Can orthotic wedges change the lower-extremity and multi-segment foot kinematics during gait in people with plantar fasciitis?

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ABSTRACT

Background: Orthotic wedges with medial posting of the forefoot and rearfoot have been shown to be effective in controlling excessive foot pronation in people with plantar fasciitis (PF), however the best prescription remains unclear.

Research question: The aim of this study was to determine the biomechanical effects of two designs of orthotic wedges with the shoe on the hip, knee, rearfoot, and forefoot kinematics in individuals with PF.

Methods: Thirty-five participants with PF were recruited. They were asked to walk under three randomized conditions; shod, shod with orthotic wedges with foot assessment technique 1 (W1), and shod with orthotic wedges from a new assessment technique (W2). Biomechanical outcomes included lower limb and multi-segment foot kinematics in each subphase of the stance gait, including contact phase, midstance phase, and propulsive phase.

Results: Compared with shod, the W1 significantly increased shoe motion of rearfoot dorsiflexion, decreased shoe motions of peak forefoot dorsiflexion, and peak rearfoot eversion during the contact phase. In addition, W1 increased shoe motion of rearfoot inversion, decreased shoe motions of hallux dorsiflexion, and peak hallux dorsiflexion during the propulsive phase. For W2, the wedge significantly decreased peak knee internal rotation, decreased shoe motions of forefoot abduction, peak forefoot dorsiflexion, and peak rearfoot eversion during the contact phase. In addition, W2 increased rearfoot inversion, decreased hallux dorsiflexion, and decreased peak hallux dorsiflexion during the propulsive phase. When comparing W1 and W2, W1 showed greater shoe motion of rearfoot dorsiflexion during the contact phase.

Significance: These findings suggest that the use of forefoot varus wedges, and the combination of forefoot and rearfoot varus wedges, can change the lower limb kinematics, the shoe motions of multi-segment foot kinematics, and the relative length of the plantar fascia which would be associated with a reduction in pain and symptoms during walking.

Keywords: Plantar fasciitis, Kinematics, Gait, Prescription, Foot Orthotics

INTRODUCTION

Plantar fasciitis (PF) is an overuse syndrome that affects up to 15% of all adult foot complaints[1]. This condition affects the tissue under the medial longitudinal arch of the foot, causing a stabbing pain in the heel[1]. PF usually resolves within 6 to 18 months without treatment, however recovery from PF can be a slow process[2], and the nature of pain from PF can lead to a reduction in daily and sporting activities[3].

Different treatment modalities have been used in the management of PF from conservative treatments to surgery[3], with foot orthotics being the most common primary intervention[1, 3], with a view to reduce tension in the plantar fascia by decreasing over pronation during gait[4, 5]. A systematic review and meta-analysis studied different types of foot orthotics, including a medial rearfoot wedge, a medial forefoot wedge as well as a combination of medial rearfoot and forefoot wedges, in people with flexible pes planovalgus[6]. No significant differences in any outcomes were reported when comparing the medial rearfoot wedge condition and the control condition. In contrast, both the forefoot and the combination wedge decreased peak rearfoot eversion when compared with the control condition, which appears to be an effective control of excessive foot pronation during stance phase[6], however the prescription of foot orthotics in people with PF remains unclear, and there is a lack of information on the kinematic changes in different types of foot orthotics used in the management of people with PF.

It has been suggested that the rearfoot and forefoot angles should be examined to prescribe the appropriate amount of correction needed[6-10]. Two different foot assessment techniques have been reported[9, 11]. The assessment following Root[11] is widely used by podiatrists to determine the rearfoot and forefoot angles before customizing foot orthotics[6, 12, 13], which considers an intrinsic reference frame that is relative to the proximal segment to determine the clinical forefoot and rearfoot angles. However, previous studies found poor correlation between the clinical rearfoot angle and rearfoot kinematics during the stance phase of gait[9, 14]. These findings indicate that the rearfoot and forefoot angles derived from this technique did not reflect the interaction between the foot and the ground[15], and showed poor inter-rater reliability which might be attributed to the technique of finding the subtalar neutral position[16]. The foot assessment proposed by Monaghan et al. was developed to reduce these limitations by using an extrinsic reference frame to determine the rearfoot and forefoot angles[9]. The clinical forefoot angle was defined as the angle between a line through the metatarsal head and the caudal edge of the table, which is parallel to a mediolateral axis of the foot and parallel to the ground when standing. Additionally, the clinical rearfoot angle was defined as the angle between a bisecting line of the calcaneus and a line perpendicular to the caudal edge of the table. It has been suggested that such an extrinsic clinical measure would better predict the rearfoot and forefoot angles and provide a better foot assessment to determine the amount of posting required[7, 9], however, there is a lack of information regarding the kinematic comparisons of foot orthotics in the management of people with PF.

This study considered two orthotic wedge designs 1 (W1) and 2 (W2), W1 following the foot assessment described by Root and W2 following the assessment by Monaghan et al.

Both designs used the same orthotic wedges but used different techniques for the foot assessment. To assign the orthotic wedges for each participant, those with rearfoot and forefoot angles between 3 and 6 degrees received the 3-degree wedge, between 6 and 8 degrees received the 6-degree wedge, and more than 8 degrees received the 8-degree wedge. Therefore, the aim of this study was to determine the biomechanical effects of two designs of orthotic wedges on the hip, knee, rearfoot, and forefoot kinematics in individuals with PF.

METHODS

This was a within-subject, randomized, cross-over design to determine the biomechanical effects between three conditions; shod, shod with W1, and shod with W2. The research protocols were approved by the center of Ethical Reinforcement for Human Research of Mahidol University (COA No. MU-CIRB 2020/178.0511).

The sample size was calculated using G*power version 3.1.9.4[17] for repeated-measures ANOVA. Twenty-seven participants were required to determine a 5% significance level to detect biomechanical differences between the three conditions with a medium effect (Cohen's d = 0.5) at a power of 80%.

The participants were diagnosed with PF by an experienced physical therapist using the following criteria: pain in the proximal attachment of the plantar fascia at the medial tubercle of the calcaneus, sharp or dull deep pain, first-step pain in the morning or during the day after prolong sitting which reduced after a few steps of walking, pain during the day after prolong walking or standing, and pain during barefoot walking and going upstairs[3]. Inclusion criteria were people between 18 and 60 years old who met the diagnosis of PF, with at least 6 weeks of symptoms[18], and an average pain intensity during the last week of at least 30-mm on a 100-mm visual analog scale (VAS). Exclusion criteria were: BMI more than 30 kg/m^2, a leg length difference more than 1 cm, a positive sciatica test, history of lower-extremity fracture, or diagnosed with any systematic diseases. All participants provided written informed consent prior to data collection.

