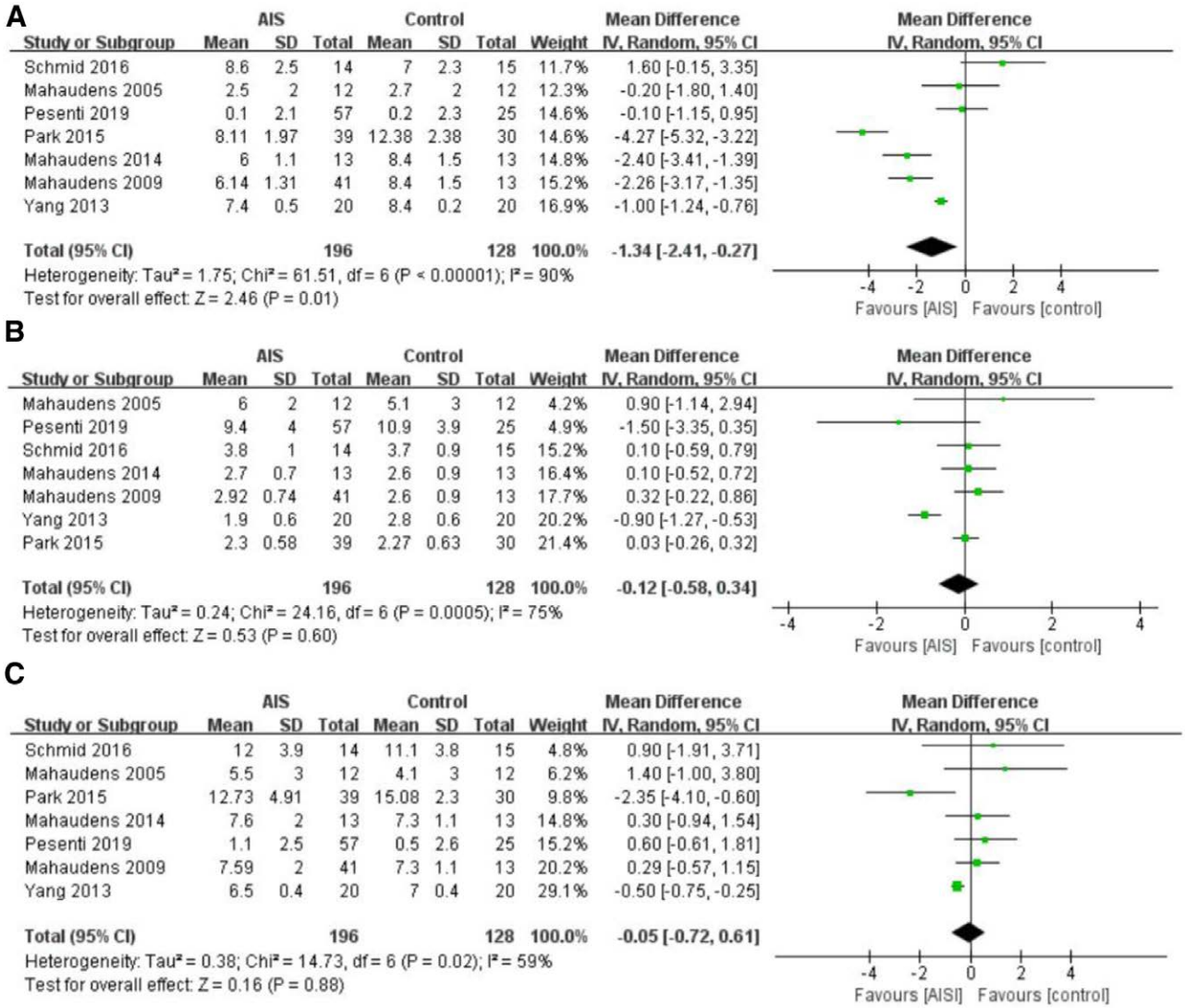

Figure 6. (A) Comparison of gait pelvic coronal tilt. (B) Comparison of gait pelvic sagittal tilt. (C) Comparison of horizontal pelvic plane tilt for gait.

