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Effects of foot orthoses application during walking on lower limb joint angles and moments in adults with flat Feet: A systematic review with Meta-Analysis

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ABSTRACT

This systematic review with *meta*-analysis aimed to investigate the effects of foot orthoses (FO) application on lower limb joint angles and moments in adults with flexible flat-feet during walking. The following five databases were systematically searched from inception until March 2024: Scopus, PubMed, EMBASE, PEDro, and Cochrane Central Register of Controlled Trials (CENTRAL). Between-group standardized mean differences (SMDs) with 95% confidence intervals were computed using a random-effects model. Study heterogeneity was assessed using the I^2-index. Twenty-four studies were identified and *meta*-analyzed. Studies were then categorized according to the applied flat-feet assessment method: (1) foot posture index (FPI-6) or clinical observation; (2) foot print arch index or radiography; (3) arch height index (including navicular drop, the arch height index, navicular height normalized to foot length [NNHT]); (4) forefoot varus method; (5) rearfoot eversion or resting calcaneal stance position (RCSP). The *meta*-analysis showed significant effects of FO application during walking on peak rearfoot eversion (ten studies: moderate SMDs), peak ankle dorsiflexion (five studies: small SMDs), and eversion (seven studies: moderate SMDs). This *meta*-analysis indicated significant effects of FO application on peak ankle eversion moment (five studies: small SMDs) and peak knee adduction moment (six studies: small SMDs). We observed greater effects of FO application on walking mechanics in the studies that used the FPI-6 method for the assessment of foot posture. Since previous research showed particularly high test–retest reliability measures for the FPI-6 method, we recommend to uniformly use this type of foot posture measure in future studies.

1. Introduction

Foot pronation can occur during standing, walking or running and is characterized by a multi-joint movement including the rear- and mid-foot segments (Lundberg et al., 1989). In dynamic situations, foot pronation serves as a shock absorber during the early to mid-stance phase of walking or running (Lafortune et al., 1994) which is why foot pronation is not per se a maladaptation. Flat-feet (FF) however may alter the mechanics of the lower limb such as altered joint kinematics and pressure distribution of the plantar surface together with increased demands on the intrinsic foot muscles that control the arch deformation (Bishop et al., 2016). Neal et al. (Neal et al., 2014) reported limited evidence in their *meta*-analysis in the form of small effects that a pronated foot posture constitutes a risk factor for the medial tibial stress syndrome and patellofemoral pain. Levinger et al. (Levinger et al., 2010) showed that individuals with FF demonstrated greater peak forefoot plantarflexion, forefoot abduction, and rearfoot internal rotation during walking compared to individuals with normal foot posture. Another study indicated that calcaneal eversion resulted in increased hip flexion, medial rotation, and pelvic anterior tilt during the stance phase of walking (Tateuchi et al., 2011). Therefore, the treatment of excessive FF is considered by some researchers and practitioners to be relevant to avoid

Abbreviations: FF, Flat-feet; FO, foot orthoses; CENTRAL, Cochrane Central Register of Controlled Trials; SMDs, standardized mean differences; CI, confidence interval; FPI, foot posture index; NNHT, navicular height normalized to foot length; RCSP, resting calcaneal stance position; MLA, medial longitudinal arch; SD, standard deviation; Std, standardized.

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acute and lower limb injuries (Farahpour et al., 2016; Jafarnezhadgero et al., 2019; Neal et al., 2014).

Foot orthoses (FO) are often applied as therapeutic tools to modulate lower limb biomechanics (Chen et al., 2010; Leung et al., 1998). In addition, there is evidence from biomechanical research indicating that FO application has a positive impact on foot arch alignment (Chen et al., 2010) in the form of correcting ankle joint eversion, elevating the medial longitudinal arch (MLA), and suppressing foot elongation (Kido et al., 2014). Yet, there are conflicting results reported in the scientific literature on the effects of FO treatment on walking kinematics and kinetics in individuals with FF. While some studies reported significantly reduced rearfoot eversion angles due to FO usage (Johanson et al., 1994; Telfer et al., 2013), others found no difference between FO application and control conditions (Hurd et al., 2010; Zifchock and Davis, 2008). The respective reasons for the discrepancy in findings might be due to methodological limitations such as heterogeneous study samples and different assessment protocols (e.g., gait speed, shoe type, foot model, etc.).

Different insole constructions are described in the scientific literature that have the potential to reduce FF. While some authors employed low-cost prefabricated insoles which only considered foot size (McCulloch et al., 1993; Moss et al., 1993), other researchers considered customizing prefabricated insoles by adding medial or lateral wedges (Braga et al., 2019; Kristanto et al., 2021). Of note, custom-made insoles manufactured through foot casting aim to position the subtalar joint in neutral position (Andreasen et al., 2013; Gijon-Nogueron et al., 2015). Previously, many different insole constructions have been used in a clinical research context (Andreasen et al., 2013; Braga et al., 2019; Gijon-Nogueron et al., 2015; Kristanto et al., 2021; McCulloch et al., 1993; Moss et al., 1993). For instance insoles with the aim to reduce foot pronation during the stance phase of walking (McCulloch et al., 1993; Moss et al., 1993).

Besides original research, a number of systematic reviews has been conducted over the past years. Most of these studies were characterized by methodological limitations such as study heterogeneity, poor methodological quality, or small sample sizes. The first systematic review with *meta*-analysis on the effects of FO application on rearfoot eversion in individuals with FF was conducted in 2011 (Cheung et al., 2011). The authors found that particularly custom-made FOs were effective in decreasing foot pronation (Cheung et al., 2011). Another systematic review article focused on adults with flexible FF and found limited evidence supporting the long-term effectiveness of FOs to improve rearfoot kinematics (e.g., peak rear foot eversion) and kinetics (e.g., impact force) (Banwell et al., 2014). Researchers from a recent systematic review with *meta*-analysis observed that FO application resulted in lower peak rearfoot eversion angles in adults with flexible FF (low level of evidence) (Desmyttere et al., 2018). Taken together, these contradictory findings in original research and systematic reviews can, amongst others, be attributed to methodological limitations (e.g., different FF definitions).

Previous systematic reviews (Banwell et al., 2014; Cheung et al., 2011; Desmyttere et al., 2018) also considered the effects of FO application on walking mechanics, including the evaluation of navicular drop or the arch height index in individuals with FF. However, the authors of the respective studies did not consider the methodological quality of different foot posture assessment methods (Banwell et al., 2014; Cheung et al., 2011; Desmyttere et al., 2018). Some researchers used the navicular drop method to assess foot mobility (McPoil et al., 2008). However, this test has been criticized lately because the navicular drop appears not to be a valid method for the assessment of foot posture (Langley et al., 2016). Despite these critical reports on the navicular drop method, previous systematic reviews (Banwell et al., 2014; Cheung et al., 2011; Desmyttere et al., 2018) included studies using the navicular drop as the preferred method for the assessment of FF. Due to the described methodological limitations of previous systematic reviews and *meta*-analyses, it appears timely to update and aggregate the available literature on the effects of FO application on walking kinematics and kinetics in adults with FF to provide helpful information for healthcare practitioners. Here, we aimed to investigate the effects of FO application (i.e., one session) on lower limb kinematics and kinetics during walking in adults with FF. In contrast to previous systematic reviews and *meta*-analyses, we attempt to report our findings according to the applied methods that were used to define 'FF'. By reporting the study results according to the applied foot posture assessment method, readers receive a more differentiated picture on the effectiveness of the application of FOs on lower limb joint angles and moments in adults with flexible FF during walking.

2. Methods

Studies were classified into five categories based on the applied FF assessment method: (1) studies that used the FPI-6 or clinical observation; (2) studies that applied the foot print arch index; (3) studies that used the arch height index (including navicular drop, arch height index, navicular height normalized to foot length [NNHT]; (4) studies that applied the forefoot varus method; (5) studies that used the rearfoot eversion or RCSP. Cornwall et al., (2008) defined the FF posture as FPI-6 scores greater ≥ 6. Morrison et al., (2004) defined FF as navicular drop values > 10 mm. Wong et al., (2012) considered a footprint arch index ranging between 0.21 and 0.26 as normal. Values > 0.26 were classified as FF (Wong et al., 2012). According to the same authors, an arch height index ≥ 0.356 has been classified as FF. The feet of individuals with a resting calcaneal stance position (RCSP) of $+5^{\circ}$ to -5° have previously been (mean RCSP $= 1.88^{\circ}$) classified as "neutral'', those with a RCSP angle $\geq 5^{\circ}$ were considered as FF (Evans et al., 2003; Pierrynowski et al., 1996; Subotnick, 1975). According to Buchanan and Davis, individuals whose forefoot angle ranged between 1.0° and 8.0° were categorized as "neutral'' feet, those with a forefoot angle $\geq 8.0^{\circ}$ were categorized to have FF (Buchanan and Davis, 2005). Hunt et al., (2000) considered rearfoot angles $\geq 5^{\circ}$ valgus as FF and 4° valgus to 4° varus a neutral foot type.