Physical assessments

Physical characteristics of the participants were assessed by a physical therapist with 7 years experience of using foot orthotics for the management of musculoskeletal problems. These included; femoral anteversion angle, tibial torsion angle, ankle inversion angle, ankle eversion angle, rearfoot angle, and forefoot angle.

Orthotic wedges

Rearfoot and forefoot angles were assessed using two techniques described by Root[11] and Monaghan et al[9] (Figure 1). Full length orthotics using a 3-mm soft foam layer (Figure 2A) were provided to each participant by the physical therapist. Orthotic wedges were made from solid rubber with a thin fabric cover, which were available in small, medium and large sizes, according to the foot length of participants (Figure 2B). Previous studies recommended the posting at 60% of the measured forefoot angle, up to a maximum of 8 degrees, for extrinsic forefoot varus wedge and the posting at 50% of the measured forefoot angle, up to a maximum of 6 degrees, for extrinsic rearfoot varus wedge, following the technique from Root[8, 10]. Regarding the amount of posting from the method introduced by Monaghan et al, the forefoot was posted at 50% of the measured forefoot angle, and the rearfoot was posted at 20% of the measured rearfoot angle[7].

Gait assessment

A 10 camera three-dimensional motion analysis system (Vicon, Vantage V5 series, Oxford, UK) was used to track the lower-extremity kinematics and the shoe motions of multi-segment foot kinematics during gait at a sampling rate of 100 Hz. The cameras were synchronized with two force plates (AMTI, model OR6-7, USA), sampling at 1000 Hz positioned within an 8-m walkway. Forty-two retro-reflective markers were attached to the participants by the same physical therapist following the Plug-In-Gait (PIG) model and the Oxford Foot Model (OFM) with the markers applied to the shoes (Figure 3)[19]. Ten sizes of the shoe were available to ensure participants were assigned the correct size. No markers were removed from the shoes during testing. Participants were asked to walk under three conditions with the same shoe; shod, shod with W1, and shod with W2, the order of which was randomized. Before data collection in each condition, the therapist checked the location of the markers on the shoe and the shoelaces were tightened with a similar tension. The participants were asked to walk for approximately one minute to familiarize themselves with each condition. Data were collected for 3-5 successful gait trials per condition at a self-selected speed. A successful gait trial was defined as the foot making contact with the force plate with no part of the foot being over the edge of the plate. The comfort level was assessed after walking in each condition ranging from 0 to 10, with the higher score representing greater comfort. Intra-rater reliability from the gait assessment showed the ICC(3,1) values ranging from 0.75 to 0.96 and the SEM values ranged from 0.01 to 1.56.

Data processing

The kinematic and kinetic data were filtered using the 4th order zero-lag, low-pass Butterworth technique with cut off frequencies of 6 Hz and 30 Hz, respectively. Joint kinematics were tracked using Nexus (version 2.8.1) to determine the pelvis, hip, knee, rearfoot (hindfoot relative to tibia), forefoot (forefoot relative to hindfoot) in all three planes of motion, and the hallux motion in sagittal plane. Initial contact and toe-off events of each foot were identified using the vertical ground reaction force (GRF) data using a 10 N threshold. The stance phase of each foot was then normalized over a gait cycle by using the custom MATLAB software (R2017a). Peak angle and range of motion of each joint were determined within each subphase of the stance, including contact phase, midstance phase, and propulsive phase. Contact phase was defined as the time from ipsilateral heel strike to contralateral heel off; midstance phase was defined as the time from contralateral heel off to contralateral heel contact; and propulsive phase was defined as the time from contralateral heel contact to ipsilateral toe off[20]. In addition, an approximately relative length of the plantar fascia which was distance from the 1^{st} metatarsophalangeal joint marker to the medial calcaneus marker[21, 22], peak anteroposterior, mediolateral, and vertical GRFs were also investigated.

Statistical analysis

Shapiro–Wilk tests were used to determine if the data were normally distributed. For the normally distributed data the kinematic and kinetic characteristics from the symptomatic limbs were shown as mean ± standard deviation (SD). Repeated Measures ANOVA (RM ANOVA) were used to compare the peak angle and the range of motion of the lower extremity and multi-segment foot as well as the ground reaction force data during gait between the three conditions; shod, shod with W1, and shod with W2. Where a significant main effect was seen post-hoc pairwise comparison test with a Bonferroni correction were performed. For the non-normally distributed data kinematic and kinetic characteristics were shown as median (25th/75th Percentiles) and non-parametric Friedman tests and post hoc Wilcoxon signed-rank test were used. All statistical analyses were performed using SPSS software version 22.0 (IBM Statistics, USA), with a statistical significance level set at $P<0.05$. Effect sizes using Cohen’s d were calculated for all variables[23].

RESULTS

Thirty-five participants with PF (26 females and 9 males), with a total of 41 symptomatic limbs, with an average age of 40.14 years (SD 10.53) and body mass index (BMI) of 26.35 kg/m^2 (SD 5.65) were included in the analysis. The symptomatic limbs showed higher forefoot varus angles when compared with previously reported normative values[8, 24, 25]. Regarding the comfort scores, there was significant difference among three conditions (*P*=0.009), the W1 showed great comfort than the shoe (*P*=0.003), but there were no significant differences between the W2 and shoe (*P*=0.100) as well as the W1 and W2 (*P*=0.666) (Table 1).

Significant differences were seen in the lower-extremity kinematics and the shoe motions of multi-segment foot kinematics between the three conditions. These included hip internal rotation (*P*=0.037), knee adduction (*P*=0.039), forefoot inversion (*P*=0.035), forefoot abduction (*P*=0.011), rearfoot dorsiflexion (*P*=0.008), hallux eversion (*P*<0.001), and relative length of the plantar fascia (*P*=0.001) during the contact phase, with the midstance phase showing differences in pelvis abduction (*P*=0.033) and rearfoot inversion (*P*=0.023). During the propulsive phase significant differences were seen in the rearfoot inversion and hallux dorsiflexion (*P*=0.001 and *P*<0.001), respectively (Table 2, Figure 4). No significant differences were seen in the GRF among three conditions (*P*≥0.05).

