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Spatiotemporal and kinematic gait changes in flexible flatfoot: a systematic review and meta-analysis

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Abstract

Objectives Foot postural alignment is linked to changes in gait patterns. This review aimed to compare spatiotemporal and kinematic parameters of the lower extremities in individuals with and without flexible flatfoot.

Methods Under PRISMA guidelines, a systematic review and meta-analysis were conducted by searching PubMed, Scopus, Web of Science, and Google Scholar databases for original and peer-reviewed articles with selected keywords from inception to November 2024. The quality of the included studies was assessed using the Joanna Briggs Institute checklist. Statistical analysis was conducted with Comprehensive Meta-Analysis software version 3. To evaluate data heterogeneity, the Q-test and I^2 statistic were applied. Egger's test was used to assess publication bias.

Results After searching the mentioned databases, 5309 articles were found. Finally, sixteen articles were included in the current review. A significant difference was found between the two groups in ankle inversion (effect size; 0.291, 95% CI = 0.053_0.053, P = 0.017), eversion (effect size; -0.568, 95% CI= -0.784_-0.352, P = 0.001), and hip flexion (effect size; -0.348, 95% CI= -0.576_-0.120, P = 0.003). Also, stride length (effect size; 0.658, 95% CI = 0.184_1.133, P = 0.007) and gait speed (effect size; 0.447, 95% CI = 0.120_0.774, P = 0.007) significantly differed between the two groups.

Conclusion This study indicated that subjects with flatfoot exhibited alterations in the inversion, eversion, hip flexion, stride length, and walking speed compared to neutral foot participants and demonstrated a distinct gait pattern throughout the entire gait cycle. Health specialists are advised to consider these findings when prescribing prevention and rehabilitation programs for musculoskeletal deformities in individuals with flexible flatfoot.

Keywords Biomechanics, Flatfoot, Gait, Meta-analysis

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Introduction

Since the foot is part of a closed kinetic chain, any malalignment in the foot can affect and be transferred to the upper parts of the lower limb [1]. The collapse of the foot's medial longitudinal arch (MLA) causes overpronation of the subtalar joint, rearfoot eversion, and dorsiflexion with forefoot abduction in pes planus, also known as flatfoot [2, 3]. It has been shown that malalignment of the lower limb axis may lead to patellofemoral joint dysfunction and anterior cruciate ligament injury [4]. Also, It was demonstrated a stronger association of flatfoot with male gender, age groups 3 to 5 years and 11 to 17 years, Asian race, and obesity [5]. Furthermore, flatfoot, can be evaluated through a combination of clinical assessments, observational analysis, and imaging techniques to determine the severity and functional impact of the condition. Clinically, the Foot Posture Index is widely used to assess static foot alignment, providing a reliable measure of pronation and supination [6]. Additionally, the navicular drop test evaluates the degree of arch collapse by measuring the difference in navicular height from a seated to a standing position, reflecting midfoot mobility with high inter- and intra-rater reliability [7]. The arch height index (AHI) is also a common tool for assessing medial longitudinal arch integrity with an ICC 0.76 [8]. Imaging modalities like standard standing X-rays are commonly utilized, with 3D CT scans employed as supplementary imaging when required [9]. The deformity of flatfoot may be associated with the shortening of specific muscles and connective tissues, including the posterior tibialis, iliotibial band, and adductors of the hip, and the weakening of other muscles, such as the gastrocnemius, anterior tibialis, and external rotators of the hip [10]. We divide this deformity into two types: flexible flatfoot and rigid flatfoot [11]. Research indicates that individuals with flexible flatfoot experience changes in muscles and ligaments, leading to deviations from their natural foot structure, a reduction in the foot arch, and various degrees of subluxation in the midfoot bones [12]. Further findings from the static examination revealed a stretched lower back, knee valgus, internal rotation of the hips and tibia, and an anterior pelvic tilt [13, 14].

Based on Spatiotemporal analysis, some researchers recognized differences among flatfoot subjects compared to neutral ones. Some studies demonstrated notable differences, including a reduced lateral-medial range during the terminal stance phase of gait, an increased center of pressure excursion velocity in terminal stance, and distinct plantar pressure patterns [15, 16]. In another study, it was stated that participants with symptomatic flatfoot exhibited greater forefoot abduction during the entire stance phase compared to those in asymptomatic groups [17]. Musculoskeletal injuries may be caused by improper foot posture [18], irregular foot motion when walking, and changed motion patterns in the lower limbs [15]. Some research has shown that during gait patterns, participants with cavus foot exhibit less motion than those with flatfoot [19], whereas those with flatfoot exhibit more motion compared to neutral foot subjects [20]. As shown earlier, these changes can expose improper biomechanical factors that impact the appearance of injuries across the lower limb [18]. Also, these injuries can also happen because flatfoot limits foot movement, reducing the ability to absorb and spread out impact forces [21]. Additionally, researchers have stated that the final 20% of the stance phase exhibited a substantially higher rearfoot inversion and adduction motion in flatfoot subjects [22], and there was a positive correlation between the rearfoot peak eversion of the subjects and the initial half of the stance phase [23].