With regards to the fabrication method, FOs were classified as customized or prefabricated.

We adhered to the standard PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). The protocol for this work was registered with PROSPERO on November, 17th 2023 (Project: https://www.crd.york.ac.uk/prospero/#myprospero, ID: CRD42023480039).

2.1. Eligibility criteria

EndNote 20 software (Bld 14672, Clarivate, Philadelphia, PA, USA) was used for the systematic search and the processing of potentially eligible papers. A PICOS (participants, intervention, comparators, outcomes, and study design) approach was applied to define inclusion and exclusion criteria (Appendix 1 Table S1) a priori (Moher et al., 2009). To be eligible for inclusion in this *meta*-analysis, articles had to be published in peer-reviewed journals in English language. Articles not written in English language were excluded (Appendix 1 Supplementary file Table S1).

2.2. Information sources, search strategy

The following five databases were systematically searched from inception until March 2024: Scopus, PubMed, EMBASE, PEDro, and Cochrane Central Register of Controlled Trials (CENTRAL). Grey literature sources (e.g., proceedings) from Google Scholar, Science Direct, Clinicaltrial.gov, PROQUEST and reference lists of already identified articles, were systematically screened for more articles to be eligible for inclusion. The literature search was developed for PubMed and adapted to each database (Appendix 1Supplementary file Search strategy). The search syntax was created using the PICOS scheme and free-text keywords as well as medical subject headings (Mesh terms). Keywords and Mesh terms were combined using a Boolean search syntax and the operators AND, OR.

2.3. Study selection

All titles and abstracts were reviewed by two authors of this paper (A. E., and A.J.) to identify potentially eligible studies according to the a priori defined inclusion and exclusion criteria. In case titles and abstracts did not provide sufficient information, full-texts were examined. Any difference in the rating of the two authors was resolved through discussion with a third reviewer (SHM).

2.4. Quality assessment

The methodological quality of the included studies was evaluated by the same two authors (A.E., A.J.) using a modified version of the Downs and Black checklist for non-randomized controlled trials (Downs and Black, 1998). The overall quality score of each study was calculated based on a percentage of the maximum score (20). In cases where there were discrepancies in the authors' rating of the quality scores, consensus was reached through discussion. Studies with quality scores of 75 % or higher were considered high quality, those with scores between 60 % and 74 % were classified as moderate quality, and those with scores of 60 % or lower were categorized as low quality (Radzimski et al., 2012).

2.5. Data collection

One author (A.E.) extracted all relevant data according to the PICOS approach (population, foot posture measurement, study protocol, intervention, orthoses design, and outcomes related to kinematic and kinetic data) from the included articles. To reduce any errors in the extraction of data, all data were checked by the author (A.J.). Values of the peak, mean angle, and joint excursion were extracted and reported as kinematic variables. Joint moments were reported as kinetic variables. If more than one type of FO was examined, each FO type within the study was allocated simple identification (A, B etc.). In case study authors did not report outcomes, we attempted to obtain them directly through the corresponding author or a freeware web-based plot digitizer (Rohatgi, 2022) to obtain data from graphs. Next, we categorized the data based on the specific foot assessment methods and compared the movement and force variables for each joint for both the FO and control conditions. The key outcomes according to validity and function are reported in the text, secondary outcomes in supplementary materials.

2.6. Statistical analyses

Quantitative data synthesis was illustrated in the form of forest plots using the Cochrane Review Manager 5.1 (The Cochrane Collaboration, Copenhagen, Denmark). To examine the main research question, within group standardized mean differences (SMDs) with 95 % confidence intervals (CI) were computed as effect size measures using a random-effects model to elucidate the effects of FO application compared to controls on kinematic and kinetic variables during walking. SMDs were categorized as trivial (0–0.2), small (0.2–0.5), moderate (0.5–0.8), and large (> 0.8) (Cohen, 1988; Kraemer and Kupfer, 2006; McGough and Faraone, 2009). Study heterogeneity was assessed using the I^2 index. The level of heterogeneity was classified as high (> 75 %), moderate (50 %–75 %), and low (25 %–50 %) (Higgins et al., 2003).

3. Results

3.1. Study selection

The initial search identified 13,597 studies. After duplicate removal, 6,381 studies remained. Following the screening of titles and abstracts, 116 full texts were further considered. Finally, 24 studies were eligible to be included in this systematic review with *meta*-analysis. Quantitative analyses were computed with all 24 articles. Fig. 1 presents a PRISMA flow chart and illustrates the study selection process.

3.2. Study characteristics

Appendix 1 Table S2 Supplementary file shows the characteristics of the included studies. The identified studies used different types of foot posture measurements (i.e., FPI-6, clinical observation, foot print arch index, radiographs, navicular drop, arch height index, NNHT, forefoot varus, rearfoot eversion, RCSP) and different foot models for kinematic and kinetic analyses. For instance, seven studies were identified with the FPI-6 or clinical observation (Costa et al., 2021; Desmyttere et al., 2021a; Hsu et al., 2022; Lourenço et al., 2022; Permsombat and Pensri, 2021; Stacoff et al., 2007; Telfer et al., 2013), four with the foot print arch index (Kulcu et al., 2007; Peng et al., 2020; Prachgosin et al., 2017; Tang et al., 2015), six with the arch height index (Bishop et al., 2016; Chen et al., 2010; Cobb et al., 2011; Han et al., 2019; Zifchock and Davis, 2008), four with the forefoot varus method (Brown et al., 1995; Hurd et al., 2010; Johanson et al., 1994; Nawoczenski and Ludewig, 2004); three with the rearfoot eversion or RCSP method (Alsaafin et al., 2023; Dedieu et al., 2013; Genova and Gross, 2000b).

With regards to the applied FO fabrication methods (prefabricated or customized), 11 studies used prefabricated FOs (Alsaafin et al., 2023; Brown et al., 1995; Costa et al., 2021; Genova and Gross, 2000b; Han et al., 2019; Hurd et al., 2010; Johanson et al., 1994; Kulcu et al., 2007; Lafortune et al., 1994; Peng et al., 2020; Stacoff et al., 2007), 14 studies customized FOs (Bishop et al., 2016; Chen et al., 2010; Cobb et al., 2011; Dedieu et al., 2013; Desmyttere et al., 2021a; Hsu et al., 2022; Kosonen et al., 2017; Lourenço et al., 2022; Nawoczenski and Ludewig, 2004; Permsombat and Pensri, 2021; Prachgosin et al., 2017; Tang et al., 2015; Telfer et al., 2013; Zifchock and Davis, 2008), and one study used two different types of FOs (Lafortune et al., 1994). In terms of the applied FO materials, 12 studies used rigid FOs, and only two studies investigated the effects of flexible FOs. Other studies did not address the FO types as flexible or rigid. Therefore, we could not *meta*-analyze the available data according to the used FO fabrication method (rigid vs. flexible) due to an insufficient number of available studies.

Researchers from six studies investigated the effects of FO application on participants with flexible FF (Alsaafin et al., 2023; Cobb et al., 2011; Han et al., 2019; Hurd et al., 2010; Kulcu et al., 2007; Tang et al., 2015). Of note, none of the included studies referred to rigid FF.

Tang et al. (Tang et al., 2015) reported values for participants with and without FF. For the purpose of this study, we only extracted data for the FF group. Additionally, we reported numerical values for all types of foot orthoses used in the respective studies (Alsaafin et al., 2023; Brown et al., 1995; Cobb et al., 2011; Costa et al., 2021; Desmyttere et al., 2021a; Han et al., 2019; Hsu et al., 2022; Hurd et al., 2010; Johanson et al., 1994; Lourenço et al., 2022; Nawoczenski and Ludewig, 2004; Stacoff et al., 2007; Telfer et al., 2013; Zifchock and Davis, 2008). We extracted data from graphs out of five studies (Costa et al., 2021; Dedieu et al., 2013; Desmyttere et al., 2021a; Lourenço et al., 2022; Zifchock and Davis, 2008).

The outcome measures peak rearfoot eversion angle, peak ankle eversion and dorsiflexion angle, peak ankle eversion moment and knee adduction moment were reported in $\geq$ five studies. The remaining outcome measures with lower clinical relevance were included in the supplementary material (Supplementary File: Appendix 2–31).

