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Double Density Foot Orthoses Altered Ground Reaction Force Characteristics and the Lower Limb Muscular Activities in Adults with Pronated Feet During Walking: A Clinical Trial Study

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Abstract

Introduction: Investigation of ground reaction forces and electromyographic activity can help clinicians examine mechanical changes in the feet of individuals in pronation during rehabilitation.

Method: Twenty adult males with pronated feet and twenty healthy adult males volunteered to participate in this study. A force plate was embedded in the middle of an 18-m walkway to collect ground reaction forces. Muscle activity was recorded using an EMG system. Ground reaction forces and lower limb muscle activities were recorded during walking with and without foot orthoses. A two-way ANOVA with repeated measures was used for statistical analysis.

Result: Paired-wise comparison demonstrated lower peak medial ground reaction force, peak anterior and posterior ground reaction forces, peak negative free moment, and time-to-peak of medial ground reaction force during walking with foot orthoses than without them. Results did not show any significant group-by-foot orthoses interactions for ground reaction force components during walking. Significant group-by-time interactions were found for rectus femoris activities. Post-hoc analysis demonstrated lower rectus femoris activity in the healthy group and greater rectus femoris activity during loading phases while walking with foot orthoses compared with without them.

Conclusion : Double-density foot orthoses can effectively alter ground reaction forces and muscle activations in individuals with pronated feet, potentially reducing the risk of injury and improving walking mechanics.

Keywords: Pronated feet, Foot orthoses, Muscle activities, Ground reaction forces, walking.

Introduction

Pronated foot (PF) alignment refers to a three-dimensional foot posture characterized by excessive rearfoot eversion, forefoot abduction, and dorsiflexion [1]. The prevalence of PF is ~11% in individuals aged 25–30 years [2]. Previous studies [3, 4] have reported that PF individuals demonstrated greater peak eversion and internal rotation of the rear foot and larger peak abduction, adduction, and plantarflexion of the forefoot during the stance phase of gait. As foot pronation and knee valgus are linked deformities, PF can also drive abnormal internal rotation at the knee and the hip [3, 4]. Furthermore, Farahpour et al. [5] reported that PF individuals showed a greater anteroposterior ground reaction force (GRF) during the waling stance phase. Moreover, it has been mentioned that PF is associated with a high incidence of overuse injuries (e.g., plantar fasciitis [3] and medial tibial stress syndrome [6]). Hence, preventive measures, such as foot orthoses (FOs) [7], have been prescribed in rehabilitation and sports medicine for individuals with PF.

FOs have been used as a conservative method to manage pain and reduce the risk of overuse injuries in PF individuals [8]. FOs designed for PF target to restore their regular foot dynamic function, which can be evaluated via joint kinematics, kinetics, and muscle activities during walking and running [9]. These corrective effects are usually achieved via appropriate configurations of orthotic components [8]. Thus, a clear relationship between the features of FO components and the corresponding biomechanical responses (e.g., the dose-response effect) is vital for the design and prescription of FOs. Medial wedge FOs are the most common type of orthosis used to reduce foot pronation and alter lower-limb biomechanics in PF individuals [10]. Posting under the rearfoot facilitates the use of insoles, as forefoot posting is challenging to fit inside the shoe and may cause some discomfort [11]. Accordingly, double-density FOs have been developed, with low density on the lateral side and high density in the medial part. Preliminary evidence suggests that this configuration reduces rearfoot pronation [12]. However, it remains unresolved whether double-density FO has distinct effects on peak GRF, time to peak (TTP), loading rates, free moments, and muscular activity in PF adults. Although there is evidence of the kinematic and kinetic effects of medial wedge FOs on walking, there is little information on the effects of using insoles with different densities on the amplitude of ground reaction forces and the electrical activity of lower limb muscles [13].

It has previously been shown that peak vertical impact GRF, TTP, free moment, and vertical loading rates are predictors of lower limb injuries [14]. More specifically, there is evidence that higher loading rates are associated with a shorter TTP of impact vertical GRF, which could increase the risk of injury [5]. Recent studies reported that free moments of the foot can serve as an index of torsional stress in the lower limbs [15]. These biomechanical variables are important for defining the etiology of injuries in people with PF and should be further explored to understand the potential benefits of double-density FOs. To the best of our knowledge, no study has examined GRFs and muscle activity during walking in adults with PF versus healthy controls using double-density FOs. Therefore, this study aimed to compare walking kinetics and muscle activity in PF adults walking at a constant speed with those of healthy controls, using double-density FOs. With reference to the relevant literature [16, 17], we hypothesized that GRF and muscle activity during walking differ in PF individuals compared with their healthy peers. In addition, we expected that double-density FO would improve GRF amplitudes and muscular activities in adults with PF.