this study was quantitative. The selected quantitative gait assessment indexes mainly focused on spatiotemporal parameters (such as stride length, stride speed, stride frequency, and stance phase time), segmental kinematic parameters (including changes in pelvis tilt and ROM of trunk and limbs during gait), kinetic parameters (magnitude of each moment of lower limb joints), and electromyographic activity parameters. Scoliosis patients exhibit a slightly different gait pattern compared to their healthy counterparts, characterized by shorter stride length, slower stride speed, reduced stride frequency, reduced ROM and torque of lower limb joints, abnormal myoelectric signals, and reduced mechanical efficiency of muscles.[40,41] Pesenti et al[42] found that patients with AIS had a reduced anterior trunk inclination and abnormal transverse planes during walking, with shoulder line orientation to the left appearing to be the most abnormal gait parameter and the degree of gait abnormality being independent of radiographic measurements, one of the largest gait analysis series to study patients with AIS.[30] However, Nadi et al[25] found no significant effect of scoliosis on the kinematic and kinetic characteristics of gait, and no characteristic differences were observed between the convex and concave sides of the spine in patients. In contrast, the present study discovered that patients with AIS had a lower coronal tilt of the pelvis during gait compared to normal healthy adolescents. However, the level of evidence for this finding is considered "controversial" due to the high heterogeneity of this indicator. It is hypothesized that this difference may be attributed to increased stiffness caused by changes in the 3D structure of the pelvis,[43] or it could serve as a compensatory mechanism for postural imbalances and pain prevention in patients. Allam et al[44] observed that coronal deformities in patients with AIS result in alterations in sagittal parameters. While scoliosis deformities predominantly manifest in the coronal plane of the spine, adjustments in the sagittal posture of both lower extremities also occur when the patient's heel makes contact with the ground during walking. These adjustments lead to changes in joint loading. The findings of this study may be influenced by the broader inclusion criteria, encompassing patients with varying degrees of scoliosis and scoliosis sites. Meanwhile, Karam et al[2] study demonstrated that axial deformity in scoliosis cannot be determined exclusively by coronal and sagittal deformities, suggesting enhanced use of 3D assessment in AIS to improve the credibility of the findings. Chow et al[45] conducted a study on patients with AIS who carried backpacks weighing 0%, 7.5%, 10%, 12.5%, and 15% of their body weight. The study aimed to measure pelvic and hip mobility in 3 planes, as well as knee and ankle mobility in the sagittal plane. The results showed that there were no significant differences in these parameters when compared to healthy controls. This suggests that patients with scoliosis may exhibit a functional compensatory mechanism, where they maintain a functional

