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Effects of foot orthoses on lower extremity joint kinematics and kinetics in runners with asymptomatic flatfeet: A systematic review and meta-analysis

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ABSTRACT

Background: Foot orthoses (FO) are commonly prescribed by clinicians to manage foot and ankle conditions and improve biomechanical function.
Research question: Are there any potential kinematic and kinetic effects of FO on individuals with asymptomatic flatfeet during running?
Methods: The database search from inception to September 2024, including PubMed, Scopus, Web of Science, Embase, ProQuest, Cochrane, and CINAHL, identified 12 studies including 18 different orthotic interventions. These included FO with either arch-support-only or arch-support with medial-side posts. The methodological quality and risk of bias were assessed using ROBINS-I index. Primary outcome measures were joint angles and moments of midfoot/arch, ankle, and knee.
Results: Our meta-analysis revealed non-significant changes with the arch-support-only FO. However, random effects analysis indicated that arch-support FO with rearfoot and forefoot medial posts significantly decreased standardized mean difference (SMD) in peak ankle eversion angles (SMD=-0.41, 95 %CI[-0.78 to −0.04]), peak ankle invertor moments (SMD=-0.51, 95 %CI[-0.97 to −0.05]), and Achilles tendon loading rates (SMD=-0.94, 95 %CI[-1.78 to −0.09]) during running.
Significance: The findings of this meta-analysis suggest that arch-support FO with strategically placed medial posts may enhance stability and alleviate internal loading on the foot-ankle complex during running in individuals with asymptomatic flatfeet. Specifically, FO with medial posts at both the rearfoot and forefoot reduced peak ankle eversion angle, although this is based on only six studies. FO with such features may also decrease loading on the invertor muscles and Achilles tendon during running in individuals with asymptomatic flatfeet. Further research is needed to confirm these findings in larger populations.

1. Introduction

Fallen arches, or flexible flatfeet, are a common condition where the entire sole contacts the floor during both static and dynamic movements [1,2]. Evidence indicates asymptomatic flatfeet affect 13.60 % and 26.62 % of the population [3,4]. Most cases of asymptomatic flatfeet are considered anatomical variants and non-pathomechanical, similar to normally arched feet, and recent studies suggest minimal association with running-related injuries [5–8]. This condition, however, is typically associated with pronation, a combination of dorsiflexion, eversion, and abduction across multiple foot joints [9,10]. Pronation occurs when the foot-ankle joints, particularly the subtalar, talonavicular, and calcaneocuboid joints, move excessively or too rapidly during weight acceptance in running, shifting greater weight onto the medial side [10, 11].

Foot orthoses (FO) or insoles are among the most common

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interventions used to modify lower extremity biomechanics during locomotion [12]. FO are often prescribed by clinicians to manage foot and ankle conditions, prevent overuse injuries during running. In a 2010 audit at a single university, 58 % of individuals with flexible flatfeet were prescribed FO [13]. Clinical trials have shown that FO with various designs, including wedges and arch-supports, can prevent or treat running-related conditions [14–18]. However, our understanding of the specific clinical benefits of FO for runners with asymptomatic flatfeet remains limited. While asymptomatic flat feet are often considered anatomical variants, understanding the effects of FO in this population could help manage/prevent future musculoskeletal issues by enhancing foot function and alignment. Moreover, this is crucial for developing evidence-based guidelines to differentiate cases that require FO from those that do not, as recommendations for symptomatic flatfeet may be improperly applied to asymptomatic cases.

FO with arch-support and medial posts are specifically designed to support the arch and reduce the risk of pronation-related injuries while running [19–21]. Several studies have evaluated their effects on lower extremity biomechanics in runners with asymptomatic flatfeet. However, the results are highly variable. Some studies indicated that FO controlled peak ankle eversion angle and reduced pronation during running, while others reported non-significant changes [21–24]. Furthermore, while FO modified frontal plane ankle kinematics and kinetics, they had inconsistent effects on other proximal lower extremity measures, such as tibia and knee joint kinematics and moments during running. These conflicting findings pose clinical challenges to orthotic management of runners with asymptomatic flatfeet. Therefore, a systematic review and meta-analysis of relevant studies are needed to provide collective evidence of FO's effects on lower extremity biomechanics during running in individuals with asymptomatic flatfeet, and guidelines for clinicians and orthotists.

Previous systematic reviews and meta-analyses on external pronation control devices have found FO effective in controlling ankle eversion [25]. More recent systematic reviews focusing on asymptomatic flatfeet have reported the influence of FO on lower extremity biomechanical and functional outcomes in walking [26–28]. However, it remains unknown if the effectiveness of FO modifications observed in walking can be generalized to running, which involves higher movement intensity and distinct biomechanics. Furthermore, the biomechanical effects of different FO modifications remain unclear.

To the best of our knowledge, no review has yet comprehensively evaluated the effects of FO on lower extremity kinematics and kinetics in individuals with asymptomatic flatfeet during running. Therefore, the primary aim of this systematic review and meta-analysis was to evaluate the effectiveness of FO interventions on the kinematics and kinetics of midfoot/arch, ankle, tibial, and knee in runners with asymptomatic flatfeet. The secondary aim was to systematically summarize the effects of FO interventions based on design modifications. We hypothesized that the FO would modify lower extremity mechanics, reduce pronation-related motion, and improve biomechanical function during running. Findings from this study could provide evidence-based guidance to maximize benefits of FO for runners with asymptomatic flatfeet.

2. Methods

2.1. Study protocol

The protocol for this systematic review and meta-analysis was registered in PROSPERO (registration number: CRD42023432918). This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [29]. The PICO (Population, Intervention, Comparison, and Outcome) framework was used to develop and refine the eligibility criteria and search strategy.

2.2. Eligibility criteria

Previous studies that met the following inclusion criteria were included for review and meta-analysis: studies that recruited healthy runners with asymptomatic flatfeet, defined by a reliable and validated foot posture or morphology index (i.e., foot posture index, navicular drop, arch index, etc.), with no history of chronic pain, disabilities or musculoskeletal disorders; studies that considered FO, including shoe inserts or insoles with arch-support, and/or medial and lateral posts/wedges; studies that compared the effects of FO with a control condition (i.e., running without FO); and studies that included lower extremity kinematics and kinetics as outcome measures. Single case studies, dissertations, abstract-only studies, and studies published in languages other than English were excluded.

2.3. Search strategy

The PICO framework was used to develop a systematic search strategy that incorporated three different categories of keywords: Population (flatfoot-related terms), Intervention (foot orthoses-related terms), and Outcome (kinematics and kinetics-related terms), which were connected with Boolean operators (i.e., OR, AND, NOT). A seasoned librarian at our institution verified the search strategy. The developed search syntax was then applied across seven electronic databases: PubMed, Web of Science, Scopus, ProQuest, Embase, Cochrane, and CINAHL via EBSCOhost, from the inception of each database to September 2024. In addition, grey literature was searched from Google, Google Scholar, ResearchGate, and the reference lists of included articles, to identify other potential studies. The detailed search strategies, including search syntax across databases, can be found in Supplementary Table S1.

