The relationship between foot posture and lower limb kinematics during walking: A systematic review

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A B S T R A C T

Variations in foot posture, such as pes planus (low-arched foot) or pes cavus (high-arched foot), are thought to be an intrinsic risk factor for injury due to altered motion of the lower extremity. Hence, the aim of this systematic review was to investigate the relationship between foot posture and lower limb kinematics during walking. A systematic database search of MEDLINE, CINAHL, SPORTDiscus, Embase and Inspect was undertaken in March 2012. Two independent reviewers applied predetermined inclusion criteria to selected articles for review and selected articles were assessed for quality. Articles were then grouped into two broad categories: (i) those comparing mean kinematic parameters between different foot postures, and (ii) those examining associations between foot posture and kinematics using correlation analysis. A final selection of 12 articles was reviewed. Meta-analysis was not conducted due to heterogeneity between studies. Selected articles primarily focused on comparing planus and normal foot postures. Five articles compared kinematic parameters between different foot postures – there was some evidence for increased motion in planus feet, but this was limited by small effect sizes. Seven articles investigated associations between foot posture and kinematics – there was evidence that increasing planus foot posture was positively associated with increased frontal plane motion of the rearfoot. The body of literature provides some evidence of a relationship between pes planus and increased lower limb motion during gait, however this was not conclusive due to heterogeneity between studies and small effect sizes.

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1. Introduction

Variations in foot posture from normal, such as pes planus (low-arched foot) or pes cavus (high-arched foot), are recognised as an intrinsic risk factor for developing lower extremity injury [1]. Foot posture, also commonly referred to as foot type in the literature, may contribute to injury via altered motion of the lower extremity. For example, it has been reported that individuals with pes planus have greater foot mobility compared to those with pes cavus [2–4]. As a consequence, running and walking studies have found that those with pes planus are more susceptible to tissue stress injuries arising from abnormal joint rotation [5] or joint coupling [6]. Conversely, those with pes cavus are reported to have less foot mobility, and are more susceptible to injuries related to reduced shock attenuation [7] or increased peak plantar pressures [8].

While the proposed link between foot posture and injury appears to be biomechanically and physiologically plausible, the results of large prospective studies do not provide definitive evidence that such a relationship exists [9–11]. Systematic and narrative reviews of prospective studies have concluded that further work is needed to develop more robust methods of classifying foot posture and clearer definitions of injury [2,12,13].

In terms of the mechanisms linking foot posture with injury, researchers have principally focused on three techniques for evaluating lower limb biomechanics. These techniques include: (i) kinetics or plantar pressures, (ii) electromyography (EMG), and (iii) kinematics. With regard to kinetics or plantar pressures, it has been found that those with cavus feet display significantly lower plantar pressure in the medial arch and increased plantar pressure in the heel and forefoot compared to individuals with normal or planus feet [8,14–16]. With regard to EMG, there is evidence that planus feet demonstrate greater EMG activation of inverter musculature and decreased activation of evertor musculature compared to those with normal or cavus feet [17]. While these findings indicate clear systematic relationships between foot...
posture and changes in plantar pressures and muscle activation, there is, to our knowledge, no single source available that has critically evaluated the kinematic literature.

Therefore, the aim of this systematic review was to investigate the relationship between foot posture and kinematics of the lower limb during walking.

2. Methods

2.1. Search strategy

A systematic literature search was undertaken in March 2012 using the following electronic databases; Ovid MEDLINE (1966 to March 2012), CINAHL (1982 to March 2012), SPORTDiscus (1830 to March 2012), Embase (1988 to March 2012) and Inspec (1898 to March 2012). Medical subject headings (MeSH) were exploded to include all relevant subheadings and matched with appropriate keywords. The search was limited to adult human subjects and no language restrictions were applied. The search strategy is presented in Table 1.

2.2. Inclusion criteria

Articles that fulfilled the following criteria were included:

(i) Foot posture was used as an inclusion criterion or independent variable;
(ii) Main outcome measures were related to kinematics of the lower limb;
(iii) Testing did not include postural perturbations or activities other than walking (i.e. running, balance exercises, hopping, etc.);
(iv) Testing included adult participants that were free of neurologically, systemic or degenerative conditions;
(v) Hypothesis testing with statistical analysis was undertaken;
(vi) Article was published in a peer-reviewed journal.

Only studies that used 3-D kinematic analysis were included, as transverse plane foot position has been found to influence frontal plane motion, which creates parallax errors in 2-D studies [18]. Furthermore, only studies that utilised stereophotogrammetry (the use of photography, radiography or video images to reconstruct coordinates of anatomical landmarks) were included, as this is the most commonly used method of movement analysis [19].

2.3. Quality assessment

There is no validated procedure to test the methodological quality of laboratory-based kinematic studies. Therefore, we used a two-stage assessment that comprised: (i) a modified version of an existing quality assessment tool, and (ii) a new set of items to assess methodological quality of 3-D kinematic gait analysis.

For the first stage, we used an adapted version of the Quality Index [20] to test methodological quality. The total maximum score available for this stage of quality assessment was 16.

