Accepted Manuscript

Title: The relationship between foot posture and plantar pressure during walking in adults: a systematic review

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PII: S0966-6362(18)30108-5
DOI: https://doi.org/10.1016/j.gaitpost.2018.02.026
Reference: GAIPOS 5978

To appear in: Gait & Posture

Received date: 19-7-2017
Revised date: 25-1-2018
Accepted date: 21-2-2018

Please cite this article as: Buldt Andrew K, Allan Jamie J, Landorf Karl B, Menz Hylton B. The relationship between foot posture and plantar pressure during walking in adults: a systematic review. Gait and Posture  https://doi.org/10.1016/j.gaitpost.2018.02.026

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The relationship between foot posture and plantar pressure during walking in adults: a systematic review

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Word count for abstract: 246

Word count for main text: 4998
Highlights

- A systematic review of the relationship between foot posture and plantar pressure.
- Database search found 16 studies; all were of moderate methodological quality.
- Evidence of differences in plantar pressure between cavus, planus and normal feet.
- Regression models explained a small amount of variance in plantar pressure variables.
- Inconsistent methods of included studies affected ability to make conclusions.

Abstract

Background

Foot posture is a risk factor for some lower limb injuries, however the underlying mechanism is not well understood. Plantar pressure analysis is one technique to investigate the interaction between foot posture and biomechanical function of the lower limb.

Research question

The aim of this review was to investigate the relationship between foot posture and plantar pressure during walking.

Methods

A systematic database search was conducted using MEDLINE, CINAHL, SPORTDiscus and Embase to identify studies that have assessed the relationship between foot posture and plantar pressure during walking. Included studies were assessed for methodological quality. Meta-analysis was not conducted due to heterogeneity between studies. Inconsistencies
included foot posture classification techniques, gait analysis protocols, selection of plantar pressure parameters and statistical analysis approaches.

Results

Of the 4,213 citations identified for title and abstract review, sixteen studies were included and underwent quality assessment; all were of moderate methodological quality. There was some evidence that planus feet display higher peak pressure, pressure-time integral, maximum force, force-time integral and contact area predominantly in the medial arch, central forefoot and hallux, while these variables are lower in the lateral and medial forefoot. In contrast, cavus feet display higher peak pressure and pressure-time integral in the heel and lateral forefoot, while pressure-time integral, maximum force, force-time integral and contact area are lower for the midfoot and hallux. Centre of pressure was more laterally deviated in cavus feet and more medially deviated in planus feet. Overall, effect sizes were moderate, but regression models could only explain a small amount of variance in plantar pressure variables.

Significance

Despite these significant findings, future research would benefit from greater methodological rigour, particularly in relation to the use of valid foot posture measurement techniques, gait analysis protocols, and standardised approaches for analysis and reporting of plantar pressure variables.

Keywords: foot, gait, biomechanics, foot posture, plantar pressure
1. Introduction

Variation in static foot posture is a risk factor for lower limb injury. A recent systematic review found feet with abnormal foot posture, such as pes planus (low medial longitudinal arch) or pes cavus (high medial longitudinal arch), are associated with increased odds of lower limb injury (OR 1.23, 95% CI 1.11 to 1.37) [1]. Similarly, systematic reviews that focused on specific lower limb pathologies have found modest significant relationships between planus foot posture and medial tibial stress syndrome [2-4], patellofemoral joint pain [2] and patellar tendinopathy [5].

The findings of these reviews suggest that planus and cavus feet display abnormal biomechanical parameters that may predispose an individual to injury. However, the biomechanical mechanisms that link foot posture to injury is still unclear, so there remains a need to further understand the interaction between foot posture and biomechanical function of the lower limb [1, 2, 6].

The predominant techniques that are used to investigate the interaction between foot posture and lower limb biomechanics are kinematics (motion of body segments), electromyography (muscle activity) and plantar pressure analysis, also referred to as pedobarography [7]. Plantar pressure analysis refers to the measurement of the magnitude and distribution of force that is applied to the plantar surface of the foot during walking [8]. This technique is important as variations in pressure are associated with alterations to moments acting on joints proximal to the foot, such as the ankle [9], thus altering stress placed on tissues that influence the joint. Indeed, from a clinical perspective, cross-sectional studies have found an association between plantar pressure patterns and conditions such as medial midfoot arthritis [10] and posterior tibial tendon dysfunction [11].
In recent years, systematic reviews have been published that have investigated the relationship between foot posture and both kinematics [12] and electromyography [13]. However, there has been no such review of the literature related to plantar pressure. Therefore, the aim of this review was to investigate the relationship between foot posture and plantar pressure during walking. In doing so, we hoped to provide further insights into the possible mechanisms responsible for lower limb overuse injuries.

2. Methods

The protocol for this systematic review was developed using the preferred reporting of systematic reviews and meta-analysis (PRISMA) guidelines [14] (Additional file 1).

2.1 Literature search strategy

An electronic database search was performed in January 2018 using Ovid MEDLINE (1966 to 2016), CINAHL (1982 to 2016), SPORTDiscus (1830 to 2007) and Embase (1998 to 2007). A set of search terms were derived from Medical Subject Headings (MeSH) and to broaden the search, some terms were truncated with wildcard symbols. The electronic database search was supplemented by cross-checking citations and reference lists from relevant published studies. The search strategy is presented in Table 1.

2.2 Inclusion criteria

A single reviewer (AKB) assessed all studies that were yielded from the search by title and abstract. Studies that fulfilled the following criteria were included.

(i) Static foot posture was used as an inclusion criterion or independent variable.

(ii) Main outcome measures were related to plantar pressure or force measurements.

(iii) Study analysed data related to walking.
(iv) Testing included adult participants who were free of neurological, systemic or degenerative conditions.

(v) Hypothesis testing with statistical analysis was undertaken.

(vi) Study was published in a peer-reviewed journal.

Data related to static standing, postural perturbations or activities other than walking, such as running, balance exercises or stair climbing were not considered in this review. Articles that measured plantar pressures using a barefoot (pressure mat) or in-shoe detection system were included.