Methods

This study was designed as a double-masked (i.e., participants and examiners) study. The data for the present study were collected on 18-30 September 2024. The authors did not have access to the information that could identify individual participants during or after data collection.

Participants

Forty male individuals aged 25–30 years with PF volunteered for this study. The participants were assigned to the PF (PF, n=20) and healthy (healthy, n=20) groups. The freeware tool G × Power (Version 3.1.9.2, University of Kiel, Germany) was used to estimate the sample size [18]. Descriptive characteristics of the participants are shown in Table 1. All participants were right-footed, as determined by a kicking-ball test. The inclusion criteria for the PF group were: (i) male gender; (ii) body mass index < 25 kg/m2; (iii) rearfoot eversion angle > 4° [19, 20]; (iv) navicular drop > 10 mm; and (v) a foot posture index > 10. The foot posture index was evaluated by a podiatrist with ~11 years of experience. The validity of the foot posture index has been reported in a previous study [21]. The foot posture index consists of 6 items in order to classify foot posture [21, 22]. These are (i) palpation of the head of the talus; (ii) above and below lateral malleolus curvatures; (iii) calcaneus position in the frontal plane; (iv) prominence of the malleolus; (v) congruence of the medial longitudinal arch; (vi) abduction/adduction of the forefoot; (vii). Each item was rated using a visual analog scale ranging from -2 to +2. Therefore, the total score ranged from -12 to +12. Negative values indicate supinated foot posture, and positive values indicate PF posture. Values of 6–10 in this index were classified as PF [21, 22].

The exclusion criteria were: (i) history of musculoskeletal surgery at the trunk and/or lower limbs; (ii) acute neuromuscular or orthopedic disorders (except PF); (iii) lower limbs length asymmetry above 5 mm [23], and (iv) strenuous physical activity for 48 hours prior to the test. All participants provided their written informed consent prior to the start of the study. Eligible participants provided written informed consent. The study conformed to the ethical guidelines of the latest version of the Declaration of Helsinki, and the procedures were approved by the Ethics Committee of Baqiyatallah Medical Sciences University, Iran (IR.BMSU.BAQ.REC.1403.066) and registered with the Iranian Registry of Clinical Trials (IRCT20220129053865N1).

Double-density foot orthoses

Before the study began, participants were familiarized with the tests and instruments to be used. All participants were equipped with the same double-density FO that best fit their feet. This FO model was used for all participants (PF and normal foot groups). The double-density foot orthoses were made of ethylene-vinyl acetate (EVA), with a Shore 60 stiffness in the medial part and a sho0 in the lateral part, and the same medial longitudinal arch support height.

Overground walking

Testing was always scheduled between 10:00 and 12:00 AM. Before testing, participants performed a standardized 10-minute warm-up protocol consisting of jogging at low-to-moderate intensities for 7 minutes, followed by dynamic stretching for 3 min. For the walking trials, an 18 m walkway with a Bertec force plate (Bertec Corporation, Columbus, OH, USA) embedded in its middle was used to collect GRF data at 1000 Hz. The force plate was 60 cm long and 40 cm wide, and was oriented lengthwise in the walking direction along the track. All participants were familiar with the laboratory situation and walked at a constant speed of 1.2 m/s ± 5% across the walkway. Six test trials were conducted per condition. Each subject received three familiarization trials to ensure they walked at a constant speed and actually stepped on the force plate with their dominant foot. Walking time was monitored using a chronometer. Objective criteria to discard a trial were: (i) the dominant foot did not land on the force plate; (ii) the participant lost balance during the trial; (iii) participants ran with a midfoot or forefoot strike pattern.

Walking kinetic

Kinetic data were processed according to a previous study [24]. Briefly, GRF was low-pass filtered at 20 Hz (4th order Butterworth filter, zero lag). The heel strike and toe-off were identified using the force plate and a 10 N threshold (onset of force). GRF during walking, their time to peak, average vertical loading rates, and free moments have been reported to be among the most clinically relevant kinetic variables related to pathological gait/running patterns [24].

