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Effect of patellofemoral pain on foot posture and walking kinematics

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ABSTRACT

Background Excessive pronation has been implicated in patellofemoral pain (PFP) aetiology and foot orthoses are commonly prescribed for PFP patients. Pronation can be assessed using foot posture tests, however, the utility of such tests depends on their association with foot and lower-limb kinematics.

Research questions Do PFP participants compared with healthy participants (1) have a more pronated foot measured with static foot tests and a kinematic multi-segmental foot model and (2) is there an association between static foot posture and foot and lower limb kinematics during walking?

Methods A case-control study including 22 participants (n = 11 PFP, 5 females per group, aged 24 ± 3 (mean ± SD) years) was conducted. Foot posture measures included Arch Height Ratio, Navicular Drop (ND), and Foot Posture Index. Between-group comparisons of foot posture, segment and joint angle magnitudes, and associations between foot posture and kinematic data during gait were evaluated.

Results There were no group differences in foot posture tests and mean joint angles. PFP participants had greater internal rotation of the shank and rearfoot segments, and adduction of the mid- and forefoot in the transverse plane (all $p < 0.05$). Greater ND was associated with increased forefoot abduction (rho = -0.68, $p = 0.02$) in healthy participants but no relationships were found between foot posture and kinematics in PFP participants.

Significance Foot posture and kinematic data did not indicate excessive pronation in PFP participants questioning the use of orthoses to correct pronation. Larger studies are needed to determine the utility of foot posture tests as indicators of gait abnormalities in PFP.

1. Introduction

Patellofemoral pain (PFP) is a common condition, yet its aetiology remains largely unknown. Patellofemoral joint stress leading to PFP is considered to be multifactorial and associated with several kinematic abnormalities. Theoretical models [1] and cadaver studies [2] have supported a biomechanical link between lower limb and foot posture and patellofemoral mechanics. Excessive foot pronation in particular may contribute to greater internal rotation of the tibia and hip, leading to altered patellofemoral contact pressures [2].

Foot pronation in weight-bearing can be defined as a combined movement of ankle dorsiflexion, rearfoot eversion and forefoot abduction. Few studies have evaluated both proximal and distal lower-limb kinematics in PFP participants during walking [3]. Barton et al. [4] identified low associations between the range of rearfoot eversion and hip adduction in both PFP and healthy controls, and between peak rearfoot eversion and tibial internal rotation only in PFP, suggesting tibial rotation is involved in PFP pathology. Other studies refuted an association between tibial rotation and peak rearfoot eversion [5] and foot pronation [6]. Discrepant findings may be partly attributable to different kinematic foot models and in particular to the use of single-segment foot modelling, which focuses on rearfoot motion. However, pronation is a complex, tri-planar motion that includes movement at the joints of the rear-, mid- and forefoot [7]. Multi-segment foot kinematic models have been established; the Oxford Foot Model [8] assesses the tibia and three foot segments, demonstrating good inter-rater reliability and repeatability and Redmond et al. [9] presented a kinematic model of the shank, rearfoot and forefoot demonstrating low error and high repeatability. These multi-segment models will provide a more comprehensive understanding of tri-planar foot motion and the relationship between foot and lower-limb kinematics in PFP.

Given the limited availability of kinematic equipment, static foot

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posture assessments are commonly used to identify pronation and inform the prescription of orthotics and corrective exercise programmes in the belief that excessive pronation is associated with PFP symptoms. Commonly used foot tests include Arch Height Ratio (AHR) [10] and Navicular Drop (ND) [11] which assess midfoot posture and Foot Posture Index (FPI) [12] which assesses multi-segmental indications of pronation. A few studies have evaluated static foot posture measures in PFP, with mixed evidence for their ability to identify those with PFP. Increased ND and FPI scores have been reported among individuals with PFP compared with healthy controls [12], although only ND has prospectively accounted for PFP risk [13]. While low AHR has been associated with more frequent knee pain among runners [14], other case-control studies suggest no differences in AHR [15]. In addition, the utility of foot posture assessments relies on their association with dynamic pronation, and on the hypothesised sequence of abnormal foot and lower limb kinematics in PFP.

This study aimed to evaluate a) whether PFP compared with healthy participants have a more pronated foot posture measured with static foot tests and a multi-segmental foot model during stance phase of walking and (b) the association between static foot posture and foot and lower limb kinematics in healthy and PFP participants. It was hypothesised that (a) PFP would exhibit greater foot pronation than healthy participants on foot posture tests and demonstrate less ankle dorsiflexion, greater internal tibial rotation, rearfoot eversion, and mid- and forefoot abduction in the kinematic foot model and (b) greater pronation on static foot tests would be associated with foot and limb kinematics indicating greater pronation and internal tibial rotation.

2. Methods

2.1. Ethical approval

Ethical approval was obtained from King's College London Research Ethics Committee. Written, informed consent was provided prior to participation.