Further pairwise comparisons showed that compared with shod, the W1 significantly increased rearfoot dorsiflexion (*P*=0.035), decreased peak forefoot dorsiflexion (*P*=0.011), decreased peak rearfoot eversion (*P*=0.035), and decreased relative length of the plantar fascia (*P*=0.029) during the contact phase. In addition, W1 increased rearfoot inversion (*P*=0.009), decreased hallux dorsiflexion (*P*=0.010), and decreased peak hallux dorsiflexion (*P*=0.006) during the propulsive phase. For W2, the wedge significantly decreased forefoot abduction (*P*=0.032), decreased peak forefoot dorsiflexion (*P*=0.001), decreased peak rearfoot eversion (*P*=0.001), decreased peak knee internal rotation (*P*=0.033), and decreased relative length of the plantar fascia (*P*=0.009) during the contact phase. In addition, W2 increased rearfoot inversion (*P*=0.002), decreased hallux dorsiflexion (*P*<0.001), and decreased peak hallux dorsiflexion (*P*<0.001) during the propulsive phase. When comparing W1 and W2, W1 showed greater rearfoot dorsiflexion (*P*=0.005) during contact phase, Table 3 and Table 4.

In the non-symptomatic sides, the orthotic wedge significantly decreased peak hallux dorsiflexion (*P*<0.001) during the propulsive phase when compared with the shod condition, which was similar to the response on the symptomatic sides. There was no significant difference between the orthotic wedges and the shod condition for the peak angle or the other segments and the relative length of the plantar fascia (*P*≥0.05), as shown in Table 5.

DISCUSSION

The aim of this study was to determine the biomechanical effects of two designs of orthotic wedges in people with PF. The results confirmed that both designs of orthotic wedges produced significant biomechanical changes when compared with shod walking during the contact and propulsive phases. Regarding the contact phase, both W1 and W2 decreased shoe motions of peak forefoot dorsiflexion and peak rearfoot eversion, as well as decreased relative length of the plantar fascia. These results imply that orthotic wedges reduce dynamic foot pronation during the contact phase, since greater rearfoot eversion and forefoot dorsiflexion are included in the components of over pronation during gait, which could then induce a greater strain in the plantar fascia [4, 5, 26]. The present findings, therefore, support the use of orthotic wedges to decrease excessive elongation in the plantar fascia during gait in individuals with PF. Such effect was found in only the symptomatic sides, with no significant difference seen in the relative length of the plantar fascia in the non-symptomatic sides between the orthotic wedge condition and the shod condition.

In addition, both W1 and W2 produced more shoe motion of rearfoot inversion, less shoe motions of hallux dorsiflexion, and peak hallux dorsiflexion during the propulsive phase. It was thus assumed from the present findings that the use of orthotic wedges could produce earlier inversion of the foot than the shod only condition. Although there were no significant differences between conditions during the midstance phase, the greater rearfoot inversion and less hallux dorsiflexion when using the orthotic wedges indicates greater foot stability during the propulsive phase than the shod only condition. Such biomechanical changes could reduce the excessive tension of plantar fascia and improve propulsion in people with PF[27-29].

This study also considered the biomechanical effects between two orthotic wedges designed based on two different foot assessment techniques. The two designs of orthotic wedges provided different effects when compared with the shod, with the W1 increasing shoe motion of rearfoot dorsiflexion during the contact phase; whereas the W2 decreased shoe motion of forefoot abduction and decreased peak knee internal rotation during the contact phase. Regarding the comparisons between the two designs of orthotic wedges, the W1 produced more shoe motion of rearfoot dorsiflexion, which can be associated with the different posting used within the two types of orthotic wedges. The amount of posting for the two designs was calculated from two different techniques of foot assessment[7, 8], with the technique suggested by Monaghan et al[9] providing less rearfoot posting than that from the assessment suggested by Root[11]. From the assessments the majority of the participants received posting of the W1 (Root) at both the rearfoot and forefoot while W2 (Monaghan et al.) mostly posted at the forefoot only. Only the participants with rearfoot varus in relaxed position of more than 15 degrees were provided with a W2 with posting at rearfoot[9].

Since W1 mostly included both the forefoot and rearfoot postings, it produced more shoe motion of rearfoot dorsiflexion than W2. One possible mechanism for PF has been suggested as a lack of shank-calcaneus dorsiflexion during the contact phase. Such a limitation could induce more midfoot dorsiflexion, resulting in over foot pronation and more stretch of the plantar fascia[4, 30]. W1 could thus reduce relative length of the plantar fascia by producing more dorsiflexion of the shank-calcaneus found in the early stance. Whereas, W2, which mainly included forefoot posting, showed superior effects than the W1 in the reduction of forefoot abduction. It is possible that only the forefoot posting was sufficient to decrease foot pronation during the weight acceptance by shifting the weight-bearing line from the medial to the lateral side of the foot[31]. When considering the coupling mechanism between the foot, tibia, femur, and hip, a reduction of foot pronation has been suggested to decrease internal rotation of the limb[26]. Therefore, the W2 could reduce over stretch of the plantar fascia by reducing the deviation of foot movement in the transverse plane and subsequently decreasing the prolong internal rotation of the knee which is supported by these present findings. No difference was seen in the relative length of the plantar fascia when comparing W1 and W2, as both provided significant changes in the kinematics on the symptomatic sides during gait. Therefore, either design of the orthotic wedge could be used for individuals with PF, however further studies are required to support longer term clinical outcomes.

To our knowledge, this is the first study to determine the biomechanical effects of orthotic wedges in people with PF, and these findings are supported by a previous meta-analysis which suggested the use of forefoot varus wedge and the combination of forefoot and rearfoot varus wedges to reduce over pronation during walking[6]. However, the results from the present study provide data only on the immediate effects of the orthotic wedges and further studies should be conducted to determine the longer term clinical effects alongside the biomechanical changes, which should also consider muscle activity within the foot and lower limb.

CONCLUSION

Both techniques of orthotic prescription indicate biomechanical changes of the lower extremity and the shoe motions of the multi-segment foot during the contact and propulsive subphases of gait. However the two orthotic wedges provided different effects with the W1 increasing shoe motion of rearfoot dorsiflexion during the contact phase, whereas the W2 decreased shoe motion of forefoot abduction and decreased peak knee internal rotation during the contact phase. These findings support the use of forefoot varus wedge and the combination of forefoot and rearfoot varus wedges to reduce the relative length of the plantar fascia which might be associated with a reduction in pain and symptoms during walking.