The second stage involved the assessment of methodological variables related to 3-D kinematic gait analysis using stereophotogrammetry. A series of items were developed using highly referenced articles related to stereophotogrammetry [19,21–23]. Other sources used to develop items were the conclusions and recommendations of 4 systematic reviews related to 3-D kinematic gait analysis [24–27]. The items are presented in Table 2. The total maximum score for this stage of quality assessment was 7.

Additional information relating to the assessment of articles included in the systematic review is presented in an additional data file at http://dx.doi.org/10.1016/j.gaitpost.2013.01.010.

2.4. Data analysis

Relevant data were extracted from all included studies, including means, mean differences, standard deviations, confidence intervals, r- and r²-values, and p-values. Where possible, percentage mean differences with 95% confidence intervals and effect sizes (difference in mean scores divided by pooled standard deviation) were calculated for studies that reported statistically significant findings. In order to provide a consistent measure, effect size (i.e. the standardised difference in means) was classified as trivial (0–0.2), small (0.2–0.6), moderate (0.6–1.2) and large (≥1.2) [28]. Pooling of data and meta-analyses were not performed due to a lack of homogeneity in techniques related to foot posture classification, kinematic methodology and kinematic parameters. Where positive and negative Euler angles were reported, negative joint angles were rectified to positive values to normalise the calculation of effect sizes.

3. Results

3.1. Search results

The results of the review process are shown in Fig. 1. A total of 3864 citations were retrieved from the search of electronic databases. After inspecting the title and abstract, 50 articles were assessed for full text review. Of these, 12 were suitable for full review.

The included studies were grouped according to method of analysis. Firstly, there were studies that compared mean differences via t-tests or analysis of variance. Secondly, there were studies that investigated associations via regression and correlation analyses. A summary of the selected articles is presented in Tables 7 and 8.
Table 2
Items for the assessment of methodological variables related to 3-D kinematic gait analysis using stereophotogrammetry.

<table>
<thead>
<tr>
<th>Item</th>
<th>Question</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Were details of the assessors carrying out the 3D kinematic gait analysis provided?</td>
<td>Assessors undertaking 3D gait analysis require specialised skills, such as the ability to consistently place markers and an understanding of biomechanical models [25,27]</td>
</tr>
<tr>
<td>2</td>
<td>Were spatiotemporal data and gait analysis procedure methodology described?</td>
<td>Variables such as walking speed, time between trials and number of trials can affect results of kinematic gait analysis [25]</td>
</tr>
<tr>
<td>3</td>
<td>Were movement tasks clearly defined?</td>
<td>Variability in dynamic tasks can affect kinematic data, particularly in participants with movement disorders [25,26]</td>
</tr>
<tr>
<td>4</td>
<td>Was marker placement clearly and accurately described and was the modelling technique described?</td>
<td>Accuracy of marker placement will improve reliability of data and reduce skin marker artefact, which relates to the artefact caused by skin movement with respect to underlying bone [22–24,27].</td>
</tr>
<tr>
<td>5</td>
<td>Was data capture equipment reported including the reporting of reliability, precision and accuracy of equipment?</td>
<td>Variables such as number, type and specifications of cameras. Marker characteristics and data processing information can influence testing as instrument error can present as a confounding factor [19,27]</td>
</tr>
<tr>
<td>6</td>
<td>Was a reference position reported?</td>
<td>The reference or ‘zero’ is the position from which joint movement is measured. It is required to be reported to accurately determine dynamic motion [24]</td>
</tr>
<tr>
<td>7</td>
<td>Were the segments, anatomical reference planes and motion between segments reported?</td>
<td>Kinematic analysis involves the description of a model that includes a series of linked rigid segments. The model used and the planes of motion investigated are essential in understanding the information presented by each study [21,24,25]</td>
</tr>
</tbody>
</table>

3.2. Quality assessment

3.2.1. Methodological quality assessment

Results for the methodological quality assessment are outlined in Table 3. Scores ranged from 50 to 94% (mean 64%). Point estimates of effect were calculated in all studies except one study that did not present numerical standard deviation values [29]. Items 11 and 12, which relate to external validity, generally scored poorly. Only 3 out of 12 articles adequately identified the source population or recruitment procedures (item 11), and 2 out of 12 articles demonstrated that confounding factors found within the sample were the same as the source population (item 12). The 6 items relating to internal validity (items 16–25) were reported variably, with the number of adequately reported items ranging between 2 and 6 for all articles.

3.2.2. Kinematic methodological assessment

Results for kinematic gait analysis methodological quality are displayed in Table 4. Overall, scores ranged between 3 and 7 out of a possible total of 7, with a median score of 6. All articles adequately reported: item 2 – the description of spatiotemporal parameters, item 3 – the definition of movement tasks, and item 4 – related to the method of foot modelling and marker placement. Item 1 scored lowest, with only one article reporting details of the assessors carrying out the research. Other items were reported with moderate to high quality as illustrated in Table 4.

3.3. Overview of included studies

3.3.1. Effect of foot posture on lower limb kinematics during walking (comparison of mean differences)

Five studies investigated the effect of foot posture on lower limb kinematics, of which four compared kinematics in planus feet to that of normal feet, and one study compared kinematics in planus feet to that of cavus feet. Two of the articles included measures of foot mobility to define foot type and none of the selected articles reported recruiting participants with a rigid pes planus. A summary of these studies, including details of how foot type was measured and the parameters of each group are presented in Table 7. The percentage difference in means, 95% confidence intervals and effect sizes are displayed in Table 5. A summary of these results is presented in Fig. 2.