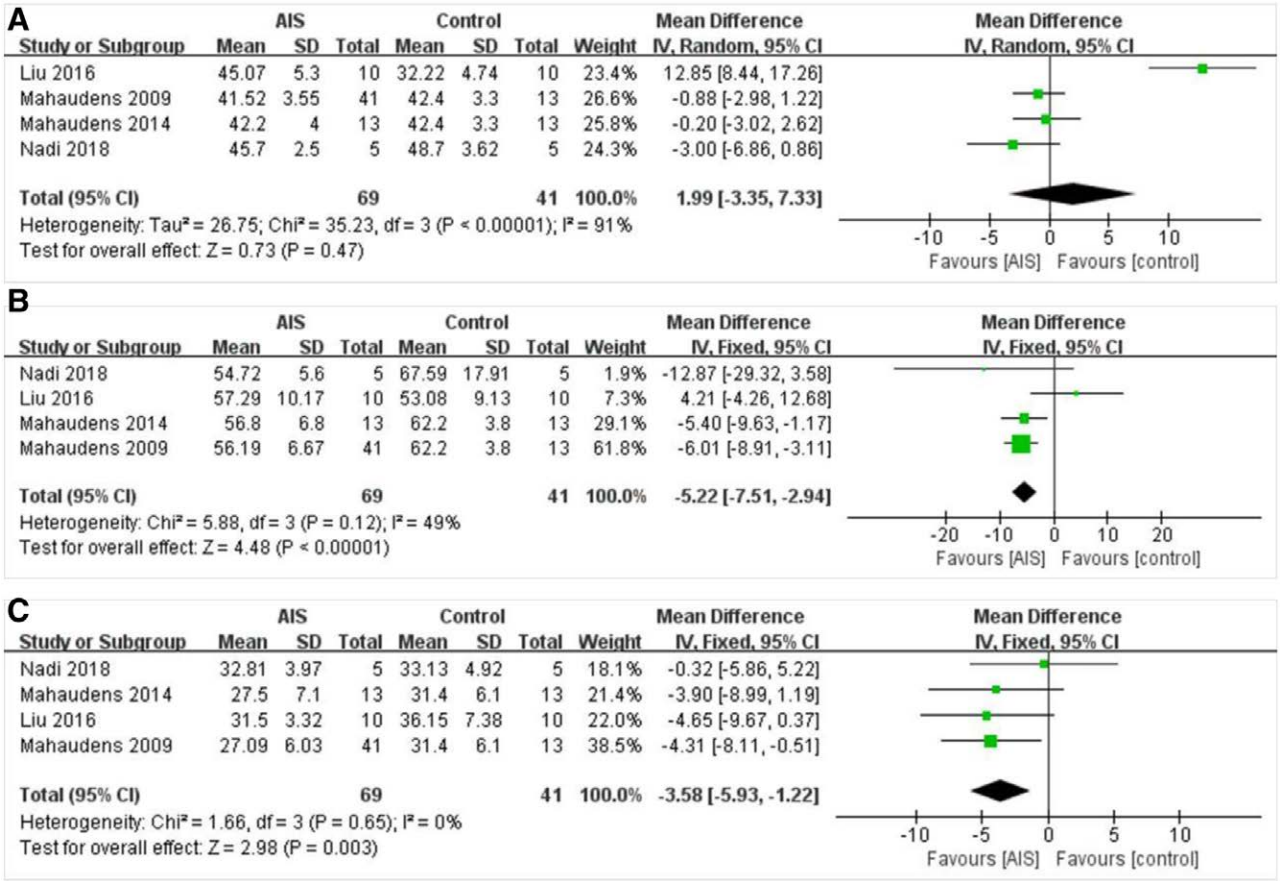

Figure 7. (A) Comparison of sagittal ROM of the gait hip joint. (B) Comparison of sagittal ROM of gait knee joint. (C) Comparison of sagittal ROM of the gait ankle joint. ROM = range of motion.

horizontal position of the pelvis and compensate for the structural tilt of the spine and pelvis by adjusting their center of gravity and muscle contraction. The abnormal balance parameters observed in patients with AIS are believed to be a result of 3D spinal deformities. This leads to a compensatory mechanism where balance is maintained through continuous muscle contraction, which in turn worsens the progression of scoliosis disease. However, it has also been suggested[46] that visual and proprioceptive functional impairments in patients with AIS may actually be the cause of scoliosis. Byl et al[47] hypothesized that defects in the vestibular system, leading to muscle imbalance in the paravertebral muscles on both sides of the spine, may be associated with the development of AIS. Subsequently, asymmetry of the lateral semicircular canal in the vestibular system was also observed in a population of patients with idiopathic scoliosis. It was then concluded that abnormalities in the vestibular system might be a cause of AIS and could even develop before birth.[48] However, it has also been shown that proprioceptors play a crucial role in regulating spinal alignment and maintaining the structural alignment of the spine by influencing Runx3 and Egr3 transcription factors in genetic mice.[49] The presence of these disorders alone in patients with idiopathic scoliosis does not directly indicate that postural imbalance necessarily causes scoliosis deformity. What is clear, however, is that a combination of factors affects sensory input in patients with AIS, and the patient's nociceptors seem to make different balance decisions than normal in an attempt to maintain the functional balance of the trunk. According to Modi et al[50] proposed a mechanism for adjusting spinal balance, suggesting that the angle of scoliosis in patients with AIS may decrease or stabilize if the spine is rebalanced. Conversely, scoliosis may progress if the spine fails to rebalance. Hence, it is advisable to focus on providing rehabilitation exercises and treatment aimed at restoring spinal balance in adolescent children with AIS during accelerated growth. This approach can help prevent and control the occurrence and progression of scoliosis disease.

The trunk, which makes up about 50% of the body weight, is significantly affected by deformed spinal curves. These changes in the distribution of trunk and body mass have a direct impact on one's movement, particularly the pelvis.[51] The joints of the human body interact with each other. When the joints are unstable, the body compensates by using trunk force to correct itself. This can lead to the development of poor posture, causing an imbalance in weight-bearing force on the lower extremities and a shift in the overall center of gravity. Consequently, the movement trajectory may deviate significantly.[52] Patients with AIS frequently exhibit kinematic abnormalities during walking, which can be attributed to the influence of vision, vestibular sensation, and somato proprioception.[53] A recent study discovered a correlation between the severity of scoliosis and a decrease in stride length among AIS patients.[54] In this study, subgroup analyses were conducted on selected spatiotemporal characteristic indices. The results indicated no significant differences in step speed, step length, and step frequency between patients with AIS with varying degrees or sites of scoliosis and normal controls. However, subgroup analysis revealed that patients with AIS exhibited reduced step length on the concave side of the spine, although the quality of evidence supporting this finding was limited. This suggests that the concave and convex sides may have some impact on the outcome, but further investigation is required to understand the relationship between the temporal and spatial characteristics of AIS patients and the direction of scoliosis. The study also found strong-quality