2.4. Study selection

Studies from research databases were imported into EndNote software, and duplicates were identified and removed. Two reviewers (AJ and NL) simultaneously searched the databases and screened the titles and abstracts of the non-duplicated articles to assess their eligibility for inclusion in this review. A third reviewer (AD) was consulted to resolve any discrepancies.

2.5. Quality and risk of bias assessment

The methodological quality and risk of bias were evaluated using the ROBINS-I index [30] as well as the Downs and Black index [31] , respectively. The ROBINS-I tool incorporates seven domains and overall risk of bias was categorized based on their evaluation on seven domains as follows: studies rated as low risk of bias for all domains were classified as 'low risk of bias', studies rated as low or moderate risk of bias for all domains were classified as 'moderate risk of bias' and studies rated as serious risk of bias in at least one domain were classified as 'serious risk of bias'. Two reviewers (AJ and AD) rated studies using the ROBINS-I index, and a third reviewer (YH) was consulted to resolve any disagreements. A modified Downs and Black scale with 20 items was employed, with each fulfilled item receiving a "no" (0 point), "unable to determine" (0 point), or "yes" (1 point). All scores were reported as a percentage of the maximum score (20). Studies were categorized based on their quality as follows: scores of 26–28 (or 91–100 %) were deemed excellent quality; scores of 20–25 (or 71–90 %) were considered good quality; scores of 15–19 (or 51–70 %) were regarded as fair quality; and scores of 14 or less (or 50 % and below) were classified as poor quality [32,33]. Two independent reviewers (AJ and NL) assessed studies using the Downs and Black index, and a third reviewer (AD) was consulted to resolve disagreements. The inter-rater agreement was evaluated using kappa statistics [34,35].

2.6. Data extraction

The following data were extracted: author(s), year of publication, study design, participants, foot status, interventions delivered, study comparisons, running pattern, adaptation time, and outcome measures. The primary outcomes of interest were kinematics and internal moments of the midfoot/arch, frontal plane ankle, and knee that are most relevant to flatfeet. Secondary outcomes of interest were the sagittal and transverse plane kinematics and internal moments of the ankle and knee, as well as vertical GRFs (v-GRFs) and v-GRF loading rates. The data were extracted by one reviewer (AJ) and carefully verified by another reviewer (NL) to ensure accuracy. Discrepancies between reviewers were resolved through discussion until a consensus was reached.

2.7. Data synthesis and analysis

Primary and secondary outcome data from each study were systematically input into data tables with mean, standard deviation, and sample size for both treatment and control groups. For studies using statistical parametric mapping or similar curve analysis techniques, we extracted the kinematic and kinetic values at initial contact, as well as peak values of the entire stance phase. For missing data, we attempted to contact the corresponding authors through email or used a plot digitizer to extract data from the graphical illustrations [36]. Due to the small sample sizes and methodological variations, such as including more than one orthotic intervention per study with different FO designs and populations, we anticipated substantial heterogeneity. To address this, we applied a random-effects model, which assumes that the true effect size may vary between studies, providing a more generalized pooled effect estimate [37]. Inter-study heterogeneity was assessed using the I^2 statistics, with values $\geq 50\,\%$ considered significant [38]. A sensitivity analysis was conducted to identify potential heterogeneity sources by systematically removing studies or subsets of orthotic trials and observing changes in the overall effect estimate and heterogeneity levels.

As all outcome measurements were continuous variables, the standardized mean difference (SMD) and 95 % confidence interval (95 % CI) were used to determine effect sizes. An SMD of 0.2–0.5 indicated a small effect, 0.5–0.8 a moderate effect, and > 0.8 a large effect from a clinical perspective [39]. Publication bias was examined using a funnel plot when the number of orthotic trials exceeded 10 and Egger's test when the number of trials was less than 10 [40,41]. All statistical analyses were performed using Comprehensive Meta-Analysis v.4 software (Biostat Inc., Englewood, NJ, USA). The statistical significance was set at $p < 0.05$.

3. Results

3.1. Study selection

After reviewing the titles and abstracts of all 2650 non-duplicated studies, irrelevant records were removed, and 58 studies were selected for full-text analysis (Fig. 1). Of these, 46 studies were excluded, with reasons detailed in supplemental Table S2. The majority of the excluded articles either did not address the primary outcome or involved runners with feet other than asymptomatic flatfeet. The remaining 12 studies

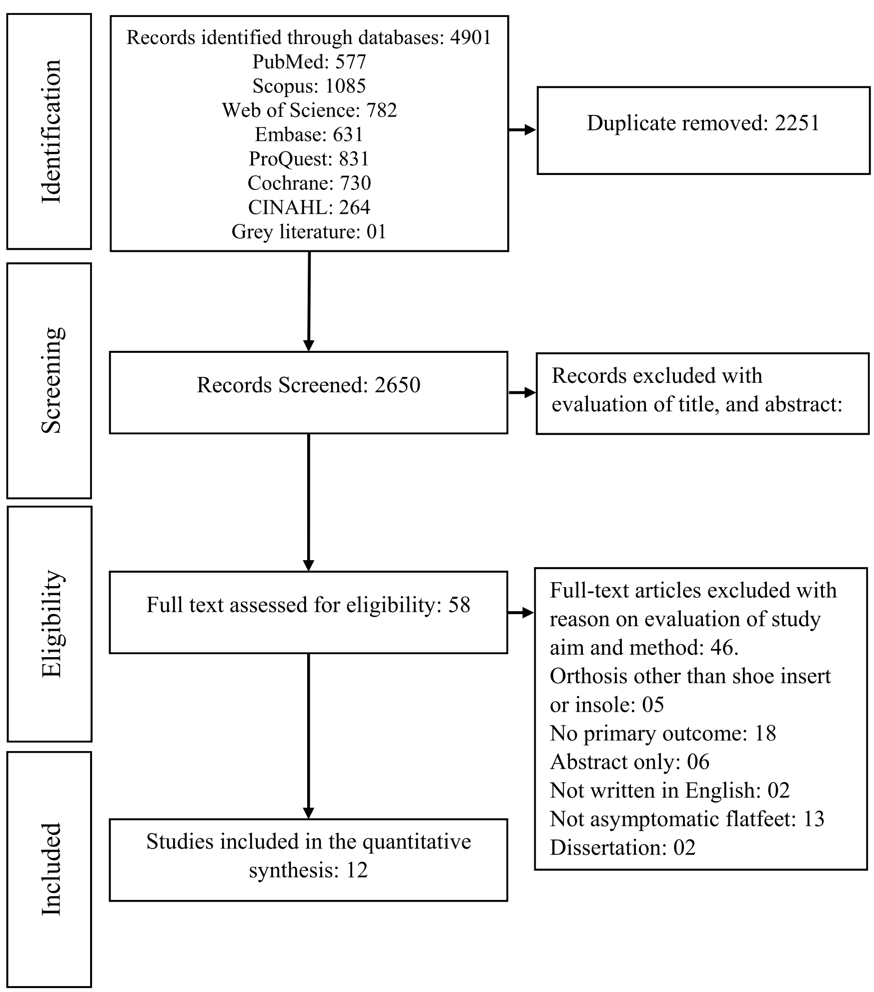


Fig. 1. Flowchart illustrating the selection of articles through the PRISMA guidelines.

that met the eligibility criteria were included in the subsequent systematic review and meta-analysis.