3.3.2. Planus feet compared to normal feet

Four studies compared planus feet to normal feet. The first study by Hunt and Smith [29] involved 15 males with “pes planus” foot posture (determined by clinical observation) and 18 male controls with “normal” foot posture. This study did not provide sufficient information to calculate confidence intervals and effect sizes, hence the findings are not presented in Table 6 or Fig. 2. The study found a significantly greater rearfoot peak plantarflexion angle at 21% of stance phase in the planus group. In addition, the forefoot of the planus group was significantly less adducted during toe off and the total stance phase range of motion in the transverse plane was significantly smaller than the control group.

The second study undertaken by Houck et al. [30] involved 14 participants classified as “normal” or “pronators” based on clinical assessments of frontal plane footset and rearfoot alignment and navicular drop. This study investigated differences in foot posture...
Table 3
Methodological quality assessment scores.

<table>
<thead>
<tr>
<th>Authors</th>
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Table 4
Methodological assessment scores for items relating to 3-D kinematic gait analysis using stereophotogrammetry.

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Fig. 2. Forest plot presenting percentage differences, 95% confidence interval and effect sizes for gait variables comparing different foot postures. Results include statistically significant results, and only results whereby point estimates and effect sizes could be calculated. Phases during stance phase of gait adapted from Cobb et al. [31]. Initial contact: 0–16%, midstance: 16–48%, terminal stance: 48–81%, pre-swing: 81–100%. All studies compared low-arch foot posture and normal foot posture; apart from Powell et al. [33] who compared low-arch foot posture and high-arch foot posture. The change in direction (i.e. positive or negative) of each plot is related to the value of the planus foot relative to the normal foot or cavus foot.
Table 5
Percentage difference in means with 95% confidence intervals and effect size for comparison of foot posture and lower limb kinematics during walking.*

<table>
<thead>
<tr>
<th>Author et al.</th>
<th>Condition</th>
<th>Gait parameter</th>
<th>Event during gait</th>
<th>% difference in means (direction of change)</th>
<th>95% CI</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobb et al. [31]</td>
<td>Low-arched mobile foot vs typical arch height and mobility</td>
<td>Calcaneonavicular complex (midfoot) abduction excursion&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Midstance</td>
<td>−0.9 (less abduction with low-arched mobile foot)</td>
<td>−1.7 to −0.1</td>
<td>−0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rearfoot inversion excursion&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Pre-swing</td>
<td>2.7 (more inversion with low-arched mobile group)</td>
<td>0.3–5.1</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rearfoot eversion excursion&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Pre-swing</td>
<td>−1.8 (less eversion with low-arched mobile group)</td>
<td>−2.9 to −0.7</td>
<td>−0.48</td>
</tr>
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<td>Pronated foot vs normal foot</td>
<td>Calcaneal inversion (ref: relaxed standing&lt;sup&gt;c&lt;/sup&gt;)</td>
<td>Initial contact</td>
<td>4.9 (more inverted with pronated group)</td>
<td>1.0–8.8</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1st metatarsal dorsiflexion (ref: sub talar joint neutral&lt;sup&gt;d&lt;/sup&gt;)</td>
<td>Initial contact</td>
<td>6.6 (more dorsiflexed with pronated group)</td>
<td>1.9–11.3</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak calcaneal eversion (ref: subtalar joint neutral&lt;sup&gt;e&lt;/sup&gt;)</td>
<td>28% of stance phase</td>
<td>3.5 (more inversion with pronated group)</td>
<td>0.6–6.4</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1st metatarsal dorsiflexion (ref: sub talar joint neutral&lt;sup&gt;d&lt;/sup&gt;)</td>
<td>73% of stance phase</td>
<td>9.1 (more dorsiflexion with pronated group)</td>
<td>4.4–13.8</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak calcaneal inversion (ref: relaxed standing&lt;sup&gt;c&lt;/sup&gt;)</td>
<td>96% of stance phase</td>
<td>4.4 (more inverted with pronated group)</td>
<td>−0.1 to 8.9</td>
<td>0.30</td>
</tr>
<tr>
<td>Levinger et al. [32]</td>
<td>Flat-arched foot vs normal foot</td>
<td>Peak tibial backward tilt</td>
<td>Initial contact</td>
<td>3.8 (more backward tilt in flat-arched group)</td>
<td>1.2–6.5</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak forefoot abduction</td>
<td>Terminal stance</td>
<td>11.1 (more abduction in flat-arched group)</td>
<td>4.7–17.4</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak rearfoot internal rotation</td>
<td>Pre-swing</td>
<td>10.6 (more internal rotation in flat-arched group)</td>
<td>2.0–19.2</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak forefoot plantarflexion</td>
<td>Pre-swing</td>
<td>7.2 (more plantarflexion with flat-arched group)</td>
<td>2.7–11.7</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak forefoot adduction</td>
<td>Pre-swing</td>
<td>−12.6 (less adduction in flat-arched group)</td>
<td>−20.6 to −4.6</td>
<td>−0.56</td>
</tr>
<tr>
<td>Powell et al. [33]</td>
<td>High-arched foot vs low-arched foot</td>
<td>Peak rearfoot eversion</td>
<td>Entire stance phase</td>
<td>3.5 (more eversion in low-arched group)</td>
<td>0.8–6.2</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak midfoot eversion</td>
<td>Entire stance phase</td>
<td>1.6 (more eversion in low-arched group)</td>
<td>0.4–2.8</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak medial forefoot eversion</td>
<td>Entire stance phase</td>
<td>5.4 (more eversion low-arched group)</td>
<td>2.0–8.8</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to peak medial forefoot eversion</td>
<td>Entire stance phase</td>
<td>0.1 (later time to peak eversion in low-arched group)</td>
<td>0.0–0.1</td>
<td>0.43</td>
</tr>
</tbody>
</table>