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Table 1 Participant characteristics (n=41). Data are shown as mean (SD), minimum and maximum

Characteristics	**Mean (SD)**	**Minimum**	**Maximum**
Femoral anteversion angle, degrees	14.67 (2.81)	9.0	21.0
Tibial torsion angle, degrees	22.51 (4.13)	13.0	35.0
Ankle inversion angle, degrees	14.66 (5.97)	7.0	31.0
Ankle eversion angle, degrees	6.32 (2.71)	3.0	15.0
Foot assessment for the orthotic wedge design 1 (W1)			
- Rearfoot varus angle, degrees	0.98 (2.34)	-4.0	7.0
- Rearfoot varus wedge, degrees	4.63 (1.80)	0	8
- Forefoot angle, degrees	11.46 (3.63)	4.0	23.0
- Forefoot varus wedge, degrees	5.32 (1.84)	0	8
Foot assessment for the orthotic wedge design 2 (W2)			
- Rearfoot angle, degrees	5.24 (3.07)	0.0	15.0
- Forefoot angle, degrees	18.05 (7.30)	6.0	33.0
- Forefoot varus wedge, degrees	6.20 (1.99)	0	8
Comfort with foot orthoses (FOs)			
- Shoe, points	5.72 (1.94)	1.65	9.80
- W1, points	6.54 (1.68)	2.65	9.05
- W2, points	6.31 (2.04)	1.45	9.68

Table 2 Comparisons of the mean (SD) or median (IQR) of the lower-extremity range of motion among the shod condition, W1 condition, and W2 condition in each subphase of stance gait (n=41)

	Contact phase					**Midstance phase**					**Propulsive phase**				
	Mean (SD) / Median (IQR)			***P***	**Effect size**	**Mean (SD) / Median (IQR)**			***P***	**Effect size**	**Mean (SD) / Median (IQR)**			***P***	**Effect size**
	Shod	**W1**	**W2**			**Shod**	**W1**	**W2**			**Shod**	**W1**	**W2**		
Pelvis															
Sagittal (˚)	1.8 (0.8)	1.9 (0.8)	1.8 (0.7)	0.469	0.293	2.7 [1.8,3.8]	2.6 [1.7,3.5]	2.6 [1.8,3.1]	0.247	0.556	2.0 (0.9)	1.9 (1.0)	2.0 (0.9)	0.703	0.191
Frontal (˚)	4.0 (1.1)	3.9 (1.1)	3.7 (1.1)	0.064	0.574	6.0 (2.0)	5.9 (1.8)	5.7 (1.7)	0.033*	0.614	4.0 [3.1,4.6]	3.8 [3.1,4.5]	3.7 [2.7,4.4]	0.540	0.366
Transverse (˚)	2.2 (1.2)	2.4 (1.2)	2.4 (1.3)	0.364	0.340	7.6 (2.2)	7.5 (1.8)	7.5 (1.7)	0.824	0.155	2.2 (1.3)	2.4 (1.3)	2.3 (1.2)	0.616	0.230
Hip															
Sagittal (˚)	12.2 (2.6)	12.6 (3.3)	12.7 (2.4)	0.235	0.398	29.2 (4.4)	28.8 (4.7)	28.6 (4.5)	0.239	0.392	8.8 (2.6)	6.3 (2.6)	9.3 (2.3)	0.115	0.496
Frontal (˚)	7.0 (2.2)	6.8 (2.1)	6.7 (2.2)	0.273	0.381	5.5 (1.8)	5.2 (1.9)	5.2 (1.7)	0.231	0.398	10.4 (2.4)	10.1 (2.6)	10.1 (2.8)	0.151	0.449
Transverse (˚)	26.5 (9.8)	27.5 (10.6)	25.6 (10.3)	0.037*	0.602	14.6 (5.7)	14.4 (5.3)	14.0 (5.4)	0.475	0.286	18.0 (9.6)	18.4 (10.6)	18.6 (10.5)	0.465	0.286
Knee															
Sagittal (˚)	8.5 [6.1,11.7]	8.4 [6.3,10.8]	8.6 [5.4,11.1]	0.140	0.690	8.5 (3.3)	8.3 (3.5)	8.1 (3.4)	0.388	0.333	25.4 (8.9)	25.8 (9.5)	25.6 (9.9)	0.863	0.127
Frontal (˚)	5.7 [3.4,7.4]	5.7 [3.6,7.4]	5.3 [3.3,7.4]	0.039*	0.907	5.0 (2.8)	4.9 (2.5)	5.1 (3.1)	0.723	0.191	21.6 (9.6)	22.5 (10.5)	22.5 (10.3)	0.142	0.464
Transverse (˚)	15.7 (4.5)	14.9 (3.8)	14.4 (3.6)	0.118	0.510	7.9 (2.7)	7.5 (2.4)	7.5 (2.3)	0.493	0.278	9.3 (4.3)	8.9 (5.2)	8.5 (4.2)	0.359	0.333
HF-TB															
Sagittal (˚)	16.1 [13.4,17.8]	17.3 [14.7,20.0]	15.6 [14.0,18.9]	0.008*	1.190	16.8 (5.0)	17.4 (4.3)	17.0 (5.2)	0.746	0.180	30.8 (7.3)	31.1 (7.5)	29.8 (6.7)	0.282	0.375
Frontal (˚)	25.4 [19.6,32.9]	26.1 [20.0,31.6]	23.3 [19.5,30.7]	0.506	0.386	19.2 (7.5)	17.7 (6.6)	17.9 (6.7)	0.023*	0.648	13.3 (6.8)	15.2 (7.4)	15.3 (6.7)	0.001*	0.912
Transverse (˚)	10.0 (3.8)	10.7 (3.9)	9.7 (3.6)	0.054	0.590	7.3 (3.3)	7.6 (4.2)	7.6 (3.1)	0.777	0.168	15.3 (9.3)	15.6 (10.7)	14.7 (8.1)	0.631	0.220
FF-HF															
Sagittal (˚)	4.8 (1.2)	4.8 (1.3)	4.5 (1.4)	0.286	0.381	2.1 (0.8)	2.1 (0.9)	2.1 (1.0)	0.844	0.142	2.8 (1.1)	3.2 (1.6)	2.9 (1.2)	0.293	0.392
Frontal (˚)	1.9 (0.6)	2.1 (0.5)	1.9 (0.5)	0.035*	0.625	1.6 (0.6)	1.5 (0.4)	1.5 (0.4)	0.801	0.168	1.6 (0.6)	1.4 (0.7)	1.4 (0.5)	0.068	0.582
Transverse (˚)	4.0 (1.3)	3.6 (1.2)	3.6 (1.1)	0.011*	0.728	1.9 [1.4,2.6]	1.8 [1.1,2.4]	1.9 [1.3,2.5]	0.238	0.580	3.5 (1.6)	3.6 (1.7)	3.5 (1.3)	0.831	0.142
Hallux															
Sagittal (˚)	5.2 (2.9)	5.1 (2.6)	5.2 (2.7)	0.868	0.127	6.2 (3.1)	6.5 (3.6)	6.7 (3.1)	0.311	0.381	24.9 (8.3)	20.8 (7.9)	19.1 (6.5)	<0.001*	1.223