2.2. Participants

A convenience sample of PFP and sex-matched healthy participants were recruited from staff and students at the university using a circular email. A physiotherapist with 5 years clinical experience screened participants using inclusion and exclusion criteria based on previous studies [16]. Inclusion criteria for participants with PFP were: aged 18–45 years; insidious onset of non-traumatic anterior or retropatellar knee pain; subjective knee pain rating of at least 3 on an 11-point Numerical Rating Scale; knee pain upon at least two of these activities: prolonged sitting, squatting, kneeling, running or negotiating stairs; knee pain on at least one of the following clinical tests: palpation of the posteromedial or posterolateral border of the patella, resisted quadriceps isometric contraction, or compression glides of the patellofemoral joint; and no current physiotherapy treatment. Inclusion criteria for healthy participants were: aged 18–45 years and no history of knee pain.

Exclusion criteria for healthy controls and participants with PFP were: low back pain with referred leg pain; knee pathology (e.g. patella tendonitis); other lower limb pathology (e.g, previous history of fracture) or a neurological condition.

2.3. Descriptive measures

2.3.1. Sociodemographic, anthropometric, and clinical characteristics

Age, gender, limb dominance (defined as the leg used to kick a ball), and presence of bilateral or unilateral pain (PFP only) were assessed by self-report. Body weight and height were obtained using standard scales.

2.3.2. Knee-related disability

The Anterior Knee Pain Scale is a 13-item questionnaire assessing symptoms and difficulties during daily and sporting activities [17] with lower scores on a 0–100 scale indicating greater knee-related disability.

2.3.3. Pain intensity

Usual and worst knee pain over the previous week were assessed using the Visual Analogue Scale ranging from 0 to 10, with higher scores reflecting higher pain intensity. The disability and pain scales have been demonstrated to be valid measures in PFP participants [16] and were included to provide descriptive data on the participants.

2.4. Foot posture measures

Three measures were included as each assesses a different component of foot posture.

2.4.1. Arch height ratio (AHR)

The AHR measures static midfoot posture [10]. Participants stood, supporting 90% of their body weight on their test leg (on a step) to simulate foot posture during single leg stance. The alternate leg was positioned on a weighing scales to maintain weight-bearing at 10% of body weight. The vertical distance from the step to the dorsal aspect of the medial longitudinal arch was measured using a Vernier calliper at 50% of foot length. AHR was calculated by dividing arch height by foot length, with scores > 0.36 or < 0.27 reflecting a high or low arch, respectively [18]. The static AHR test is reliable and has been associated with dynamic AHR in healthy participants [19].

2.4.2. Foot Posture Index-6 (FPI-6)

The FPI-6 measures the fore-, mid- and rearfoot in the three cardinal planes [9]. Participants marched on the spot before assuming a natural stance with equal weight on both legs. The calcaneal angle, curvature above and below the lateral malleoli, talonavicular joint prominence, medial longitudinal arch congruence, forefoot to rearfoot alignment and talar head position were scored according to standard criteria. Total FPI-6 scores range from -12 to 12, with negative values indicating supinated, 0–5 neutral and 6–12 pronated foot posture. The index is reliable and sensitive to group differences in PFP patients [12].

2.4.3. Navicular drop (ND)

ND measures the sagittal displacement of the navicular when moving from subtalar neutral to relaxed calcaneal stance [11]. Participants stood with equal weight on both legs. The vertical height from the floor to the antero-inferior aspect of the navicular tuberosity during relaxed calcaneal stance was subtracted from the height obtained in subtalar neutral stance. The ND is reliable [12], normal scores range between 2–8 mm [20] and is associated with rearfoot motion in healthy participants [21].

2.5. Procedure

Kinematic data were collected for the affected or most-affected limb of unilateral or bilateral PFP participants respectively, and for the right limb of healthy participants.

Two CODA mpx30 cameras (Charnwood Dynamics, Rothley, UK) were aligned and positioned ˜0.3 m apart on a 12 m walkway in a gait laboratory. Twenty six light emitting diode (LED) markers were placed on bony landmarks or on pelvic, thigh and shank wands following standard protocols [22], and on the rear-, mid- and forefoot following the protocol developed by Redmond et al. [9], with 3 additional midfoot markers (Fig. 1).

Participants were instructed to walk at their usual pace. Following familiarisation, data were collected over 5 s commencing from 6 m along the walkway to facilitate acquisition of steady state kinematics. A minimum of 12 walking trials were recorded at 200 Hz, from which 10

Segment	Marker position
Pelvis	Pelvic wand, anterior tip
	Pelvic wand, posterior tip
	Iliac crest, superior lateral aspect
Thigh	Femoral wand, anterior tip
	Femoral wand, posterior tip
	Knee joint line, lateral aspect
Shank	Tibial wand, anterior tip
	Tibial wand, posterior tip
	Lateral malleolus, inferior tip
Rearfoot	Calcaneus, superior aspect
	Calcaneus, inferior aspect
	Calcaneus, lateral aspect
	Calcaneus, medial aspect
Midfoot	Cuboid, superior aspect of notch
	Navicular tuberosity
	Naviculocuneiform joint line
Forefoot	Fifth metatarsal base
	Fifth metatarsal head
	First metatarsal head
	Third metatarsal head
Hallux	Hallux distal phalanx, anterior aspect
Contralateral foot	Hallux distal phalanx, anterior aspect
	Calcaneus, lateral aspect