<sup>a</sup> Results include statistically significant results, and only results whereby point estimates and effect sizes could be calculated.
<sup>b</sup> Excursion relates to the difference in motion during phases or events of gait.
<sup>c</sup> Relaxed standing reference position (reference position refers to the ‘zero’ point from which motion is measured).
<sup>d</sup> Subtalar joint neutral reference position.

Table 6
Significant findings for studies investigating the relationship between foot posture and foot and lower limb kinematics during walking.

<table>
<thead>
<tr>
<th>Author</th>
<th>Significant findings between</th>
</tr>
</thead>
</table>
|Allen et al. [41] | Dorsal 1st ray mobility and −
  - Midfoot peak eversion: r=0.59 (p<0.05)
  - Midfoot total range of motion: r=0.61 (p<0.05)
  - Rearfoot time to peak eversion: r=0.72 (p<0.01)
  - Rearfoot total range of motion: r=0.73 (p<0.01) |
|Barton et al. [36] | FPI and −
  - Rearfoot eversion total range of motion relative to the laboratory: r=0.61 (p<0.01) |
|Chuter [35] | FPI and −
  - Peak rearfoot eversion across both groups: r=0.92 (p<0.05)
  - Peak rearfoot eversion of normal group: r=0.76 (p<0.05)
  - Peak rearfoot eversion of pronated group: r=0.81 (p<0.05)
  - Frontal plane component of FPI scores and:
    - Peak rearfoot eversion across both groups: r=0.83 (p<0.05)
    - Peak rearfoot eversion of normal group: r=0.71 (p<0.05)
    - Peak rearfoot eversion of pronated group: r=0.79 (p<0.05) |
|Hunt et al. [38] | 2-Dimensional calcaneal deviation and −
  - Peak rearfoot eversion r=0.46 (p<0.05) |
|Levinger and Gilleard [39] | 2-Dimensional calcaneal deviation and −:
  - Peak rearfoot eversion r=−0.77 (p<0.01) |
|Reischl et al. [34] | No significant correlation was found between magnitude or timing of peak foot pronation and magnitude or timing of peak tibia and femur rotation |
|Wilken et al. [40] | Arch height and<sup>ab</sup>
  - Calcaneal eversion/calcaneal abduction: r=−0.62 (no p value reported) |

<sup>a</sup> Reported during period of stance phase between peak arch elongation (maximally dorsiflexed position of the 1st metatarsal relative to the calcaneus) to the minima in forward rotation of the velocity of the 1st metatarsal relative to the floor.
Table 7
Summary of articles investigating the effect of foot type on lower limb kinematics during walking.