*** Significant difference of the main effect**

Table 3 Pairwise comparisons of the mean or median of the lower-extremity range of motion among the shod condition, W1 condition, and W2 condition in each subphase of stance gait (n=41)

	Contact phase						**Midstance phase**						**Propulsive phase**					
	Mean difference (SE) / Z score			***P** **	***P** ***	***P** ****	**Mean difference (SE) / Z score**			***P** **	***P** ***	***P** ****	**Mean difference (SE) / Z score**			***P** **	***P** ***	***P** ****
	Shod VS W1	**Shod VS W2**	**W1 VS W2**				**Shod VS W1**	**Shod VS W2**	**W1 VS W2**				**Shod VS W1**	**Shod VS W2**	**W1 VS W2**			
Pelvis																		
Sagittal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frontal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	0.2 (0.1)	0.3 (0.1)	0.1 (0.1)	0.345	0.055	0.717	N/A	N/A	N/A	N/A	N/A	N/A
Transverse (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hip																		
Sagittal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frontal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Transverse (˚)	-1.0 (0.6)	0.9 (0.8)	1.9 (0.8)	0.311	0.730	0.062	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Knee																		
Sagittal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frontal (˚)	-0.335	-1.704	-1.835	0.738	0.088	0.067	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Transverse (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HF-TB																		
Sagittal (˚)	-2.110	-0.566	-2.814	0.035	0.572	0.005	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frontal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	1.5 (0.6)	1.3 (0.7)	-0.3 (0.5)	0.058	0.163	1.000	-1.9 (0.6)	-2.0 (0.5)	-0.1 (0.6)	0.009	0.002	1.000
Transverse (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FF-HF																		
Sagittal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frontal (˚)	-0.2 (0.1)	-0.01 (0.1)	0.1 (0.1)	0.080	1.000	0.092	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Transverse (˚)	0.4 (0.2)	0.5 (0.2)	0.1 (0.2)	0.077	0.032	1.000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hallux																		
Sagittal (˚)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.0 (1.3)	5.8 (1.1)	1.7 (1.1)	0.010	< 0.001	0.326

*** Comparison between shod and W1**

**** Comparison between shod and W2**

***** Comparison between W1 and W2**

Table 4 Comparisons of the mean (SD) or median (IQR) of the peak angle, arch height index, relative length of the plantar fascia, and ground reaction force among the shod condition, W1 condition, and W2 condition (n=41)

	Condition			***P***	**Effect size**	***P ****	***P *****	***P ******
	Shod	**W1**	**W2**					
Hip								
Peak adduction (˚)	6.88 (2.99)	6.48 (3.27)	6.40 (3.18)	0.107	0.492	N/A	N/A	N/A
Peak internal rotation (˚)	25.00 [11.02, 35.50]	28.16 [7.45, 37.22]	26.76 [9.09, 38.88]	0.298	0.522	N/A	N/A	N/A
Knee								
Peak adduction (˚)	3.41 [-0.86, 7.16]	3.42 [-1.25, 6.35]	2.94 [-1.98, 6.13]	0.332	0.490	N/A	N/A	N/A
Peak internal rotation (˚)	0.60 [-17.88, 13.11]	0.96 [-22.69, 8.73]	-0.43 [-25.09, 8.01]	**0.040**	**0.904**	0.078	0.033	0.115
HF-TB								
Peak plantarflexion (˚)	-16.50 (6.99)	-15.97 (7.35)	-15.81 (7.50)	0.465	0.313	N/A	N/A	N/A
Peak eversion (˚)	-28.96 [-48.37, -5.55]	-18.93 [-46.82, -6.15]	-25.19 [-43.28, -1.52]	**0.005**	**1.211**	0.035	0.001	0.068
Peak abduction (˚)	-5.46 [-8.59, -2.46]	-5.58 [-9.09, -3.41]	-6.24 [-9.37, -3.02]	0.165	0.713	N/A	N/A	N/A
FF-HF								
Peak dorsiflexion (˚)	10.16 (7.03)	9.69 (6.97)	9.27 (7.00)	**0.001**	**1.553**	0.011	0.001	0.101
Peak inversion (˚)	0.04 [-1.50, 2.88]	0.75 [-1.38, 2.93]	0.11 [-1.96, 2.79]	0.101	0.752	N/A	N/A	N/A
Peak adduction (˚)	4.00 [0.16, 8.12]	5.11 [0.64, 7.71]	5.10 [1.08, 7.62]	0.225	0.592	N/A	N/A	N/A
Hallux								
Peak dorsiflexion (˚)	38.21 (13.57)	33.97 (12.80)	32.14 (11.49)	**< 0.001**	**2.548**	0.006	< 0.001	0.189
Peak inversion (˚)	-15.84 (9.43)	-15.29 (9.44)	-15.60 (9.25)	0.534	0.017	N/A	N/A	N/A
Peak abduction (˚)	-3.67 [-5.42, -1.23]	-3.81 [-4.87, -0.95]	-3.27 [-4.21, -0.99]	**0.021**	**1.131**	0.194	0.045	0.005
Arch								
Arch height index	1.97 (0.92)	1.80 (0.86)	1.66 (0.88)	0.156	0.483	N/A	N/A	N/A
Relative length of the plantar fascia	4.71 (1.81)	4.03 (1.47)	3.90 (1.52)	**0.001**	**0.956**	0.029	0.009	1.000
Anteroposterior GRF								
First peak	16.13 (3.99)	15.51 (3.88)	15.59 (3.78)	0.324	0.352	N/A	N/A	N/A
Second peak	21.15 (3.21)	20.62 (3.32)	20.55 (3.41)	0.159	0.444	N/A	N/A	N/A
Mediolateral GRF								
First peak	5.60 (1.38)	5.71 (1.45)	5.54 (1.53)	0.729	0.191	N/A	N/A	N/A
Second peak	4.38 (1.92)	4.47 (2.07)	4.03 (1.90)	0.057	0.565	N/A	N/A	N/A
Vertical GRF								
First peak	108.87 (8.85)	108.46 (9.53)	108.41 (9.30)	0.885	0.110	N/A	N/A	N/A
Second peak	105.24 (7.89)	105.24 (8.03)	104.65 (7.89)	0.808	0.155	N/A	N/A	N/A

