Immediate Neuromuscular Responses to Customized Foot Orthoses with Rearfoot-Forefoot and Forefoot-Only Wedge Designs During Gait in Plantar Fasciitis: A Comparative EMG Study Part I

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ABSTRACT

Background: Plantar fasciitis (PF) is a prevalent foot condition significantly impacting daily functioning. While customized foot orthoses (CFOs) are commonly recommended, limited objective research exists on their neuromuscular effects during gait. This first study investigates and directly compares the immediate effects of different CFO designs on lower-extremity muscle activity and gait parameters during stance in PF patients.

Methods: Forty-five participants with PF underwent gait analysis under four conditions: shod, CFOs without wedge, CFO W1 (dual rearfoot and forefoot posting), and CFO W2 (forefoot posting). Spatiotemporal gait parameters and lower-extremity muscle activity were assessed using an instrumented walkway and wireless electromyography (EMG). Comfort scores were reported at the end of each condition.

Results: Exploratory post-hoc analysis, based on the unadjusted result, indicated that all CFO conditions significantly increased comfort scores compared to shod conditions ($p < 0.001$). The CFO W1 notably increased stance phase duration ($p < 0.05$) and prolonged double support phase ($p < 0.001$). The CFO W1 design increased tibialis anterior (TA) activity and reduced biceps femoris (BF) activation compared to CFO W2 (both $p < 0.05$), indicating selective, limited changes in TA and BF peak activity.

Conclusion: Different CFO designs produced distinct immediate biomechanical modifications. The CFO W1 may reflect a more cautious gait pattern or altered temporal coordination, accompanied by selective changes in peak neuromuscular activity. While these results underscore the potential value of considering not just pain reduction but also specific functional biomechanical responses, clinical recommendations for individualized orthotic prescription require longitudinal evidence.

Keywords: Plantar fasciitis, customized foot orthoses, gait analysis, electromyography, biomechanics

INTRODUCTION

Plantar fasciitis (PF) is the most prevalent foot condition, diagnosed in over a million individuals annually (Martin et al., 2014; McPoil et al., 2008). It is characterized by a thickened plantar fascia and soft tissue edema, which may contribute to reduced medial arch height and excessive midfoot pronation (Karabay et al., 2007; Kibler et al., 1991; Pohl et al., 2009). This structural compromise can impair the plantar fascia's natural spring effect, potentially leading to increased compensatory muscle activation for balance during ambulation and contributing to lower extremity biomechanical deficits (Chuter & Janse de Jonge, 2012; Schmitt et al., 2022). Consequently, individuals with PF frequently experience pain during weight-bearing activities, which may significantly alter gait patterns and reduce overall mobility (Goff & Crawford, 2011).

Given these challenges, foot orthoses are commonly prescribed for PF to modify lower-limb biomechanics and redistribute plantar loads. While customized foot orthoses (CFOs) consistently demonstrated efficacy in pain reduction and improved foot function (Koc et al., 2023; Martin et al., 2014; McPoil et al., 2008), the clinical trial and meta-analysis have suggested that these subjective improvements do not always correlate with objective gains in walking ability or overall function (Wang et al., 2025; Wrobel et al., 2015). This indicates that pain scores alone might overestimate the true extent of biomechanical recovery. For instance, detailed gait analyses demonstrated that CFOs could modify lower-limb and multi-segment foot kinematics and improve temporal-spatial gait parameters, such as cadence and walking velocity, thereby supporting their role in correcting pathological gait patterns (Harutaichun et al., 2023). However, the other longitudinal study in PF reported that despite significant pain reduction with CFOs, electromyographic (EMG) activity, gait parameters, and stabilometric measures remained unchanged throughout the entire protocol (Moyne-Bressand et al., 2018). Previous investigation into flatfoot management with 3D-printed CFOs demonstrate that biomechanical shifts can occur without altering neuromuscular control; specifically, adding a rearfoot posting can shift the COP posteriorly during late stance and modify pressures under the rearfoot. Despite these structural and biomechanical adjustments, the added postings produce no significant changes in lower limb muscle activity during walking (Cherni et al., 2022). This implies that mechanical pain relief can occur independently of neuromuscular control normalization.

As plantar fascia loading is influenced by both joint kinematics and muscle function (Cervera-Garvi et al., 2023; Harutaichun et al., 2022; Moyne-Bressand et al., 2018; Yoo et al., 2017), a comprehensive assessment of CFO effectiveness necessitates combining EMG outcomes and spatiotemporal gait parameters with traditional pain and plantar pressure measures. Such an integrated approach can reveal whether orthoses not only alleviate symptoms and alter joint motion but also restore more normal muscle activation patterns and gait behavior, which are crucial for durable functional recovery in individuals with PF.