We extracted the first vertical peak force (FzHC) from vertical GRF data [24]. We calculated the positive (lateral) peak (FxHC) from the medial–lateral curve, which occurs right after heel strike. These variables were chosen as the most relevant components based on previous research on GRF during walking [25]. GRF amplitudes were normalized to body weight (BW) and reported in %BW. Time-to-peak was defined as the time between initial heel contact and the peak of the impact vertical component. Average vertical loading rates were computed as the average slope over 20-80% of the vertical GRF at the point of interest [24].

Here, ΔFmax is the maximum change in vertical GRF, Δt is the time period between adjacent data points, t20% corresponds to 20% of the time to peak impact, and t80% corresponds to 80% of the time to peak impact. The free moment of the foot was computed as follows:

where: Mz is the moment around the vertical axis; x and y are the horizontal components of the center of pressure (COP), and Fx and Fy are the horizontal GRF components. Moreover, FM amplitudes were normalized with regard to BW × height. All walking variables were averaged across six trials.

Muscular activities

A wireless EMG system (Biometrics Ltd., Nine Mile Point Ind. Est, Newport, United Kingdom) with eight pairs of bipolar Ag/AgCl surface electrodes was applied to assess tibialis anterior (TA), gastrocnemius medialis (Gas-M), biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), and gluteus medius (Glut-M) muscle activities of the dominant limb [26]. Center-to-center electrode distance was 25 mm. The input impedance and common-mode rejection ratio were set to 100 MΩ and >110 dB, respectively.

According to the European recommendations for surface electromyography (SENIAM), the skin surface was shaved and cleaned with 70% ethanol (C_2H_5OH) over the respective muscle bellies. Thereafter, the skin was gently abraded before electrode placement. The surface electrodes were placed on the muscle belly, longitudinally to the muscle fibers [26]. Participants performed two familiarization trials before the actual tests were recorded. The raw EMG signals were digitized at 1000 Hz. GRF and EMG data were synchronized using Nexus software (Oxford Metrics, Oxford, United Kingdom). EMG data were processed in accordance with a previous study and root mean square (RMS) values [26]. For EMG analyses, the gait cycle was divided into the loading phase (0–20 % of gait cycle), the mid-stance (20–47 % of gait cycle), and the push-off phase (47–70 % of gait cycle) (26). Maximum voluntary isometric contraction (MVIC) was assessed using a handheld dynamometer to normalize EMG during walking to MVIC. For each participant, three walking trials were recorded in each condition (with and without FO). A trial was considered successful if the foot landed in the middle of the force plate and if EMG signals were artifact-free upon visual examination of the online screen. MVIC tests were applied after the walking trials for each muscle separately to normalize EMG data. For normalization, the mean RMS values during walking trials were divided by the peak MVIC and multiplied by 100. Muscle activity was reported as a percentage of MVIC.

Data analysis

The normality of data distribution was verified using the Shapiro–Wilk tests. A two-way ANOVA with repeated measures was used for statistical analysis. Post-hoc testing was performed with a Bonferroni correction using a paired-samples t-test. Effect sizes in the form of

Cohen's d were used to describe effect size values [27]. According to Cohen [28], d < 0.50 indicates minor effects, 0.50 < d < 0.80 indicates medium effects, and d ≥ 0.80 indicates significant effects. The significance level was set as P < 0.05. Statistical analysis was conducted with SPSS (Version 26).

Table 1. Demographic characteristics of the participants.

Characteristics	Healthy group	PF group	Sig.
Age (years)	25.37±0.25	26.44±0.98	0.091
Height (cm)	177.26±7.24	181.66±6.37	0.883
Weight (kg)	73.21±14.83	84.61±13.24	0.407
Navicular drop (mm)	7.5±1.2	13.4±1.5	<001*
Foot posture index	3.2±0.5	7.8±0.9	<001*
Notes: PF, pronated feet. * stand for significant level p<0.05.			