2.3 Assessment of methodological quality

Two reviewers (AKB and JJA) independently scored methodological quality using a modified version of the Quality Index [15]. This index has demonstrated high internal consistency for non-randomised studies (Kuder Richardson 20 reliability coefficient = 0.88) and good test-retest ($r = 0.88$) and inter-rater reliability ($r = 0.75$). The 27-item checklist was condensed to only include items that were relevant across the following subscales: reporting (items: 1, 2, 3, 5, 6, 7, 10), external validity (11, 12), internal validity – bias (16, 18, 20), internal validity – confounding (22, 25). The two reviewers discussed any discrepancy in scoring of items and a final score was agreed upon. The maximum total score available for the Quality index was 16. Scores were expressed as a percentage to allow for comparison across categories. Condensed versions of the Quality Index have been used in similar systematic reviews [12, 13].

2.4 Data analysis

Pooling of data and meta-analyses were not performed due to a lack of homogeneity in relation to the methods used to classify foot posture, selection of plantar pressure variables, and statistical analyses undertaken. For studies that compared foot posture groups, mean
differences with 95% confidence intervals and effect sizes (Cohens d) were calculated for statistically significant findings when raw mean scores and error were presented. For studies that used regression techniques, appropriate $r$ and $r^2$ values were extracted.

3. Results

3.1 Search results

The literature search generated a combined total 4,213 citations from all databases. After all citations were screened, a full text review was carried out on 47 studies, and of these 16 studies were suitable for final inclusion. A summary of all included studies including participant characteristics, gait analysis protocol, plantar pressure variables measured, quality analysis score and main findings are presented in Table 2.

In order to provide a clear description of results, the included studies were grouped according to their methodological approach. The first group included 10 studies [16-25] that aimed to compare plantar pressure variables between groups of which foot posture was the independent variable. The second group of seven studies investigated association between static foot posture and plantar pressure via correlation and regression analysis [23, 25-31]. Two studies [23, 25] used both forms of analysis and qualified for both groups. For all included studies, sample sizes ranged from 19 to 1,000, with the median number of participants being 61. The age range of participants was reported in 8 studies, with 5 studies recruiting healthy participants 60 years of age and older. A number of interchangeable synonyms were used between studies to define foot posture categories. Therefore, to avoid confusion, the terms pes planus, pes cavus and normal will be used throughout this review.
3.2 Methodological quality

The mean score for all studies using the modified version of the Quality index was 54% (range 40 to 66%). In all studies, information about participant selection and the source population (item 11), as well as the period of time over which participants were recruited (item 22), was either not reported or was unable to be determined. Adjustment for confounders in analyses was carried out in four studies [21, 28-30], three included confounding co-variates in regression analyses [28-30], and one [21] conducted generalised estimating equation modelling to account for the lack of independence when collecting paired (i.e. left and right) foot data [32]. Scores for each item of the Quality index are presented in Additional file 2.

3.3 Foot posture classification

Using the categories suggested by Razeghi and Batt [33], the predominant method of foot posture classification was the measurement of anthropometric values. These methods included arch height [30], arch height index [17, 21, 27, 28, 30], foot posture index [16, 19, 25, 31], resting calcaneal stance position [22, 23], malleolar valgus index [21, 28], non-weightbearing forefoot to rearfoot alignment [23, 24], navicular height [18, 20] arch angle [18] and rearfoot angle [18, 20]. Two studies used radiographic measures; Fernández-Seguin et al. [19] used the Bartani-Costa angle, while Cavanagh et al. [26] used 14 different measurements from lateral radiographs. One study [29] used a footprint parameter (arch index) and one study [18] used visual non-quantitative inspection methods (assessment of alignment of rearfoot, midfoot and forefoot by an orthopaedic surgeon).

Of the 10 studies that allocated participants to foot posture groups, five used more than one classification method to allocate participants to a group. In one study, participants were
allocated into a cavus or normal group based on a different foot posture classification method for each group [19].

3.4 Statistical reporting

Eight of the included studies used either ANOVA or t-tests to compare means [17-24]. However, of these, no study reported mean differences and 95% confidence intervals, or effect sizes. Two studies used non-parametric tests [16, 25] and one study [17] did not report error values, therefore mean differences could not analysed.

The approach that was used to collect data from one foot of each individual participant was described in ten studies [16, 20, 22, 23, 25, 26, 28-31], while in three studies, the approach for selecting the foot for data collection was not clear [17, 19, 24]. In three studies [21, 22, 27] paired data from the left and right foot were combined for analysis. Of these, only one study accounted for the covariance of dependant measures (left and right feet) by using generalised estimation equation modelling [21]. The other two studies did not account for paired foot data, which may affect the validity of results [22, 27].

3.5 Gait analysis protocol and plantar pressure analysis

The protocol for gait data collection was specified in all but four studies [19, 20, 22, 24]. Six studies used the mid-gait protocol [16, 21, 23, 25, 28, 29], while single studies used a three-step [17], two-step [30, 31], and one-step protocol [26].

Participants were asked to walk at a self-selected walking pace in nine studies [16, 17, 19, 21, 23-25, 28, 30, 31], while two studies controlled walking speed during over ground walking [18, 29] and one controlled walking speed during treadmill walking [27]. The remaining three studies provided no description of walking speed [20, 22, 26]. Two studies used in-shoe pressure detection equipment that was inserted into the participants’ own running shoes [18]
or into standardised shoes provided by the investigators [27]. All other included studies instructed participants to walk barefoot over a pressure detection interface (pressure mat).

Plantar pressure data were analysed according to predefined regions of the foot, referred to as ‘masks’. There was considerable variability between studies for the techniques to define each mask. For example, the entire foot was divided into as few as 3 regions [16, 31] and as many as 12 regions [21, 28], with variation in the location of borders that define each region. For this review, data relating to each region of the foot was extracted as per the description made in each article that reported the findings of each study.

A range of plantar pressure variables, including peak plantar pressure, pressure-time integral, maximum force, force-time integral, centre of pressure indices and contact area were reported in the included studies. Each of these variables are examined in the following sections. One study did not specify the specific variable analysed, but used the term ‘pressure’ [19], hence results could not be attributed to any specific plantar pressure measure (i.e. peak pressure, average pressure, or pressure-time integral).

3.6 Studies that compared plantar pressures between foot posture groups

Overview of studies
Studies in this group reported a variety of comparisons. Four studies compared planus and normal feet [18, 20, 22, 24], three studies compared cavus to normal feet [16, 17, 19], and three studies compared all three foot postures (planus, cavus and normal) [21, 23, 25].