Despite the research, contradictory findings have been reported in some studies. For example, in a study, a decrease in dorsiflexion and internal rotation at the ankle was shown [20]. In contrast, other studies reported increased dorsiflexion [24] and internal rotation [25]. Additionally, the reduction in extension, abduction, and external rotation in the knee and hip [20] was in contrast to studies that showed an increase in extension and external rotation [26] and an increase in abduction and external rotation of the hip and knee [27]. However, some studies reported no significant difference in the kinematics of the ankle and hip in three planes of motion between the two groups [28, 29]. Although the importance of kinematic and spatiotemporal parameters in understanding movement disorders is increasingly recognized, few studies have systematically analyzed these factors to compare individuals with flexible flatfoot to healthy controls. A more robust and integrated approach is needed to provide a clearer picture of the biomechanical differences between the two groups. Moreover, understanding the biomechanical changes caused by flatfoot at different levels of movement is essential because joint mechanics have been altered. Therefore, the present study compares the lower extremities' spatiotemporal and kinematics parameters in individuals with and without flatfoot.

Methodology

Search strategy

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [30]. All relevant articles were extracted using the search approach. Using a mix of phrases related to "lower extremity," "lower limb," "biomechanics," "flatfoot," and "kinematics," we conducted a systematic search throughout Scopus, Web of Science, and PubMed from the database's inception until November 2024 to find pertinent papers. Google Scholar was also looked up. The references of pertinent papers were also carefully screened by two independent reviewers to see more possibly relevant literature.

Search keyword

For this research, the following keyword combinations were used with the help of AND and OR operators as follows: (“Pes planus” OR “pes cavus” OR “pes planovalgus” OR “high arch* foot” OR “low arch* foot” OR “foot arch” OR “medial longitudinal arch” OR “foot posture” OR “foot structure” OR pronat* OR supinat* OR evert* OR invert* OR “flat*foot” OR “Flat*feet” OR “foot alignment” OR “Convex Foot” OR “Convex Pes Valgus” OR “Rocker-Bottom Foot” OR Splayfoot OR “Talipes Calcaneovalgus” OR “Talipes Valgus” OR “Vertical Talus” OR “Calcaneal Valgus” OR “Calcaneal Varus” OR Calcaneo*valgus OR Calcaneo*varus) AND (Kinematics or kinetics OR Biomechanics OR “human movement analysis” OR “motion analysis” OR “lower limb motion” OR “Force plate*”(AND (Thigh OR Shank OR hip OR knee OR ankle OR foot OR feet OR “lower extremit*” OR “lower limb*” OR “lower-limb*” OR “lower-extremit*”).

Eligibility criteria

The review includes studies with a cross-sectional or case-control design. It compares two groups: those with flatfoot (experimental group) and those without (control group), using 3D kinematic analysis to assess gait mechanics. The research examines the differences in kinematics and spatiotemporal gait parameters between individuals with and without flatfoot. Exclusion criteria were studies that relied on qualitative methods to assess kinematics parameters, studies in which injury or medical conditions can affect participants’ ability to walk, and measuring another movement task other than walking. Also, studies related to fatigue protocols that primarily involved uphill walking were excluded because specific biomechanical differences, neuromuscular adaptations, and physiological responses occur during uphill and downhill walking [31]. Furthermore, the non-English articles, conference papers, book chapters, and thesis were excluded. Studies that did not compare individuals with and without flatfoot regarding kinematics and spatiotemporal parameters of gait were also excluded from the analysis.

Study selection

In this study, two authors (SAN, FS) independently examined and selected the articles’ titles and abstracts according to the inclusion criteria and PRISMA standard methodology, utilizing a standardized Excel data extraction sheet [32]. All human studies and trials published until the end of the search period (November 2024) were included. The supervising author addressed and assessed discrepancies between the researchers (RS). Their searched records were imported into EndNote 20. The software was also used to remove duplicate articles.

Data extraction and quality assessment

Two researchers (SAN, HP) employed the Joanna Briggs Institute (JBI) Critical Appraisal tools [33] to evaluate the potential for bias, selecting the specific tool according to each research design included in the review and case-control analysis. The JBI Checklist offers a structured and reliable method for evaluating the quality of cross-sectional studies. A study’s quality range is determined by how well it meets the checklist’s criteria, and the score assists in categorizing the study as high, moderate, or low quality. The study is considered high quality if 7 or 8 of the eight questions are answered with “Yes” (87.5-100%). If 5 or 6 of the eight questions receive a “Yes” (62.5-75%), the study is rated as moderate quality. A study is rated low quality if four or fewer of the eight questions are answered with “Yes” (50% or lower).