*** Comparison between shod and W1** **** Comparison between shod and W2** ***** Comparison between W1 and W2**

Table 5 Comparisons of the mean (SD) or median (IQR) of the peak angle, arch height index, relative length of the plantar fascia, and ground reaction force among the shod condition, W1 condition, and W2 condition in the non symptomatic sides (n=29)

	Condition			***P***	**Effect size**	***P ****	***P *****	***P ******
	Shod	**W1**	**W2**					
Hip								
Peak adduction (˚)	7.70 (4.97)	7.65 (5.41)	7.78 (5.27)	0.919	0.127	N/A	N/A	N/A
Peak internal rotation (˚)	19.16 [5.73, 29.25]	16.66 [5.56, 29.12]	18.01 [5.56, 32.51]	0.584	0.443	N/A	N/A	N/A
Knee								
Peak adduction (˚)	3.50 [-0.38, 5.64]	2.86 [-0.32, 5.99]	3.61 [-0.55, 5.93]	0.535	0.480	N/A	N/A	N/A
Peak internal rotation (˚)	1.93 [-6.54, 16.54]	-0.91 [-11.70, 13.08]	0.73 [-12.63, 11.42]	0.153	0.884	N/A	N/A	N/A
HF-TB								
Peak plantarflexion (˚)	-15.59 (7.24)	-15.52 (8.77)	-14.82 (8.68)	0.723	0.247	N/A	N/A	N/A
Peak eversion (˚)	-20.32 [-47.88, -8.89]	-18.27 [-36.80, -5.43]	-21.14 [-34.40, -6.83]	0.125	0.939	N/A	N/A	N/A
Peak abduction (˚)	-6.98 [-10.62, 0.55]	-6.74 [-10.32, -0.57]	-6.44 [-11.33, -0.32]	0.866	0.226	N/A	N/A	N/A
FF-HF								
Peak dorsiflexion (˚)	8.52 (4.17)	8.24 (6.30)	7.63 (6.34)	0.657	0.271	N/A	N/A	N/A
Peak inversion (˚)	1.45 [-0.60, 4.09]	1.28 [-0.66, 3.28]	0.81 [-0.14, 3.31]	0.247	0.727	N/A	N/A	N/A
Peak adduction (˚)	3.02 [-0.12, 8.00]	3.99 [0.99, 8.13]	4.53 [1.01, 8.15]	0.257	0.714	N/A	N/A	N/A
Hallux								
Peak dorsiflexion (˚)	48.75 [29.85, 59.24]	43.10 [25.74, 54.32]	32.14 [30.28, 51.72]	**< 0.001**	**2.990**	0.003	0.007	0.819
Peak inversion (˚)	-13.35 [-27.56, -7.11]	-14.48 [-26.69, -3.25]	-12.92 [-28.09, -6.85]	0.926	0.164	N/A	N/A	N/A
Peak abduction (˚)	-4.00 [-5.40, -1.02]	-2.40 [-4.85, 0.25]	-2.76 [-5.10, -0.99]	0.123	0.920	N/A	N/A	N/A
Arch								
Arch height index	2.28 (1.10)	2.17 (1.19)	1.87 (0.95)	0.071	0.696	N/A	N/A	N/A
Relative length of the plantar fascia	4.28 (1.54)	4.10 (1.63)	3.89 (1.62)	0.519	0.387	N/A	N/A	N/A
Anteroposterior GRF								
First peak	14.85 [11.82, 18.59]	15.28 [12.21, 17.38]	15.59 [12.05, 18.31]	0.867	0.224	N/A	N/A	N/A
Second peak	20.44 (3.18)	20.13 (3.24)	19.62 (3.35)	0.020	0.883	0.686	0.065	0.194
Mediolateral GRF								
First peak	6.16 (1.98)	6.14 (1.96)	6.05 (1.99)	0.928	0.110	N/A	N/A	N/A
Second peak	4.86 (2.46)	4.83 (2.58)	4.99 (2.45)	0.864	0.168	N/A	N/A	N/A
Vertical GRF								
First peak	106.08 [101.31, 115.18]	107.38 [100.35, 113.68]	106.10 [101.63, 114.44]	0.108	0.953	N/A	N/A	N/A
Second peak	104.57 [98.43, 110.97]	106.58 [97.13, 111.78]	103.21 [99.29, 111.76]	0.872	0.215	N/A	N/A	N/A

*** Comparison between shod and W1** **** Comparison between shod and W2** ***** Comparison between W1 and W2**

Figure 1 The foot assessment technique 1 (W1: Right side) and the foot assessment technique 2 (W2: Left side). A represents the rearfoot angle formed between a bisection line at distal one third of lower leg and a bisection line at calcaneus in subtalar neutral position. B represents the forefoot angle formed between a bisection line at calcaneus and a parallel line through the metatarsal heads in subtalar neutral position. C represents the rearfoot angle formed between a bisection line at calcaneus and a line perpendicular to the caudal edge of the table. D represents the angle formed between a line through the metatarsal head and a line parallel to the caudal edge of the table.