Peak plantar pressure
Peak plantar pressure relates to the maximum pressure value recorded in a predetermined region of the foot during the gait cycle [34]. Six studies measured peak plantar pressure [16-18, 20, 21, 23], with all but one reporting significant differences between foot posture groups [17]. The unit of measurement differed among studies; three studies reported peak pressure
using N/cm² [16, 21, 23], two reported kPa [18, 20], and one did not specify the unit of measurement [17].

When all studies are considered, the results indicate a trend towards higher peak pressure in the heel and lateral forefoot of cavus feet and higher peak pressure in the 2nd metatarsophalangeal joint (MTPJ), hallux and 2nd toe of planus feet. Moderate effect sizes [35] were found for all significant findings except for those reported by Han et al. [20] and Chuckpaiwong et al. [18], who found large effect sizes of 1.40 and 2.80, respectively [35]. Unlike all other studies in this section that measured barefoot plantar pressures, Chuckpaiwong et al. used in-shoe measurement [18]. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 3.

**Pressure-time integral**

Pressure-time integral, also referred to as impulse, is a measure of the cumulative exposure to pressure over time in a predetermined region of the foot [34], and is calculated as the area under the pressure-time curve [16]. Two studies reported pressure-time integral [16, 21] and both were consistent in the unit of measurement reported (N s/cm²).

Hillstrom et al. [21] identified five significant results; all of which indicated normalised pressure-time integral was higher for the medial midfoot and lower for the 5th MTPJ in planus feet compared to normal and cavus feet. Burns et al. [16] found higher pressure-time integral in rearfoot, forefoot and the plantar surface of the entire foot in cavus compared to normal feet. All effect sizes were moderate or large in magnitude [35]. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 4.

**Maximum force**

Maximum force relates to the highest force detected in a pre-defined region of the foot, which differs to pressure in that it is not dependant on area. Four studies analysed maximum force,
and all found significant findings [17, 18, 21, 22]. Of these studies, three used Newtons (N) [17, 21, 22], while Chuckpaiwong et al. [18] used units that represent percentage of bodyweight.

Hillstrom et al. [21] found lower maximum force in the medial midfoot in cavus feet compared to normal and planus feet. They also found higher maximum force in the hallux and 2nd toe and lower maximum force in the combined 1st and 2nd MTPJs and the 5th MTPJ in planus feet compared to both the normal and cavus feet. Effect sizes were moderate to large (range 0.62 to 1.23) in all studies, except for the one significant finding from the study by Chuckpaiwong et al. [18], which had a comparatively large effect size of 3.50 for lower maximum force in the lateral forefoot in planus feet compared to normal feet [35]. Unlike the other studies that reported significant results, the study by Chuckpaiwong et al [18] did not measure plantar pressures barefoot, but used an in-shoe measurement technique.

Two studies did not report data that allowed for effect sizes and confidence intervals to be calculated. Ledoux et al. [22] found higher maximum force under the hallux in planus feet compared to normal feet \((p = 0.008)\). Carson et al. [17] found significantly higher maximal force in the lateral rearfoot \((p = 0.008)\) and medial midfoot \((p < 0.001)\) in cavus feet compared to normal feet. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 5.

**Force-time integral**

The force-time integral is a measure of the cumulative exposure to force over time in a predetermined area of the foot. Three studies [17, 18, 21] investigated force-time integral with two finding significant results [17, 21]. The unit of measurement again differed and was either Newtons per second (N s) [17, 21] or units that represent a percentage of bodyweight per second [18]. Hillstrom et al [21] found lower force-time integrals in the medial midfoot.
and hallux and higher force-time integrals in the 5th MTPJ of cavus feet compared to normal and planus feet. Effect sizes were moderate for all comparisons [35]. Carson et al [17] found higher force-time integral ($p = 0.004$) in the medial forefoot of cavus feet compared to normal feet. However, no numerical values were provided to enable effect size calculations. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 6.

**Centre of pressure excursion**

Centre of pressure, also referred to as the ‘gait line’, measures the path of the vertical component of ground reaction force during stance phase of gait [36]. Centre of pressure excursion is the measurement of the deviation of the centre of pressure from a reference line. Two studies [21, 24] used a reference line created by connecting the location of the initial and final centre of pressure values, while one study [25] used a reference line created by bisecting the foot.

Two studies found significant results for the centre of pressure excursion index [21, 24], while one study [25] found significant results for centre of pressure total excursion area. All significant results indicated a more medially deviated centre of pressure in planus feet, and, conversely, a more laterally deviated centre of pressure in cavus feet. Effect sizes for all significant findings were moderate to large [35]. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 7.

**Contact area**

Four studies [16, 18, 19, 21] reported significant results for contact area. The unit of measurement that was reported in these studies was cm$^2$ [16, 21], contact area normalised to total contact area [18], or percentage of total contact area [19]. Significant results indicated greater contact in the medial midfoot in planus feet compared to normal and cavus feet, and
greater contact area of the 4th and 5th MTPJ compared to normal and planus feet. In the study by Chuckpaiwong et al. [18] there was a large effect size of 3.60 for the difference in contact area of the medial midfoot between planus and normal feet. This was a far larger effect size than other significant findings that ranged between range 0.80 to 1.99, which can be classified as moderate to large [35]. Fernández-Seguin [19] found significantly less contact area in cavus feet compared to normal, however no statistical information was provided. Mean differences, confidence intervals and effect sizes from studies with significant findings are shown in Table 8.

3.7 Studies that investigated the association between static foot posture and plantar pressures

Seven studies [23, 25-30] investigated associations between foot posture and plantar pressures. Six studies used multivariate regression analyses, utilising either a step-wise linear regression [23, 26, 28, 30], multiple linear regression [27], or best-subset regression approach [29]. One study [25] calculated bivariate correlations between foot posture and plantar pressure variables.

Five studies [23, 26-29] attempted to identify the best combination of foot posture variables and related co-variates that could predict plantar pressure variables. Of these studies, Mootanah et al. [28] found the strongest associations, finding that arch height, along with total foot area, forefoot to rearfoot relationship and height of the individual could explain 64% of the variance in maximum force of the entire foot. Mootanah et al. [28] also found that arch height, with total foot area, age and forefoot to rearfoot relationship, could explain 47% of the variance in peak plantar pressure in the medial midfoot. This finding was similar to Morag and Cavanagh [29] who found that arch index, along with age, weight, inferior calcaneal inclination and rearfoot eversion could explain 55% of the variance in midfoot peak
pressure. These results indicate that foot posture may play a role in the prediction of peak pressure in the midfoot.