Using a standard Excel data extraction sheet, the researchers independently collected data and subsequently compared their findings to evaluate coherence; furthermore, the supervising author addressed and assessed any discrepancies between the researchers (RS). The subsequent statistics were extracted from the included research based on the first author’s name and year of publication, study characteristics, participants’ demographic information, biomechanical measurement (such as spatiotemporal parameters and joint angles), type of foot measurement, type of kinematics assessment, data collection instruments, and main results (Table 1).

Data analysis

Data required for analysis, including standard deviation, means, P values, sample size, and, if applicable, standard deviation and mean difference, were extracted from articles meeting the inclusion criteria. The Comprehensive Meta-Analysis 3.3 software was employed. A random effects model analysis was utilized for standard differences in means effect size. The standard difference in means and 95% confidence interval (CI) were used to report the overall effect size. The heterogeneity of the studies was evaluated using I^2, with values of 25%, 50%, and 75% indicating low, medium, and high heterogeneity [34], respectively, and the Q-test, with a significance level of <0.05 [34]. Egger’s regression test was employed to evaluate the statistical significance of publication bias. P-values less than 0.05 were deemed significant for indicating publication bias [35]. Additionally, a funnel plot was used to assess the risk of bias. When a potential risk of bias was identified, the trim-and-fill method was employed. To ascertain the number of studies required for the symmetrical distribution of effect sizes, the

Table 1 Characteristics of included articles

	Study	Participant	Geographic region	Sex (M/F)	Foot posture measurement	Biomechanical measurement	Lab device	Study design	Main outcome in comparison with controls
1	Houck et al., 2008 [39]	21 participants (14 pronators, 7 control)	USA	3/18	Goniometrically, Navicular drop test	Kinematics: Calcaneus eversion, Calcaneus dorsiflexion	Motion Analysis System, force plate	Cross sectional study	Increased rearfoot eversion during early stance
2	Levinger et al., 2010 [42]	20 participants aged 18 years or more (10 flatfoot, 10 normal)	Australia	13/7	radiographic measurements obtained from weight bearing X-rays	Kinematics: Hindfoot relative to tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	Motion analysis system, force plates	Cross-sectional study	Increased rearfoot internal rotation. increased rearfoot eversion
3	Shih et al., 2012 [29]	30 children aged 7–10 years (20 flexible flatfoot, 10 normal)	Taiwan	Both	Navicular drop test (Feiss line)	Kinematics: maximum and minimum angles calcaneal and knee and hip	LIBERTY electromagnetic Tracking system	A case-control	No significant differences
4	Twomey & mcintosh, 2012 [27]	24 children aged 11–12 years (12 low arch, 12 normal)	Australia	Both	Static (foot print index and arch index), dynamic (navicular drop test)	Tempo-spatial Parameters: cadence, stride time, step time, stride length, step length. Kinematics: Hip; flexion, rotation, abduction. Knee flexion, varus, valgus. Ankle; flexion	Motion Analysis System	Cross-sectional study	Increased external hip rotation throughout the stance phase and in terminal swing. There was also a significant difference between the two groups in the left knee varus/valgus angle.
5	Hösl et al., 2014 [36]	46 children and adolescents aged 7 years or more (ASFF: $n=21$, SFF: $n=14$, TDF: $n=11$)	Germany	27/19	Oxford Foot Model	Tempo-spatial Parameters: Velocity, Step length, Step width Kinematics: Hindfoot relative to tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	A Vicon Nexus system and force plate	Cross sectional study	SFF walked significantly slower than TDF and decreased their step length to a similar extent. Concerning ROM values, both ASFF and SFF showed significant restrictions in dorsiflexion, as well as less plantarflexion during push-off.
6	Buldt et al., 2015 [26]	97 participants aged 18–47 years (30 pes-planus, 30 pes-cavus, 37 normal foot)	Australia	46/51	Foot Posture Index, Arch Index, normalized Navicular height	Tempo-spatial Parameters: Velocity Kinematics: Knee; flexion, extension, adduction, abduction, external rotation, internal rotation	Motion analysis system, force plates	Cross sectional study	Planus group increased external rotation angle at heel contact compared to both normal and cavus groups.
7	Prachgosin et al., 2015 [40]	28 participants aged 18–50 years (13 flatfoot, 15 normal)	Thailand	4/24	Footprint (arch index), foot radiographs	Tempo-spatial Parameters: Velocity, Stride length, Cadence Kinematics: Hindfoot relative to tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	Motion analysis System, force plates	Cross-sectional study	Increased peak eversion MLA moment and a smaller peak MLA deformation angle during specific subphases. The increased peak of hindfoot plantarflexion and internal rotation and the peak of forefoot abduction in the specific subphases.