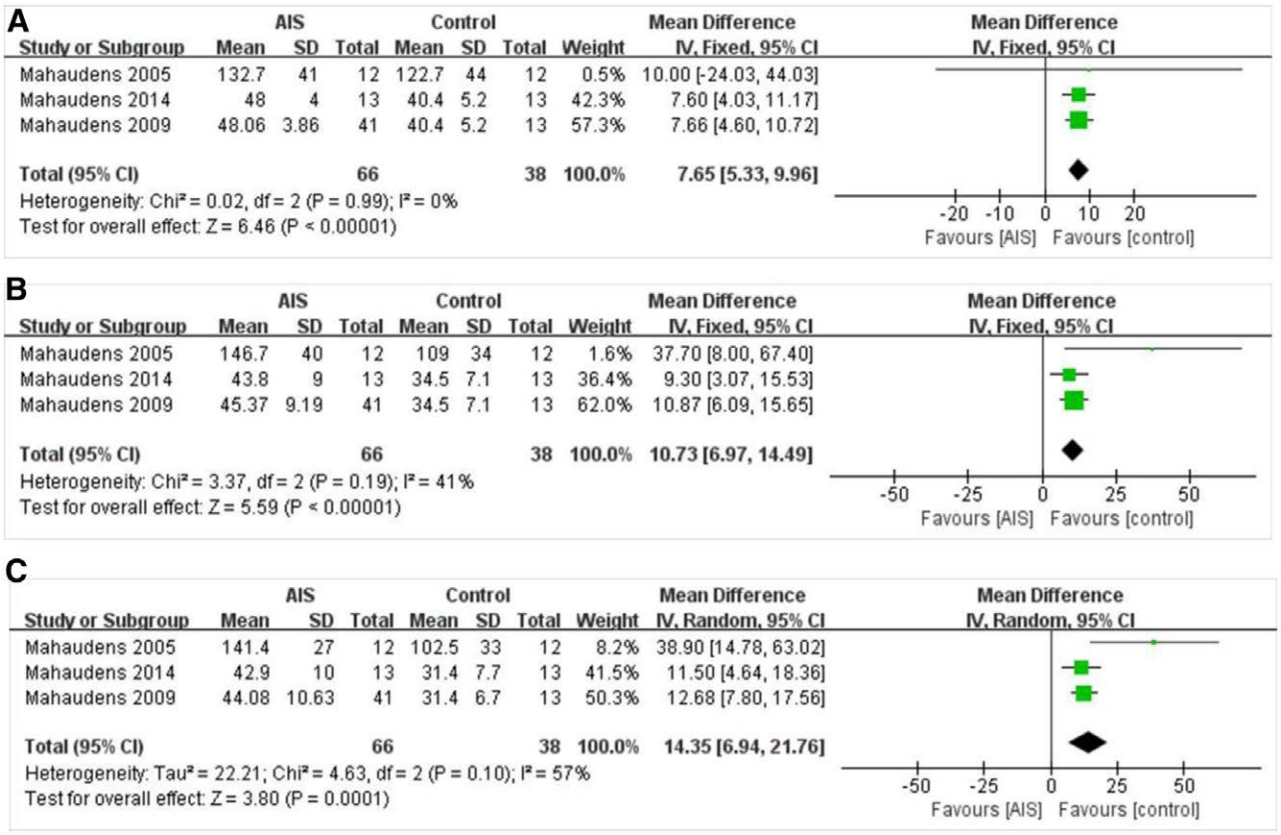

Figure 8. (A) Comparison of the duration of electromyographic activity of the gluteus medius muscle. (B) Comparison of the duration of EMG activity in the lumbar square muscle. (C) Comparison of the duration of EMG activity in the erector spinae muscle. EMG = electromyogram.