3.2. Quality and risk of bias assessment

The overall risk of bias according to the ROBINS-I index was moderate for nine studies [21–24,42–46], and high for three studies [47–49] (Table 1). The risk of bias was low for the classification of interventions, randomization, missing data, and selective outcome reporting. However, a high risk of bias related to participant selection and confounding was found in approximately 17 % of the studies. A moderate risk of bias attributed to confounding was observed in about 83 % of the studies, primarily due to the non-randomized controlled design. Additionally, a moderate risk of bias with the blinding of study participants and outcome assessors was identified in 67 % of the studies.

The overall mean methodological quality score of the included studies was 14.41 (72 %), ranging from 12 (60 %) to 17 (85 %) on the modified Downs and Black scale (Supplemental Table S3). Six studies [22,24,42,44–46] were rated as good quality, while six studies [21,23,43,47–49] were rated as fair quality. The majority (> 84 %) of studies [21–24,43,44,46–49] included participants who were not blinded to intervention and outcome measures, and lacked randomization sequence concealment, presenting a risk of bias. More than 30 % of the studies [47–49] did not include an a priori power analysis for sample size estimation. The kappa coefficients for inter-rater agreement were 0.80 for quality assessment and 0.63 for risk of bias assessment, indicating substantial agreement between reviewers [50,51].

3.3. Study characteristics

The characteristics of the 12 included studies are summarized in Table 2. This review included 240 participants (122 male and 118 female) across 12 single-group quasi-experimental studies. Asymptomatic flatfeet were defined as flatfeet in participants without chronic pain, disabilities, or musculoskeletal disorders and were determined by metrics such as foot posture index [22,44,49], navicular drop [23,42,43,46,47], calcaneal valgus angle [45,46], heel bi-section line relative to shank bi-section line [21,24], or forefoot varus angle [48].

All participants from the included studies were rearfoot strikers and ran on either an overground track [21–24,43,44,47–49] or a treadmill [42,45,46] with a fixed speed range of 1.7 m/s to 4.0 m/s [21,23,24,42,43,45–49] or a self-selected speed [22,44]. All included studies investigated the immediate effects of FO on the lower extremities (n = 12, 100 %). Five studies [23,42,45,47] allowed 5–30 min of adaptation time before starting the experiment, four studies [24,44,48,49] provided unspecified adaptation time, two studies [22,43] allowed for 2–4 weeks, and the remaining two studies [21,46] allowed less than 5 min for adaptation.

Some studies evaluated more than one type of FO, and collectively, the 12 studies examined 18 different orthotic conditions or trials. Each FO trial represents a unique orthotic condition tested within the studies. There are two main types of FO: (1) arch-support-only FO (ASFO) (arch-support: designed primarily to provide support to the arch of the foot), and (2) Arch-support FO with rearfoot only medial post (ASFO-RMP) and arch-support FO with rearfoot and forefoot medial post (ASFO-RFMP) (medial posts: additional structural elements to the inner side of the foot, such as medial posts or wedges to control foot pronation). The detailed features of these FO are included in Table 3. ASFO were assessed in six orthotic trials across four studies [24,46,48,49] while ASFO-RMP and ASFO-RFMP with 3-to-6-degree medial posts were assessed in twelve orthotic trials across nine studies [21–24,42–45,47]. Of these, five orthotic trials from four studies [21,24,43,45] used AFO-RFMP (medial post positioned at both the rearfoot and forefoot), whereas seven orthotic trials from five studies [22,23,42,44,47] used ASFO-RMP (medial post positioned only at the rearfoot). The materials used for fabricating FO varied considerably. Two studies specified the use of thermo-moldable EVA with a Shore A hardness of 40–45 [21,22], and nylon with a Shore D hardness of 58 [45]. Other studies provided less detailed descriptions, reporting materials such as high-density EVA [23], polypropylene with a thickness of 3–4 mm [24,42,44,45,49], PORON with a thickness of 3 mm [45], graphite polyurethane [48], and thermoplastic polyurethane [47]. In one study, the materials used for FO fabrication were not specified [43]. Primary and secondary outcome measures focused on joint angles and range of motion (ROM) of the midfoot/arch [42,43], ankle [21–23,43–45,48], knee [21–23,43,49], and tibia [24,43], ankle joint velocity [24,45], joint moments of the ankle [21–23,43,44,47,48] and knee [21–23,43], as well as vertical GRFs and loading rates [24,45,46].

3.4. Meta-analysis

The primary and secondary outcome measures reported in the included studies were considered for pooled analysis. The forest plots of the primary and secondary outcomes regarding ASFO are displayed in Fig. 2, while those for ASFO-RMP and ASFO-RFMP are displayed in Figs. 3–4. Each FO trial was treated as a separate data point to independently examine the effects of each distinct orthotic condition. No publication bias was identified for any of the outcome measures in the included studies, as indicated by Egger's test ($P > 0.05$).

3.4.1. Arch-support-only FO: lower extremity kinematics and kinetics

There were no significant changes in the pooled analysis of peak ankle eversion angle (SMD=0.00, 95 %CI −0.40–0.38) when compared with the no-FO control condition (Fig. 2A). Similarly, there were no significant effects on peak ankle invertor moments in the pooled analysis (SMD=-0.29, 95 %CI −0.83–0.25) (Fig. 2B). No significant changes were found for v-GRF impact peak (SMD=-0.04, 95 %CI −0.39–0.48), v-GRF active peak (SMD=-0.05, 95 %CI −0.49–0.39), or v-GRF loading rates (SMD=0.25, 95 %CI −0.55–1.04) (Fig. 2C-2E).

3.4.2. Arch-support FO with medial post: lower extremity kinematics and kinetics

The pooled analysis of FO on ankle inversion at heel strike showed no significant changes (SMD=0.05, 95 %CI −0.40–0.50) (Fig. 3A). A comparison of effects on peak ankle eversion angle revealed a significant change with small effect size (SMD=-0.41, 95 %CI −0.78 to −0.04) (Fig. 3B). In the subgroup analysis, ASFO-RMP (SMD=-0.29, 95 %CI −1.18–0.58) showed no significant changes in pooled effects. However, ASFO-RFMP (SMD=-0.43, 95 %CI −0.84 to −0.03) revealed significant changes in pooled analysis with a small effect size. The peak ankle dorsiflexion (SMD=-0.16, 95 %CI −0.69–0.38) revealed no significant changes were in the pooled analysis (Fig. 3C). Regarding knee kinematics, it showed no significant changes in peak knee adduction in pooled analysis (SMD=0.39, 95 %CI −0.03–0.80) (Fig. 3D). However, one trial showed a significant increase in peak knee adduction with ASFO-RFMP, demonstrating a large effect size (SMD=1.04, 95 %CI 0.36–1.71). The peak knee internal rotation was reduced with ASFO-RFMP in a single trial within the subgroup analysis, with a medium effect size (SMD=-0.73, 95 %CI −1.39 to −0.07). The pooled effects of ASFO-RFMP on peak tibial internal rotation showed no significant changes (SMD=-0.09, 95 %CI −0.58–0.40) (Fig. 3E). Additionally, there were no significant effects on sagittal plane arch ROM (SMD=-0.13, 95 %CI −0.54–0.28) in pooled analysis (Fig. 3F).