Results

Walking kinetics

Results demonstrated a significant main effect of "group" for FxPO (p=0.007; η2=0.219), TTPFxPO (p=0.001; η2=0.293), TTPFyHC (p=0.003; η2=0.260), TTPFyPO (p=0.015; η2=0.183), TTPFzHC (p=0.002; η2=0.273), TTPFzMS (p=0.001; η2=0.338), and TTPFzPO (p=0.003; η2=0.256). Paired-wise comparison demonstrated lower FxPO in the PF group than in the healthy group. Paired-wise comparison demonstrated greater TTPFxPO, TTPFyHC, TTPFyPO, TTPFzHC, TTPFzMS, and TTPFzPO in the PF group than in the healthy group.

Results demonstrated significant main effect of "FO" for FxPO (p=0.010; η2=0.200), FyPO (p=0.030; η2=0.147), FyHC (p=0.001; η2=0.418), FzHC (p=0.001; η2=0.445), FzMS (p=0.001; η2=0.565), peak negative free moment (p=0.004; η2=0.242), TTPFxHC (p=0.009; η2=0.207), TTPFxPO (p=0.019; η2=0.170), TTPFyHC (p=0.002; η2=0.273), TTPFzMS (p=0.005; η2=0.239), and TTPFzPO (p=0.005; η2=0.234). Paired-wise comparison demonstrated greater FxPO, FyPO, FyHC, peak negative free moment, FzHC, TTPFzMS, and TTPFxHC during walking with FO than without it. Paired-wise comparisons demonstrated lower FzMS, TTPFxPO, TTPFyHC, and TTPFzPO during walking with FO than without it. Results did not show significant group-by-FO interactions for GRF components during walking (p > 0.05) (Table 2).

Muscle activities

Results demonstrated a significant main effect of "group" for VL (p=0.006; η2=0.223), VM (p=0.004; η2=0.247), and RF (p=0.003; η2=0.261) activities during the loading phase. Paired-wise comparisons showed greater VL, VM, and RF activity in the PF group than in the healthy group. Results demonstrated a significant main effect of "FO" for VL (p=0.005; η2=0.233), BF (p=0.040; η2=0.133), ST (p=0.008; η2=0.215), and Glut-M (p=0.030; η2=0.147) activities. Paired-wise comparisons demonstrated lower ST, VL, BF, and Glut-M activities during the FO condition than during the no-FO condition. Significant group-by-time interactions were found for RF (p=0.009; η2=0.207) activities. Post hoc analysis demonstrated lower RF activity in the healthy group and greater RF activity during loading phases while walking with FO compared with without it (Table 3).

Results demonstrated a significant main effect of "group" for VL (p=0.031; η2=0.146), RF (p=0.001; η2=0.301), BF (p=0.008; η2=0.210), and Glut-M (p=0.016; η2=0.178) activities during the mid-stance phase. Paired-wise comparison demonstrated greater VL, RF, BF, and Glut-M activities in the PF group than in the healthy group (Table 4). Results did not demonstrate any significant main effect of "FO" and group-by-FO interactions for muscle activities during the mid-stance phase (Table 4, p>0.05).

Results demonstrated a significant main effect of "group" for VM (p=0.048; η2=0.124), RF (p=0.004; η2=0.243), and BF (p=0.005; η2=0.230) activities during the push-off phase. Paired-wise comparison demonstrated greater VM, RF, BF, and Glut-M activities in the PF group than in the healthy group. Results did not demonstrate any significant main effect of "FO" for muscle activities during the push-off phase (Table 5, p>0.05). Significant group-by-time interactions were found for ST activities during the push-off phase (p=0.043; η2=0.130). Post-hoc analysis demonstrated lower ST activities in the healthy group and greater ST activities during the push-off phase while walking with FO compared with without it (Table 5).

Table 2. Data are means and standard deviations for ground reaction forces (GRF) and time to peak (TTP), during walking in pronated feet (PF) group compared with healthy group