Table 1 (continued)

	Study	Participant	Geographic region	Sex (M/F)	Foot posture measurement	Biomechanical measurement	Lab device	Study design	Main outcome in comparison with controls
8	Zhang et al., 2017 [24]	26 participants (17 over-pronated foot, 9 normal)	Belgium	15/11	Foot Posture Index	Kinematics: Hindfoot relative to Tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	Three-dimensional motion analysis system, force plate, An ultrasound system	Cross-sectional study	Increased rearfoot peak eversion and forefoot peak supination during walking.
9	Kerr et al., 2018 [17]	106 participants aged 5–18 years (53 asymptomatic neutral foot, 27 asymptomatic mild flatfoot, 17 asymptomatic flatfoot, 19 symptomatic flatfoot)	UK	51/65	Oxford Foot Model	Kinematics: Hindfoot relative to Tibia; inversion. Knee; flexion, varus. Hip; flexion	Vicon Motion Systems, Force-plates	Cross sectional study	The SF group also had slightly more (4º) hindfoot-tibia eversion than the AN group. AF group had increased forefoot-hindfoot abduction (3°) compared to AN. AF group had less forefoot-hindfoot adduction (4°) than AN.
10	Shin et al., 2019 [43]	78 participants (16 severe flat foot, 20 moderate flat foot:52–80 years, 42 non-flat-foots:60–69 years)	Republic of Korea	0/78	Navicular drop test	Tempo-spatial Parameters: Cadence, Speed, Stride length, Step width, Step time Kinematics: Hindfoot relative to Tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	Optical motion capture system	Cross sectional study	Decreased cadence, speed, stride length, and step width, Decreased ROM of sagittal and transverse plane of the hindfoot.
11	Dodelin et al., 2020 [25]	154 participants aged 20–50 years (63 pronated foot, 91 neutral foot)	France	154/0	Foot Posture Index, dynamic Center of Pressure Excursion Index	Tempo-spatial Parameters: Velocity, Step length, Cadence. Kinematics: Hindfoot relative to Tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	A 3-dimensional motion analysis system, pressure distribution platforms	Cross-sectional	Increased Anterior-posterior pelvic tilt ROM, peak knee internal rotation, forefoot dorsiflexion ROM, peak forefoot abduction, and rearfoot eversion. Increased Hallux contact time and time to peak force under the medial forefoot.
12	Alahmri et al., 2021 [28]	40 participants aged mean 21.45 years (20 asymptomatic pronated foot, 20 non-pronated foot)	Saudi Arabia	40/0	Navicular drop and rearfoot Angle tests	Kinematic: Hip; flexion, extension, adduction, abduction, external rotation, internal rotation	MVN Xsens system	Cross sectional study	no significant differences in hip joint kinematics during gait

Table 1 (continued)

	Study	Participant	Geographic region	Sex (M/F)	Foot posture measurement	Biomechanical measurement	Lab device	Study design	Main outcome in comparison with controls
13	Marouvo et al., 2021 [20]	31 participants aged18-40 years (15 flatfoot, 16 normal foot)	Portugal	18/13	Navicular Drop Test, Resting Calcaneal Stance Position test	Kinematics: Ankle; Dorsiflexion, Plantarflexion, Abduction, Adduction, Internal rotation, External rotation. Knee; Flexion, Extension, Abduction, Adduction, Internal rotation, External rotation. Hip; Flexion, Extension, Abduction, Adduction, Internal rotation, External rotation	3d motion capture system	Cross sectional study	Decreased ankle peak dorsiflexion, abduction, and internal and external rotation, knee and hip peak extension, external rotation, and knee abduction.
14	Kim et al., 2021 [38]	47 participants aged 18–35 years (11 normal weight with normal arch heights, 10 normal weights with lower arch heights, 8 obesity with normal arch heights, 18 obesity with lower arch heights)	USA	22/25	Arch height index, Navicular drop test	Tempo-spatial Parameters: Step length, Step width, Velocity. Kinematics: Ankle; Dorsiflexion, Plantarflexion, Abduction, Adduction, Internal rotation, External rotation. Knee; Flexion, Extension, Abduction, Adduction, Internal rotation, External rotation.	Pressure-sensitive gait carpet, motion capture system, force plates	Cross-sectional study	Step length decreased in individuals with obesity than individuals with normal weight, Step width and double-limb support time increased in individuals with obesity than individuals with normal weight.
15	Son et al., 2023 [41]	20 participants aged 20–40 years (10 flexible flatfoot, 10 normal foot)	Republic of Korea	20/0	AP and lateral foot radiographs	Kinematics: Tibiotalar joint; Dorsiflexion, Plantarflexion, Abduction, Adduction, Internal rotation, External rotation.	Motion capture cameras, force plate	Cross sectional study	Increased lateral contact force and posteriorly located center of pressure in the tibiotalar joint
16	Vijittrakarnrung et al., 2024 [43]	22 participants aged 18–23 (11 symptomatic flexible flatfoot, 11 control)	Thailand	12/10	Radiographic/ Oxford Foot Model	Tempo-spatial Parameters: Cadence, Cycle time, Velocity, Stride length, Step width Kinematics: Hindfoot relative to Tibia; Dorsiflexion, Plantarflexion, Eversion, Inversion, Internal rotation, External rotation	motion analysis system, force plates	Case-control	For hindfoot relative to tibia, the hindfoot internal rotation consistently demonstrated a higher value within the flexible flatfoot group vs. control group throughout the gait cycle.

significance threshold for the pooled effect analyses was established at a P-value of less than 0.05.