3.3. Quality assessment

The methodological quality of the included 24 studies amounted to 77 % on the modified version of the Downs and Black checklist (Downs and Black, 1998). This is indicative of high methodological quality (Supplementary file Appendix 1 Table S3). Among the 24 included

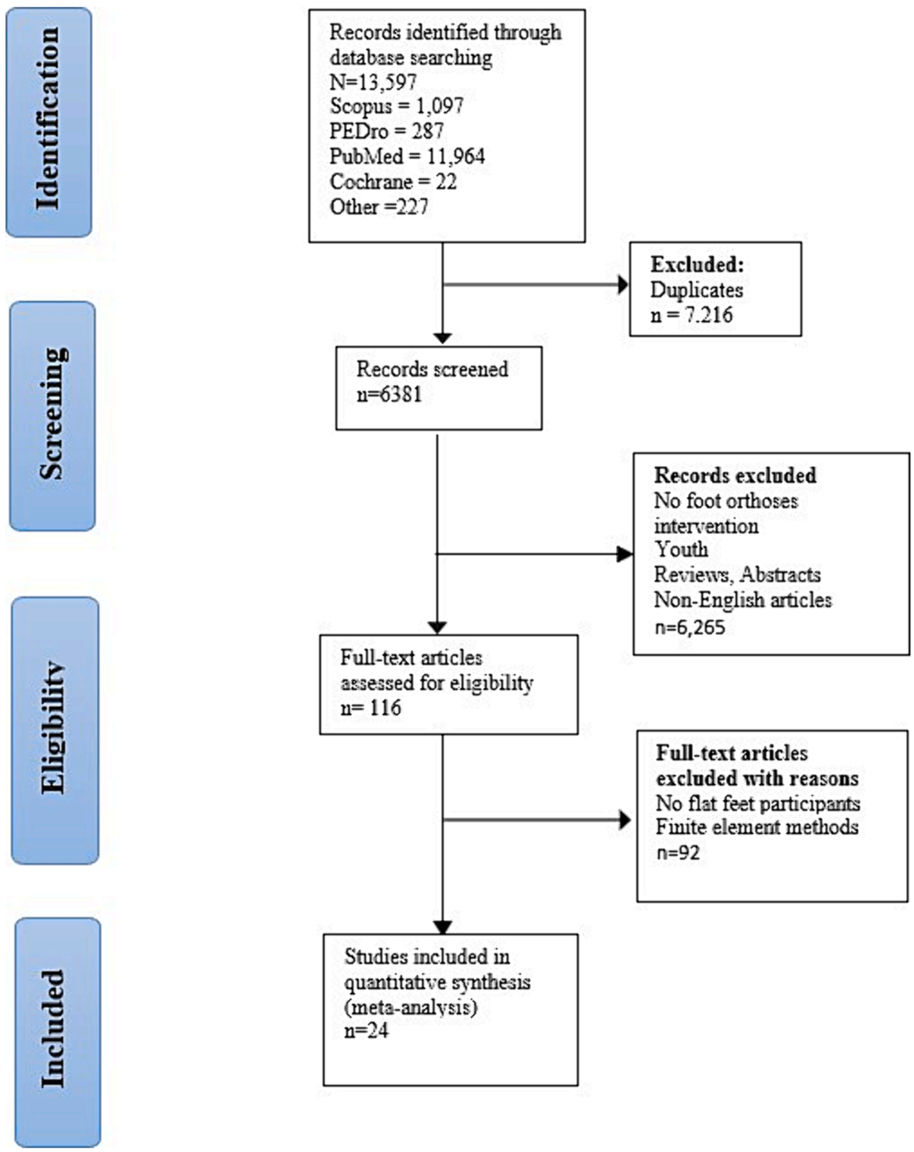

Fig. 1. PRISMA flow diagram of studies included in this systematic review with *meta*-analysis.

studies, 15 were rated high quality (Alsaafin et al., 2023; Bishop et al., 2016; Brown et al., 1995; Chen et al., 2010; Costa et al., 2021; Han et al., 2019; Hsu et al., 2022; Hurd et al., 2010; Kosonen et al., 2017; Lourenço et al., 2022; Nawoczenski and Ludewig, 2004; Peng et al., 2020; Prachgosin et al., 2017; Telfer et al., 2013; Zifchock and Davis, 2008), and nine moderate quality (Cobb et al., 2011; Dedieu et al., 2013; Desmyttere et al., 2021a; Johanson et al., 1994; Permsombat and Pensri, 2021; Stacoff et al., 2007; Tang et al., 2015). Only two studies (Desmyttere et al., 2021a; Telfer et al., 2013) involved assessors who were blinded for the experimental condition (FO or control) during testing. Authors from 11 studies (Alsaafin et al., 2023; Bishop et al., 2016; Chen et al., 2010; Costa et al., 2021; Han et al., 2019; Hurd et al., 2010; Kosonen et al., 2017; Nawoczenski and Ludewig, 2004; Peng et al., 2020; Zifchock and Davis, 2008) reported the calculation of a priori power analysis to estimate the sample size.

3.4. *Effects of FO application on lower limb joint angles*

3.4.1. *Rearfoot*

Ten studies reported the effects of FO application on peak rearfoot eversion (Bishop et al., 2016; Brown et al., 1995; Dedieu et al., 2013; Genova and Gross, 2000b; Han et al., 2019; Hurd et al., 2010; Johanson et al., 1994; Stacoff et al., 2007; Tang et al., 2015; Telfer et al., 2013). Findings indicated moderate effects of FO application. The analysis further revealed moderate level of heterogeneity (moderate SMDs = 0.65, 95 % CI 0.34 to 0.95, $p < 0.0001$, $I^2 = 71$ %). More specifically, across the ten included studies, the peak rearfoot eversion was 1.74° (95 % CI 1.04 to 2.44) lower in the FO condition compared to control (Fig. 2). The subgroup analyses of FO fabrication revealed significantly lower peak rearfoot eversion in both prefabricated (Brown et al., 1995; Genova and Gross, 2000b; Han et al., 2019; Hurd et al., 2010; Johanson et al., 1994; Stacoff et al., 2007) (six studies: SMDs 0.43, 95 % CI 0.24, 0.61, $p < 0.00001$, I2 = 0 %, $I^2 = 0$ %) and customized (Bishop et al., 2016; Dedieu et al., 2013; Tang et al., 2015; Telfer et al., 2013) (four studies: SMDs 1.55, 95 % CI 0.46 to 2.64, $p = 0.005$, $I^2 = 87$ %) FOs compared to the control condition (Fig. 2, Supplementary file [Appendix 1 Table S4]).

The subgroup analyses taking the methodological approach for the assessment of FF into account showed no significant effect of FO wearing for the studies that assessed foot posture using the arch height index (Bishop et al., 2016; Han et al., 2019) (two studies: SMDs = 0.33, 95 % CI −0.07 to 0.73, $p = 0.10$) or the foot print arch index (Tang et al., 2015) (one study SMDs = 0.64, 95 % CI −0.26 to 1.55, $p = 0.16$) and the rearfoot eversion or RCSP methods (Dedieu et al., 2013; Genova and

Study or Subgroup	control Mean	control SD	control Total	orthoses Mean	orthoses SD	orthoses Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.9.6 Customized								
Bishop 2016	6.8	3.3	18	7.8	3.7	18	5.6%	-0.28 [-0.94, 0.38]
Dedieu 2013	9.87	2.74	12	6.67	2.03	12	4.6%	1.28 [0.39, 2.17]
Tang 2015	11.3	3.5	10	9.2	2.7	10	4.6%	0.64 [-0.26, 1.55]
Telfer 2013 A	6.3	1.2	12	3.84	1.06	12	4.1%	2.10 [1.07, 3.13]
Telfer 2013 B	6.3	1.2	12	2.84	1.25	12	3.6%	2.73 [1.56, 3.89]
Telfer 2013 C	6.3	1.2	12	2.37	1.16	12	3.3%	3.22 [1.94, 4.49]
Subtotal (95% CI)			**76**			**76**	**25.8%**	**1.55 [0.46, 2.64]**
Heterogeneity: Tau² = 1.60; Chi² = 39.72, df = 5 (P < 0.00001); I² = 87%								
Test for overall effect: Z = 2.78 (P = 0.005)								
2.9.7 Prefabricated								
Brown 1995 A	0.9	3.7	14	0.6	3.8	14	5.2%	0.08 [-0.66, 0.82]
Brown 1995 B	0.9	3.7	14	-0.2	3.4	14	5.2%	0.30 [-0.45, 1.05]
Genova and Gross 2000	14.7	6.6	13	12.5	5.1	13	5.1%	0.36 [-0.41, 1.14]
Han 2019 A	5.4	4.1	28	2.89	3.1	28	6.1%	0.68 [0.14, 1.22]
Han 2019 B	5.4	4.1	28	2.7	2.4	28	6.1%	0.79 [0.25, 1.34]
Hurd 2010 A	3.4	4.94	15	2.8	3.87	15	5.4%	0.13 [-0.59, 0.85]
Hurd 2010 B	3.4	4.94	15	2.7	4.54	15	5.4%	0.14 [-0.57, 0.86]
Johanson MA 1994 A	0.8	3.01	22	-1.35	2.84	22	5.8%	0.72 [0.11, 1.33]
Johanson MA 1994 B	0.8	3.01	22	-0.88	3.29	22	5.9%	0.52 [-0.08, 1.13]
Johanson MA 1994 C	0.8	3.01	22	-0.36	3.03	22	5.9%	0.38 [-0.22, 0.97]
Johanson MA 1994 D	0.8	3.01	22	-0.44	3.25	22	5.9%	0.39 [-0.21, 0.99]
Stacoff 2007 A	4.5	1.5	8	5.5	1.7	8	4.2%	-0.59 [-1.60, 0.42]
Stacoff 2007 B	4.5	1.5	8	2.2	1.9	8	3.8%	1.27 [0.17, 2.37]
Stacoff 2007 C	4.5	1.5	8	4.6	2.1	8	4.3%	-0.05 [-1.03, 0.93]
Subtotal (95% CI)			**239**			**239**	**74.2%**	**0.43 [0.24, 0.61]**
Heterogeneity: Tau² = 0.00; Chi² = 12.92, df = 13 (P = 0.45); I² = 0%								
Test for overall effect: Z = 4.57 (P < 0.00001)								
Total (95% CI)			**315**			**315**	**100.0%**	**0.65 [0.34, 0.95]**
Heterogeneity: Tau² = 0.32; Chi² = 62.26, df = 19 (P < 0.00001); I² = 69%								
Test for overall effect: Z = 4.12 (P < 0.0001)								
Test for subgroup differences: Chi² = 3.96, df = 1 (P = 0.05), I² = 74.7%								