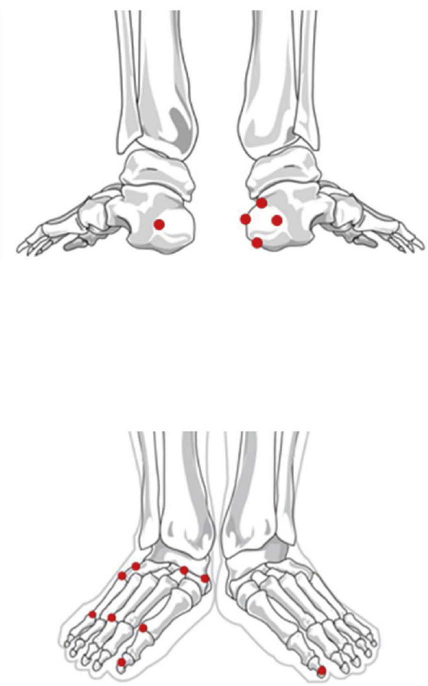

Fig. 1. 3-Dimensional marker placement. A total of 24 markers were included. Red dots indicate LED marker placement on bony landmarks of foot. There were 13 markers on the test foot and two markers on the contralateral foot (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

with the most markers in view of the cameras during a single stride were analysed. One 5 s stationary trial with the feet positioned in subtalar neutral was recorded as a reference.

2.6. Data analyses

2.6.1. Kinematic and spatiotemporal analysis

Codamotion analysis software (version 4.80; Charnwood Dynamics, Leicestershire, UK) was used to compute the 3D Cartesian coordinates of each marker within the laboratory framework. Kinematics records were imported to a customised program in MATLAB software (version 7.6.0; The MathWorks Inc, MA, USA) designed to identify marker position for further analyses.

At least three markers each provided data on the pelvis, leg and foot segments, and data from one only marker was available for the hallux (Fig. 1). Embedded vector bases (EVB) for the segments and virtual markers were calculated for the pelvic, hip, knee,ankle and foot joints using standing data as a reference. Segment angles were calculated using Euler angles [23] and the sequence of rotations used was “zxy”. Segment angles were measured relative to the laboratory reference framework. Pelvic joint angles were measured relative to the laboratory framework and limb joint angles were defined relative to the nearest proximal joint. Means and confidence intervals for joint and segment angles were calculated and kinematic data presented as percentage of stride with 1% representing two data points. Stride was defined by heel contact and determined from the lowest vertical displacement of the lateral heel marker on the z axis. Spatiotemporal variables (e.g. stance duration) were calculated following standardised procedures [24]. Foot segment data were removed for two time points, as markers on the medial aspect of the foot were out of view when the contralateral leg was swinging past.

2.6.2. Statistical analyses

Ratio data were assessed for normal distribution using the Shapiro Wilk test, and group comparisons of descriptive, foot posture measures, and kinematic data were evaluated using Student’s t, Mann-Whitney or Chi-squared tests as indicated. In the results presented, Student’s test was used unless indicated otherwise. Graphical representations of joint and segment angles were visually examined. To reduce the likelihood of a type I error, statistical analyses was only undertaken on mean angle data where group differences were observed during stance phase. Correlations between foot posture measures and mean ankle dorsiflexion, rearfoot eversion and mid- and forefoot abduction joint angles during stance were determined using Pearson’s r or Spearman’s rho. Statistical significance was defined as $p < 0.05$. Statistical analyses were conducted using SPSS (version 19; SPSS Inc., Chicago, USA). Data are presented as mean $\pm$ SD unless otherwise stated.

Table 1
Participant characteristics.

Variable	PFP (n = 11)	Healthy participants (n = 11)
Age, years	23.7 (2.8)	25.0 (4.6)
Male gender, n (%)	6 (54.5)	6 (54.5)
Body mass, kg	69.6 (11.2)	67.6 (14.7)
Height, m	1.7 (0.1)	1.7 (0.1)
Right leg tested, n (%)	8 (72.7)	11 (100.0)
Dominant leg tested, n (%)	8 (72.7)	11 (100.0)
Knee-related disability scale[a,b]	**80.0 (75.0, 83.0)**	**100 (100.0, 100.0)**
Pain intensity scale[a,c]		
Usual, cm	**2.0 (1.0, 3.0)**	**0.0 (0.0, 0.0)**
Worst, cm	**6.0 (5.0, 7.0)**	**0.0 (0.0, 0.0)**
Duration of knee pain, months	58.6 (71.9)	
Bilateral pain, n (%)	9 (81.8)	
Ankle dorsiflexion, m	0.1 (< 0.1)	0.1 (< 0.1)

Data are mean (± SD) unless otherwise indicated and bold font indicates significant group differences ($p < 0.05$).
[a] Data are median (IQR).
[b] Anterior Knee Pain Scale (range 0–100).
[c] Visual Analogue Scale (range 0–10 cm).