evidence suggesting prolonged duration of electromyographic activity in the gluteus medius, lumbar square, and erector spinae muscles in patients with AIS. However, the quality of evidence for the erector spinae muscle's duration of electromyographic activity is limited due to high heterogeneity. Garg et al[29] and Mahaudens et al[20] compared patients with AIS, patients with congenital scoliosis, and healthy adolescents. They found that there was a prolonged duration of EMG activity in the gluteus medius, lumbar square, and erector spinae muscles. Normally, the erector spinae and lumbar square muscles stabilize the spine and pelvis during walking. They provide opposing forces to counteract the forward rotation of the upper trunk during the weight-bearing response period and also provide deceleration forces for the contralateral pelvis and spine.[55] In patients with scoliosis, abnormal changes in electromyographic activity lead to stiffness in the lumbar spine and pelvis. This, in turn, alters the position of the body's center of gravity, resulting in a failure of the "inverted pendulum" mechanism of movement during gait.[56] In addition, higher load accumulation has been observed in the convex segments of the spine in patients with AIS compared to other segments during movement.[57] Additionally, AIS patients experience a progressive increase in energy costs from the ankle to the knee and hip joints.[58] As a result, AIS patients need to exert more energy for habitual movement compared to healthy individuals. The biomechanics of movement and body posture contribute to the asymmetry in orientation, which can further lead to stiffness in spinal deformity or prolonged activation of muscles such as the lumbar spine and pelvis. Some of the strong levels of evidence suggest it reduced sagittal plane mobility in the knee and ankle joints in patients with AIS. It is suggested that the reduced ROM in the knees and ankles on both sides of the body in patients with AIS is believed to be linked to stiff spinal deformity and asymmetric muscle activity. The structural deformity of the spine affects the pelvis, which in turn affects hip motion. Syczewska et al[40] found that the deformity on the right side of AIS had a more pronounced impact on the hip joint, resulting in a lower ROM. However, this study did not find a significant difference in gait hip sagittal plane mobility between AIS patients and healthy subjects. Possibly because most of the current research in this area does not break down scoliosis by the concave and convex sides of the spine, but different scoliosis types and orientations lead to the formation of different compensatory patterns in the pelvis and proximal spine. Consequently, the measured data metrics in these studies might obscure the inherent characteristics of scoliosis. To ensure the rapid development of the field, it is crucial to establish and adhere to uniform standards in future research.

Overall, scoliosis of the spine has a significant impact on various aspects of gait, including spatiotemporal kinematics, segmental kinematics, mechanical characteristics, and electromyographic parameters. These biomechanical changes are closely related to the development and progression of AIS disease. Therefore, in clinical practice, it is essential for clinicians to carefully evaluate and analyze the abnormal gait patterns of patients with scoliosis, taking into account the individual patient's condition. This evaluation can help guide the appropriate rehabilitation treatment for scoliosis.

4.1. Limitations

The study has some limitations in evaluating the strength of the evidence. The quality of the evidence for certain indicator characteristics was not high, possibly due to the significant heterogeneity among studies. There was limited included literature specific to each indicator, and some studies had