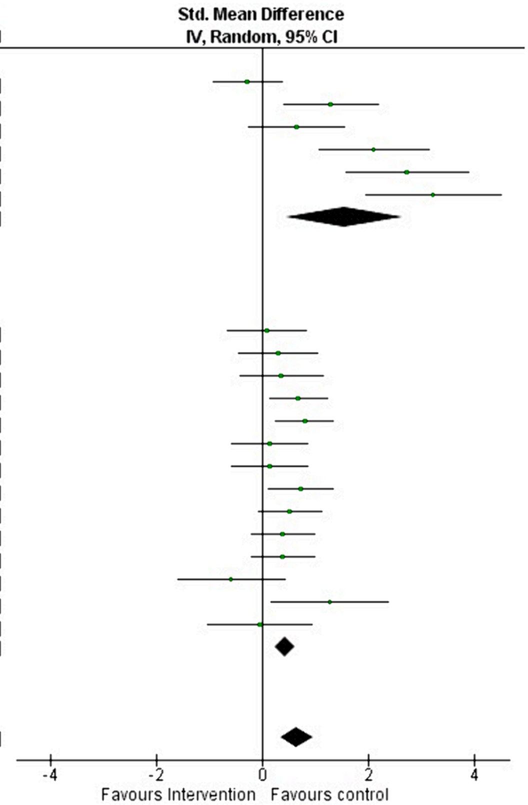

Fig. 2. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak rearfoot eversion during walking in individuals with flat-feet. The subgroup effect of FO fabrication methods was calculated for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

Gross, 2000b) (two studies: SMDs = 0.79, 95 % CI −0.11 to 1.69, p = 0.08). Moreover, this *meta*-analysis revealed significant effects of FO application in studies that used the forefoot varus method (Brown et al., 1995; Hurd et al., 2010; Johanson et al., 1994) (three studies: small SMDs = 0.42, 95 % CI 0.16 to 0.68, p = 0.001), the FPI-6 or clinical observation (Stacoff et al., 2007; Telfer et al., 2013) (two studies: large SMDs = 1.42, 95 % CI 0.20 to 2.63, p = 0.02, I^2 = 87) for determination of foot pronation (Fig. 3, Supplementary file [Appendix 1 Table S5]).

3.4.2. Ankle

Peak ankle dorsiflexion was measured in five studies (Alsaafin et al., 2023; Chen et al., 2010; Desmyttere et al., 2021a; Hsu et al., 2022; Peng et al., 2020). Overall, the findings indicated small effects of FO application (five studies: small SMDs = -0.33, 95 % CI −0.54 to −0.12, p = 0.002, I^2 = 0 %). More specifically, the mean (five studies) peak ankle dorsiflexion was 0.61° (95 % CI 1.05 to 2.75) greater in the FO compared to the control condition (Fig. 4). The subgroup analyses of FO fabrication revealed significantly greater peak ankle dorsiflexion in customized FOs (Chen et al., 2010; Desmyttere et al., 2021a; Hsu et al., 2022) (three studies: SMDs −0.49, 95 % CI −0.89 to −0.08, p = 0.02, I^2 = 0 %). This effect was not found in prefabricated FOs (Alsaafin et al., 2023; Peng et al., 2020) (two studies: SMDs −0.86, 95 % CI −2.90 to 1.18, p = 0.41, I^2 = 54 %) (Fig. 4, Table S4). Also, the subgroup analyses of the assessment methodology of FF showed no significant effects of FO application in those studies that assessed foot posture using the arch height index (Chen et al., 2010) (one study: SMDs = -0.19, 95 % CI −1.03 to 0.65, p = 0.18) or the foot print arch index (Peng et al., 2020) (one study: SMDs = 0.42, 95 % CI −0.30 to 1.15, p = 0.26). Significant effects of FO application were found for the studies that used the FPI-6 or clinical observation (Desmyttere et al., 2021a; Hsu et al., 2022) (two studies: small SMDs = -0.42, 95 % CI −0.72 to −0.12, p = 0.007, I^2 = 0 %) and rearfoot eversion or RCSP (Alsaafin et al., 2023) (one study: small SMDs = -0.42, 95 % CI −0.78 to −0.06, p = 0.02, I^2 = 0 %) to determine the foot posture (Fig. 5, Supplementary file [Appendix 1 Table S5]).

Peak ankle eversion was measured in seven studies (Brown et al., 1995; Costa et al., 2021; Desmyttere et al., 2021a; Hsu et al., 2022; Johanson et al., 1994; Lourenço et al., 2022; Peng et al., 2020). Based on findings from the seven included studies, the analysis indicated significant moderate effects of FO application (moderate SMDs = 0.58, 95 % CI 0.27 to 0.90, p = 0.0003) (Fig. 4) with a moderate level of study heterogeneity (I^2 = 72 %). More specifically, the mean (seven studies) peak ankle eversion was 1.10° (95 % CI 0.58 to 1.62) lower in the FO condition compared to control. The FO fabrication subgroup analyses revealed significantly lower peak ankle eversion in prefabricated (Brown et al., 1995; Costa et al., 2021; Johanson et al., 1994; Lourenço et al., 2022; Peng et al., 2020) (five studies: SMDs 0.44, 95 % CI 0.24 to 0.63, p < 0.00001, I^2 = 1 %) versus customized FOs (Desmyttere et al., 2021a; Hsu et al., 2022) (two studies: SMDs 1.00, 95 % CI −0.03 to 2.03, p = 0.06, I^2 = 89 %) (Fig. 6, Table S4). With regards to the applied FF assessment methodology, the subgroup analysis showed no significant effects of FO application in the studies that assessed foot posture using the foot print arch index (Peng et al., 2020) (one study: SMDs = 0.55, 95 % CI −0.18 to 1.28, p = 0.14). Significant effects were observed for the studies that used the FPI-6 or clinical observation (Costa et al., 2021; Desmyttere et al., 2021a; Hsu et al., 2022; Lourenço et al., 2022) (four studies: moderate SMDs = 0.68, 95 % CI 0.13 to 1.23, p = 0.01, I^2 = 83 %) and forefoot varus (Brown et al., 1995; Johanson et al., 1994) (two studies: moderate SMDs = 0.5, 95 % CI 0.24 to 0.77, p = 0.0002, I^2 = 0 %) to determine FF (Fig. 7, Supplementary file [Appendix 1 Table S5]).