There were significant changes with a small effect size in peak ankle invertor moments in the pooled analysis (SMD=-0.35, 95 %CI −0.66 to −0.04) (Fig. 4A). In the subgroup analysis, no significant changes were observed in the pooled effects with the ASFO-RMP (SMD=-0.11, 95 %CI −0.60–0.38). However, peak ankle invertor moments were significantly reduced in the pooled analysis with the ASFO-RFMP, showing a medium effect size (SMD=-0.51, 95 %CI −0.97 to −0.05). No significant changes were found in the pooled effects of ankle eversion velocity (SMD=-0.06, 95 %CI −0.47–0.35) (Fig. 4B). The pooled analysis of ASFO-RMP

Table 1
Methodological quality and risk of bias assessment using ROBINS-1 tool.

	Risk of Bias Domains							
Studies	D1	D2	D3	D4	D5	D6	D7	Overall
Mündermann (2003)[24]	−	+	+	+	+	+	+	−
Hurd (2010)[48]	×	×	−	+	+	−	+	×
Hutchison (2015)[49]	×	+	+	+	+	−	+	×
Kosonen (2017)[43]	−	+	+	+	+	−	+	−
Joo (2018)[47]	−	×	−	−	+	−	−	×
Braga (2019)[21]	−	+	+	+	+	+	+	−
Lee (2019)[44]	−	+	+	+	+	−	+	−
Mo (2019)[45]	−	+	+	+	+	+	+	−
Costa (2021)[22]	−	+	+	+	+	−	+	−
Crago (2021)[42]	−	+	+	+	+	+	+	−
Ng (2021)[46]	−	+	+	+	+	−	+	−
Ataabadi (2022)[23]	−	+	+	+	+	−	+	−

Domains
D1: Bias due to confounding
D2: Bias in selection of participants into the study
D3: Bias in classification of interventions
D4: Bias due to departures from intended interventions
D5: Bias due to missing data
D6: Bias in measurement of outcomes
D7: Bias in selection of reported results

Judgment

+	Low risk
−	Moderate risk
×	Serious risk

Table 2
Study characteristics.

Author (Year)	Trial design	Participants (M/F/U, age, runner status)	Foot status	Study Comparisons		Running methods (speed, surface, type/distance)	Adaptation time	Outcomes measures
				Control	Experimental trial			
Mündermann [24]	SGQE	21 (9/12; 25.4 ± 5.6; recreational runner)	Asymptomatic flatfeet (heel bisection line by shank bisection line: 16.2 ± 3.2°)	Running sandal+Flat FO	a. ASFO (C) + sandal, b. ASFO-RFMP (C) + sandal	4.0 ± 0.2 m/s; overground running with a rearfoot strike	Allowed unspecified time to familiarize	Kinematics: tibia, ankle; Kinetics: ankle, GRFs, loading rates
Hurd [48]	SGQE	15 (4/11; 10–51 ± 10; recreational runner)	Asymptomatic flatfeet (forefoot varus: 6° (5–10°)	Motion control running shoe	a. ASFO (P-E) + shoe, b. ASFO (P-N) + shoe	1.7 ± 5 % m/s; overground jogging with rearfoot strike	Allowed unspecified time to familiarize	Kinematics: ankle; Kinetics: ankle
Hutchison [49]	SGQE	14 (5/9; 22.3 ± 2.3; recreational runner)	Asymptomatic flatfeet (FPI: ≥+6)	Neutral running shoe	a. ASFO (C) + shoe, b. ASFO (P) + shoe	2.94–2.97 m/s; overground running with a rearfoot strike	Allowed multiple practice trials to familiarize	Kinematics: knee
Kosonen [43]	SGQE	11 (11/0; runner)	Asymptomatic flatfeet (Navicular drop: 12.0 ± 1.1 mm)	Running shoe+Flat FO	ASFO-RFMP (C) + shoe	4.0 ± 0.17 m/s; overground running with a rearfoot strike	2 weeks	Kinematics: knee, ankle; foot Kinetics: knee, ankle
Joo [47]	SGQE	15 (15/0; 22.87 ± 8.48; recreational runner)	Asymptomatic flatfeet (Navicular drop: 13.2 ± 1.00 mm	Standard running shoe+Flat FO	ASFO-RMP (C) + shoe	1.38–1.66 m/s; overground running with a rearfoot strike	10 min	Kinetics: ankle
Braga [21]	SGQE	19 (11/8; 35.7 ± 7.72; recreational runner)	Asymptomatic flatfeet (metatarsus bisection line by shank bisection line: >10°)	Neutral running shoe+ arch-support FO	ASFO-RFMP (P) +shoe	3.30 ± 0.37 m/s; overground running with a rearfoot strike	1 min	Kinematics: knee, ankle; Kinetics: knee, ankle
Lee [44]	SGQE	12 (12/0; 25.3 ± 1.2; recreational runner)	Asymptomatic flatfeet (FPI: 6–12)	Personal running shoe	ASFO-RMP (C) + shoe	self-selected speed ±5 %; overground running with a rearfoot strike	Allowed unspecified time to familiarize	Kinematics: ankle; Kinetics: ankle, Achilles tendon load
Mo [45]	SGQE	13 (0/13; 36.4 ± 8.8; recreational runner)	Asymptomatic flatfeet (calcaneal valgus angle: 9.0 ± 2.0)	Neutral running shoe	a. ASFO-RFMP (C-plaster-molded) + shoe, b. ASFO-RFMP (C−3D-printed) + shoe	1.9 ± 0.1 m/s; treadmill running with a rearfoot strike	15–20 min	Kinematics: ankle; Kinetics: loading rates
Costa [22]	SGQE	16 (7/9; 26.63 ± 7.94; recreational runner)	Asymptomatic flatfeet (FPI: ≥ 6 (9.94 ± 1.57)	Running shoe+FO	a. ASFO-RMP (P−3deg) + shoe, b. ASFO-RMP (P−6deg) + shoe	self-selected speed; overground running with a rearfoot strike	30 days	Kinematics: knee, ankle; Kinetics: knee, ankle
Crago [42]	SGQE	23 (11/12; 28 ± 6; recreational runner)	Asymptomatic flatfeet (Navicular drop (normalized truncated to foot length): 0.18 ± 0.03)	Standard running shoe+sock liner+Flat FO	a. ASFO-RMP (C-flexible) + shoe, b. ASFO-RMP (C-standard) + shoe	3.3 m/s; treadmill running with a rearfoot strike	30 min	Kinematics: foot arch
Ng [46]	SGQE	20 (20/0; 26.1 ± 3.1: recreational runner)	Asymptomatic flatfeet (Navicular drop: > 10.0 mm, resting calcaneal valgus angle: ≥ 4°)	Running shoe+Flat FO	ASFO (P) + shoe	slow, medium, and high speed; treadmill sprinting with a rearfoot strike	2 min	Kinetics: GRFs, loading rates
Ataabadi [23]	SGQE	20 (12/8; 26.9 ± 2.90; professional runner)	Asymptomatic flatfeet (Navicular drop: > 10.0 mm)	Running shoe	ASFO-RMP (P) + shoe	2.11 m/s ± 5 %; overground running with a rearfoot strike	10 min	Kinematics: knee, ankle; Kinetics: knee, ankle