Broader orthoses research indicated that different designs and postings could modulate lower-limb muscle activity in phase-specific ways, demonstrating their capacity to influence EMG patterns, potentially through load redistribution and tissue stress reduction (Mündermann et al., 2006; Murley et al., 2010). Clinically, CFOs often incorporate a varus forefoot wedge alongside medial arch support to manage excessive pronation and adjust multi-segment foot and lower-limb biomechanics (Hajizadeh et al., 2019).

During dynamic function, medial forefoot wedges independently shift the center of pressure (CoP) laterally during the stance phase, effectively redistributing plantar loading and substantially reducing pressure under the medial heel, hallux, and second metatarsal. Arch supports, conversely, have a more limited kinetic impact and usually require a height of 24 mm to significantly decrease pressure in these areas. Since they operate independently, arch supports and medial forefoot wedges can be strategically combined for targeted pressure relief, thereby lowering the risk of exercise-related leg pain (Zhang et al., 2022; Zhang et al., 2024) and improving symptoms and function in individuals with PF (Thong-On & Harutaichun, 2023).

Furthermore, combining varus forefoot and rearfoot wedges with enhanced medial longitudinal arch stiffness generates superior corrective reaction forces compared to unposted devices (Pelaez et al., 2023). During gait, CFOs featuring both medial wedges effectively address pathological biomechanics by immediately restricting excessive lower limb and multi-segment foot motion in the frontal and transverse planes in individuals with PF. One month of using these tailored CFOs significantly reduces pain intensity and enhances overall foot function. These clinical improvements are supported by objective enhancements in spatiotemporal gait parameters, including increased walking velocity and cadence (Harutaichun et al., 2023). In demanding contexts, such as landing on valgus-inclined surfaces, medially wedged orthoses more effectively counteract slope-induced pronation than thin, flexible designs without medial wedges by reducing midfoot dorsiflexion and ankle eversion. This distal correction creates a proximal "cascading effect," enhancing hip stability and promoting more efficient overall lower limb function (Dami et al., 2024).

For static tasks, CFOs provide benefits through structural features—including medial arch supports, heel cups, and shock-absorbing materials—that mechanically redistribute pressure away from the painful heel toward the midfoot. This support prevents arch collapse, decreases tensile strain on the plantar fascia, and stimulates plantar skin mechanoreceptors. These combined mechanical and neuromuscular interventions significantly improve static postural balance, evidenced by a reduction in both CoP area and mean velocity (Hammami et al., 2024).

While CFOs are known to reduce pain in the short and medium terms for PF, and their kinematic mechanisms are increasingly documented across both level and inclined surfaces, the underlying biomechanical and neuromuscular mechanisms of different orthotic designs remain unclear. Previous research indicates that CFOs, especially those with varus forefoot and rearfoot wedges, provide superior corrective forces, effectively restricting pathological foot motion during gait to improve pain and function (Harutaichun et al., 2023; Pelaez et al., 2023), and also enhance hip stability and static postural balance (Dami et al., 2024; Hammami et al., 2024). Despite these advancements, no prior EMG study has directly compared these three specific orthotic designs (no wedge, dual rearfoot-forefoot posting, forefoot-only posting) in PF patients during gait. Addressing this critical gap, the present study is the first to investigate and directly compare the immediate effects of different orthotic prescriptions on lower-extremity muscle activity in individuals with PF, specifically evaluating these three distinct designs (no wedge, dual rearfoot-forefoot posting, and forefoot-only posting) during gait. This is particularly important given that several studies have demonstrated orthoses and related mechanical interventions can produce measurable, immediate changes in gait biomechanics and muscle activity (Moisan et al., 2019; Mündermann et al., 2004; Wyndow et al., 2014). This rapid response indicates an acute adaptation of the foot–leg system to altered loading and support, revealing primary neuromuscular adaptations before long-term learning or habituation occurs. Therefore, examining the immediate effects of different posting designs on gait parameters and lower-limb EMG is justified. Such an investigation will help characterize the primary neuromechanical response to specific orthotic configurations and explore acute biomechanical and neuromuscular markers that may be linked to longer-term clinical benefits in people with PF.

This study aimed to compare the immediate effects of different orthotic conditions on lower-limb EMG and gait parameters in individuals with PF. We investigated three distinct CFO conditions: CFOs without additional wedges (representing standard conservative care); CFOs with dual varus forefoot and rearfoot wedges (CFO W1), designed to potentially increase orthosis stiffness and amplify biomechanical effects; and CFOs with only a varus forefoot wedge (CFO W2), intended to specifically address forefoot loading and pronation control. A shod condition served as a control for comparison. We hypothesized that CFO W1 would increase tibialis anterior activity and prolong the stance phase compared to the CFO W2 and shod conditions. Finally, as part of this broader comprehensive investigation, the second part of this series would address balance parameters and lower-limb EMG during standing across different sensory conditions.