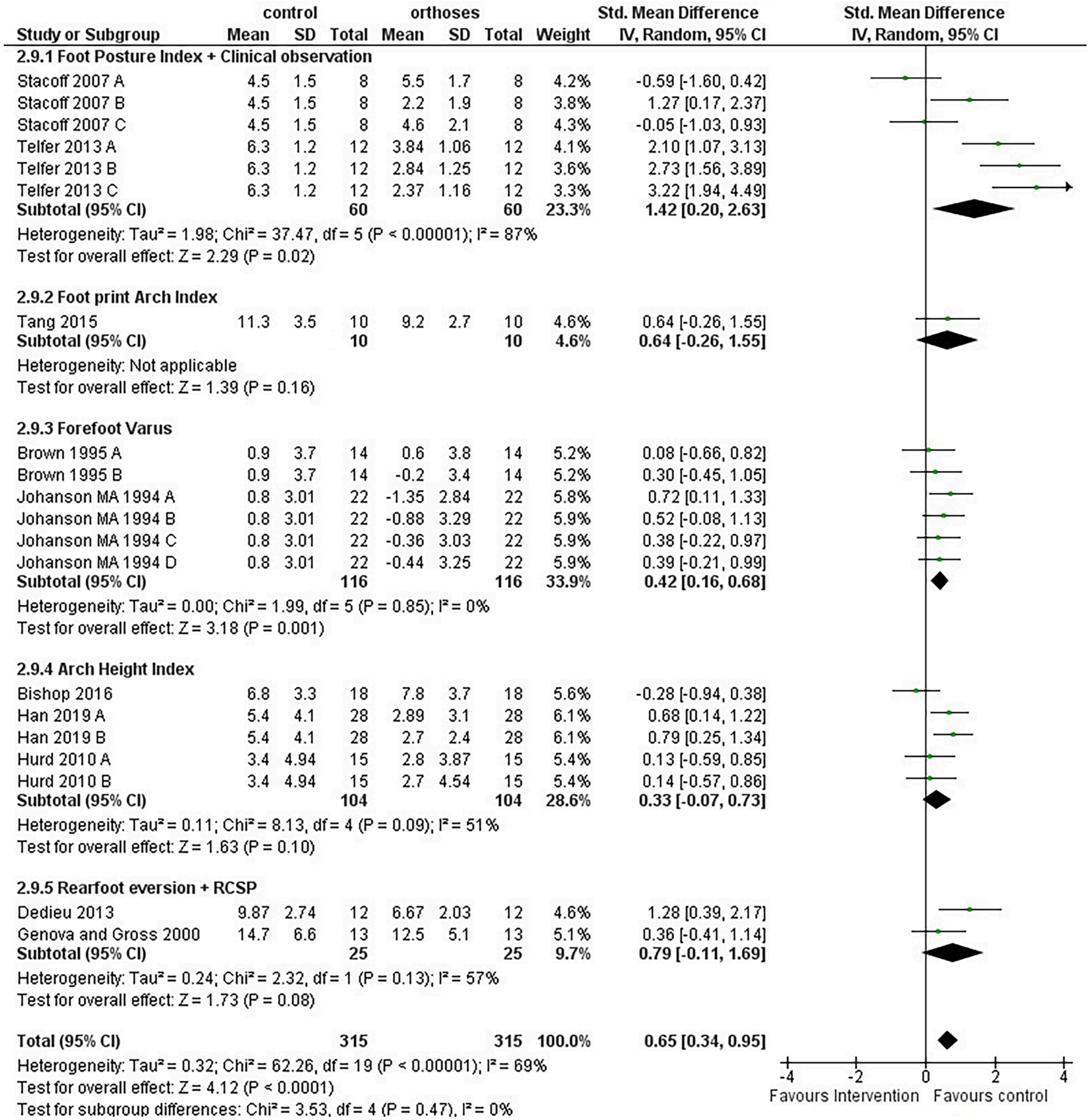

Fig. 3. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak rearfoot eversion during walking in individuals with flat-feet. The subgroup effect with regards to the methodological approach for flat-feet assessment was calculated for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

3.5. Effects of FO application on lower limb joint moments

3.5.1. Ankle

Five studies reported peak ankle eversion moment in Nm/kg (Costa et al., 2021; Han et al., 2019; Hsu et al., 2022; Lourenço et al., 2022; Prachgosin et al., 2017). Overall, the analysis indicated no evidence of study heterogeneity ($I^2 = 0$ %) and yielded significant differences between FO application and control (five studies: small SMDs = 0.38, 95 % CI 0.17 to 0.59, p = 0.0004) (Fig. 5). More specifically, the peak ankle eversion moment was 0.07 Nm/kg (95 %CI 0.04 to 0.11) smaller in the FO condition. The subgroup analyses of FO fabrication revealed significantly lower ankle eversion moment in prefabricated (Costa et al., 2021; Han et al., 2019; Lafortune et al., 1994) (three studies: SMDs 0.48, 95 % CI 0.23 to 0.74, p = 0.0002, $I^2 = 0$ %) in contrast to customized FOs (Hsu et al., 2022; Lafortune et al., 1994; Prachgosin et al., 2017) (three studies: SMDs 0.17, 95 % CI −0.20 to 0.54, p = 0.37, $I^2 = 0$ %) (Fig. 8, Table S4). The applied subgroup analysis of the FF assessment methods showed a significant difference only for the study that used the arch height index (Han et al., 2019) (Fig. 9, Supplementary file [Appendix 1 Table S5]).

3.5.2. Knee

Six studies reported the effects of FO application on peak knee adduction moments (Chen et al., 2010; Costa et al., 2021; Desmyttere

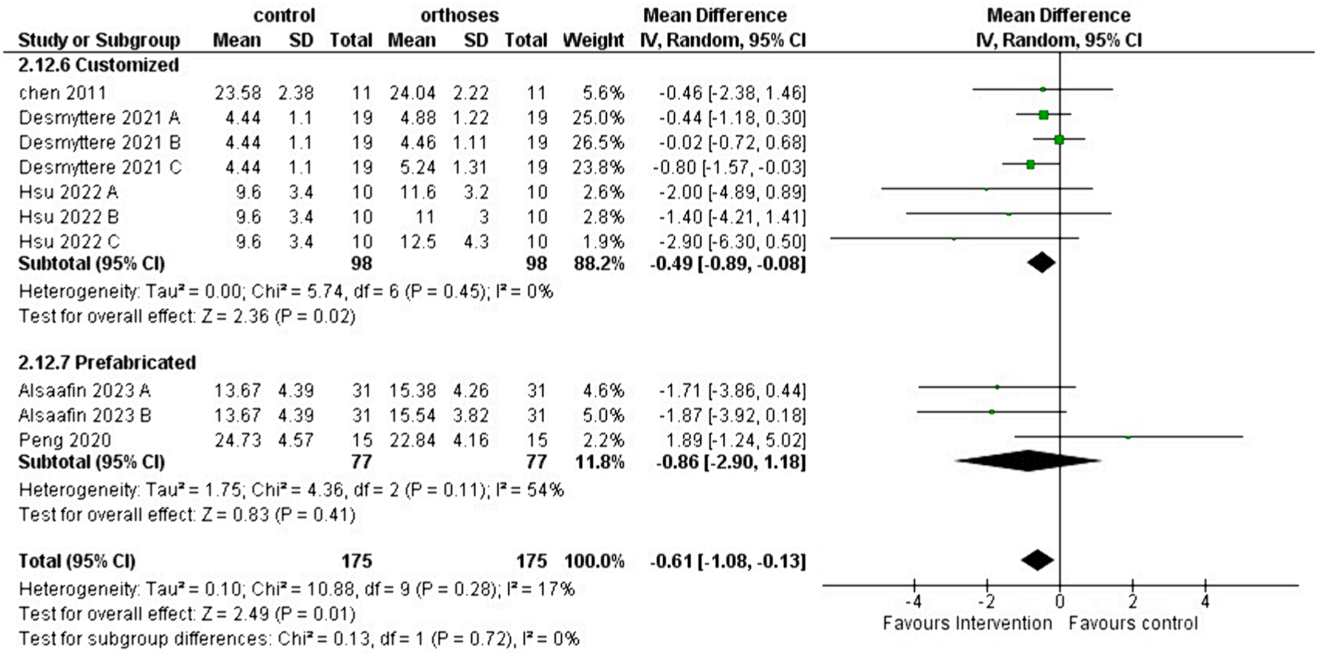

Fig. 4. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle dorsiflexion during walking in individuals with flat-feet. The subgroup effect of FO fabrication methods was computed for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

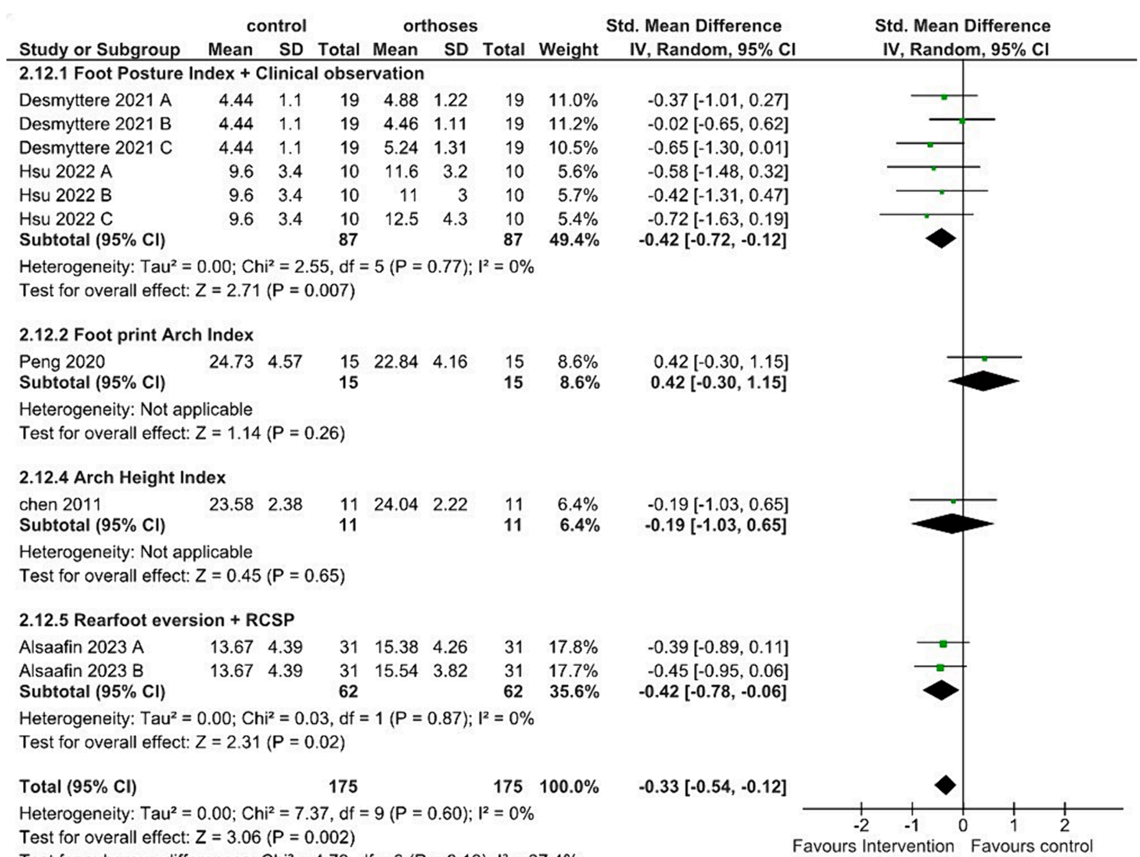

Fig. 5. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle dorsiflexion during walking in individuals with flat-feet. The subgroup effect with regards to the methodological approach for flat-feet assessment was computed for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