GRF	Group-by-FO interaction (Eta square)	Main effect of FO (Eta square)	Main effect of Group (Eta square)	PF group				Healthy group			
				95 %CI	*Δ%*	*Post*	*Pre*	*95 %CI*	*Δ%*	*Post*	*Pre*
FxHC (% BW)	0.219(0.050)	0.382(0.026)	0.333(0.031)	-1.44,0.07	15.28	5.13±1.86	4.45±1.56	-1.01,1.25	-2.15	5.46±1.78	5.58±3.43
FxPO (% BW)	0.034(141)	0.01(0.200)*	0.007(0.219)*	-0.71,0.99	2.04	-7.00±2.35	-6.86±1.96	0.75,2.08	16.44	-9.42±1.71	-8.09±1.60
FYPO (% BW)	0.631(0.008)	0.030(0.147)*	0.967(0.001)	-2.39,-0.21	5.62	24.40±3.95	23.10±2.93	-2.54,0.85	3.63	24.22±3.90	23.37±3.15
FYHC (% BW)	0.267(0.041)	0.001(0.418)*	0.937(0.001)	1.67,6.46	18.68	-25.85±4.88	-21.78±4.17	0.65,4.29	10.93	-25.16±3.26	-22.68±4.40
FZHC (% BW)	0.613(0.009)	0.001(0.445)*	0.788(0.002)	-10.85,-3.91	6.22	126.05±8.57	118.66±6.55	-15.38,-2.82	7.78	126.12±6.44	117.01±14.32
FZMS (% BW)	0.791(0.002)	0.001(0.565)*	0.435(0.020)	3.24,9.35	-8.83	65.04±8.01	71.34±6.40	3.00,8.55	-8.34	63.50±7.02	69.28±6.43
FZP0 (% BW)	0.534(0.013)	0.103(0.086)	0.519(0.014)	-5.57,0.90	2	118.79±9.60	116.46±6.59	-3.90,1.78	0.89	119.99±9.42	118.93±7.79
MAXFM(% BW*Height)	0.704(0.005)	0.088(0.094)	0.142(0.071)	-0.55,0.05	18.93	1.57±0.81	1.32±0.74	-0.55,0.23	9.35	1.87±0.63	1.71±0.71
MINFM(% BW*Height)	0.947(0.001)	0.004(0.0242)*	0.600(0.009)	0.04,0.61	39.53	-1.20±0.61	-0.86±0.34	-0.02,0.72	37.23	-1.29±0.72	-0.94±0.50
TTPFxHC (ms)	0.395(0.024)	0.009(0.207)*	0.505(0.015)	-141.50,15.00	24.4	11.56±32.52	6.65±26.14	-12.01,58.64	11.46	32.85±5.35	11.22±29.47
TTPFxPO (ms)	0.861(0.001)	0.019(0.170)*	0.001(0.293)*	-18.94,134.48	-14.66	336.08±203.20	393.85±175.43	-2.08,102.25	-23.21	165.60±103.59	215.68±102.77
TTPFYHC (ms)	0.929(0.001)	0.002(0.273)*	0.003(0.260)*	4.41,46.08	-4.12	587.52±53.43	612.77±50.67	0.66,47.21	-4.24	540.25±40.09	564.18±40.97
TTPFYPO (ms)	0.358(0.028)	0.314(0.034)	0.015(0.183)*	-7.73,7.11	0.26	119.06±21.68	118.75±20.18	-19.11,5.79	6.85	104.00±22.35	97.33±23.95
TTPFZHC (ms)	0.385(0.025)	0.616(0.008)	0.002(0.273)*	-5.59,7.51	-0.61	154.41±24.49	155.37±22.98	-12.22,5.13	2.71	133.70±16.92	130.16±17.03
TTPFZMS (ms)	0.757(0.003)	0.005(0.239)*	0.001(0.338)*	-16.44,-0.68	2.68	326.93±22.15	318.37±21.63	-14.36,0.40	2.4	297.77±22.73	290.79±20.37
TTPFZP0 (ms)	0.533(0.013)	0.005(0.234)*	0.003(0.256)*	1.37,41.21	-3.87	528.06±37.94	549.35±40.72	-0.88,28.76	-2.73	495.91±22.17	509.85±38.39

BW, body weight; x, medio-lateral direction; y, anterior-posterior direction; z, vertical direction; FzHC; peak vertical ground reaction force during heel contact; FzPO; peak vertical ground reaction force during the push-off phase; FyHC, braking force; FyPO, propulsion force; FxHC, peak lateral ground reaction force during heel contact; FxPO, peak medial ground reaction force during the push-off phase; MINFM, peak negative free moment; TTP, time-to-peak; 95% CI, confidence interval refers to the confidence interval of the difference between with and without FO. Significant results were denoted in bold.

Table 3. Data are means and standard deviations for muscle activity during the loading phase [% Maximum voluntary isometric contraction (MVIC)] when walking in pronated feet (PF) individuals compared with healthy controls (with and without FO).