The strength of the associations reported by Mootanah et al. [28] and Morag and Cavanagh [29] were not indicative of the overall ability of foot posture to predict plantar pressure. For example, Cavanagh et al. [26] found that radiographic angles of the foot, along with plantar soft tissue thickness could explain 38 and 31% of the variance in peak pressures of the heel and 1st MTPJs, respectively. In addition, the strongest association found by Rao et al. [23] was that foot posture and early 1st MTPJ joint flexibility could predict 20% of the variance in peak pressure of the hallux. Similarly, Jonely et al. [27] found that arch height could only predict 8, 7 and 5% of the variance in peak pressure of the hallux, medial forefoot and medial rearfoot, respectively. However, unlike all other studies in this section which measured plantar pressures barefoot, the study by Jonely et al. [27] used an in-shoe measurement technique.

An alternative approach was taken by Teyhen et al. [30], who examined the ability of pressure parameters to classify foot posture. This study found a five variable model including force-time integral of the lateral rearfoot, force-time integral of the 1st MTPJ, mean pressure in the region of the 3rd, 4th and 5th MTPJ, excursion of the centre of pressure and forefoot width, which could explain 60% of the variance in static arch height.

Finally, two studies reported bivariate correlations between foot posture and plantar pressures. The first article by Wong et al. [25] reported significant Spearman’s $r$ values between -0.31 and -0.45 which suggested an association between increasing cavus foot posture and lateral deviation of the centre of pressure. The second study by McKay et al. [31] reported only weak correlations between FPI and plantar pressures. The only significant
finding was a weak correlation ($r = 0.259, p > 0.001$) between greater planus foot posture and increased pressure-time integral beneath the whole foot in older individuals (60+ years).

4. Discussion

The aim of this review was to investigate the relationship between foot posture and plantar pressures during walking. Fifteen studies fulfilled the selection criteria, however inconsistencies relating to methodological issues and clinical and statistical heterogeneity did not allow for pooling of data.

The included studies were grouped according to their statistical approach. Ten studies compared mean differences between different foot postures for plantar pressure variables. Fifty nine significant findings were reported, and of these, 44 were reported by a single study [21]. In contrast, seven studies investigated associations between foot posture measures and plantar pressures. Most studies used multi-variate regression techniques, largely finding that a modest amount of variance in plantar pressure variables could be explained with foot posture measures.

4.1 Quality assessment and effect size

All studies demonstrated moderate methodological quality, with poor scores for external validity and internal validity relating to confounders. The study with the highest overall quality score (66%) by Hillstrom et al. [21] provided the majority of significant results that contribute to the findings of this review.

No study explicitly reported confidence intervals and effect sizes. However, most reported probability values with mean effects and standard error. This allowed for effect sizes to be subsequently calculated for this review. Most effect sizes were moderate in magnitude [35].
4.2 Plantar pressure measurement and gait analysis techniques

Our review found substantial variation in the gait analysis protocol, units of measurement and masking techniques. This heterogeneity between studies did not allow for pooling of results and made comparisons between studies difficult. In regards to gait analysis protocols, the mid-gait and two-step protocols were used in seven studies. These protocols are appropriate for such research as they have adequate reliability [37, 38]. However, four studies did not describe a gait protocol, thus affecting reproducibility of methods. Furthermore, three studies did not mention the walking speed protocol used, which may influence the findings as walking speed has been found to affect plantar pressure in all regions of the foot during gait [39-41].

Two studies used in-shoe plantar pressure detection equipment. When compared to studies using a barefoot approach, Chuckpaiwong et al. [18] reported far higher effect sizes for findings that indicated lower peak pressure (effect size: 2.80) and maximum force (effect size: 3.50) measurements for the lateral forefoot in planus feet compared normal feet. It is possible that the materials used in the midsole or design of the footwear (participants’ own running shoes) may have contributed to reducing force on the lateral forefoot. However, further research is required to determine the effect that shoe design has on plantar pressures in planus feet.

The units of measurement also differed among articles, including some, such as units that represent units of bodyweight, which answered specific questions posed by the authors rather than adopting a consistent approach for comparison. Likewise, there is not an agreed method of dividing the foot into regions (‘masks’) for analysis. Rather, the mask technique differed according to the specific questions posed by the authors. For example, Burns et al. [16, 28] measured pressure parameters for the entire forefoot, while others divided the forefoot into as
many as eight separate regions [21, 28]. This variability in the definition of borders between masks did not allow for direct comparison of results between studies.

4.2 Method of foot posture classification

Among the many foot posture measures used in selected studies, several have been validated to accurately reflect the static alignment of the foot during standing by comparing them to the gold standard measure of radiographic angles [33]. These include the foot posture index [42], dorsal arch height [43], navicular height [42] and the arch index [44]. In contrast, other methods, such as resting calcaneal stance position, have been found to have poor reliability and validity [45-47]. Despite the relative merits of each measurement technique in predicting static foot posture, the use of 12 different measurement techniques in the studies included in our review made comparison of results difficult.

4.3 Cavus feet

Despite the inability to pool data, the included studies allowed for some plantar pressure characteristics of cavus feet to be identified. There was some evidence that cavus feet display lower maximum force [21], force-time integral [21] and contact area [16, 18, 21] in the medial midfoot region compared to normal and planus feet. Such findings are consistent with the proposition that cavus feet have comparatively less compliance of the medial arch under load, and subsequently generate less medial midfoot contact and loading when walking [48]. This is supported by kinematic studies that have reported decreased peak dorsiflexion, or deformation of the medial arch in cavus feet compared to planus feet [49].

Some evidence also indicates that pressure-time integral [21], force-time integral [21] and contact area [21] are comparatively higher in the lateral regions of the forefoot in cavus feet compared to normal and planus feet. Centre of pressure is also more laterally deviated in cavus feet compared to planus and normal feet, thus indicating relatively increased load on
the lateral regions of the forefoot [21, 25]. From a clinical perspective, this could be linked with increased incidence of stress fracture in the lateral forefoot in runners who display a cavus foot posture [50]. However, the evidence for an association between foot posture, plantar pressures distribution and injury is far from conclusive and needs further investigation.