3. Results

3.1. Participants

A sample of 11 participants with PFP (aged 23.7 ± 2. 8 years, 5 females) and 11 healthy controls (aged 25 ± 4.6 years, 5 females) was included (Table 1). As expected, knee disability and pain were higher among PFP participants. There were no group differences in anthropometric data (Table 1).

3.2. Foot posture

There were no differences in AHR ($p = 0.72$), ND ($p = 0.40$) or FPI-6 ($p = 0.31$, Chi squared test) between groups. Both groups had AHR values < 0.27 (0.22 ± 0.01 and 0.22 ± 0.02 for PFP and healthy controls respectively) which based on previous data [18] indicated that participants were classified as having a low arch. ND scores (6.2 ± 2.7 and 5.0 ± 3.1 mm for PFP and healthy controls respectively) were within normal range [20]. Four participants with PFP and one healthy subject had FPI-6 scores indicating pronation (median FPI-6 = 4 in PFP and 3 in healthy controls).

3.3. Spatiotemporal parameters and kinematics

There were no group differences in cadence (123.9 ± 1.0 and 120.4 ± 9.1 steps.min^{-1} for PFP and healthy controls respectively; $p = 0.39$), or duration of stance (0.6 ± 0.1 s and 0.6 ± 0.1 s for PFP and healthy controls respectively; $p = 0.65$), swing (0.4 ± 0.01 s and 0.40 ± 0.01 s for PFP and healthy controls respectively, $p = 0.23$), or stride (1.0 ± 0.1 s and 1.0 ± 0.1 s for PFP and healthy controls respectively; $p = 0.49$).

Participants with PFP had greater mean internal rotation of the shank ($p = 0.01$) and rearfoot ($p < 0.01$), and adduction of the mid- ($p = 0.04$) and forefoot ($p = 0.01$, Mann-Whitney U) segments in the transverse plane during stance phase (Fig. 2). There were no group differences in mean joint angles (Fig. 3).

3.4. Relationship between kinematics and foot posture

No relationships were observed between kinematics and foot posture in participants with PFP (Table 2). In healthy control participants, a greater ND was associated with more forefoot abduction in the transverse plane (rho = -0.7, $p = 0.02$).

4. Discussion

This study found greater angles during stance in participants with PFP compared with healthy participants for internal rotation of the shank and rearfoot and adduction of the mid- and forefoot segments. There were no differences in foot posture between groups, and no associations between foot posture measures and kinematics in participants with PFP, whereas a greater ND was associated with more forefoot abduction in healthy participants.

Participants with PFP demonstrated abnormal segmental motion during stance, defined by greater internal rotation and adduction of the distal lower limb and foot relative to the laboratory framework. While increased shank internal rotation may increase patellofemoral joint contact pressures, greater adduction of the mid- and forefoot segments were contrary to theory [2], inconsistent with a pronated foot, and only noted in the transverse plane. Therefore, the clinical significance of these findings may be questionable. Similarly, other case-control studies have not found excessive pronation in PFP [25], suggesting variations in the aetiology, and consistent with evidence that pronation occurs only in a subpopulation of individuals with PFP [26]. In addition, our study found no group differences in joint angles. Measurement of limb joint angles provides a more clinically relevant assessment and this may explain the similar range of motion found between groups, despite differences in segment angle positions.

In this study, PFP and healthy participants had a low arch based on previous AHR data, consistent with pronation, yet ND was in the normal range and only a small proportion of participants, mostly PFP, were classified as pronators using FPI-6 scoring. A plausible explanation for these inconsistent findings is that the tests assess different aspects of foot posture with the FPI-6 being the only to assess hind, mid and forefoot region and the ND may better reflect the dynamic foot compared with other static measures [21]. An association between ND and forefoot abduction was the only link identified between foot posture and joint motion but occurred in healthy participants only. Prospective and cross-sectional studies do not consistently link pronation identified using ND or other clinical tests, including AHR and FPI-6, to PFP [13,27]. A systematic review identified four prospective studies evaluating foot posture as a risk factor for PFP [13] and only one of these found that ND was associated with a small, increased risk, suggesting pronation may be a precursor in some individuals only. Therefore, while foot posture tests are easy to do and require no special equipment, their use is limited by the inconsistent findings across PFP samples and the limited evidence linking these tests with kinematics [27]. Although excessive pronation is not consistently found, studies have demonstrated that orthotics are effective in reducing PFP, at least in the short-term [28]. However, the mechanism of effect is perhaps via the shock attenuation properties of orthotics [29] rather than their kinematic effects.

Our study is among the first to evaluate a multi-segmental foot model in individuals with PFP, and the only study to evaluate the midfoot. Applying a two-segment model, Barton et al. [25] found greater ankle dorsiflexion, but no differences in forefoot joint angles among participants with PFP and healthy controls. Other studies evaluating a single segment model only present varied patterns of motion in PFP [3], and may oversimplify foot kinematics. Discrepancies between studies may be explained in part by different kinematic modelling and small, heterogeneous samples. Further research, combining distal and proximal measures, and larger samples, is needed to understand the role of foot and lower-limb walking kinematics in participants with PFP.