Results

Search result

The search strategy found 5309 studies. Following the elimination of duplicates, 3730 studies persisted. Title and abstract screening revealed 43 possibly suitable research. Twenty-eight studies were removed for irrelevant data or failure to fulfill inclusion criteria. Fifteen original studies satisfied the inclusion criteria. However, 3680 supplementary papers were incorporated through a search on Google Scholar, and only one article was eligible for inclusion in this study. Consequently, 16 papers were included in the study. Figure 1 illustrates the PRISMA flow diagram, detailing the quantity of

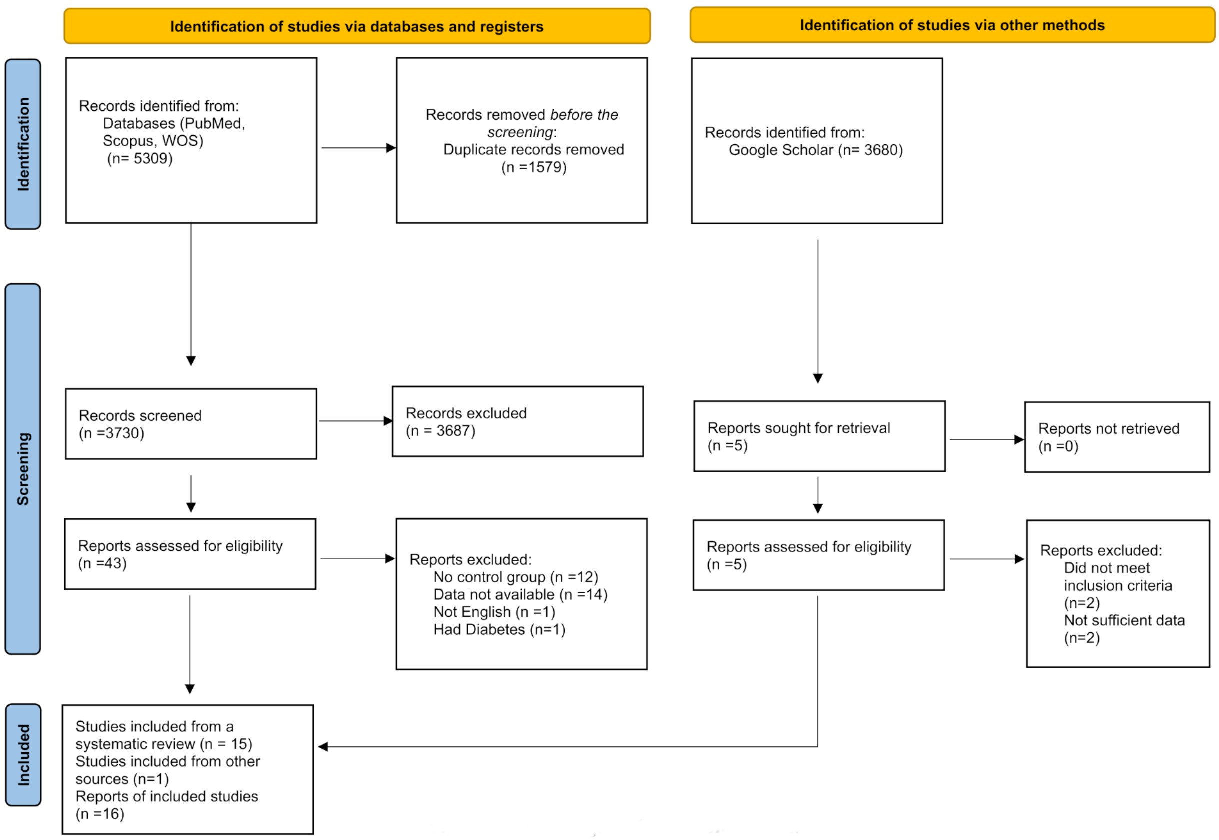

Fig. 1 Flow diagram for eligible studies

publications removed at each phase of the systematic review and meta-analysis. Some studies included a control group and two or more experimental groups [17, 36, 37]. In our data extraction process, we examined each experimental group separately against the control group. Additionally, one study included four groups, with each experimental and control group consisting of two subgroups: normal weight and obese [38]. Outcome variables included kinematics of hip, knee, and ankle angles in three planes of motion, as well as gait spatiotemporal parameters (stride length (cm), step length (cm), cadence (steps per minute), and gait speed (m/s)).Moreover, the critical appraisal results of the included studies are presented in detail in Table 2.

Description of the selected variables

Foot posture measurement

Several measurement approaches have been used to measure foot posture. Eight studies utilized navicular drop [20, 26–29, 37–39], three studies used radiographic measurement [40–42], three studies used the Oxford foot model [17, 36, 43], and two studies utilized foot posture index [24, 25] to assess foot posture measurement.