4.4 Planus feet

Some plantar pressure characteristics of planus feet were also evident using the data from included studies. The most substantial differences compared to normal and cavus feet were in the forefoot and hallux. There is evidence of an imbalance in pressure distribution across the forefoot in planus feet compared to cavus and normal feet, with higher peak pressure of the 2nd MTPJ [21, 23] and lower peak pressure [18, 20], pressure time integral [21], maximum force [21], and force-time integral of the 4th and 5th MTPJs [21]. This finding suggests greater stress to the 2nd metatarsal in planus feet, which may place this bone under risk of a stress related injury, such as stress fracture. However, the link between plantar pressure parameters and the development of metatarsal stress fracture is still unclear [51, 52]. Further research is needed to determine the influence foot posture and plantar pressure have on stress-related bony injury, particularly in the context of fatigue, which has been found to influence forefoot plantar pressure distribution [53].

In addition to higher plantar pressures under to the 2nd MTPJ, lower maximum force under the 1st MTPJ [21] and greater peak pressure [21, 23], and pressure-time integral [21] under the hallux was found in planus feet. This is consistent with a more medially deviated centre of pressure and supports the theory of increased mobility of the 1st ray in planus feet under load [54]. However, the relationship between plantar pressure distribution and 1st ray and 1st MTPJ kinematics is still not clear [23, 55] and needs further investigation.
4.5 Limitations

Unlike other biomechanical techniques such as electromyography [56], there are no widely accepted standards for the collection of plantar pressure data. To highlight this issue, the included studies displayed wide variations in the methods used to collect plantar pressure gait data. As such, we acknowledge that studies of low methodological quality were included in our review. To minimise this issue, we suggest that clear and valid guidelines are necessary for plantar pressure research in the future. A further limitation is the risk of type 1 error among studies that carried out multiple hypothesis tests. It is possible that some significant results that are highlighted in this article will be spurious. Finally, the Quality Index appeared to be the most appropriate checklist for assessing the quality of laboratory-based biomechanical studies. However, some items were considered irrelevant and were omitted, potentially affecting the validity of the checklist.

5. Conclusion

Plantar pressure characteristics differ according to foot posture. Planus feet display evidence of higher peak pressure, pressure-time integral, maximum force, force-time integral and contact area values predominantly in the medial arch, central forefoot and hallux, while these variables were lower in the lateral and medial forefoot. Conversely, cavus feet display higher peak pressure and pressure-time integral in the heel and lateral forefoot, while values for pressure-time integral, maximum force, force-time integral and contact area were lower for the midfoot and hallux. Centre of pressure was more laterally deviated in cavus feet and more medially deviated in planus feet. Overall, effect sizes were moderate in magnitude for all significant findings, but regression models could only explain a small amount of variance in plantar pressure variables. Limitations in the studies included in this review, such as statistical heterogeneity, inconsistencies related to foot posture classification, gait analysis
protocol and plantar pressure analysis methodology, affected the ability to make definitive conclusions from the data. Further research should use validated foot posture classification techniques and develop standardised methods for plantar pressure data collection and analysis.

**Contributions**

AKB and HBM conceived the idea for the study. AKB screened, selected and extracted data from appropriate studies. AKB and JJA assessed methodological quality. AKB drafted the manuscript with input from HBM, JJA and KBL. All authors have read and approved the final manuscript.

**Conflict of interest statement**

The authors have no conflict of interest.

**Acknowledgements**

HBM is currently a National Health and Medical Research Council Senior Research Fellow (ID: 1020925).
References

Tables:

**Table 1: Search strategy**

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<td>(2) <strong>Keywords:</strong> Pes planus OR Pes cavus OR Pes planovalgus OR ‘high arch* foot’ OR ‘low arch* foot’ OR ‘foot arch’ OR ‘foot posture’ OR ‘foot structure’ OR ‘foot type’ OR ‘foot morphology’ OR pronat* OR supinat* OR eversion OR inversion OR evert* OR invert*</td>
<td></td>
</tr>
<tr>
<td>(3) <strong>Combine:</strong> 1 or 2</td>
<td></td>
</tr>
<tr>
<td>(4) <strong>Subject heading:</strong> biomechanical phenomena</td>
<td></td>
</tr>
<tr>
<td>(5) <strong>Keywords:</strong> Biomechanics OR ‘plantar pressure*’ OR ‘peak pressure’ OR ‘centre of pressure’ OR ‘centre of pressure excursion’ OR force* OR load* OR baropodography OR stress</td>
<td></td>
</tr>
<tr>
<td>(6) <strong>Combine:</strong> 4 or 5</td>
<td></td>
</tr>
<tr>
<td>(7) <strong>Subject heading:</strong> walking OR gait OR locomotion</td>
<td></td>
</tr>
<tr>
<td>(8) <strong>Keywords:</strong> walk* OR locomotion OR ambulation</td>
<td></td>
</tr>
<tr>
<td>(9) <strong>Combine:</strong> 7 or 8</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Summary of included studies