Muscles	Healthy group				PF group				Main effect of Group (Eta square)	Main effect of FO (Eta square)	Group-by-FO interaction (Eta square)
	Pre	Post	Δ%	95 %CI	Pre	Post	Δ%	95 %CI			
TA	10.86±7.99	8.61±5.11	-20.71	-0.86,5.36	10.99±2.45	11.97±3.76	8.91	-3.38,1.22	0.287(0.038)	0.497(0.016)	0.090(0.093)
Gas-M	4.17±2.16	3.40±1.21	-18.64	-0.26,1.81	4.16±3.03	1.59±3.97	-4.56	-5.16,2.16	0.665(0.006)	0.200(0.054)	0.430(0.021)
VL	2.89±1.95	1.08±1.92	-33.56	-1.23,1.92	6.18±5.00	3.29±1.77	-46.76	-0.23,4.77	0.006(0.223)*	0.005(0.233)*	0.144(0.070)
VM	1.40±2.38	1.32±1.94	-18.48	-0.57,2.09	4.37±3.19	4.19±3.43	-4.11	-2.18,2.54	0.004(0.247)*	0.602(0.009)	0.822(0.002)
RF	3.58±0.69	3.22±0.74	-10.05	0.05,0.72	6.07±3.46	7.32±4.73	20.59	-2.42,-0.07	0.003(0.261)*	0.137(0.072)	0.009(0.207)*
BF	5.14±4.19	4.22±2.77	-17.89	-0.68,2.53	6.54±5.71	4.28±2.98	-34.55	-0.46,4.97	0.562(0.011)	0.040(0.133)*	0.376(0.026)
ST	8.25±6.38	5.32±3.79	-35.51	0.32,5.53	5.55±4.23	4.02±2.37	-27.56	-0.52,3.57	0.152(0.067)	0.008(0.215)*	0.375(0.026)
Glut-M	8.73±7.59	6.70±4.05	-23.25	-1.63,5.69	13.17±9.29	9.62±7.49	-26.95	-0.19,7.28	0.120(0.079)	0.030(0.147)*	0.542(0.013)

PF, pronated feet; TA, tibialis anterior; Gas-M, gastrocnemius medialis; BF, biceps femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; Glut-M, gluteus medius; 95% CI, confidence interval refers to the confidence interval of the difference between with and without FO. Significant results were denoted in bold.

Table 4. Data are means and standard deviations for muscle activity during the mid-stance phase [% Maximum voluntary isometric contraction (MVIC)] when walking in pronated feet (PF) individuals compared with healthy controls (with and without FO).

Muscles	Healthy controls				PF individuals				Main effect of Group (Eta square)	Main effect of FO (Eta square)	Group-by-FO interaction (Eta square)
	Pre	Post	Δ%	95 %CI	Pre	Post	Δ%	95 %CI			
TA	10.14±6.08	9.85±6.84	-2.85	-2.98,3.56	10.41±4.41	12.24±4.56	17.57	-5.45,1.79	0.413(0.022)	0.507(0.015)	0.363(0.028)
Gas-M	18.74±8.92	16.85±5.40	-10.08	-2.16,5.93	17.73±9.35	18.11±7.23	2.14	-5.66,4.91	0.956(0.001)	0.633(0.008)	0.476(0.017)
VL	2.77±2.53	3.56±2.62	28.51	-2.38,0.80	4.65±2.28	4.72±2.26	1.50	-1.48,4.97	0.031(0.146)*	0.429(0.021)	0.506(0.015)
VM	2.58±1.77	3.47±3.15	34.49	-2.53,2.00	4.54±3.62	4.08±1.68	-10.13	-1.58,2.50	0.095(0.090)	0.722(0.004)	0.268(0.041)
RF	3.07±0.73	3.37±0.82	9.77	-0.66,0.07	5.86±2.87	5.89±3.01	0.51	-0.73,0.67	0.001(0.301)*	0.390(0.025)	0.478(0.017)
BF	3.60±2.04	2.81±1.52	-21.94	-0.07,2.40	5.24±3.99	4.76±2.60	-9.16	-2.46,7.92	0.008(0.210)*	0.380(0.026)	0.828(0.002)
ST	6.30±4.25	4.70±2.73	-25.39	-5.00,5.94	4.35±2.34	5.73±4.61	31.72	-4.24,3.73	0.643(0.007)	0.895(0.001)	0.080(0.099)
Glut-M	7.71±5.58	7.12±3.73	-7.65	-2.09,3.28	14.52±10.37	10.15±6.20	-30.09	-1.41,10.14	0.016(0.178)*	0.108(0.084)	0.217(0.050)

Table 5. Data are means and standard deviations for muscle activity during the push-off phase [% Maximum voluntary isometric contraction (MVIC)] when walking in pronated feet (PF) individuals compared with healthy controls (with and without FO).