Biomechanical measurement

Various kinematics devices were used to examine gait kinematics. Four studies used a Motion capture system [20, 37, 38, 41]. One study used an MVN Xsens system [28], and another used an electromagnetic tracking system [29]. Ten studies also used motion analysis and force plate [17, 24–27, 36, 39, 40, 42, 43].

Eight studies assessed spatiotemporal gait parameters [25–27, 36–38, 40, 43], fourteen assessed ankle kinematics [17, 20, 24, 25, 27, 29, 36–43], five assessed knee kinematics [17, 20, 26, 27, 38], and four assessed hip kinematics [17, 20, 27, 28].

Data synthesis

Spatiotemporal gait parameters

Eight studies compared spatiotemporal parameters (stride length, step length, cadence, gait speed) of gait in individuals with and without flexible flatfoot [25–27, 36–38, 40, 43]. According to the meta-analyses, there were significant differences between the two groups in stride length (95% CI = 0.184_1.133, P = 0.007) and gait speed (95% CI = 0.120_0.774, P = 0.007), as those individuals without flatfoot had higher walking speed and stride length. However, no significant differences were

Table 2 Critical appraisal results of eligible systematic reviews

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total
Houck et al. [39]	Y	Y	U	Y	N	N	Y	Y	5
Levinger et al. [42]	Y	Y	Y	Y	Y	N	Y	Y	7
Shih et al. [29]	Y	Y	Y	Y	Y	N	Y	Y	7
Twomey & mcintosh. [27]	Y	Y	Y	Y	Y	N	Y	Y	7
Ho¨sl et al. [36]	U	Y	Y	Y	Y	N	Y	U	5
Buldt et al. [26]	Y	Y	Y	Y	Y	N	Y	Y	7
Prachgosin et al. [40]	U	Y	Y	Y	Y	N	Y	Y	6
Zhang et al. [24]	U	Y	Y	Y	Y	N	Y	Y	6
Kerr et al. [17]	Y	Y	Y	U	N	N	Y	Y	5
Shin et al. [37]	Y	Y	Y	Y	Y	U	Y	Y	7
Dodelin et al. [25]	Y	Y	Y	Y	Y	N	Y	Y	7
Alahmri et al. [28]	Y	Y	Y	Y	Y	N	Y	Y	7
Marouvo et al. [20]	U	Y	Y	Y	Y	N	Y	Y	6
Kim et al. [38]	Y	Y	Y	Y	U	N	Y	Y	6
Son et al. [41]	Y	Y	Y	Y	Y	N	Y	Y	7
Vijittrakarnrung et al. [43]	Y	Y	Y	Y	Y	N	Y	Y	7

JBI Critical Appraisal Checklist for Systematic Reviews and Research Syntheses: Q1. Were the criteria for inclusion in the sample clearly defined? Q2. Were the study subjects and the setting described in detail? Q3. Was the exposure measured in a valid and reliable way? Q4. Were objective, standard criteria used for measurement of the condition? Q5. Were confounding factors identified? Q6. Were strategies to deal with confounding factors stated? Q7. Were the outcomes measured in a valid and reliable way? Q8. Was appropriate statistical analysis used?

demonstrated in step length (95% CI = 0.609_0.507, $P = 0.859$) and cadence (95% CI = 0.036_0.474, $P = 0.093$) (Supplementary file 2). The Q-test and I^2 test results indicated significant heterogeneity across step length ($P = 0.003$, $I^2 = 74.806$), gait speed ($P = 0.005$, $I^2 = 63.299$), and no significant heterogeneity across cadence ($P = 0.307$, $I^2 = 16.586$) and stride length ($P = 0.060$, $I^2 = 55.818$). Egger's test demonstrated that publication bias is not statistically significant in stride length ($P = 0.731$), step length ($P = 0.817$), cadence ($P = 0.807$), and gait speed ($P = 0.308$).

Kinematics of ankle, hip, and knee

Ankle Fourteen studies compared ankle kinematics in individuals with and without flexible flatfoot [17, 20, 24, 25, 27, 29, 36–43]. According to the meta-analyses, there were significant differences between the two groups in inversion (95% CI = 0.053_0.053, $P = 0.017$) and eversion (95% CI= -0.784_-0.352, $P = 0.001$) angles. In addition, no significant differences were demonstrated in dorsiflexion (95% CI = 0.002_0.330, $P = 0.053$), plantarflexion (95% CI = 0.273_0.197, $P = 0.749$), internal rotation (95% CI= -0.273_-0.070, $P = 0.246$), and external rotation (95% CI= -0.122_0.280, $P = 0.439$) angles. The Q-test and I^2 test results indicated significant heterogeneity across plantarflexion ($P = 0.001$, $I^2 = 77.339$), eversion ($P = 0.018$, $I^2 = 52.007$), inversion ($P = 0.001$, $I^2 = 77.400$), internal rotation ($P = 0.031$, $I^2 = 45.864$), and external rotation ($P = 0.001$, $I^2 = 65.273$) except dorsiflexion ($P = 0.060$, $I^2 = 55.818$) angles. According to the high heterogeneity of ankle, subgroup analyses were done for genders, and the findings were significantly different in some studies [27, 29] that examined both genders in dorsiflexion (95% CI = 0.183_0.579, $P = 0.001$), internal rotation (95% CI= -0.539_-0.068, $P = 0.012$), and external rotation (95% CI = 0.163_0.698, $P = 0.002$) angles (Supplementary file 2). Egger's test and Funnel plot demonstrated that publication bias is not statistically significant in dorsiflexion ($P = 0.435$), plantarflexion ($P = 0.648$), inversion ($P = 0.238$), eversion ($P = 0.516$), external rotation ($P = 0.515$) except internal rotation ($P = 0.001$) angles. The trim and fill methods were used to check the possible effect of future studies on the research results. The results showed that adding six randomly hypothetical studies may not affect the meta-analysis results (Supplementary file 2).