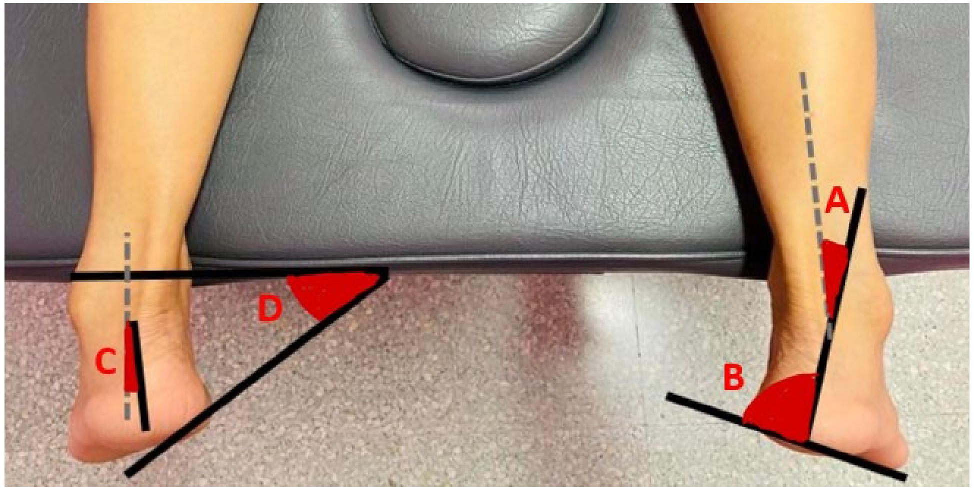


Figure 2 Orthotic wedges in the present study (A: orthotic wedges with a full length of soft foam layer, B: medial forefoot and rearfoot varus wedge with three different sizes i.e. small (S), medium (M), large (L). Blue color is the 3-degree wedge, Yellow color is the 6-degree wedge, Red color is the 8-degree wedge)