<table>
<thead>
<tr>
<th>Author/s</th>
<th>Foot posture measurement</th>
<th>Participant characteristics: mean (± standard deviation)</th>
<th>Gait analysis protocol</th>
<th>Planar pressure variables</th>
<th>Quality score</th>
<th>Significant findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burns et al.</td>
<td>Foot posture index</td>
<td>Cavus group: 30 participants, age 30.6 (13.5) years, BMI 25.4 (5.3) kg/m². Normal group: 30 participants, age 31.7 (11.1) years, BMI 24.3 (3.8) kg/m².</td>
<td>Five step mid-gait protocol. Walk barefoot at self-selected speed. Three trials analysed.</td>
<td>Peak pressure, PTI, contact area, contact time.</td>
<td>60%</td>
<td>Pes cavus compared to normal: • ↑ peak pressure rearfoot • ↑ PTI heel, forefoot and whole foot • ↑ contact area midfoot.</td>
</tr>
<tr>
<td>Carson et al.</td>
<td>Arch height index</td>
<td>Cavus group: 10 participants, age 17.6 (0.4) years, height 180.1 (5.0) cm, mass 88.5 (11.7) kg. Normal group: 16 participants, age 17.3 (0.4) years, height 179.2 (6.7) cm, mass 81.2 (10.8) kg.</td>
<td>Three step approach. Walk a barefoot at self-selected speed. Three trials analysed.</td>
<td>Peak pressure, maximum force, FTI.</td>
<td>46%</td>
<td>Pes cavus compared to normal: • ↑ max force lateral rearfoot and medial forefoot • ↑ FTI in the medial forefoot.</td>
</tr>
<tr>
<td>Cavanagh et al.</td>
<td>Fourteen radiographical angular measurements</td>
<td>50 participants (15 females, 35 males), age 63.3 (13.1) years, height 169.4 (8.1) cm, mass 70.0 (10.5) kg.</td>
<td>First step approach. Barefoot walking. Speed not described. Three trials analysed.</td>
<td>Peak pressure.</td>
<td>53%</td>
<td>Regression models including radiographical angular measurements can explain between 31 to 38% of the variance in peak pressure in the heels and 1st MTPJ.</td>
</tr>
<tr>
<td>Chuckpaiwong et al.</td>
<td>Arch angle Rearfoot angle</td>
<td>Planus group: 34 participants, age 24.7 (4.3) years, height 1.8 (0.1) m, mass 81.5 (17.5) kg. Normal group: 16 participants, age 25.2 (3.3) years, height 1.8 (0.1) m, mass 74.8 (13.2) kg.</td>
<td>Walk over 10m walkway. In-shoe measurement Walk at a speed of 1.8 m/s ± 5%. Five trials analysed.</td>
<td>Peak pressure, maximum force, FTI, contact area.</td>
<td>60%</td>
<td>Pes planus compared to normal: • ↑ peak pressure and max force lateral forefoot • ↑ contact area whole foot.</td>
</tr>
<tr>
<td>Fernández-Seguin et al.</td>
<td>Foot posture index</td>
<td>Cavus group: 34 participants, age 24.2 (5.2) years, BMI 22.1 (2.6) kg/m². Normal group: 34 participants, age 27.9 (10.5) years, BMI 22.3 (3.0) kg/m².</td>
<td>Walking protocol not described. Walk barefoot at self-selected speed. Six trials analysed.</td>
<td>Pressure, contact area.</td>
<td>40%</td>
<td>Pes cavus compared to normal: • ↑ pressure in all areas except the 5th MTPJ • ↑ contact area whole foot.</td>
</tr>
<tr>
<td>Han et al.</td>
<td>Navicular height</td>
<td>Planus group: 9 participants, age 22.1 (1.6) years, height 162.3 (8.8) cm, mass 58.7 (8.4) kg. Normal group: 10 participants, age 20.6 (0.7) years, height 164.6 (9.7) cm, mass 55.5 (9.1) kg.</td>
<td>Walking protocol not described. Walking barefoot. Speed not described. Two trials analysed.</td>
<td>Peak pressure, centre of pressure excursion.</td>
<td>40%</td>
<td>Pes planus compared to normal: • ↑ peak pressure in the heel 4th, 5th MTPJ.</td>
</tr>
<tr>
<td>Hillstrom et al.</td>
<td>Resting calcaneal stance position Forefoot to rearfoot relationship</td>
<td>Planus group: 24 participants (12 females, 12 males) counted as 44 feet, age 35.6 (11.0) years, BMI 23.3 (4.3) kg/m². Cavus group: 12 participants (6 females, 6 males) counted as 24 feet, age 42.8 (16.2) years, BMI 24.0 (3.5) kg/m². Normal group: 27 participants (19 females, 8 males) counted as 54 feet, age 33.1 (9.8) years, BMI 24.4 (9.8) kg/m².</td>
<td>Mid-gait protocol. Walk barefoot at self-selected speed. Five trials analysed. Both feet analysed, however adjustment for paired data was undertaken using generalised estimation equation modelling.</td>
<td>Peak pressure, maximum force, PTI, FTI, contact area, centre of pressure excursion index.</td>
<td>66%</td>
<td>Pes cavus compared to normal: • ↑ contact area normalised 4th MTPJ, 5th MTPJ, normalised 5th MTPJ • ↑ PTI normalised medial arch, normalised 5th MTPJ • ↑ max force medial arch, normalised medial arch • ↑ PTI medial arch, normalised hallux • ↑ contact area medial arch, normalised medial arch. Pes planus compared to normal: • ↑ max pressure 2nd MTPJ, normalised 2nd MTPJ and 2nd toe • ↑ max force normalised 1st MTPJ, 1st and 2nd MTPJ • ↑ max force 2nd toe, normalised 2nd toe.</td>
</tr>
</tbody>
</table>
Jonely et al. Arch index Navicular drop Navicular drift 92 participants (50 females, 42 males) counted as 184 feet, age 25.8 (6.7) years, mass 72.9 (16.7) kg. A range of foot postures recruited.

Treadmill walking at a speed of 3.0 mph. In-shoe measurement. Eight consecutive foot strikes analysed. Both feet analysed, no adjustment made for paired foot data.

Peak pressure. 60%

Greater planus foot posture is associated with increasing peak pressure under the hallux, medial forefoot and medial midfoot, but the strength of the relationship are poor to fair. Amount of variance explained in regional peak pressure ranged from 5% to 18%.

Ledoux and Hillstrom. Resting calcaneal stance position Planus group: 8 participants, counted as 16 feet, age 25.6 years, mass 78.9 kg. Normal group: 11 participants, counted as 22 feet, age 26.6 years, mass 79.6 kg.

Walking protocol not described. Walking barefoot. Speed not described. Ten trials analysed. Both feet analysed, no adjustment made for paired foot data.

Peak pressure, peak force, centre of pressure excursion index. 53%

Pes planus compared to normal:

- ↑ max force hallux.

McKay et al. Foot posture index 100 people per decade in age groups of 20-29, 30-39, 40-49, 50-59, 60-69, 70-79 and 80+ years.

Two step protocol. Walk barefoot at a comfortable walking pace. Three trials analysed.

Maximum mean pressure, peak pressure, PTI, Maximum force, FTI, contact area 60%

Greater planus foot posture was associated with increasing peak plantar pressure across the whole foot in older individuals (r=0.259, p<0.001).

Mootanah et al. Resting calcaneal stance position Forefoot to rearfoot relationship 61 participants, age between 18-77 years. Sample included planus, cavus, normal foot postures.

Mid-gait protocol. Walk barefoot at self-selected speed. Number of trials not described.

Peak pressure, maximum force, contact area, centre of pressure excursion index. 53%

Regression models including foot posture as co-variates can explain 10-37% of the variance in plantar pressure parameters.

Morag and Cavanagh Arch index 55 participants (26 females, 29 males). 11 participants recruited in each decade between 20 and 70 years. Sample included a range of foot postures.

Mid-gait protocol. Controlled walking speed (statures per second). Walking barefoot. Five steps analysed.