<table>
<thead>
<tr>
<th>Author/s</th>
<th>Participant characteristics: age, height, mass (±standard deviation)</th>
<th>Measurement of foot type and group assignment</th>
<th>Spatiotemporal data and number of trials processed</th>
<th>Purpose of investigation</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobb et al. [31]</td>
<td>Typical foot posture group: 4 males and 7 females. 25.2 (±3.2) years, 176 (±12) cm, 84.8 (±22.1) kg, Low mobile foot posture group: 8 males and 3 females. 24.5 (±0.1) years, 172 (±11) cm, 72.3 (±15.2) kg</td>
<td>Groups assigned using arch ratio and relative arch deformity ratio (90% weightbearing). Participants assigned to typical foot posture group if measures were between −0.5 and 1 standard deviation (SD) of the mean of 51 random volunteers. Low arch group: ≥1 SD of the mean</td>
<td>Controlled velocity based on average speed of the investigated age group (1.3–1.4 m/s). Minimum of 5 successful trials recorded</td>
<td>Compare the effect of foot posture on rearfoot and midfoot total range of motion across 4 subphases of gait. Compared typical foot posture with low mobile foot posture</td>
<td>Significantly less magnitude of midfoot abduction during midstance and rearfoot eversion during pre-swing in low mobile foot group. Significantly greater magnitude of rearfoot eversion during pre-swing in low mobile foot group</td>
</tr>
<tr>
<td>Houck et al. [30]</td>
<td>Normal group: n = 7, 22 (±1) years, 166 (±6) cm, 66.3 (±10.9) kg, Pronator group: n = 14, 22.2 (±1.3) years, 168 (±9) cm, 67.1 (±15.7) kg</td>
<td>Groups assigned using measures of prone non weightbearing forefoot varus, static weightbearing rearfoot eversion and navicular drop. Participants assigned to pronator groups if forefoot varus: &gt;10°, rearfoot eversion beyond vertical and navicular drop: ≥10 mm</td>
<td>Walking at self selected pace. Minimum of 5 walking trials recorded</td>
<td>Compare the effect of foot posture on peak angle and total range of motion of the rearfoot and medial forefoot in normal and pronated foot groups. Compare the difference when kinematic values are calculated using two different reference positions (sub-talar joint neutral and relaxed weightbearing).</td>
<td>Significantly greater rearfoot inversion angle at initial contact and peak inversion at 96% of stance in pronator group for relaxed reference position. Significantly greater peak calcaneal inversion at 28% of stance phase and 1st metatarsal dorsiflexion ROM across entire stance phase in pronator group with sub-talar joint neutral reference position</td>
</tr>
<tr>
<td>Hunt and Smith [29]</td>
<td>Normal group: n = 15 males, 25 (±5) years, 178 (±7) cm, 78.3 (±10.8) kg, Pes planus group: n = 18 males, 26 (±7) years, 176 (±7) cm, 77.5 (±13.2) kg</td>
<td>Participants assigned to pronated foot groups if they reported previous musculoskeletal injuries attributed to ‘planus’ or ‘pronated’ foot posture</td>
<td>Walking at a self selected pace. (maintained ±5% of mean). Normal group: 1.6 (±0.3) m/s Pes planus group: 1.6 (±0.2) m/s. 10 acceptable walking trials recorded</td>
<td>Compare the effect of foot posture on rearfoot and midfoot peak angle and total range of motion between normal and pes planus foot groups</td>
<td>Significantly greater rearfoot sagittal plane angle at 21% of stance in pronated group. Significantly less midfoot adduction during toe off and significantly less total midfoot range of motion in pronated foot group</td>
</tr>
<tr>
<td>Levinger et al. [32]</td>
<td>Normal-arched group: 6 males and 4 females. 24.3 (±8.7) years, 174 (±10) cm, 70.0 (±12.3) kg, Flat-arched group: 2 females and 7 males. 20.1 (±1.3) years, 174.6 (±7.5) cm, 72.6 (±19.5) kg</td>
<td>Groups assigned using weightbearing radiographic angles: (talus-2nd metatarsal angle, talonavicular coverage angle, calcaneal inclination angle, calcaneal-1st metatarsal angle). Participants assigned to flat arch group if measures were 1 standard deviation from mean values of the normal arched group</td>
<td>Comfortable self-selected walking pace, normal-arched gait velocity 1.30 (±0.18 m/s) and flat-arched 1.33 (±0.14 m/s). 5 acceptable walking trials recorded</td>
<td>Compare the effect of foot posture on peak angle and time to peak angle of the rearfoot, forefoot and tibia between normal and flat-arched subjects</td>
<td>Significantly greater forefoot plantarflexion in late stance, forefoot abduction in midstance, rearfoot internal rotation in late stance and tibia backward tilt in initial contact in the flatfoot group. Significantly less forefoot adduction peak angle in terminal stance in flat foot group</td>
</tr>
<tr>
<td>Powell et al. [33]</td>
<td>High-arched group: 10 females. 20.8 (±2.5) years, 160 (±7) cm, 58.3 (±5.4) kg, Low arched group: 10 females. 21.1 (±2.3) years, 160 (±10) cm, 58.9 (±10.9) kg</td>
<td>Arch index: dorsum foot height divided by truncated foot length. Participants assigned to high- or low-arched groups if arch index was 1.5 standard deviations above or below the mean of 604 feet</td>
<td>Walking barefoot at a self selected speed maintained ±5% determined during three practice trials</td>
<td>The effect of foot posture on peak angle and time to peak angle of the rearfoot and forefoot in high arch and low arch subjects</td>
<td>Significantly greater peak rearfoot eversion, peak midfoot eversion, peak medial forefoot eversion, time to peak medial forefoot eversion in the low arch group</td>
</tr>
</tbody>
</table>
### Table 8
Summary of articles investigating the relationship between foot type and lower limb kinematics during walking.