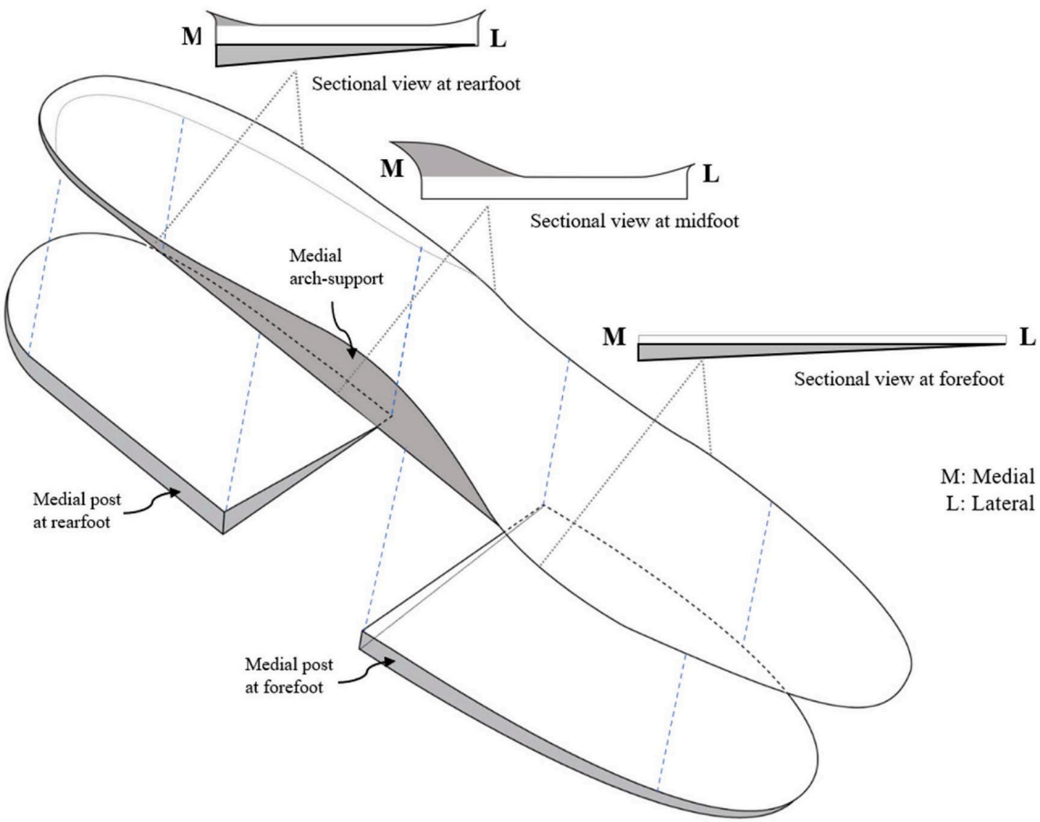
FPI-6: six item foot posture index; ASFO: arch-support-only FO; ASFO-RMP: arch-support FO with rearfoot only medial post; ASFO-RFMP: arch-support FO with rearfoot and forefoot medial post; P: prefabricated; C: custom-made; E: existing; N: new; SGQE: single group quasi-experimental; a and b: indicate different FO conditions

indicated an increase of the peak knee adductor moments with a small effect size (SMD=0.49, 95 %CI −0.10–1.09) (Fig. 4C). Non-significant changes were also revealed in subgroup analysis based on medial post position. A significant change was found in the pooled effect of peak ankle plantarflexor moments, with a medium effect size (SMD=-0.52, 95 %CI −1.08 to −0.00) (Fig. 4D). In the subgroup analysis, ASFO-RMP showed a significant decrease in peak plantarflexor moments in the pooled analysis, exhibiting a large effect size (SMD=-0.84, 95 %CI −1.53 to −0.14). The pooled effects of ASFO-RFMP on v-GRF loading rates showed no significant changes (SMD=-0.06, 95 %CI −0.47–0.35) (Fig. 4E). Moreover, Achilles tendon loading rates with ASFO-RMP were significantly reduced, with a large effect size (SMD=-0.94, 95 %CI −1.78 to −0.09). The removal of heterogeneity sources did not alter the effects observed in the sensitivity analysis.

4. Discussion

This systematic review and meta-analysis aimed to summarize the efficacy of FO in modifying lower extremity kinematics and kinetics while running with asymptomatic flatfeet. Our findings identified two

Table 3
Visual illustration of foot orthoses intervention.

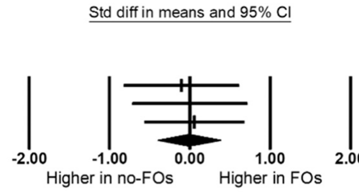
<table>
<tr><th>Visualization</th><th>Explanation/features</th></tr>
<tr><td rowspan="2">

Medial arch-support foot orthosis with medial post at rearfoot and forefoot</td>
<td>Arch-support-only FO : [24, 46, 48, 49]
• Prefabricated or custom-made by the manufacturer.
• Arch-heights were reported as 29mm [46], or unspecified with design/fit considerations for the arch-region.
Arch-support FO with medial posts : [21-24, 42-45, 47]
• Medial post is designed to control excessive pronation.
• Additional wedge is integrated at the medial side of arch-support FO.
• Position of the medial wedge might be at the rearfoot and forefoot [21, 24, 43, 45] or rearfoot only [22, 23, 42, 44, 47].
• Inclination varied from 3-6 degrees (3-degree wedge [22], 4-degree wedge, 5-degree wedge [21, 23, 24, 43-45], 6-degree wedge [22], and degrees based on severity of pronation to normal foot [47])</td></tr>
<tr><td>Materials:
High density EVA [23], thermo moldable EVA (shore A 40-45) [21, 22], 3-4 mm polypropylene [24, 42, 44, 45, 49], graphite polyurethane [48], thermoplastic polyurethane [47], Nylon (shore D 58) [45], and an unspecified material [43] was used for the fabrication of FO in the included studies.</td></tr>
</table>

A. Arch-support-only FO: Peak ankle eversion

Study name	Std diff in means	Lower limit	Upper limit	Z-Value	p-Value
Hurd a 2010	-0.104	-0.820	0.612	-0.285	0.776
Hurd b 2010	0.000	-0.716	0.716	0.000	1.000
Mundermann a 2003	0.056	-0.564	0.676	0.176	0.860
Pooled	-0.009	-0.401	0.383	-0.044	0.965