The present findings do not support the theory which attributes excessive pronation to the aetiology of PFP and contribute to the wider literature which is equivocal. New theoretical models to explain the factors contributing to PFP appear to be required. Perhaps, proximal musculoskeletal factors, such as deficits in hip or knee muscle strength [30], may provide more consistent and robust indicators of changes contributing to altered patellar tracking or contact pressures.

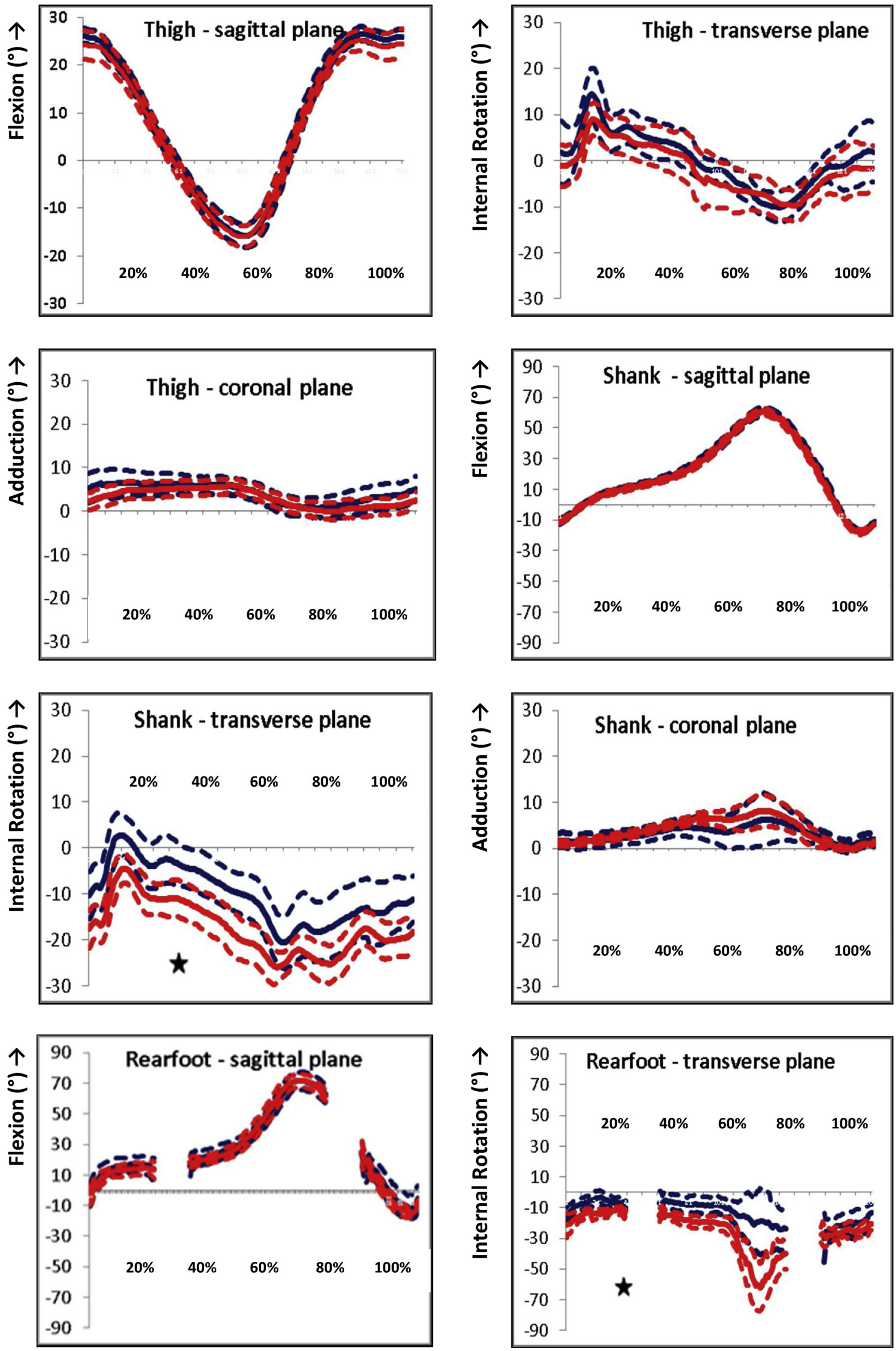

Fig. 2. Thigh, shank, and foot segment angles during a single stride of the gait cycle. PFP and healthy participants are indicated by blue and red lines, respectively, mean data by a solid line, and 95% confidence intervals by dashed lines. The asterisk indicates significant differences between groups and the arrow on the horizontal axis represents stance phase duration. Data for the hallux are unidimensional as only one marker was placed at this position. Data are omitted at two time points during mid-stance when individual markers were out of recorded view (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