MATERIALS AND METHODS

Design

The study investigated the immediate effects of different orthotic conditions; CFO without wedge, CFO W1, or CFO W2 on lower-extremity muscle activity and gait parameters during the stance phase of gait. The protocol was approved by the Mahidol Central Institutional Review Board (MU-CIRB 2023/013.0102).

Participants

A licensed physical therapist confirmed a diagnosis of PF based on the criteria (Martin et al., 2014): tenderness upon palpation of the medial calcaneal tubercle and the proximal portion of the plantar fascia; heel pain during the first steps in the morning or after rest, which improves with initial walking but is aggravated by sustained weight-bearing; persistent symptoms for a minimum of six weeks; and a self-reported maximum pain intensity of 3 or greater on the visual analog scale (VAS) within the previous week. Exclusion criteria were: signs of L5-S1 nerve root irritation; history of lower extremity fracture or surgical procedures; existing diagnosis of a systemic condition that could be a confounding factor.

Sample size calculation

The primary outcome of this study was designated as the normalized EMG amplitude during the stance phase; all other spatiotemporal, and comfort measures were considered secondary outcomes. The required sample size was determined using G*Power software for a repeated-measures ANOVA with four within-subject conditions. Since no prior study reported EMG data across these specific four orthotic conditions in PF, a reliable EMG-based effect size could not be directly derived. Therefore, the calculation was conservatively based on kinematic data from a prior study (Harutaichun et al., 2022), which compared three similar foot orthotic conditions (shod, W1, W2) during gait and reported partial eta squared values ranging from 0.055 to 0.619 for hip, knee, ankle, and foot kinematics. We acknowledge that EMG variables generally exhibit smaller effect sizes and higher variability compared to kinematic data. To explicitly compensate for this disparity and ensure an adequately powered study, we deliberately selected the lowest reported effect size (partial eta square = 0.055, representing arch kinematics) to serve as a highly conservative proxy, combined with a high 95% power threshold. Using this conservative estimate (partial eta squared of 0.055), with a significance level (α) of 0.05 and 95% power for four repeated measures, the analysis indicated that a minimum of 39 participants were required. Accounting for a potential 15% dropout rate during testing, a total of 45 participants were recruited.

Interventions

All CFOs were prescribed and fitted by a primary experienced physical therapist specializing in musculoskeletal management. Each CFO was individually customized using heat-molding. This process was performed with the participant positioned prone, with the heel off the bed, to ensure a neutral subtalar joint alignment (Landorf et al., 2004; Redmond et al., 2009). The orthoses were constructed from a dual-layer material, consisting of a 3mm polycaprolactone shell for structural support, overlaid with a full-length ethylene propylene diene monomer (EPDM) rubber top cover for cushioning and comfort. The base design for all orthoses, including the condition referred to as “CFO without wedges”, incorporated a medial longitudinal arch support and a cushioned heel cup, but no additional varus postings (Figure 1a).

Extrinsic posts or wedges were constructed from fabric-covered solid rubber and were available in forefoot varus options of 3°, 6°, and 8°, and rearfoot varus options of 3° and 6°. To determine the appropriate orthotic correction, participants' forefoot and rearfoot angles were meticulously examined using two distinct, standardized assessment techniques (Monaghan et al., 2013; Root, 1973). Intra-rater reliability for both methods was evaluated prior to the study.

For the CFO W1 condition (Figure 1b), posting adhered to the Root method (Root, 1973), a widely used podiatric technique for CFOs (Desmyttere et al., 2018; Genova & Gross, 2000; MacLean et al., 2008). This assessment considers an intrinsic reference frame, determining the clinical rearfoot and forefoot angles relative to the bisection of the lower leg and calcaneus, respectively. For W1, both the extrinsic forefoot and rearfoot varus posts were determined from the measured forefoot angle: the forefoot post was set to 60% of this angle (maximum 8°), and the rearfoot post was set to 50% of this angle (maximum 6°) (Brown et al., 1995). While this method is traditional, previous studies indicated poor correlation between its clinical rearfoot angle measurements and actual gait kinematics (Monaghan et al., 2013; Pierrynowski & Smith, 1996), suggesting it may not fully reflect foot-ground interaction (Jarvis et al., 2017). In this study, the intra-rater reliability for Root's method was ICC(3,1) = 0.71 for forefoot angle and ICC(3,1) = 0.78 for rearfoot angle.