<table>
<thead>
<tr>
<th>Author/s</th>
<th>Participant characteristics: age, height, mass (±standard deviation)</th>
<th>Measurement of foot type and group assignment</th>
<th>Spatiotemporal data and number of trials processed</th>
<th>Purpose of investigation</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen et al. [41]</td>
<td>6 males and 9 females: 28.9 years, 171 cm, 73 kg. Standard deviations not provided</td>
<td>Static 1st ray dorsiflexion range of motion. Dorsal displacement measured with 55 N of force applied to planter 1st head of metatarsal</td>
<td>Gait velocity maintained at 1.88 m/s. 5 successful trials recorded</td>
<td>Relationship between static 1st ray dorsiflexion and peak motion, time to peak angle and total range of motion of the rearfoot, midfoot and 1st ray</td>
<td>Significant correlation between static 1st ray dorsiflexion and peak midfoot inversion: r = 0.59 (p &lt; 0.05), midfoot total range of motion: r = 0.61 (p &lt; 0.05), reafoot time to peak eversion r = 0.72 (p &lt; 0.01) and reafoot total range of motion r = 0.73 (p &lt; 0.01)</td>
</tr>
<tr>
<td>Barton et al. [36]</td>
<td>4 males and 16 females: 23.4 (±2.3) years, 171.1 (±8.4) cm, 66.0 (±15.4) kg</td>
<td>6 item Foot Posture Index (FPI)</td>
<td>Natural comfortable walking speed. 5 successful trials recorded</td>
<td>Relationship between FPI and peak angle, timing of peak angle and total range of motion of forefoot dorsiflexion, forefoot abduction and rearfoot eversion in controls and subjects with patello-femoral joint pain syndrome</td>
<td>Results only reported from control group as this fulfilled selection criteria for systematic review – significant correlation between FPI and rearfoot total range of motion relative to the laboratory: r = 0.61 (p = 0.009)</td>
</tr>
<tr>
<td>Chuter [35]</td>
<td>20 males and 20 females: 32.4 (±4.7) years, 171 (±4.7) cm. 69.5 (±4.1) kg. Pronated group: n = 20. Normal group: n = 20.</td>
<td>6-item Foot Posture Index. Participants assigned to the normal group if FPI: 0 to +5 and the pronated group if FPI: +6 to +9</td>
<td>Constant gait velocity of 1.4 m/s (±10%). 5 acceptable walking trials</td>
<td>Relationship between FPI and the frontal plane component of FPI and frontal plane peak angle of the rearfoot in both normal and pronated foot types groups and all participants</td>
<td>Significant correlations between FPI and maximum rearfoot eversion angle in normal: r = 0.76 (p &lt; 0.05), pronated: r = 0.81 (p &lt; 0.05) and all participants: r = 0.92 (p &lt; 0.05). Significant correlations between frontal plane component of FPI and maximal rearfoot eversion in normal r = 0.71 (p &lt; 0.05), pronated: r = 0.79 (p &lt; 0.05) and all participants: r = 0.83 (p &lt; 0.05)</td>
</tr>
<tr>
<td>Hunt et al. [38]</td>
<td>19 males: 21.6 (±1.9) years, 182 (±5) cm, 78 (±8.02) kg</td>
<td>Weightbearing 2D static measurements of calcaneal deviation (deviation from line perpendicular to the floor) and medial arch angle (obtuse angle formed by line connecting medial malleolus and navicular tuberosity, and navicular tuberosity and the 1st metatarsal head)</td>
<td>Walking at self selected natural walking pace (cadence ± 5%). 10 trials recorded</td>
<td>Relationship between 2D measures of weightbearing calcaneal deviation or medial arch angle with peak rearfoot motion and total range of motion of the rearfoot during stance of walking</td>
<td>Significant correlation between calcaneal deviation and peak rearfoot eversion angle r = 0.46 (p = 0.048)</td>
</tr>
<tr>
<td>Levinger et al. [39]</td>
<td>14 females: 25.1 (±8.7) years, 166 (±8) cm, 61.3 (±7.6) kg</td>
<td>Static rearfoot frontal plane angle</td>
<td>Self selected speed, five acceptable walking trials recorded</td>
<td>Relationship between relaxed static rearfoot angle and peak rearfoot inversion and eversion during walking, calculated to a relaxed standing and a vertical rearfoot neutral reference position</td>
<td>Results only reported from control group as this fulfilled inclusion criteria of systematic review. Significant negative correlation between relaxed rearfoot angle and peak eversion when calculated from a relaxed standing neutral position</td>
</tr>
<tr>
<td>Reischl et al. [34]</td>
<td>11 males and 19 females: 26.7 (±3.7) years, 172.2 (±9.1) cm, 69.8 (±13.6) kg</td>
<td>Weightbearing and non-weightbearing static assessment and observational gait analysis to select a range of foot postures</td>
<td>Walk at comfortable cadence. Mean walking velocity: 81.2 (±9.3) m/min</td>
<td>Relationship between peak angle of rearfoot pronation during stance and peak motion of the tibia and femur in the transverse plane</td>
<td>No significant correlation was found</td>
</tr>
<tr>
<td>Wilken et al. [40]</td>
<td>8 males and 9 females: 25 (±4.5) years. 170 (±10) cm, 74 (±14) kg</td>
<td>Subjects with self-reported high or low arches to ensure a wide range of Arch heights. All subjects had anterior–posterior and lateral weightbearing radiographs taken to determine static foot alignment</td>
<td>Walked at a controlled speed of 0.78 statures</td>
<td>Relationship between arch height and 4 foot coupling ratios. Coupling ratios taken from median angle values during peak arch elongation to propulsion</td>
<td>Significant correlation between arch height ratios of calcaneal eversion/ calcaneal abduction r = –0.62</td>
</tr>
</tbody>
</table>
when applying two different reference positions (zero positions from which angular measurements are calculated). As shown in Table 5, both reference positions were associated with significant differences in kinematics when comparing groups. Using a relaxed weightbearing reference position, the pronators displayed significantly greater peak rearfoot inversion angles during the periods of initial contact and propulsion (96% of stance phase). However, the application of a subtalar joint neutral reference position produced differing results. In this instance, the pronators displayed significantly greater peak rearfoot evasion during midstance (28% of stance phase) and greater first metatarsal dorsiflexion at initial contact and terminal stance (73% of stance phase).