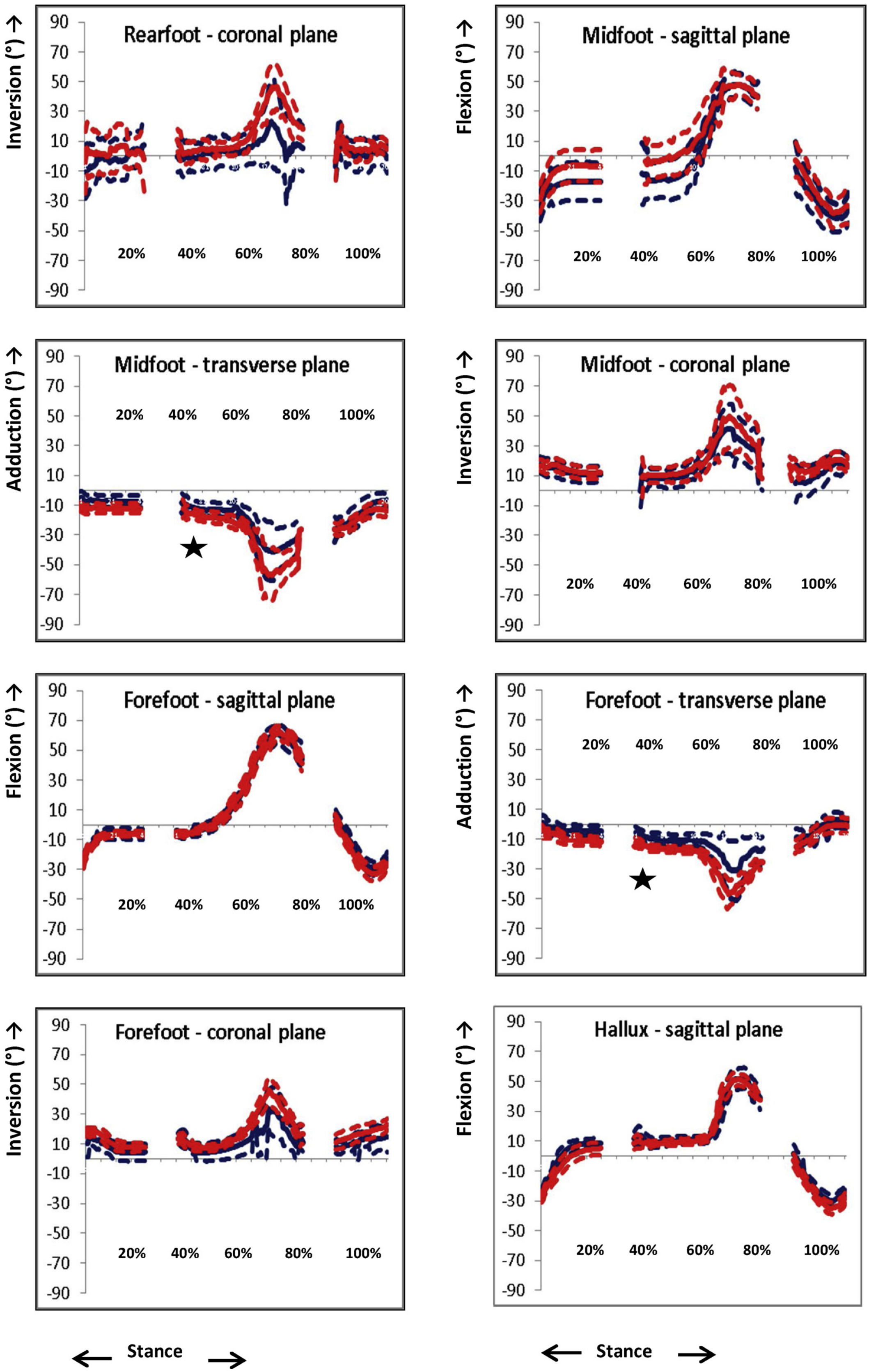

Fig. 2. (*continued*)

This study had a number of strengths. First we reported spatio-temporal parameters of gait, which are frequently unaccounted for in the literature, and may be altered in PFP [3]. There were no group differences in our study, suggesting that spatiotemporal aspects of gait do not account for our findings. We employed a robust 3D lower-limb kinematic model [9], capturing detailed motion of all aspects of the foot.