Muscles	Healthy controls				PF individuals				Main effect of Group (Eta square)	Main effect of FO (Eta square)	Group-by-FO interaction (Eta square)
	Pre	Post	Δ%	95 %CI	Pre	Post	Δ%	95 %CI			
TA	12.47±6.13	9.30±4.85	-25.42	0.89,5.43	12.34±5.14	13.09±6.96	6.07	-4.47,2.97	0.314(0.034)	0.247(0.044)	0.065(0.109)
Gas-M	30.24±14.68	25.79±9.62	-14.71	-2.22,11.11	27.97±11.54	30.62±10.02	9.47	-10.44,5.14	0.704(0.005)	0.712(0.005)	0.151(0.068)
VL	3.39±2.70	2.98±1.73	-12.09	-0.75,1.56	6.46±6.32	5.91±3.61	-8.51	-2.15,3.26	0.020(0.166)	0.493(0.016)	0.918(0.001)
VM	2.98±2.44	2.81±2.60	-5.70	-1.29,2.77	4.87±4.52	5.55±4.07	13.96	-2.65,1.29	0.048(0.124)*	0.646(0.007)	0.435(0.020)
RF	3.32±0.87	3.57±1.01	7.53	-0.65,0.13	6.38±3.81	6.58±4.30	3.13	-1.71,1.30	0.004(0.243)*	0.532(0.013)	0.943(0.001)
BF	3.76±2.63	2.29±1.05	-39.09	0.05,2.87	6.49±5.70	5.07±2.85	-21.87	-1.79,4.62	0.005(0.230)*	0.090(0.093)	0.974(0.001)
ST	6.87±6.00	4.48±3.35	-34.78	-2.09,6.62	4.68±2.97	6.29±3.53	34.40	-4.18,0.95	0.869(0.001)	0.683(0.006)	0.043(0.130)*
Glut-M	6.80±4.41	6.44±4.70	-5.29	-2.08,2.81	16.02±11.91	9.85±6.00	-40.19	-0.61,12.96	0.004(0.250)*	0.063(0.110)	0.096(0.089)

Discussion

This study aims to evaluate the effects of double-density foot orthoses on ground reaction force characteristics and lower-limb muscular activity during walking in adults with PF.

Ground reaction force components

The present study demonstrated lower FxPO in the PF group than in the healthy group. Authors have postulated that reducing foot pronation with a foot orthosis could contribute to repositioning the tibia and femur into their normal positions, thereby optimizing the mechanical properties of the lower limb joints [29]. These results are consistent with Farahpour et al. [5], who stated that the elevated peak medial force can be explained in part by altered length-tension relationships of the invertors and evertors due to foot pronation. Plantar flexor inverters play significant roles in medially accelerating the center of mass during late stance [5]. Finding demonstrated greater TTPFxPO, TTPFyHC, TTPFyPO, TTPFzHC, TTPFzMS, and TTPFzPO in the PF group than in the healthy group. The temporal parameters, such as TTPFxPO and TTPFyHC, reflect the timing of force application during the gait cycle [30].