The third study, undertaken by Cobb et al. [31] used measures of arch height and foot mobility to classify foot posture as “normal” or “low-mobile”. The sample consisted of 11 participants with low-mobile feet and 11 normal controls. This study found those with low-mobile feet displayed significantly less midfoot abduction excursion during midstance (16–48% of the gait cycle) compared to those with normal feet. Furthermore, the rearfoot of the low-mobile feet displayed significantly greater rearfoot inversion excursion and significantly less rearfoot evasion excursion during pre-swing (81–100% of the gait cycle).

The fourth study by Levinger et al. [32] used radiographic measurements obtained from weightbearing X-rays to recruit 9 participants with “flat-arched” feet and 10 with “normal” feet. This study found that the flat-arched group displayed significantly greater backward tilt of the tibia (proximal aspect of the tibia positioned posterior to the distal aspect in the sagittal plane during initial contact). Furthermore, four significantly different peak values were found during propulsion (heel rise to toe off) between flat-arched feet and normal feet. When compared to the normal feet, the flat-arched feet displayed: greater internal rotation of the rearfoot, greater plantarflexion of the forefoot, and greater abduction of the forefoot followed by significantly less adduction of the forefoot.

3.3.3. Planus feet compared to cavus feet

One study compared kinematics from planus and cavus feet. Powell et al. [33] used a footprint measure (the Arch Index) to classify female recreational athletes into “low-arched” or “high-arched” groups (each of 10 participants). This study found significantly greater rearfoot, midfoot and medial forefoot peak eversion values in the low-arched group. Furthermore, the time to peak medial forefoot eversion was significantly delayed in the low-arched foot.

3.3.4. Association between foot posture and lower limb kinematics during walking

The association between foot posture and lower limb kinematics was investigated using regression or correlation analysis in seven studies, of which six investigated motion of the foot and one study investigated rotation of the tibia and femur [34]. Significant findings reported from these studies are presented in Table 6.

Two studies used the Foot Posture Index (FPI) to determine foot type [35,36]. The FPI involves six anthropometric observations. Each observation is scored between −2 and +2, and the summed score is used to classify foot posture ranging from “highly pronated” (FPI > 10) through to “highly supinated” (FPI < −5) [37]. Neither study included participants with supinated foot posture. The first study by Chuter [35] tested 40 young adult participants. A significant and strong positive relationship (r = 0.92, p < 0.05) was found between increasing FPI scores (i.e, more planus or pronated foot posture) and peak rearfoot evasion. The second article by Barton et al. [36] compared 26 young participants with patellofemoral pain syndrome to 20 matched control participants while walking. The asymptomatic control group in this study recorded a significant positive relationship between increasing FPI and total rearfoot range of motion in the frontal plane (r = 0.61, p < 0.01).

Three studies used goniometric assessment of frontal plane calcaneal alignment (i.e. inverted or everted) to classify foot posture. The first study, by Hunt et al. [38] tested 19 young adult males. A weak positive correlation was found (r = 0.46, p < 0.05) between increasingly everted calcaneal alignment (one component of pes planus) and peak dynamic rearfoot evasion. This study also assessed sagittal plane arch angle using goniometry, but reported no significant association with foot kinematics. The second study undertaken by Levinger and Gillett [39] recruited 14 young adult females, which were controls for a larger study of patellofemoral pain syndrome. Two different reference positions (relaxed standing and vertical alignment of the rearfoot) were recorded and analysed. In contrast to the findings of Hunt et al. [38], this study found a significant negative correlation (r = −0.77, p < 0.01) between increasingly everted calcaneal alignment and peak dynamic rearfoot evasion. However, this finding only applied when using the relaxed standing reference position and not with the vertical rearfoot reference position. The third study by Reischl et al. [34] also used calcaneal stance position to classify foot type, although this study was the only one to investigate the association between a measure of foot type and kinematics of structures proximal to the foot. No association was found between peak peak rearfoot eversion and peak tibial or peak femoral rotation during walking in the 30 healthy young adults recruited for this study.

The final two articles used two different foot classification measures. Wilken et al. [40] used a radiographic measure of “arch height” (the angle between the first metatarsal and calcaneal inclination in the sagittal plane) to determine foot posture in 17 young healthy participants. A significant correlation (r = −0.62, no p value was reported) between arch height and rearfoot coupling ratios (eversion/abduction) was found during the propulsive phase of gait. The second study by Allen et al. [41] recruited 15 asymptomatic participants and classified feet by measuring the degree of displacement of the first ray with the application of 55 Newtons of force applied dorsally. Significant associations were reported between first ray dorsiflexion and rearfoot eversion excursion (r = 0.73, p < 0.01) and rearfoot time to peak eversion (r = 0.72, p < 0.01).

4. Discussion

The aim of this review was to investigate the relationship between foot posture and kinematics of the lower limb during walking. Twelve articles were suitable for full review. Five studies used comparisons of mean differences and seven studies investigated the association between foot posture and lower limb kinematics using regression analyses.