A limitation of this study is the small convenience sample recruited,

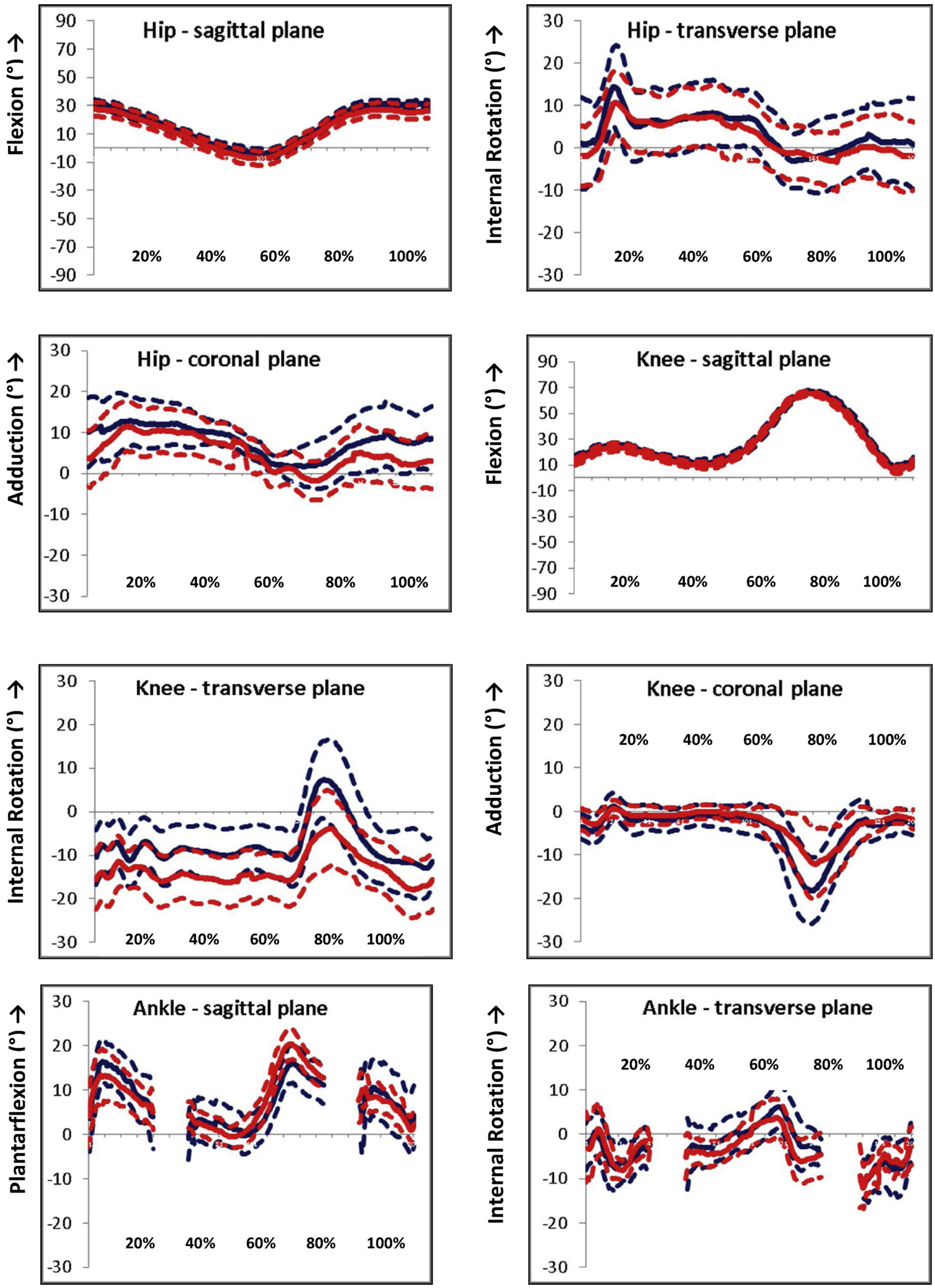

Fig. 3. Hip, knee, ankle, and foot joint angles during a single stride of the gait cycle. PFP and healthy participants are indicated by blue and red lines, respectively, mean data are represented by a solid line, and 95% confidence intervals by dashed lines. Data for the hallux are unidimensional as only one marker was placed at this position. Data are omitted at two time points during mid-stance when individual markers were out of recorded view (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