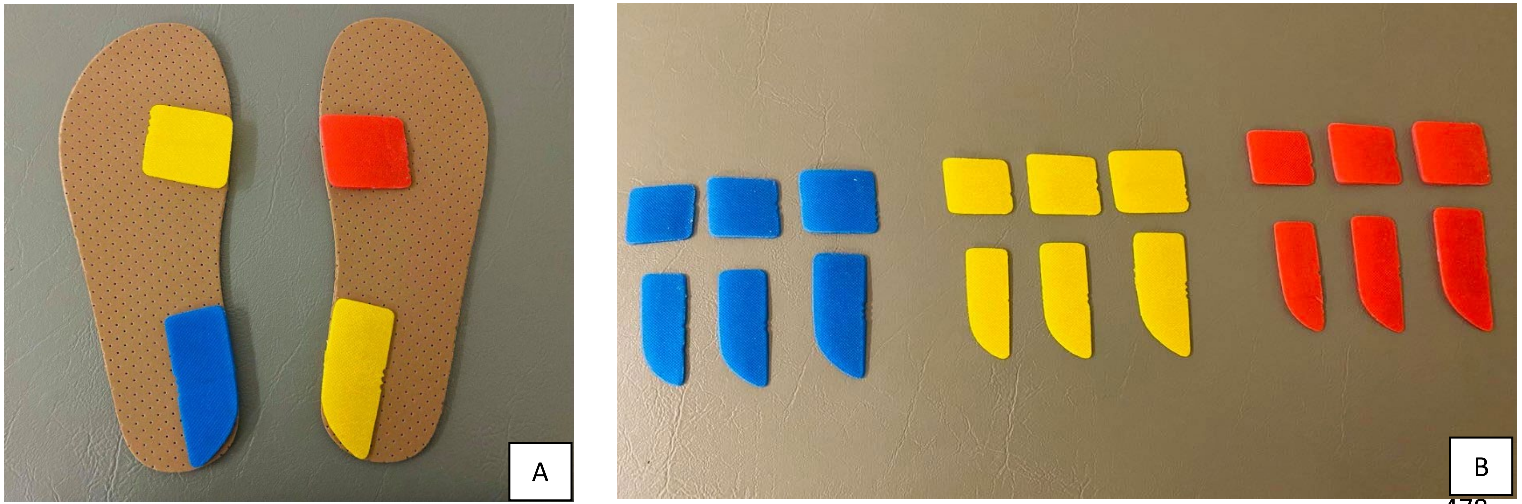
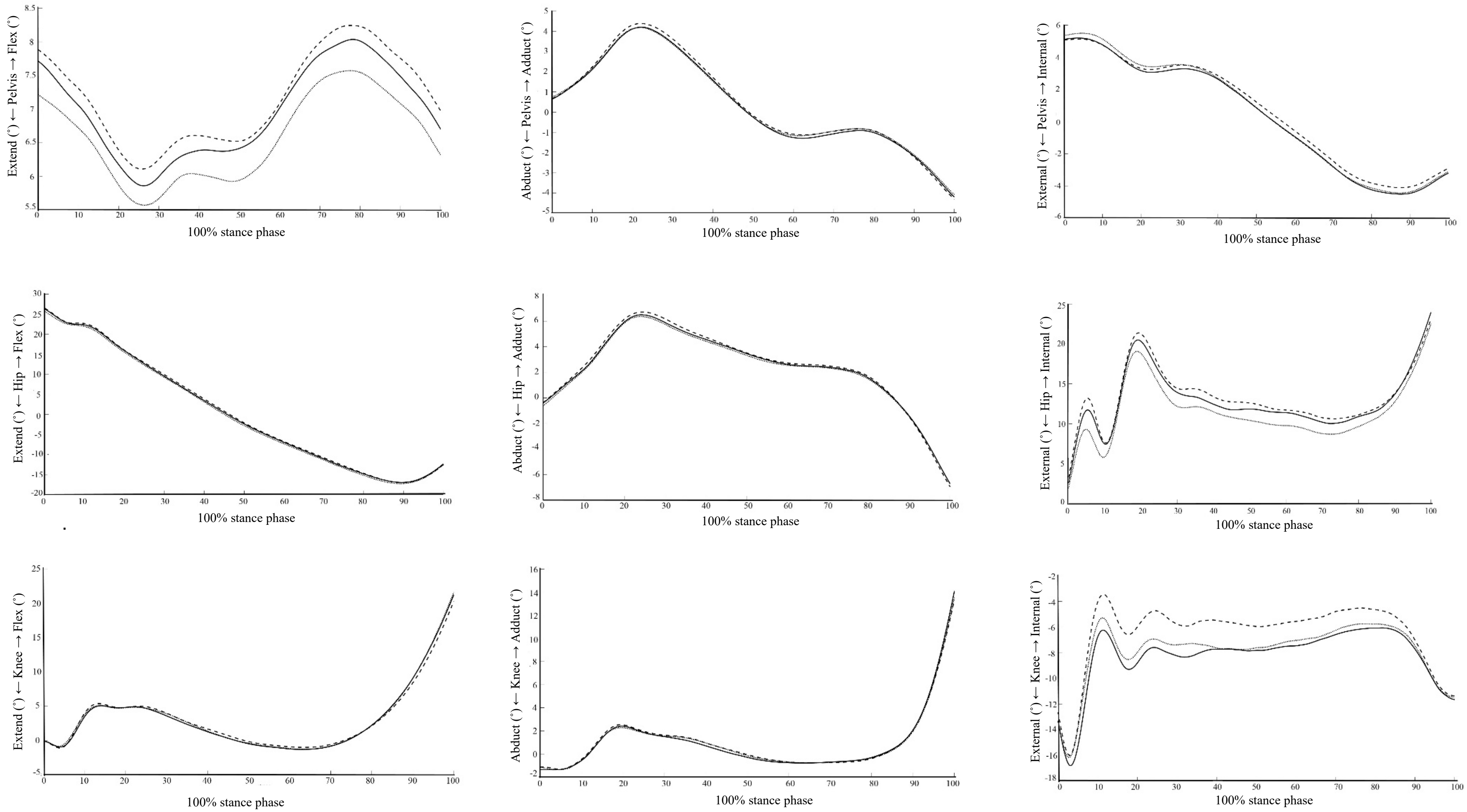
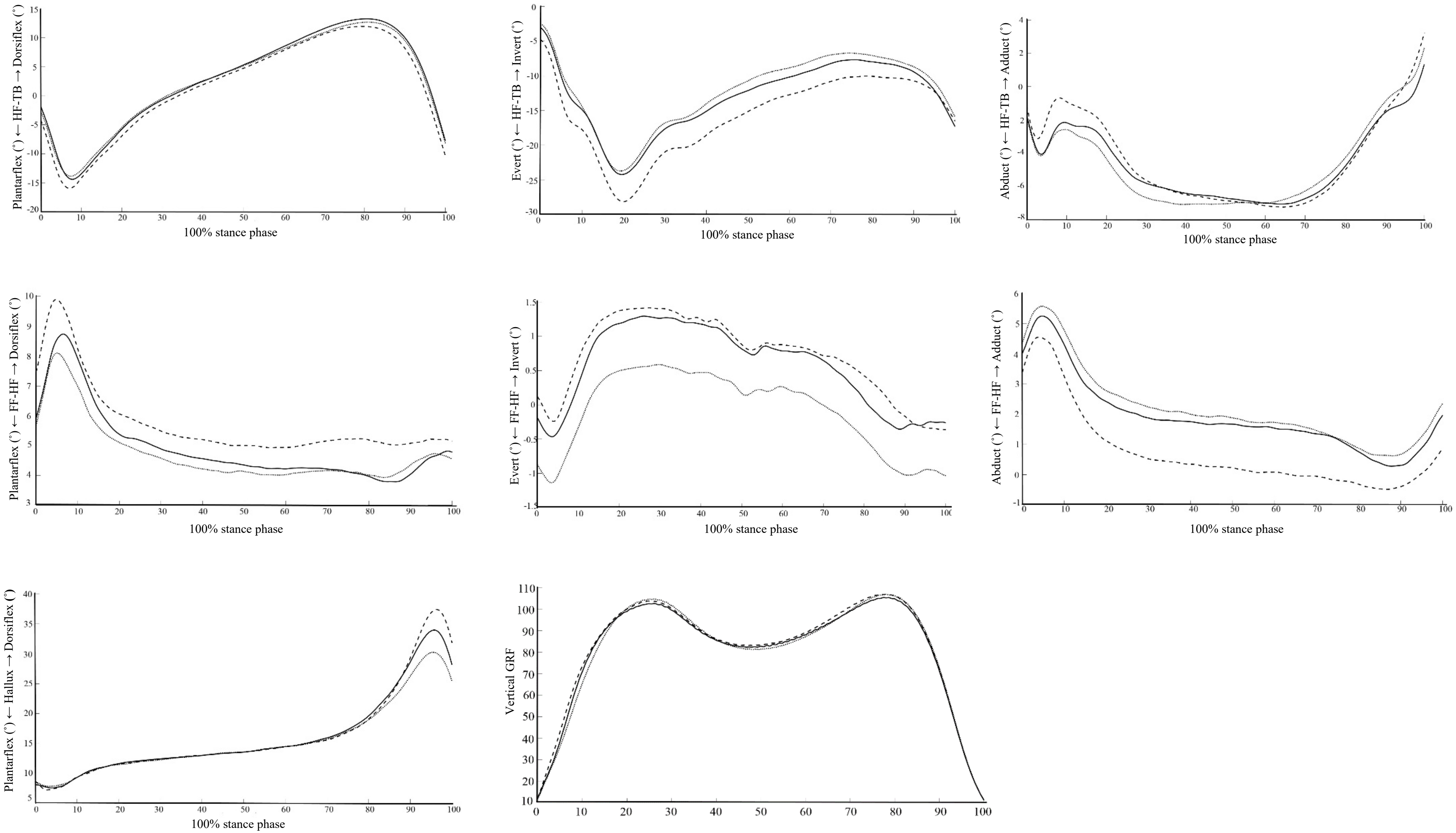


Figure 3 Marker placement of the lower extremity and multi-segment foot (A: lateral view, B: anterior view, C: posterior view, D: anterior view of barefoot)

Figure 4 Comparisons of the lower-extremity kinematics and the vertical GRF among the shod condition, W1 condition, and W2 condition in each subphase of stance gait (n=41) (Shod represented by a dashed line, W1 represented by a straighted line, and W2 represented by a dotted line)




Plantarflex (°) ← HF-TB → Dorsiflex (°)
100% stance phase
Evert (°) ← HF-TB → Invert (°)
100% stance phase
Abduct (°) ← HF-TB → Adduct (°)
100% stance phase
Plantarflex (°) ← FF-HF → Dorsiflex (°)
100% stance phase
Evert (°) ← FF-HF → Invert (°)
100% stance phase
Abduct (°) ← FF-HF → Adduct (°)
100% stance phase
Plantarflex (°) ← Hallux → Dorsiflex (°)
100% stance phase
Vertical GRF