4.1. Quality assessment and effect size

The results of the methodological quality assessment indicated that the majority of articles scored in a low to moderate range, with only 4/12 studies scoring over 65%. In particular, external validity scored poorly, limiting the ability to generalise the results to the wider population. As shown in Table 4, the results of 3-D kinematic methodological quality were moderate, with 10/12 studies scoring 5 or more out of a possible total of 7. This indicates that kinematic methodology was generally repeatable. However, only one study reported information regarding the assessor, which is relevant as specialised knowledge and training is required to carry out 3-D kinematic analysis [25]. Spatiotemporal parameters and movement tasks were reported consistently, as were items related to foot modelling, equipment configuration, reference positions and reference frames. Skin mounted markers were used in all studies
except for one [30]. Therefore, it is evident that a limitation for the majority of studies relates to movement artefact from skin over bony prominences [23].

Whilst the descriptions of kinematic gait analysis methods were adequate, studies generally lacked uniformity in kinematic gait analysis protocols. This has been identified as a limitation by previous literature [24] and is therefore an issue when interpreting evidence from this systematic review. The degree to which variation in methodology may affect kinematic results can be highlighted by comparing two studies [30,39]. Both studies applied two reference or ‘zero’ positions as part of their testing protocol, and both studies reported considerably different results for each position. Therefore, future 3-D kinematic studies require greater consistency in methodology.

Mean percentages with confidence intervals and effect sizes were calculated from all studies except one. As illustrated in Table 6 and Fig. 2, all effect sizes were small, except for one result of 0.61. A small effect size reflects substantial uncertainty about whether the effects are clinically meaningful.

4.2. Methods of classifying foot posture

The method of classifying foot posture varied between studies, most likely due to there being no currently-accepted universal method of foot classification [42]. This was a major limitation when interpreting articles in our review. Five studies [32,33,35,36,40] used methods with previously published normative data. For the remaining studies, however, there is uncertainty about the boundaries for each classification of foot posture. This may affect the interpretation of results particularly in the studies that dichotomised foot posture based on theoretical boundaries. These studies may not have detected differences between groups because participants’ foot type may not have been appropriately classified.

Only one study included a group with high-arched feet [33]. Future research should therefore focus on a broader range of foot postures, including those with cavus feet, to develop a more comprehensive picture of the broader clinical population.

4.3. Effect of foot posture on lower limb kinematics during walking

As is illustrated in Fig. 2 and reported in Table 5, there is some evidence that the planus foot undergoes increased motion throughout the stance phase of gait. In particular, the majority of significant differences were found after heel rise during the propulsive phases of gait, (terminal stance, pre-swing). When considering motion of the rearfoot, significant differences were mostly found in the frontal plane [30,31,33]. Additionally, the midfoot and forefoot displayed increased [29,33] and prolonged [31] transverse plane motion in the planus foot compared to the normal foot. This may indicate that frontal plane motion of the rearfoot and transverse plane motion of the midfoot and forefoot may be important clinical considerations when comparing the gait of different foot postures.

4.4. Association between foot posture and foot and lower limb kinematics during walking

The results from these studies indicate that increasing planus foot posture is associated with increased rearfoot peak excursion and total rearfoot range of motion during the stance phase of gait. The strongest associations (i.e. r-values) were found in the studies that summated a number of observations (e.g. the PPI) to classify foot type – these studies produced consistent findings. In contrast, the studies that used one observation (e.g. 2-D frontal plane calcaneal alignment) produced inconsistent findings, with one producing a conflicting result to the studies that summated a number of observations. This indicates that a clinical anthropometric assessment of foot posture using a number of observations may provide a more consistent indication of dynamic rearfoot motion than a single observation.

Importantly, it should be noted that correlation does not imply causation. In fact, it is possible that the motion of the foot during gait may be a factor in causing variations in foot posture over time (i.e. reverse causation). Equally, a common causal relationship is also possible, whereby a third factor that might be unknown is responsible for both foot posture and foot kinematics. Further prospective research is required, therefore, to investigate the relationship between altered foot posture, altered lower limb kinematics and lower extremity injury.

4.5. Limitations

The findings of this systematic review should be viewed in light of some limitations. Firstly, all articles that met the inclusion criteria were included in this study. We acknowledge that some articles that scored poorly for the methodological quality assessment were still included, and these may have affected our conclusions. For example, some studies scored poorly on external validity, which may affect their generalisability. Secondly, it is possible that by only including 3-D kinematic studies, some meaningful data were not included from studies using 2-D kinematic measurements. Thirdly, there was significant variation in both foot posture classification methods and kinematic models used in these studies, which prevented any pooling or meta-analysis of the results. Finally, no work has been undertaken to measure the validity and reliability of the kinematic methodological quality assessment tool developed for this systematic review.

5. Conclusion

This systematic review found evidence that individuals with pes planus display increased motion of the lower limb during walking. Specifically, there is evidence of an association between planus foot posture and increased frontal plane motion of the rearfoot. However, the quality of evidence is poor due to methodological issues with the included studies and the small effect sizes reported. Therefore, although interesting there is still some uncertainty about the clinical meaning of these findings. In order to establish better quality evidence that is generalisable to all foot postures, future research should include a broader range of foot postures and develop greater consensus for the methods used in kinematic analysis of the lower limb. Higher quality research will assist in understanding the mechanism linking foot posture to injury.

Conflict of interest statement

The authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2013.01.010.

References