Statistics for each study



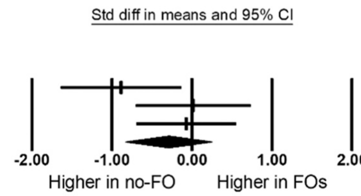
Test for heterogeneity: $I^2 = 0\%$

Random effects

B. Arch-support-only FO: Peak ankle inverter moment

Study name	Std diff in means	Lower limit	Upper limit	Z-Value	p-Value
Hurd a 2010	-0.886	-1.636	-0.136	-2.316	0.021
Hurd b 2010	0.016	-0.700	0.732	0.043	0.965
Mundermann a 2003	-0.071	-0.691	0.549	-0.224	0.822
Pooled	-0.291	-0.828	0.246	-1.063	0.288

Statistics for each study



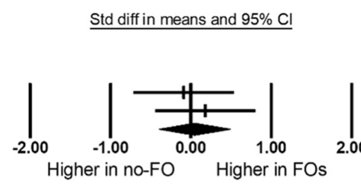
Test for heterogeneity: $I^2 = 44\%$

Random effects

C. Arch-support-only FO: v-GRF impact peak

Study name	Std diff in means	Lower limit	Upper limit	Z-Value	p-Value
Mundermann a 2003	-0.089	-0.709	0.532	-0.280	0.779
Ng 2021	0.178	-0.443	0.799	0.561	0.575
Pooled	0.044	-0.394	0.483	0.198	0.843

Statistics for each study



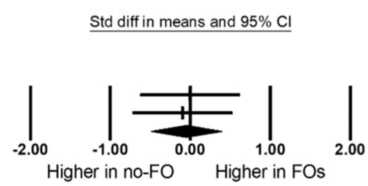
Test for heterogeneity: $I^2 = 0\%$

Random effects

D. Arch-support-only FO: v-GRF active peak

Study name	Std diff in means	Lower limit	Upper limit	Z-Value	p-Value
Mundermann a 2003	-0.003	-0.623	0.617	-0.010	0.992
Ng 2021	-0.098	-0.718	0.522	-0.310	0.757
Pooled	-0.051	-0.489	0.388	-0.226	0.821

Statistics for each study



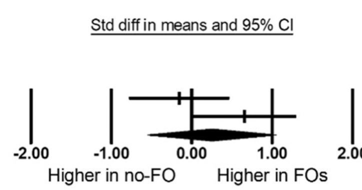
Test for heterogeneity: $I^2 = 0\%$

Random effects

E. Arch-support-only FO: v-GRF loading rates

Study name	Std diff in means	Lower limit	Upper limit	Z-Value	p-Value
Mundermann a 2003	-0.156	-0.776	0.465	-0.492	0.623
Ng 2021	0.656	0.020	1.292	2.020	0.043
Pooled	0.247	-0.548	1.042	0.608	0.543

Statistics for each study



Test for heterogeneity: $I^2 = 68\%$

Random effects

Fig. 2. Forest plots of pooled analysis: effects of arch-support FO on lower extremity kinematics and kinetics. The letters 'a' and 'b' refer to different types of FO being tested, please see table 2 for clarification.

main types of FO employed in modifying biomechanics in flatfeet: arch-support-only FO (ASFO) and arch-support FO integrated with medial posts (ASFO-RMP and ASFO-RFMP). Running with ASFO revealed no significant changes in lower extremity kinematics or kinetics, suggesting that this design may be ineffective in modifying lower extremity biomechanics during running. In contrast, arch-support FO with medial posts, particularly ASFO-RFMP might be effective in modifying frontal plane foot and ankle kinematics and kinetics of asymptomatic flatfeet.

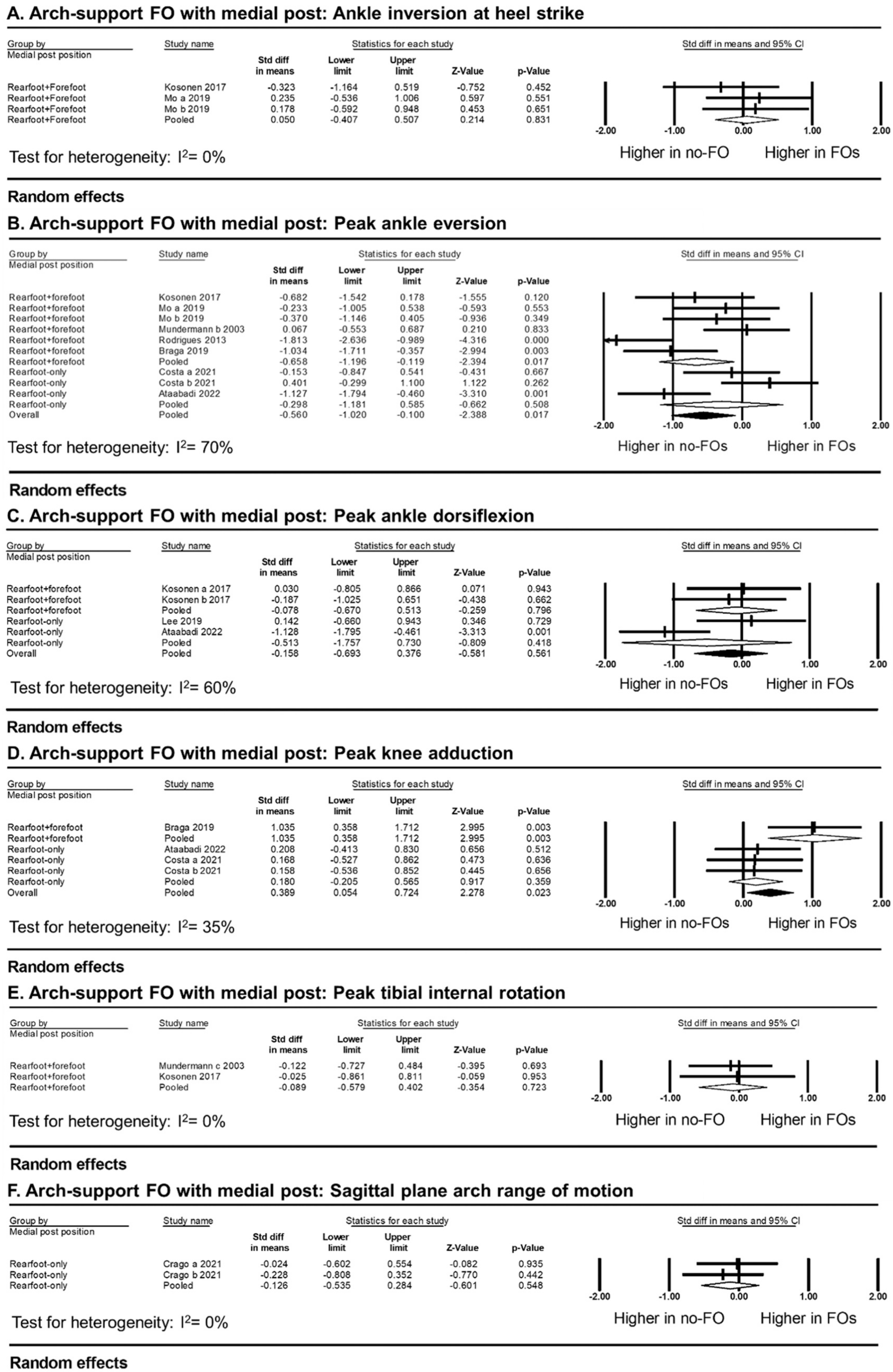


Fig. 3. Forest plots of pooled analysis: effects of medial posts FO on lower extremity kinematics. The letters 'a' and 'b' refer to different types of FO being tested, please see table 2 for clarification.