Knee Five studies compared knee kinematics in individuals with and without flexible flatfoot [17, 20, 26, 27, 38]. According to the meta-analyses, the two groups had no significant differences in flexion (95% CI= -0.606_0.148, $P = 0.233$), extension (95% CI= -0.078_0.631, $P = 0.126$), abduction (95% CI= -0.528_0.213, $P = 0.405$), adduction (95% CI= -0.404_0.200, $P = 0.509$), internal rotation (95% CI= -0.255_0.292, $P = 0.894$), and external rotation (95% CI= -0.596_0.956, $P = 0.649$) angles (Supplementary file 2). The Q-test and I^2 test results indicated significant heterogeneity across flexion ($P = 0.002$, $I^2 = 68.675$), abduction ($P = 0.027$, $I^2 = 60.511$), and external rotation ($P = 0.015$, $I^2 = 76.316$) and no considerable heterogeneity across extension ($P = 0.674$, $I^2 = 0$), adduction ($P = 0.855$, $I^2 = 0$), and internal rotation ($P = 0.138$, $I^2 = 38.064$) angles. Egger's test and Funnel plot demonstrated that publication bias is not statistically significant in flexion ($P = 0.870$), extension

($P = 0.476$), abduction ($P = 0.279$), adduction ($P = 0.920$), and internal rotation ($P = 0.074$) except external rotation ($P = 0.047$) angles. The results showed that adding two randomly hypothetical studies may not affect the meta-analysis results (Supplementary file 2).

Hip Four studies compared hip kinematics in individuals with and without flexible flatfoot [17, 20, 27, 28]. According to the meta-analyses, the results showed a significant difference between the two groups in flexion (95% CI= -0.576_-0.120, $P = 0.003$) angle, indicating greater hip flexion in the flatfoot group. Also, no significant differences were seen in extension (95% CI= -0.208_0.589, $P = 0.349$), abduction (95% CI= -0.352_0.362, $P = 0.977$), adduction (95% CI= -0.234_0.239, $P = 0.982$), or internal (95% CI= -0.442_0.082, $P = 0.178$) and external rotation (95% CI= -0.363_0.760, $P = 0.489$) angles (Supplementary file 2). The Q-test and I^2 test results indicated no significant heterogeneity across flexion ($P = 0.826$, $I^2 = 0$), extension ($P = 0.484$, $I^2 = 0$), abduction ($P = 0.499$, $I^2 = 0$), adduction ($P = 0.425$, $I^2 = 0$), internal rotation ($P = 0.308$, $I^2 = 16.378$), and external rotation ($P = 0.146$, $I^2 = 48.093$) angles. Egger's test demonstrated that publication bias is not statistically significant in flexion ($P = 0.745$), extension ($P = 0.054$), abduction ($P = 0.463$), adduction ($P = 0.288$), internal rotation ($P = 0.441$), and external rotation ($P = 0.364$) angles.

Finally, 16 articles were subject to quality assessment, and all discrepancies were resolved through a consensus meeting between the two reviewers. Based on the quality assessment results, studies with low quality were excluded from the analysis of variables exhibiting high heterogeneity, allowing for a reanalysis to obtain more accurate and reliable results.

Sensitivity analysis

Sensitivity analysis revealed that sequentially excluding the studies by Houck et al. [39], Hösl et al. [36], and Kerr et al. [17], classified as low-quality during the quality assessment, had no impact on the analysis results for variables with high heterogeneity.

Discussion

In this study, significant differences in spatiotemporal parameters of walking were found between individuals with and without flexible flatfoot, so shorter stride length and lower gait speed were noticed in individuals with flexible flatfoot. Also, the comparison of lower extremity kinematics of walking between individuals with and without flexible flatfoot showed a significant difference, so that individuals with flexible flatfoot showed decreased inversion, increased eversion, and larger hip flexion during walking. These findings indicate distinct biomechanical adjustments in the gait of individuals with flexible flatfoot compared to those with normal foot structure.