Peak pressure. 60%

Regression models including foot posture as co-variates can explain approximately 50% of the variance in peak pressure with variation in regions of the foot. Foot posture was dominant in predicting peak pressure in midfoot and 1st MTPJ.
<table>
<thead>
<tr>
<th>Study</th>
<th>Resting calcaneal stance position</th>
<th>Forefoot to rearfoot angle</th>
<th>Planus group</th>
<th>Cavus group</th>
<th>Normal group</th>
<th>Mid-gait protocol</th>
<th>Peak pressure</th>
<th>Pes planus compared to normal</th>
<th>Pes planus compared to pes cavus</th>
<th>Pes planus compared to normal:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rao et al.</td>
<td>22 participants, age 35.6 (11.1) years, BMI 22.2 (3.3) kg/m²</td>
<td>Forefoot to rearfoot angle</td>
<td>22 participants</td>
<td>12 participants</td>
<td>27 participants</td>
<td>Walk barefoot at a self-selected speed. Number of trials not described.</td>
<td>60%</td>
<td>✰ peak pressure 2nd MTPJ. Pes planus compared to pes cavus: ✰ peak pressure 2nd MTPJ. Regression model containing arch height and 1st MTPJ joint flexibility could explain 20% of the variance in peak pressure in the hallux.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Song et al.</td>
<td>10 participants (5 females, 5 males), age 25.8 (3.4) years, mass 69.2 (23.3) kg.</td>
<td>Subtalar joint neutral position</td>
<td>11 participants (4 females, 7 males), age 25.6 (4.0) years, mass 72.9 (16.9) kg.</td>
<td>Walking protocol not described. Walk barefoot at a self-selected speed. Number of trials not described.</td>
<td>Peak pressure, centre of pressure excursion index.</td>
<td>53%</td>
<td>Pes planus compared to normal: ✰ medial deviation of the centre of pressure.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teyhen et al.</td>
<td>1,000 participants (434 females, 566 males), age 30.6 (8.0) years, height 171.1 (9.3) cm, mass 76.9 (14.7) kg. Convenance sample including a range of foot postures.</td>
<td>Arch height index</td>
<td>Two-step protocol. Walk barefoot at a self-selected pace. Five trials recorded.</td>
<td>Peak pressure, maximum force, PTI, FTI, contact area.</td>
<td>A five-variable regression model could explain 60% of the variability in arch height. Covariates included mean pressure of 3rd, 4th, 5th MTPJs, FTI 1st MTPJ, FTI lateral rearfoot, total area between the gait line and foot axis, forefoot width.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wong et al.</td>
<td>16 participants, age 25.7 (9.5) years, BMI 23.0 (3.5) kg/m².</td>
<td>Foot posture index</td>
<td>29 participants, age 31.9 (11.3) years, BMI 24.5 (3.6) kg/m².</td>
<td>Walk barefoot at self-selected speed. Three trials recorded.</td>
<td>Five step mid-gait protocol. Walk barefoot at self-selected speed. Three trials recorded.</td>
<td>Medial excursion index, lateral excursion index, total excursion index.</td>
<td>53%</td>
<td>Pes cavus compared to normal: ✰ Laterally deviated centre of pressure. Pes planus compared to pes cavus: ✰ Medially deviated centre of pressure.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BMI: body mass index  
PTI: pressure-time integral.  
FTI: force-time integral.  
MTPJ: metatarsophalangeal joint.
Table 3. Mean differences, 95% confidence intervals and effect sizes for comparison of peak plantar pressure between foot posture groups

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Region</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Burns et al.⁹⁻¹⁰</td>
<td>Rearfoot</td>
<td>4.7</td>
<td>0.5 to 8.9</td>
<td>0.58</td>
</tr>
<tr>
<td>Pes planus vs normal</td>
<td>Chuckpaiwong et al.⁹⁻¹⁰</td>
<td>Lateral forefoot</td>
<td>-33.5</td>
<td>-40.3 to -26.3</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>Han et al.⁹⁻¹⁰</td>
<td>Heel</td>
<td>-49.3</td>
<td>-83.2 to -15.3</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4th – 5th MTPJ</td>
<td>-46.7</td>
<td>-99.4 to -6.0</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Hillstrom et al.⁹⁻¹⁰</td>
<td>2nd MTPJ</td>
<td>12.6</td>
<td>6.1 to 19.0</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 2nd MTPJ</td>
<td>0.14</td>
<td>0.06 to 0.22</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe 2</td>
<td>16.6</td>
<td>10.8 to 22.4</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Rao et al.⁹⁻¹⁰</td>
<td>2nd MTPJ</td>
<td>12.6</td>
<td>3.5 to 21.7</td>
<td>0.79</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Rao et al.⁹⁻¹⁰</td>
<td>2nd MTPJ</td>
<td>14.8</td>
<td>2.6 to 27.0</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Hillstrom et al.⁹⁻¹⁰</td>
<td>2nd MTPJ</td>
<td>12.6</td>
<td>3.7 to 21.5</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 2nd MTPJ</td>
<td>0.11</td>
<td>0.01 to 0.21</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hallux</td>
<td>16.3</td>
<td>8.5 to 24.0</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised hallux</td>
<td>0.21</td>
<td>0.10 to 0.32</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe 2</td>
<td>8.1</td>
<td>3.6 to 12.5</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.

Unit of measurement: N/cm².

Unit of measurement: kPa.

Peak pressure value normalised to total peak pressure.

Non-parametric tests used in source study.
Table 4. Mean differences, 95% confidence intervals and effect sizes for comparison of pressure-time integral between foot posture groups\(^a\)

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Region</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Burns et al.(^b)(^d)</td>
<td>Rearfoot</td>
<td>1.9</td>
<td>0.8 to 3.0</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Entire forefoot</td>
<td>5.7</td>
<td>2.1 to 9.2</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Entire foot</td>
<td>5.9</td>
<td>2.6 to 9.2</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Hillstrom et al.(^b)</td>
<td>Normalised medial midfoot(^c)</td>
<td>-0.005</td>
<td>-0.008 to -0.001</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5(^{th}) MTPJ(^c)</td>
<td>0.020</td>
<td>0.010 to 0.030</td>
<td>1.00</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Hillstrom et al.(^b)</td>
<td>Normalised medial midfoot(^c)</td>
<td>0.009</td>
<td>0.004 to 0.014</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5(^{th}) MTPJ(^c)</td>
<td>-0.030</td>
<td>-0.040 to -0.020</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hallux</td>
<td>2.9</td>
<td>1.3 to 4.5</td>
<td>0.96</td>
</tr>
</tbody>
</table>