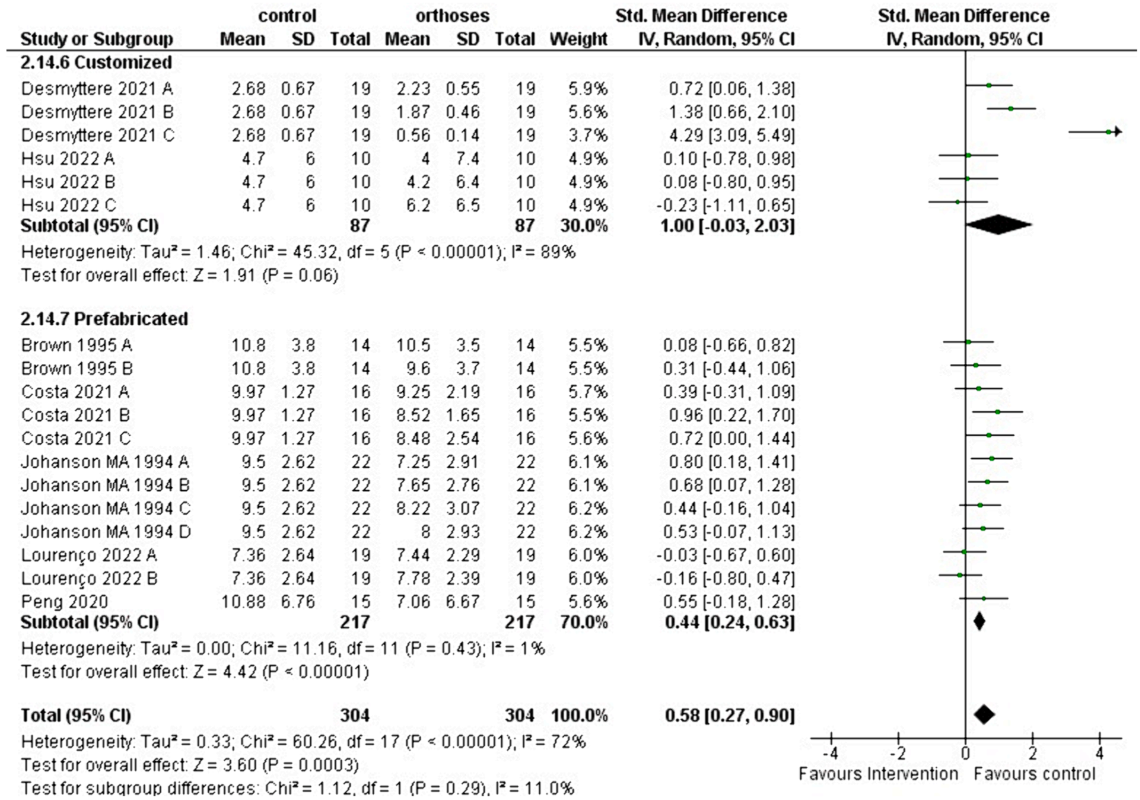

Fig. 6. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle eversion during walking in individuals with flat-feet. The subgroup effect of FO fabrication methods was calculated for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

et al., 2021a; Hsu et al., 2022; Kosonen et al., 2017; Lourenço et al., 2022). The subgroup analyses of FO fabrication revealed significantly greater peak knee adduction moments in the prefabricated (Cohen, 1988; Desmyttere et al., 2021a; Hsu et al., 2022; Kosonen et al., 2017; Lourenço et al., 2022) (five studies: SMDs −0.47, 95 % CI −0.81 to −0.12, p = 0.008, $I^2 = 0$ %) compared with the customized FOs (Costa et al., 2021; Lourenço et al., 2022) (two studies: SMDs −0.21, 95 % CI −0.46 to 0.04, p = 0.1, $I^2 = 0$ %) (Fig. 10, Supplementary file [Appendix 1 Table S4]). With regards to the FF assessment methodology, the subgroup analyses included four studies for the FPI-6 and the clinical observation assessment foot posture method and showed greater peak knee adduction moments (0.04 Nm/kg; 95 % CI −0.07 to −0.02) in the FO compared to the control condition (Appendix 32, Table S5). For the arch height index, findings from two studies did not reach the level of significance (Appendix 32). Overall, there was a significant small effect of FO application on the knee adduction moment (six studies: SMDs = -0.30, 95 % CI −0.50 to −0.10, p = 0.004, $I^2 = 0$ %) (Appendix 32, Supplementary file Appendix 1 Table S5). More specifically, the peak knee adduction moment was 0.07 Nm/kg (95 % CI −0.11 to −0.03) greater in the FO condition compared to control.

4. Discussion

With regards to joint angles, the *meta*-analysis showed significant effects of FO application on peak rearfoot eversion (lower in FO condition), peak ankle dorsiflexion (greater in FO condition) and eversion (lower in FO condition). In terms of joint moments, the *meta*-analysis revealed significant effects of FO application on the peak ankle eversion moment (lower in FO condition) and the peak knee adduction moment (greater in FO condition).

4.1. *Rearfoot*

Our *meta*-analysis revealed that the application of FOs resulted in significantly lower peak rearfoot eversion and therefore less FF (Bishop et al., 2016; Brown et al., 1995; Dedieu et al., 2013; Han et al., 2019; Hurd et al., 2010; Johanson et al., 1994; Stacoff et al., 2007; Tang et al., 2015; Telfer et al., 2013). Findings from this *meta*-analysis showed significant effects of FO application on the peak rearfoot eversion angle only in those studies that used the forefoot varus method for the assessment of FF (Brown et al., 1995; Hurd et al., 2010; Johanson et al., 1994), the FPI-6 or clinical observation (Stacoff et al., 2007; Telfer et al., 2013). Nonetheless, both customized (Bishop et al., 2016; Dedieu et al., 2013; Tang et al., 2015; Telfer et al., 2013) and prefabricated (Brown et al., 1995; Genova and Gross, 2000b; Han et al., 2019; Hurd et al., 2010; Johanson et al., 1994; Stacoff et al., 2007) FOs have significant effects on peak rearfoot eversion. While customized FOs showed a large effect on peak rearfoot eversion angles, prefabricated FOs indicated small effects only. Reducing calcaneal eversion is a viable and achievable biomechanical target (Cheung et al., 2011). Adult individuals with FF lack a medial longitudinal arch to cushion the body mass during the stance phase of standing, walking, running due to lower arch height caused by several congenital factors or other acquired predisposing factors (Souza et al., 2010). The available evidence in the literature is weak with regards to the association between FO-related improved motion control and reduced injury rates in individuals with FF (Ryan et al., 2011). It has been hypothesized that the acquired FF and rearfoot motion regularly seen in inflammatory conditions such as rheumatoid arthritis (Turner et al., 2008; Woodburn et al., 2002a) are related to ultrasound and MRI confirmed features of joint and tendon damage, particularly those involved in controlling the frontal plane motion of the foot (Dubbeldam et al., 2013; Woodburn et al., 2002b). While cause and effect relations have not been fully established, there is good evidence