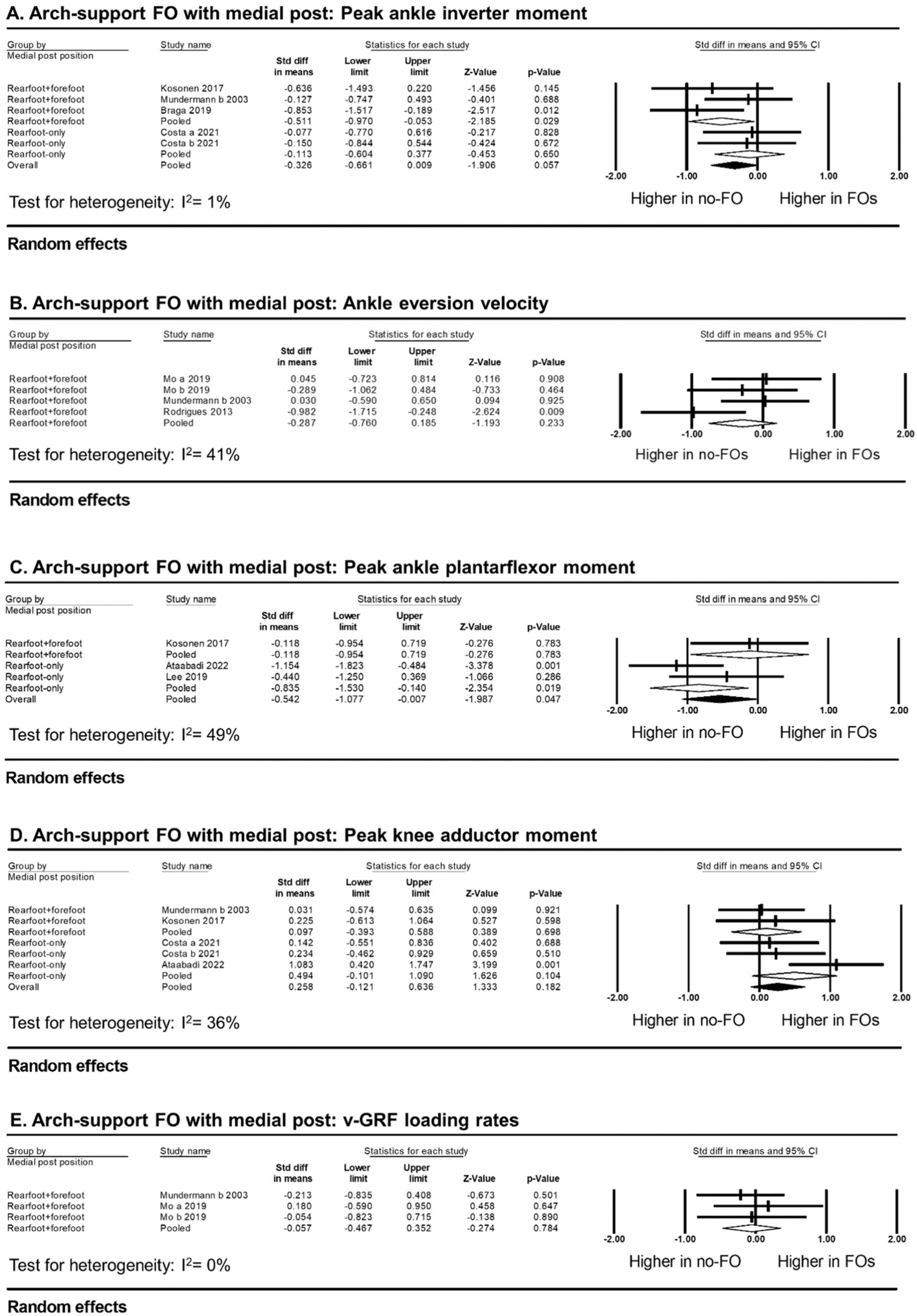


Fig. 4. Forest plots of pooled analysis: effects of medial posts FO on lower extremity kinetics. The letters 'a' and 'b' refer to different types of FO being tested, please see table 2 for clarification.

4.1. Arch-support-only FO

FO with arch-support structures are often recommended to resist the collapsed arch in individuals with flatfeet [52]. However, our meta-analysis revealed no significant changes in ankle and knee kinematics and kinetics during running. Previous meta-analyses have also found that ASFO failed to adequately control pronation in flatfeet during walking [26]. For FO to effectively replicate the function of the foot arch, two key distinct features are needed [53]. First, during the loading response to the midstance phase of running, the arch should flatten slightly to absorb shock and store potential energy. Second, during the terminal stance to push-off phase of running, the arch should form a rigid lever for efficient propulsion. Evidence suggests that arch-support structure increases total foot contact area and redistributes peak plantar pressure in flatfeet with collapsed arches [54], contributing to improved shock absorption, cadence, and perceived comfort [55–57]. However, our meta-analysis on lower extremity joint biomechanics does not support these contentions. One possible explanation is that ASFO may lack the necessary stiffness to support the natural deformation of the medial longitudinal arch and induce biomechanical effects. Supporting this notion, a study on healthy subjects reported that ASFO with greater stiffness influenced rearfoot eversion during walking [58]. Furthermore, many studies on FO use generic orthoses that are not tailored to individual biomechanical characteristics. This universal design may significantly reduce their impact on lower extremity biomechanics, as they may not adequately accommodate individual foot morphology.

4.2. Arch-support FO with medial posts

FO with medial posting is often recommended to help control eversion by limiting potentially adverse movements at the subtalar and midtarsal joints [59]. This meta-analysis examined two distinct design concepts of medial post FO. A combination of medial posts at both the rearfoot and forefoot (ASFO-RFMP) effectively reduced peak ankle eversion angle, though with a small effect size. These findings are aligned with recent studies that reported reduced peak ankle eversion angle during walking [58,60]. A previous meta-analysis on FO and gait also supports these findings, showing that rearfoot eversion can be reduced by 2–3 degrees with small effect sizes [61]. Additionally, like peak eversion angle, a reduction in peak ankle invertor moments was observed in our meta-analysis, consistent with studies examining anti-pronation FO during walking [62].

In contrast, the effects of ASFO-RMP were not statistically significant, and these can be attributed to the materials used and the design of the support structures. Specifically, these configurations may lack sufficient stiffness to effectively influence lower extremity biomechanical outcomes. The stiffness of the ASFO-RMP, which is typically measured by assessing its resistance to deformation under load, must reach a certain threshold to have measurable biomechanical effects during running. If the medial arch-support stiffness in FO is insufficient, the impact on lower extremity joint biomechanical outcomes may be limited. A previous study reported that adding both rearfoot and forefoot medial posts in arch-support FO increased medial arch stiffness by 205 % [63]. In contrast, rearfoot only posts increased medial arch stiffness by only 35 % [64]. This significant difference suggests that incorporating both rearfoot and forefoot posts is critical for enhancing medial arch stiffness, particularly during the midstance phase of running. These enhanced support structures are crucial for resisting pronation during the loading response to midstance, thereby contributing to improved biomechanical control.