Results demonstrated greater FxPO, FyPO, FyHC, peak negative free moment, FzHC, TTPFzMS, and TTPFxHC, and lower FzMS, TTPFxPO, TTPFyHC, TTPFzMS, and TTPFzPO during walking with FO than without it. The observed decrease in force metrics such as FxPO, FyPO, and FyHC during walking while using FO suggests that the orthoses may help reduce the overall load on the lower extremities, especially in the frontal and horizontal planes [31]. This reduction in forces could be particularly beneficial for individuals with conditions such as patellofemoral pain or other musculoskeletal disorders, as it may alleviate joint and surrounding tissue stress [32]. The lower peak negative free moment further supports this notion, indicating a potential decrease in the rotational forces acting on the knee and hip joints during the push-off phase of gait [33]. This reduction could lead to improved joint stability and decreased risk of injury, particularly in populations with compromised musculoskeletal integrity [33]. The increased time to peak forces during the push-off phase (TTPFxPO) and the heel contact phase (TTPFyHC) may suggest that individuals using FO apply force more gradually and more controlled [5]. This could be advantageous for individuals who require a more stable and supportive gait pattern, as it may improve shock absorption and facilitate a more fluid transition between walking phases [5]. Specifically, the findings indicate that FO use significantly alters various force metrics and temporal parameters during gait, with implications for both rehabilitation and athletic performance [34].

Results showed greater FzHC and FzMS during walking with FO than without it. Conversely, the increased values of FzHC and FzMS during walking with foot orthoses highlight a complex interaction between the orthotic device and gait biomechanics. The elevation in vertical ground reaction forces (FzHC and FzMS) suggests that while the orthoses may reduce specific lateral and anterior-posterior forces, they may also increase vertical loading during specific phases of the gait cycle [35].

Muscle activities

Results demonstrated greater VL, VM, and RF activities in the PF group than in the healthy group during the loading phase. Recent studies reported that individuals with PF received greater loads on the VM than those with standard feet, due to weakened plantar flexor muscles [36]. Drawing in a slant line of the patella by the VM muscles has an important meaning in the stabilization and direction of the patella when they pass or slip through the intercondylar areas of the femurs [36]. This condition accounts for the higher VL muscle activation in individuals with PF [37]. Findings showed lower ST, VL, BF, and Glut-M activities during the FO condition than during the loading phase without FO. The eccentric Glut-M and VL activities are relevant during early stance to control knee flexion and improve shock absorption [38]. Therefore, an increase in VL and Glut-M activation after FO use during the loading phase may be associated with improved shock-absorption capacity. Glut-M is one of the most important hip muscles that control this coronal plane motion. It is morphologically suited to generate the large abduction torques required to maintain femoropelvic equilibrium in the coronal plane [39]. The function of the Glut-M is primarily to assist in the absorption of GRF during the loading phase [40].

Results demonstrated greater VL, RF, BF, and Glut-M activities in the PF group than in the healthy group during mid-stance. Findings demonstrated lower ST activity in the healthy group and greater ST activity during the push-off phase of walking with FO compared with without it. In contrast, the increased ST activity during push-off in the PF group when using FO may reflect a strategy to enhance force generation and propulsion, as the orthoses may alter the timing and magnitude of muscle activation during this critical phase of gait [41].

Limitations

This study has a few limitations that must be considered. The study had a relatively small number of participants. However, the study had sufficient statistical power to detect between-group differences. Further investigations are needed to evaluate the effects of walking speed and slope. This study did not address muscle activity during walking across different groups. Combining kinematics with the electrical activity of the effective muscles during walking may provide additional insights into risk factors in people with PF.

Conclusion

The findings suggest that double density foot orthoses can effectively alter ground reaction forces and muscle activation patterns in individuals with pronated feet, potentially reducing the risk of injury and improving walking mechanics.

Conflict of Interest Disclosures

The authors declare that they have no conflict of interest.

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Authors' Contributions

Ebrahim Piri contributed to the study conception and design, data collection, data analysis and interpretation, drafting of the manuscript and manuscript revision. Vahid Sobhani and Alireza Shamsoddini contributed to study supervision and critical revision of the manuscript. Amir Ali Jafarnezhadgero contributed to methodology development and data interpretation. Ehsan Arabzadeh and Saeid Alihosseini assisted in data collection. All authors read and approved the final version of the manuscript.

Ethical Statement

All procedures performed in this study involving human participants were conducted in accordance with the ethical standards of the institutional research committee and the latest version of the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of Baqiyatallah University of Medical Sciences, Iran (IR.BMSU.BAQ.REC.1403.066). The study was also registered in the Iranian Registry of Clinical Trials (IRCT20220129053865N1). Written informed consent was obtained from all participants prior to participation in the study.

Declaration of Generative AI and AI-assisted technologies

The authors declare that no generative AI or AI-assisted technologies were used in the design of the study, data collection, data analysis, or preparation of this manuscript.

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