\(^a\) Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.
\(^b\) Unit of measurement: N s/cm\(^2\).
\(^c\) Pressure-time integral normalised to total pressure-time integral.
\(^d\) Non-parametric tests used in source study.
Table 5. Mean differences, 95% confidence intervals and effect sizes for comparison of maximum force between foot posture groups.a

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Region</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Hillstrom et al.</td>
<td>Medial midfoot</td>
<td>-7.5</td>
<td>-12.6 to -2.4</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised medial midfoot</td>
<td>-0.012</td>
<td>-0.019 to -0.005</td>
<td>0.97</td>
</tr>
<tr>
<td>Pes planus vs normal</td>
<td>Chuckpaiwong et al.</td>
<td>Lateral forefoot</td>
<td>-0.035</td>
<td>-0.041 to -0.030</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>Hillstrom et al.</td>
<td>Normalised 1st MTPJ</td>
<td>-0.043</td>
<td>-0.069 to -0.017</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1st MTPJ and 2nd MTPJ</td>
<td>-0.3</td>
<td>-0.4 to -0.1</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe 2</td>
<td>7.4</td>
<td>3.0 to 11.7</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised toe 2nd</td>
<td>0.010</td>
<td>-0.004 to -0.016</td>
<td>0.62</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Hillstrom et al.</td>
<td>Medial midfoot</td>
<td>18.1</td>
<td>4.4 to 31.8</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised medial midfoot</td>
<td>0.021</td>
<td>0.007 to 0.035</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 1st MTPJ</td>
<td>-0.047</td>
<td>-0.077 to -0.017</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5th MTPJ</td>
<td>-0.028</td>
<td>-0.044 to -0.012</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hallux</td>
<td>49.9</td>
<td>27.4 to 72.5</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised hallux</td>
<td>0.062</td>
<td>0.031 to 0.093</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe 2</td>
<td>10.1</td>
<td>4.1 to 16.1</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised toe 2nd</td>
<td>0.014</td>
<td>0.006 to 0.022</td>
<td>0.87</td>
</tr>
</tbody>
</table>

a Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.

b Unit of measurement: N.

c Unit of measurement: units of bodyweight.

d Maximum force normalised to total maximum force.
Table 6. Mean differences, 95% confidence intervals and effect sizes for comparison of force-time integral between foot posture groups.\(^a\)

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Region</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Hillstrom et al.(^b)</td>
<td>Medial midfoot</td>
<td>-1.5</td>
<td>-2.6 to -0.4</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised hallux(^d)</td>
<td>-0.110</td>
<td>-0.197 to -0.023</td>
<td>0.69</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Hillstrom et al.(^b)</td>
<td>Medial midfoot</td>
<td>3.5</td>
<td>1.1 to 5.9</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5(^{th}) MTPJ</td>
<td>-8.2</td>
<td>-11.4 to -5.0</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5(^{th}) MTPJ(^d)</td>
<td>-0.130</td>
<td>-0.190 to -0.070</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hallux</td>
<td>7.4</td>
<td>4.1 to 10.8</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised hallux(^d)</td>
<td>0.130</td>
<td>0.078 to 0.182</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\(^a\) Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.
\(^b\) Unit of measurement: Ns.
\(^d\) Force-time integral value normalised to total force-time integral.

Table 7. Mean differences, 95% confidence intervals and effect sizes for comparison of centre of pressure excursion between foot posture groups.\(^a\)

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Wong et al.(^c)</td>
<td>2.0</td>
<td>0.4 to 3.6</td>
<td>0.58</td>
</tr>
<tr>
<td>Pes planus vs normal</td>
<td>Hillstrom et al.(^b)</td>
<td>-3.0</td>
<td>-5.1 to -0.9</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Song et al.(^b)</td>
<td>-5.8</td>
<td>-9.4 to -2.1</td>
<td>1.45</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Hillstrom et al.(^b)</td>
<td>-5.5</td>
<td>-8.7 to -2.3</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Wong et al.(^c)</td>
<td>-3.9</td>
<td>-6.3 to -1.5</td>
<td>1.06</td>
</tr>
</tbody>
</table>

\(^a\) Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.
\(^b\) Unit of measurement: centre of pressure excursion index (the distance of the centre of pressure from the reference line in the anterior third of the foot normalised to foot width and expressed as a percentage).
\(^c\) Unit of measurement: centre of pressure total excursion area (the sum of the medial and lateral excursion areas of the centre of pressure from the midline of the foot expressed as a percentage).
Table 8. Mean differences, 95% confidence intervals and effect sizes for comparison of contact area between foot posture groups

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Authors</th>
<th>Region</th>
<th>Mean difference</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pes cavus vs normal</td>
<td>Burns et al.</td>
<td>Midfoot</td>
<td>-5.8</td>
<td>-9.5 to -2.1</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Hillstrom et al.</td>
<td>Midfoot</td>
<td>1.3</td>
<td>-2.0 to -0.6</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised medial midfoot</td>
<td>-0.012</td>
<td>-0.018 to -0.006</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 4th MTPJ</td>
<td>0.007</td>
<td>0.003 to 0.010</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5th MTPJ</td>
<td>1.1</td>
<td>0.6 to 1.6</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5th MTPJ</td>
<td>0.009</td>
<td>0.006 to 0.012</td>
<td>1.50</td>
</tr>
<tr>
<td>Pes planus vs normal</td>
<td>Chuckpaiwong et al.</td>
<td>Midfoot</td>
<td>0.022</td>
<td>0.018 to 0.025</td>
<td>3.60</td>
</tr>
<tr>
<td>Pes planus vs pes cavus</td>
<td>Hillstrom et al.</td>
<td>Midfoot</td>
<td>3.5</td>
<td>1.1 to 5.9</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised medial midfoot</td>
<td>0.023</td>
<td>0.009 to 0.037</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 4th MTPJ</td>
<td>-0.009</td>
<td>-0.013 to -0.005</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalised 5th MTPJ</td>
<td>-0.013</td>
<td>-0.016 to -0.009</td>
<td>1.99</td>
</tr>
</tbody>
</table>

*a* Only statistically significant results, whereby point estimates and confidence intervals could be calculated are included.

*b* Unit of measurement: cm².

*c* Unit of measurement: NICA (normalised insole contact area: expressed as units of the entire contact area).

*d Contact area value normalised to total contact area.
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