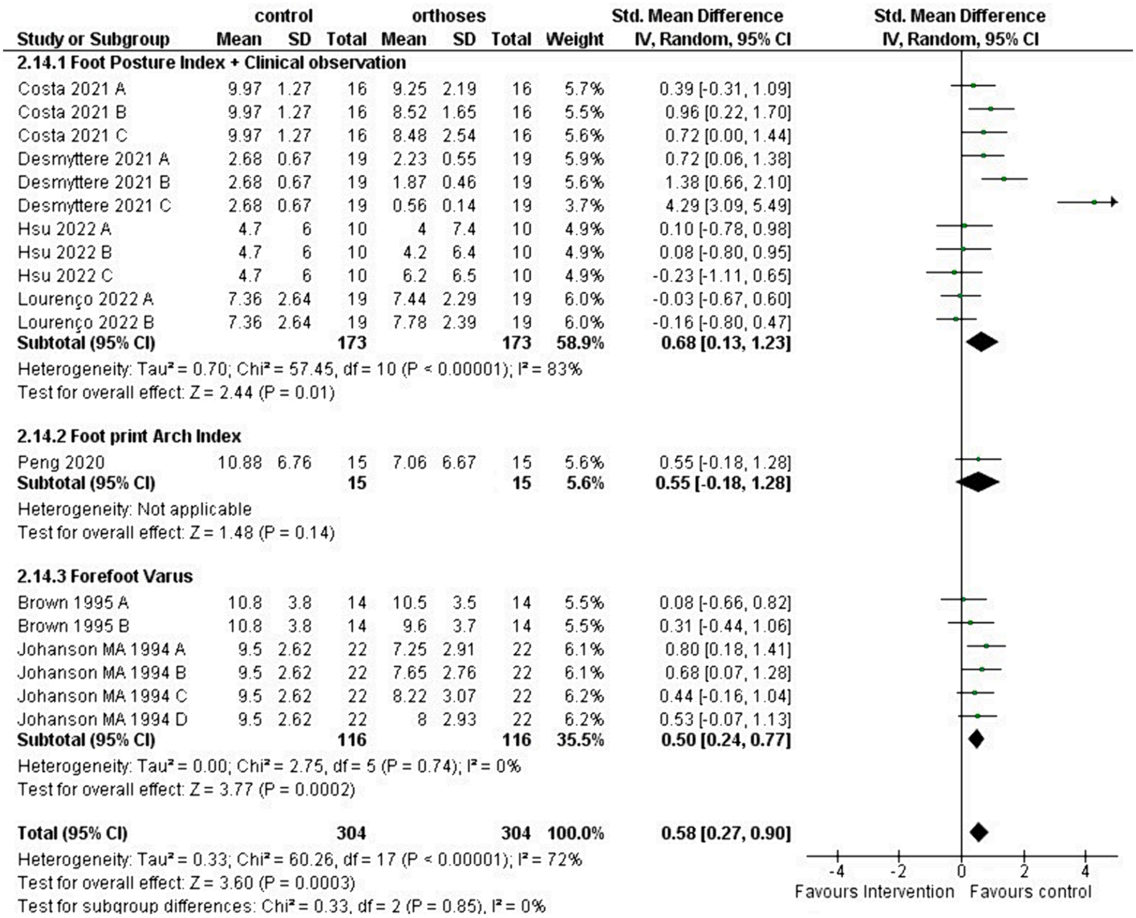

Fig. 7. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle eversion during walking in individuals with flat-feet. The subgroup effect with regards to the methodological approach for flat-feet assessment was computed for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

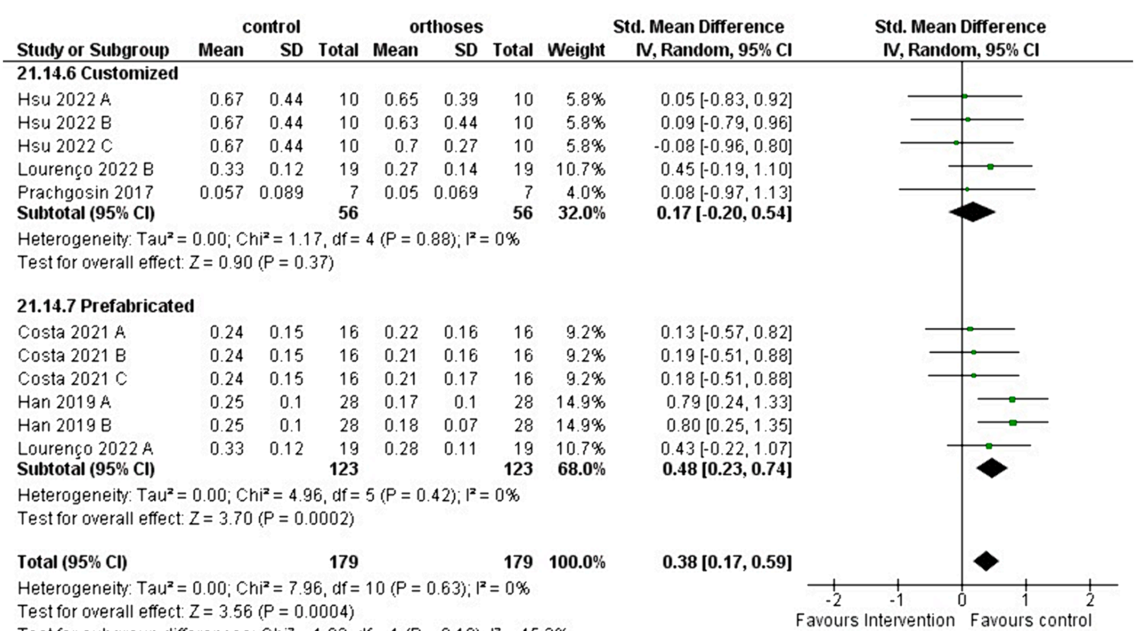

Fig. 8. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle eversion moment during walking in individuals with flat-feet. The subgroup effect of FO fabrication methods was calculated for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

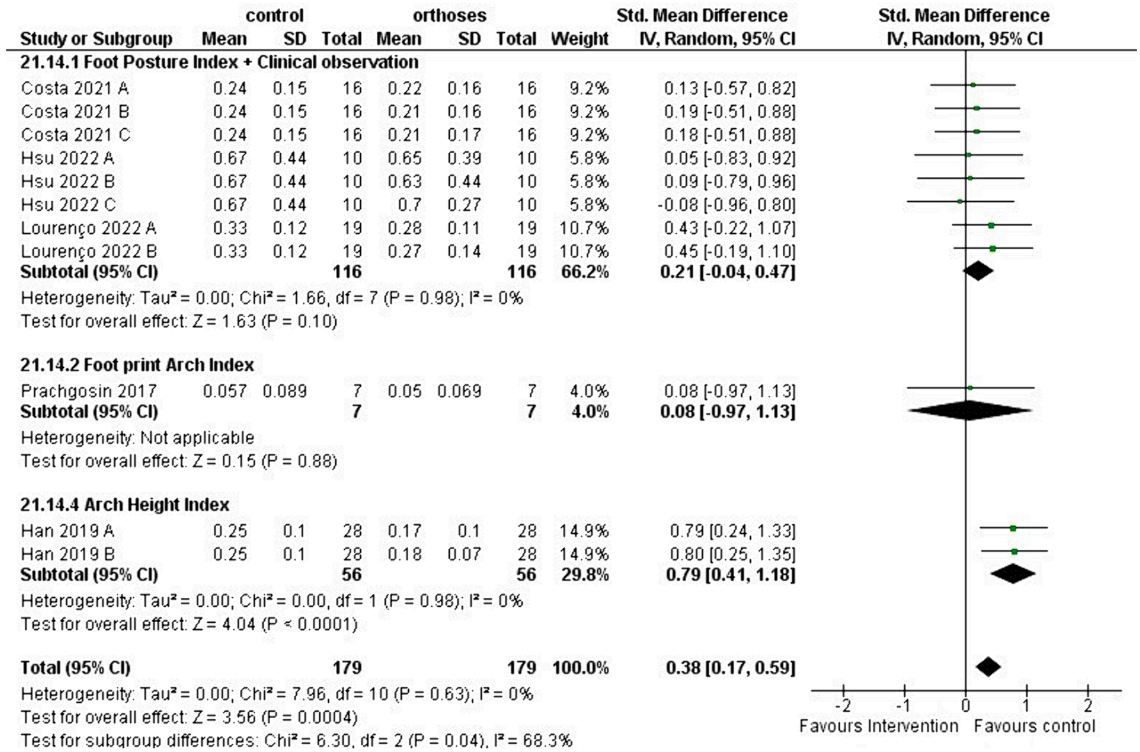

Fig. 9. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on peak ankle eversion moment during walking in individuals with flat-feet. The subgroup effect with regards to the methodological approach for flat-feet assessment was computed for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