During the loading response to the midstance phase, the tibia internally rotates. In individuals with flatfeet, this often results in the triple joints comprising the subtalar, talonavicular, and calcaneocuboid joints, adopting an excessively everted or valgus position due to insufficient support from the posterior tibialis tendon [53] and plantar aponeurosis. The posterior tibialis muscle group, which eccentrically controls ankle eversion during this phase, can experience increased demands, leading to excessive invertor moments. As a key dynamic stabilizer of the medial arch [65], its overload may contribute to biomechanical inefficiencies. Increasing the stiffness of the foot can help resist this excessive joint eversion by preventing the triple joints from moving into adverse positions. The triple joints are integral to the foot structure, connecting with the tarsus, metatarsal bones, and midfoot plantar ligaments to form the foot arches. By incorporating arch-support structures with medial posts, it is possible to provide additional passive stiffness and reduce eversion [66]. This external support provided by ASFO-RFMP against foot eversion can effectively reduce excessive invertor moments. Consequently, this support helps limit excessive pronation during running.

In individuals with flatfeet, the flexibility of the foot arch can also affect running mechanics, particularly during the push-off phase. Typically, the triceps surae muscles (i.e., soleus, medial and lateral gastrocnemius) work with the Achilles tendon to facilitate forward propulsion by leveraging the rigid foot arch. However, in individuals with flatfeet, this propulsive impulse is often delayed due to the flexible nature of the foot arch, which shifts from midstance to terminal stance with increased tension in the triceps surae muscles [53]. This suggests that increasing arch rigidity could provide a more stable foot structural platform for effective propulsion mechanics to address the delayed push-off. In our meta-analysis, the reduction in peak plantarflexor moments may be attributed to decreased triceps surae activity and a more stabilized foot position during forward propulsion. By providing additional support to the arch, medial posts can enhance structural rigidity, contributing to a more stable foot posture and a more efficient push-off.

Consequently, the loading rate of the Achilles tendon decreased with ASFO-RMP. Reduced tension in the Achilles tendon and triceps surae during propulsion lowers the forces across the tibiotalar joints and shifts the weight bearing from the forefoot to the midfoot by enhancing the lever function of the arch. This redistribution of weight and reduction in tibiotalar joint forces may help alleviate excessive stress on the Achilles tendon [67,68]. The significant changes in peak knee adduction with the ASFO-RFMP may be due to the coupled motion of ankle and knee within a closed kinematic chain [69,70]. The increase in peak knee adduction was also reflected in peak knee adductor moments, consistent with previous studies on anti-pronation control [62]. This increased peak knee adductor moment might reduce the risk for tibial stress syndrome [71].

4.3. Limitations

Several limitations should be considered when interpreting this systematic review and meta-analysis. First, only a small number of studies examined the effectiveness of FO during running with asymptomatic flatfeet. These studies addressed various outcome measures of the lower extremity, resulting in each outcome being evaluated across a limited number of studies. Few studies assessed specific outcomes, such as midfoot/arch angles and moments, frontal plane ankle moments, velocity, and ROM, sagittal plane ankle moments and ROM, frontal plane knee angles and moments, and Achilles tendon loading. Moreover, many outcome measures included in the meta-analysis were peak or discrete values at heel strike, which may introduce bias related to variable selection and reduce the robustness of the findings about the FO efficacy. Statistical parametric mapping, which allows continuous curve analysis of biomechanical data, could be useful in identifying specific joint and muscle groups that limit performance.

This review did not perform a subgroup analysis based on the degree of pronation, adaptation time, or materials used in the FO fabrication because of the limited number of relevant studies for each outcome measure. It should be noted that materials and their corresponding thickness and stiffness may introduce different biomechanical effects and consequently modulate their efficacy. All included studies focused on the immediate effects of FO on the lower extremity, thus, their effects of medium- and long-term uses remained unknown. Additionally, the studies included primarily focused on the FO effects during running, with limited information on their use during walking. Asymptomatic flatfeet is an anatomical variant rather than a pathomechanical disorder, thus, using FO during running could potentially influence walking biomechanics over time. Future research should explore the same FO effects on both walking and running to better understand their influence and efficacy on gait patterns. Some studies used flat FO with shoes as controls, which might potentially influence the outcomes. The outcome measures of this review did not include plantar pressure, muscle activity, or stress/strain of tendons/ligaments, which would be valuable for understanding the mechanisms of arch-support FO in managing pronated feet.

4.4. Clinical implications

Overall, our findings suggest that the effectiveness of FO in modifying lower extremity pronation-related joint movement is strongly associated with their design, particularly the positioning of medial posts. Positioning medial post at both the rearfoot and forefoot in the arch-support FO could offer clinical benefits, although this has been evaluated in only a few studies. This configuration was the only one in our meta-analysis that showed robust effects on lower extremity biomechanics. Thus, reduced peak ankle eversion angle and invertor moments, along with decreased Achilles tendon loading rates, might help alleviate internal stress, decrease the likelihood of running-related injuries, and improve performance. However, while some metrics showed statistically significant changes with small effect sizes, the clinical relevance of these changes remains uncertain. Additionally, the short adaptation time used in the included studies may limit our understanding of the long-term effects of FO use. Although two previous studies examined short-term dose-response effects (one on running and the other on walking), both used rearfoot-only posts [22,72]. To address this gap, future research should explore the dose-response effects of rearfoot and forefoot medial posts for long-term use in individuals with asymptomatic flatfeet. This research could provide critical insights into the underlying mechanisms of FO designs and modifications and help determine the clinical relevance and ultimately optimize their therapeutic benefits.

5. Conclusions

Although a limited number of studies were evaluated, ASFO-RFMP were effective in modifying subtalar joint biomechanics in adults with asymptomatic flatfeet. Using ASFO-RFMP could help reduce pronation and address related biomechanical factors associated with certain musculoskeletal conditions in runners with flatfeet. Among the interventions, ASFO did not show statistically significant modifications in lower extremity kinematics and kinetics in this meta-analysis. Further research is needed to examine dose-response effects, long-term outcomes, and the impact on muscle activity, along with tendon/ligament biomechanics during both running and walking. This would provide a more comprehensive understanding of the medial longitudinal arch function with varying arch-supports, medial posts, and movements.

CRediT authorship contribution statement

Noelle W.K. Lau: Writing – review & editing, Methodology, Investigation. **Aliyeh Daryabor:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Yufan He:** Writing – review & editing, Methodology, Investigation. **Hiroaki Hobara:** Writing – review & editing, Investigation. **Wing-Kai Lam:** Writing – review & editing, Investigation. **Toshiki Kobayashi:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Fan Gao:** Writing – review & editing, Investigation. **Abu Jor:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors report there are no competing interests to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.06.003.

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