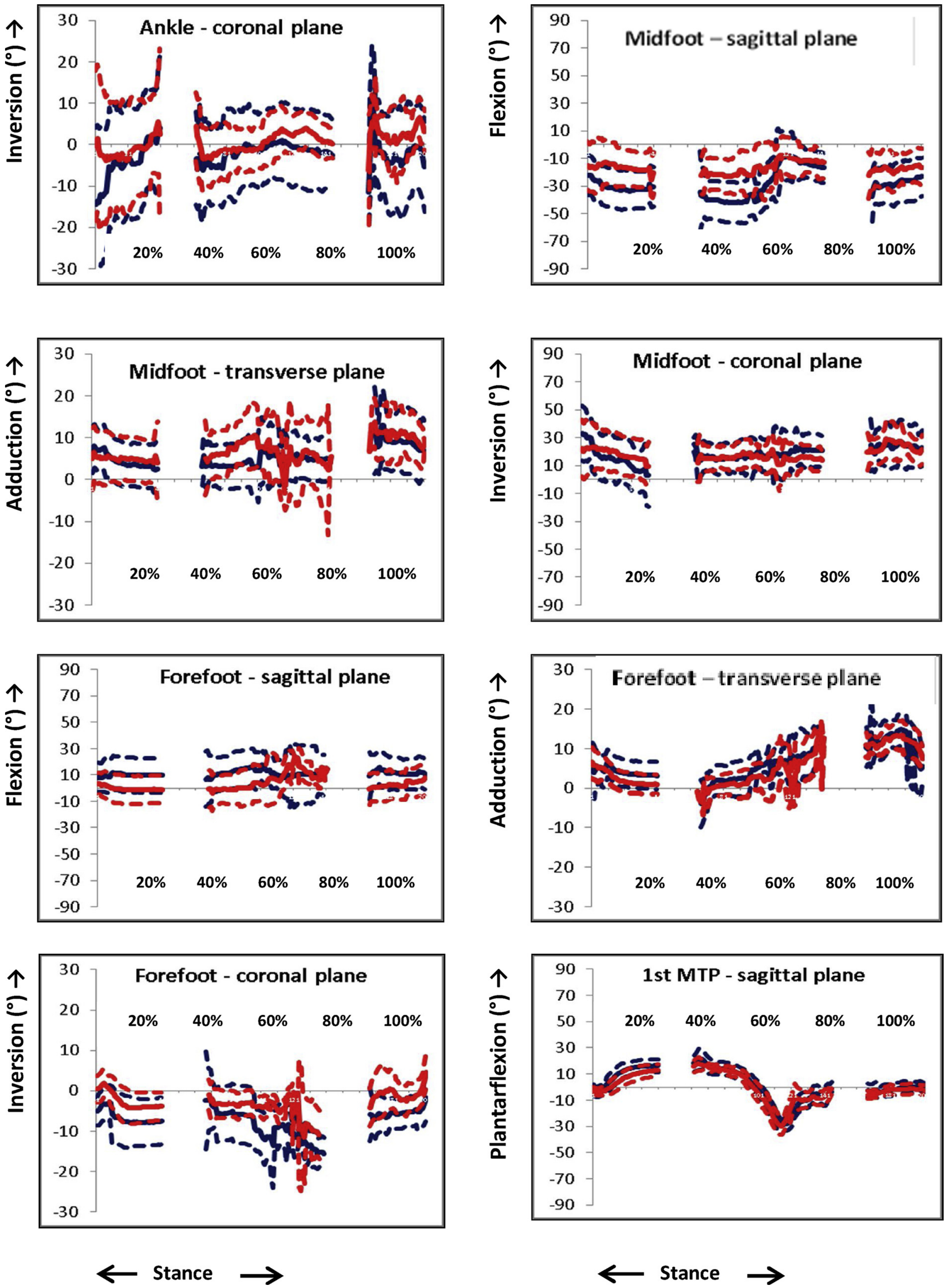

Fig. 3. (*continued*)

which means that this study was underpowered to detect group effects on kinematics or foot posture but while any conclusions must be made with caution, the small inconsistent changes identified in kinematics are likely not to be clinically important. Midfoot kinematic data were removed from analyses due to markers being out of view, slightly limiting interpretation; however, movement patterns were consistent between groups and across planar views, and so it is unlikely that effects were overlooked.

Table 2
Correlations between static foot posture tests and kinematic measures of pronation.

Joint angles	ND – PFP	ND – Control	FPI-6 – PFP	FPI-6 – Control	AHR – PFP	AHR – Control
Ankle Dorsiflexion	r = 0.24; p = 0.48	r = 0.12; p = 0.72	rho = 0.06; p = 0.85	rho = 0.60; p = 0.05	r = 0.22; p = 0.52	r = −0.44; p = 0.17
Rearfoot Eversion	r = −0.02; p = 0.48	r = 0.29; p = 0.39	rho = −0.40; p = 0.22	rho = 0.37; p = 0.26	r = 0.25 p = 0.45	r = 0.11; p = 0.75
Midfoot Abduction	r = 0.02; p = 0.96	r = −0.26 p = 0.44	rho = −0.03; p = 0.94	rho = −0.43; p = 0.18	r = −0.05; p = 0.87	r = −0.12; p = 0.73
Forefoot Abduction	r = 0.16; p = 0.63	r = −0.68 p = 0.02*	rho = −0.20; p = 0.55	rho = −0.17; p = 0.61	r = 0.50; p = 0.12	r = 0.37; p = 0.27

ND = Navicular drop test; FPI-6 = Foot posture index-6 test; AHR = Arch height ratio test; PFP = participant with patellofemoral pain; Control = healthy participant. Pearson's Correlation Coefficient was used to calculate all correlations except for FPI; Spearman rank tests were used for correlations involving FPI and other variables.

* indicates that the $p < 0.05$ for correlation.

5. Conclusions

This study evaluating foot posture and lower-limb kinematics found no evidence of excessive pronation in PFP participants based on clinical foot posture measures and a multi-segmental kinematic foot model, and no differences compared with healthy participants. PFP was linked to greater angles for internal rotation of the shank and rearfoot, and adduction of the mid- and forefoot during stance, but these kinematic abnormalities were not associated with foot posture. Larger studies are needed to determine the utility of foot posture tests as indicators of gait abnormalities in PFP.

Conflict of interest statement

The authors declare no competing interests.

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