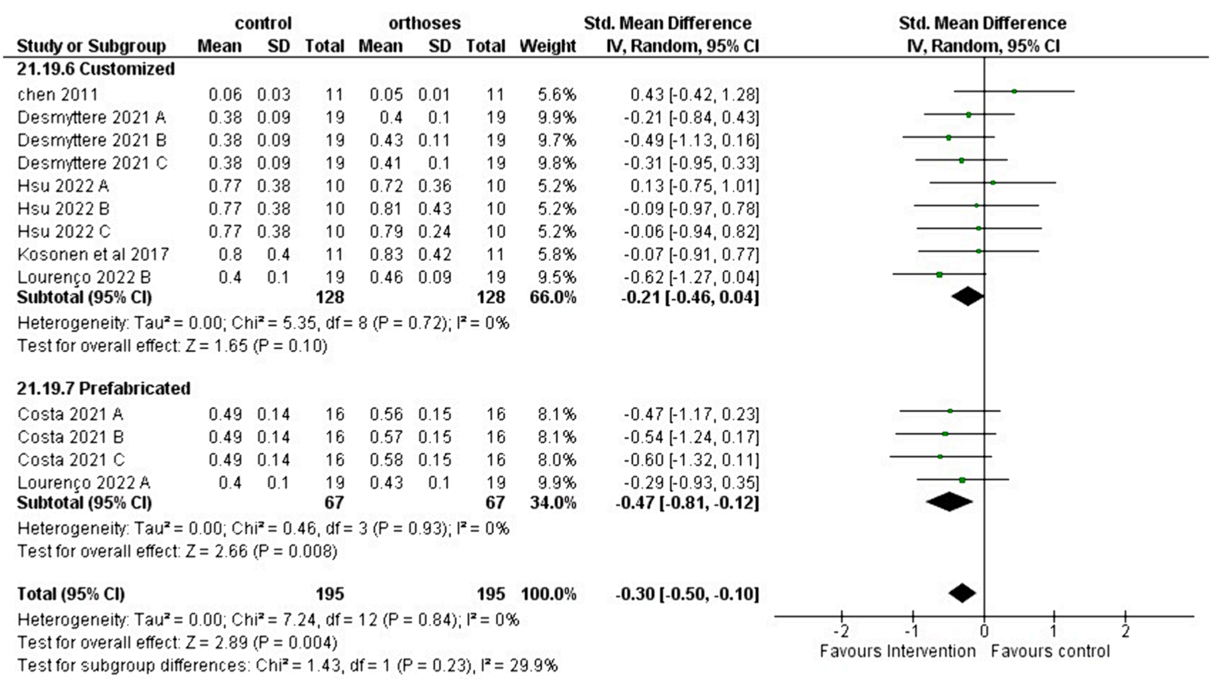

Fig. 10. Forest plot illustrating the effects of foot orthoses application (intervention) versus control on the peak knee adduction moment during walking in individuals with flat-feet. The subgroup effect of the applied FO fabrication methods was calculated for each parameter and the total effect as standardized mean difference (95% CI). SD: Standard deviation; Std: Standardized; CI: Confidence interval.

from randomized controlled trials that an early intervention using customized FO improved walking kinematics and patient reported outcomes such as pain (Hennessy et al., 2012; Woodburn et al., 2003).

4.2. Ankle

Based on the results of this *meta*-analysis, FO application resulted in a significant difference in the peak ankle dorsiflexion (Alsaafin et al., 2023; Chen et al., 2010; Desmyttere et al., 2021a; Hsu et al., 2022; Peng et al., 2020) and eversion in the FO versus control condition during walking with the lower values in the FO condition compared to the control condition (Brown et al., 1995; Costa et al., 2021; Desmyttere et al., 2021a; Hsu et al., 2022; Johanson et al., 1994; Lourenço et al., 2022; Peng et al., 2020). In addition, our analyses revealed a significant effect of FO application versus control on ankle joint dorsiflexion in those studies that used the FPI-6 or clinical observation (Desmyttere et al., 2021a; Hsu et al., 2022) and the rearfoot eversion method or RCSP (Alsaafin et al., 2023) to assess FF. Furthermore, subgroup *meta*-analysis of peak ankle eversion showed significant effects of FO application only in those studies that used the FPI-6 or clinical observation (Costa et al., 2021; Desmyttere et al., 2021a; Hsu et al., 2022; Lourenço et al., 2022) and forefoot varus to determine FF. The subgroup analyses with regards to the FO fabrication method revealed significantly greater peak ankle dorsiflexion only in customized FOs (Chen et al., 2010; Desmyttere et al., 2021a; Hsu et al., 2022). Furthermore, the FO fabrication subgroup analyses showed significantly lower peak ankle eversion angle in prefabricated FOs (Brown et al., 1995; Costa et al., 2021; Johanson et al., 1994; Lourenço et al., 2022; Peng et al., 2020). The *meta*-analysis yielded significant differences between the FO and control conditions in the peak ankle eversion moment. The peak ankle eversion moment was lower in the FO condition compared to the control. Subgroup analyses showed significant differences only in one study that used the arch height index. The subgroup analyses with regards to the FO fabrication method revealed significantly lower peak ankle eversion moments in prefabricated FOs (Costa et al., 2021; Han et al., 2019; Lafortune et al., 1994). Medially posted FOs are designed to bring the calcaneus back to normal alignment with the shank, and maintain the subtalar joint in neutral position. Thus, FOs can be used to prevent pronation and excessive movement of the whole foot (Alsaafin et al., 2023; Permsombat and Pensri, 2021). Genova and Gross (Genova and Gross, 2000a) assumed that using the posting might be associated with clinical improvements. To compensate for the reduction in rearfoot eversion, and since rearfoot and midfoot frontal motion are strongly coupled (Takabayashi et al., 2018), an increase in midfoot eversion was observed when using the posting (Desmyttere et al., 2021b). In addition, the greater forefoot inversion that usually accompanied the higher rearfoot eversion in individuals with FF was lower in this study (Desmyttere et al., 2021b). Chen et al. (Chen et al., 2010) observed lower peak ankle plantarflexion angles and moments when walking with foot insoles compared with controls in individuals with FF. This reduction can be attributed to the control of foot motion provided by the orthoses, suggesting a positive impact on foot mechanics by limiting excessive ankle movements (Alsaafin et al., 2023).

The magnitude of the joint moment during walking could be considered a good indicator of injury prevention (Novacheck, 1998). A biomechanical aspect directly affected by the FO is that the use of a smaller evertor moment could positively reduce injury risk induced through muscle fatigue or overuse (Williams 3rd et al., 2003). The results from our *meta*-analysis showed that peak eversion moments of the ankle joint in the FO conditions were significantly smaller than those of the normal condition.

4.3. Knee

Our *meta*-analysis showed that there was a significant small effect of FO application on the knee adduction moment during walking. Based on the results of our *meta*-analysis the peak knee adduction moments was greater in the FO condition compared to the control. Moreover, the analysis revealed significant effects of FO application on the peak knee adduction moment if the FPI-6 method or clinical observation were used to assess foot posture. The subgroup analyses for the applied FO fabrication method revealed significantly greater peak knee adduction moments in the prefabricated FOs (Cohen, 1988; Desmyttere et al., 2021a; Hsu et al., 2022; Kosonen et al., 2017; Lourenço et al., 2022). This study revealed that the medially FO resulted in greater knee adduction moment. Whilst we did not observe a change in the knee adduction angle, this might be due to the fact that we assessed the effects of FO usage. In a longitudinal approach, it can be hypothesized that the change in adduction moments might produce a change in adduction knee motion. If so, this would lead to changes in the distribution of load between the medial and lateral femoral-tibial compartments. For example, Kostuik et al. (Kostuik et al., 1975) found that a 3° change in knee adduction motion was needed to totally unload the lateral compartment of osteo-ligamentous cadaver knees.

Lack and colleagues found that the effects of FOs were significantly lower for knee internal rotation during a step-up task in individuals with patellofemoral pain (Lack et al., 2014). These authors described that a change in knee kinematics appears to be associated with an altered rearfoot kinematics, as the subtalar joint provides an anatomical connection between the talus and the tibia. Of note, the knee joint is a hinge-type synovial joint, which mainly allows motion in sagittal plane and a limited motion in the frontal and transversal planes. In contrast, the hip and ankle joints allow angular motion in multiple directions and rotational movements. Thus, the observed changes may likely occur in the hip and ankle joints rather than the knee joint.

In this context, Chen et al. (Chen et al., 2010) showed that custom-made insoles produced significant changes in ankle joint angles but had only minor effects on the knee and hip joint kinematics in adults during walking. Similarly, Nester et al. (Nester et al., 2003) demonstrated that both medially and laterally wedged FOs had the greatest effect on the kinematics and moments of the rearfoot complex, while the knee, hip, and pelvis were generally unaffected.

Clinical implications and limitations and methodological considerations of the present study were mentioned in the Appendix 33 and Appendix 34, respectively.

5. Conclusions

Results from this study showed that FO application compared with control conditions resulted in lower peak rearfoot eversion and peak ankle dorsiflexion and eversion angles. This *meta*-analysis further revealed that the peak ankle eversion moment was greater in the control condition and the peak knee adduction moment turned out to be larger in the FO condition. Since previous research showed particularly high test–retest reliability measures for the FPI-6 method (Langley et al., 2016), we recommend to uniformly use this type of foot posture measure in future studies. In addition, the present study revealed the need to better standardize participant recruitment and the FO assessment protocol. This should make health practitioners' management of individuals with FF easier in the future.

6. Authors' contributions

AE collected the data, analyzed the data, and wrote the manuscript; AAJ analyzed the data and wrote the manuscript; SHM collected the data and wrote the manuscript; UG analyzed the data and wrote the manuscript. All authors revised the article and have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

CRediT authorship contribution statement

AmirAli Jafarnezhadgero: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Esmaeili:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation. **Seyed Hamed Mousavi:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Urs Granacher:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.112345.

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