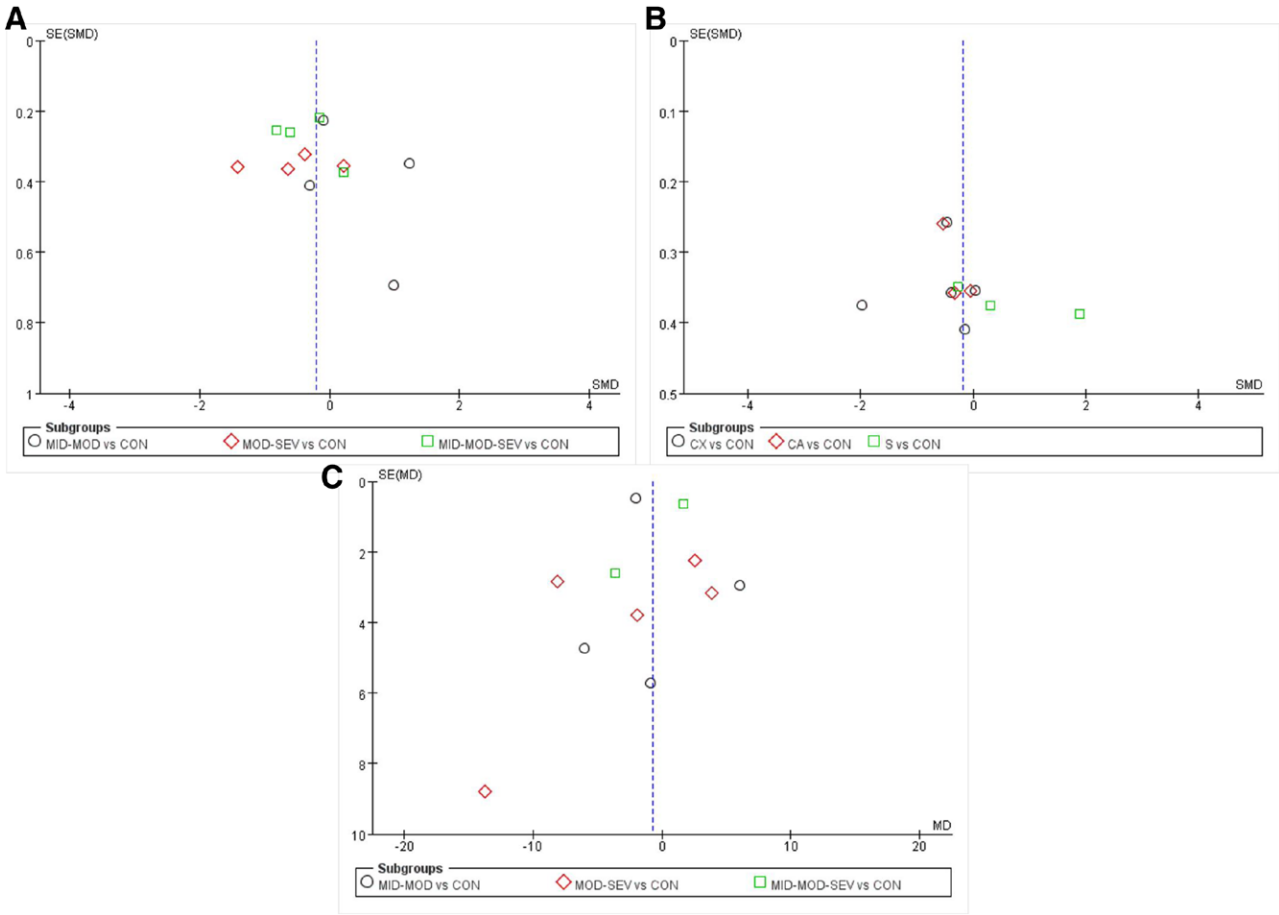

Figure 9. (A–C) are the funnel plots of step speed, step length, and step frequency, respectively.

small sample sizes. The included studies were cross-sectional, leading to inevitable selection and measurement bias. Most studies were not rater-blinded, resulting in some blinding bias. Additionally, the indicators did not consider the type of scoliosis, and differences in orientation and concave/convex sides could potentially impact the study results. Averaging some data may also mask biomechanical differences unique to patients with AIS. Furthermore, the literature search was limited to English and Chinese literature, which further contributed to the limitations.

4.2. Prospects

The type of scoliosis is complex and there is variation in the condition of the patients included in each study. Additionally, many of the study indicators were not subdivided according to the severity of scoliosis and the concave and convex sides of scoliosis. Therefore, the lack of uniformity in the description and classification of AIS across studies is a significant source of heterogeneity. Future studies should adopt a standard scoliosis classification system. Furthermore, incorporating biomechanical mechanism analysis as an assessment tool for AIS and even evaluation indexes will enhance the measurement method and assessment system of AIS. This can be used for guiding AIS treatment and developing individualized scoliosis rehabilitation intervention programs, which is crucial for both scientific research and clinical practice in this field.

5. Conclusion

This review examines the characteristic biomechanical changes observed in patients with AIS during walking. It was found that during walking, AIS patients experienced a decrease in pelvic coronal plane tilt, as well as reduced sagittal plane mobility in both the knee and ankle joints. Additionally, AIS patients exhibited a decrease in knee extension moment and ankle plantarflexion moment, and a prolonged duration of electromyographic activity in the gluteus medius, lumbar square, and erector spinae muscles. Subgroup analysis revealed that the step length of the concave side of the spine was smaller in AIS patients compared to normal controls. Further comprehensive studies are required in the future to analyze the biomechanical and electromyographic differences among different degrees and types of scoliosis, as well as the differences between the concave and convex sides of scoliosis during walking.

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Funding acquisition: Xiaobing Luo.
Project administration: Xiaobing Luo.
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