The reduced ankle inversion and increased eversion observed in individuals' flexible flatfoot are consistent with the biomechanical effects of medial longitudinal arch collapse and increased pronation. Increased eversion in individuals' flexible flatfoot can be attributed to excessive mobility or inability to control pronation properly during dynamic movement such as walking. Increased eversion during walking also reflects the impaired function of an active subsystem of the foot core system. Increased eversion can be linked to extrinsic and intrinsic foot muscle weakness. Kobayashi et al. (2024) showed that in individuals with flatfoot, excessive stretching of intrinsic muscles occurs under loading [44]. Greater eversion might increase the effort required to resupinate and invert the foot for propulsion [42]. Greater eversion also reflects the defect in the reverse windlass mechanism and shock absorption ability in the flatfoot gait [40].

Our findings are consistent with previous studies [45, 46] that reported greater calcaneal eversion excursion and maximum calcaneal eversion in participants with low arch foot. Levinger and colleagues also reported a greater rearfoot eversion in participants with flexible flatfoot [42]. In a systematic review undertaken by Buldt et al. (2013), it was reported that there is evidence of a correlation between flatfoot posture and increased motion of the rearfoot in the frontal plane. However, the authors reported that due to methodological concerns and the small effect sizes, the quality of evidence is mediocre [19].

A significant difference in hip flexion angle during walking was found between individuals with and without flatfoot, so individuals with flatfoot demonstrated higher hip flexion angles. This finding suggests that flatfoot modifies lower extremity biomechanics, leading to compensatory adjustments at proximal joints, such as the hip, to accommodate the biomechanical inefficiencies at the foot. Our findings are consistent with Marouvo et al. (2021), that reported a greater hip flexion in participants with flexible flatfoot compared to normal ones. The increase in hip flexion during walking has been attributed to a greater need to absorb impact forces that are not absorbed at the foot level [20].

Our results showed a significant difference in stride length between individuals with and without flatfoot, so stride length was longer in those with normal foot structure. Flexible flatfoot is associated with a low MLA, which leads to overpronation during the stance phase of walking. This phenomenon precludes the foot to act as a rigid lever during the push-off phase of walking. Consequently, individuals with flexible flatfoot create less effective propulsive force, which results in shorter stride lengths.

Observed significant reduction in walking speed in individuals with flexible flatfoot can be attributed to a weakened propulsion mechanism and increased proportion of the stance phase in a gait cycle in flatfoot participants [1, 37]. Similarly, Karimi et al. (2013) found that flatfoot was associated with increased energy expenditure during walking, which might contribute to slower overall speeds [47]. Decreased walking speed might be an adaptive strategy to reduce abnormal joint moments [48]. In contrast, in a study [37] investigating the effect of flatfoot on kinematics was shown cadence and step width are lower in flatfoot patients that our findings are inconsistent with the mentioned study. This discrepancy in the results may be due to the age of the participants and their classification based on the severity of flatfoot.

Besides, understanding the biomechanics and gait patterns of individuals with flatfoot during walking can be valuable for researchers in developing therapeutic protocols and preventing musculoskeletal injuries [23]. Regarding this matter, a study showed a fall prevention exercise program should be prescribed based on four movement pillars (locomotion, level changes, pulling and pushing, and rotations) to stimulate the motor control of lower limb joints and promote spatial and temporal parameters [49].

Several limitations must be considered when interpreting the findings of this systematic review and meta-analysis. First, the studies included in this analysis varied in sample size, participant demographics (age, sex, and comorbidities), and methodological quality, which may introduce heterogeneity and limit the generalizability of the results. Second, the variability in measurement techniques across studies, such as differences in gait analysis equipment, motion capture systems, and the methods used to assess foot structure, may have contributed to inconsistencies in the data. Additionally, the cross-sectional nature of most studies precludes the ability to establish causal relationships between flexible flatfoot and altered gait mechanics. Another limitation of this study is that it was not registered in PROSPERO, as PROSPERO primarily focuses on systematic reviews in the health and clinical domains. Furthermore, we didn't have any limitation of participants' age and didn't differentiate between the unilateral and bilateral flexible flatfoot and the flatfoot assessment methods. Finally, while the meta-analysis provides pooled estimates of effect sizes, the limited number of studies available for specific parameters reduces the power to detect more minor, potentially clinically relevant differences. Future research with larger, more homogeneous cohorts, longitudinal designs, and standardized protocols is needed to elucidate further the possible impact of flexible flatfoot on lower extremity function.

Conclusion

This study indicated that subjects with flatfoot exhibited alterations in the inversion, eversion, hip flexion, stride length, and walking speed compared to neutral foot participants and demonstrated a distinct gait pattern throughout the entire gait cycle. Health specialists are advised to consider these findings when prescribing prevention and rehabilitation programs for musculoskeletal deformities in individuals with flexible flatfoot.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

SAN, RS, HP, FS, and EE contributed to the study design and data collection. SAN, RS, HP, and EE drafted the manuscript and made critical revisions to the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets generated and analyzed during the current study are available in supplementary file 1.

Declarations

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Ethics approval, guidelines, and consent to participate

Not applicable.

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