To address these recognized limitations, the second protocol, for CFO W2, utilized the foot assessment proposed by Monaghan et al. (Monaghan et al., 2013), which employs an extrinsic reference frame. This technique defines the clinical forefoot angle as the angle between the metatarsal heads and the caudal table edge (parallel to the foot's mediolateral axis and ground during standing), and the clinical rearfoot angle as the angle between the calcaneus bisection and a line perpendicular to the caudal table edge. This extrinsic approach is suggested to better predict forefoot and rearfoot angles and provide a more effective assessment for determining required posting (Hsu et al., 2014; Monaghan et al., 2013). In this study, the intra-rater reliability for Monaghan's method yielded ICC(3,1) of 0.85 for forefoot angle and 0.91 for rearfoot angle. For CFO W2, a forefoot post was applied at 50% of the measured forefoot angle, and a rearfoot post was set to 20% of the measured rearfoot angle. Notably, for the W2 condition in this study, the calculated 20% rearfoot angle did not result in an applied rearfoot varus post for any participant, effectively making CFO W2 a forefoot-only intervention (Figure 1c).

Physical assessment

Prior to the gait assessment, a comprehensive physical examination was conducted. This involved identifying the more symptomatic limb, and then measuring characteristics such as body mass index (BMI), self-reported daily weight-bearing hours, the duration of heel pain, static alignment and range of motion of the tibiofemoral (ICC = 0.76) and foot progression angles (ICC = 0.84), hallux valgus angle (ICC = 0.91), passive first metatarsophalangeal (MTP) joint dorsiflexion (ICC = 0.74), gastrocnemius-soleus flexibility using the weight-bearing lunge test (ICC = 0.89), and Foot Posture Index (FPI) (ICC = 0.85) and Lateral Step Down (LSD) test (ICC = 0.81) were recorded.

Experimental protocol

Before the testing phase, all participants were given a standardized pair of 'CROCS Off Court Clogs' in their appropriate size. They were instructed to wear these shoes with their CFOs for about one week to allow for familiarization. Adherence to this familiarization period was self-reported; participants were required to wear the footwear combination for a minimum of 4 hours per day, which was confirmed via the LINE messaging application prior to the gait assessment. This particular shoe model was chosen for its compatibility with the study's CFOs and its appeal to participants who favored sandal-like footwear.

Spatiotemporal gait parameters were captured using a 3-meter Zebris FDM instrumented walkway (Zebris Medical GmbH, Germany) sampling at 100 Hz. During testing, a second independent physical therapist, who was strictly blinded to the specific orthotic condition assigned to each participant, instructed participants to walk across the platform at their self-selected, comfortable speed under four orthotic conditions including shod only (the standardized CROCS without orthoses), shod with CFOs, shod with CFO W1, and shod with CFO W2. To minimize order effects, the testing sequence of these four conditions was randomized for each participant using a computer-generated random number sequence in Microsoft Excel, utilizing a random permuted block design with a block size of four. Three successful trials were recorded for each condition. Comfort scores were reported at the end of each condition, where a higher score indicated greater comfort. The average values for key spatiotemporal parameters including; step length, step time, stance phase (%), double support phase (%), stride length, stride time, step width, cadence, and velocity were recorded.

Surface electromyography (EMG) data were recorded using a Delsys Trigno™ Wireless EMG System (Delsys Inc., USA) (Hashiguchi et al., 2023). Five lower-limb muscles were selected for bilaterally recording: tibialis anterior (TA), medial gastrocnemius (MG), peroneus longus (PL), biceps femoris (BF), and rectus femoris (RF). This selection aimed to capture key agonist–antagonist pairs acting at the ankle (TA, PL, MG) and knee/hip (RF, BF), consistent with standard lower-limb surface EMG gait protocols that monitor one flexor–extensor pair per joint, utilizing bi-articular muscles where possible (Agostini et al., 2020; Ericson et al., 1986).

Prior to electrode placement, the skin over each muscle belly was shaved, if necessary, and cleaned with alcohol to reduce impedance and improve conductivity, following established surface EMG protocols. Delsys Trigno Avanti wireless sensors, which incorporate a bipolar electrode pair with a fixed center-to-center inter-electrode distance of 10 mm, were then placed over the largest portion of each muscle belly. They were aligned with the presumed fiber direction and positioned between the innervation zone and tendon (Agostini et al., 2020; Di Nardo et al., 2025). This placement adhered to Surface EMG for the Non-Invasive Assessment of Muscles (SENIAM) guidelines and landmarking approaches used for lower-limb muscles (Hermens et al., 2000). Signal quality was rigorously monitored during quiet standing and initial test gait trials to check for baseline noise, movement artifacts, and signal dropout, consistent with recommendations for clinical gait EMG and Trigno-based assessments (Farago et al., 2022; Papagiannis et al., 2019). Specific attention was given to muscles prone to crosstalk and location sensitivity, such as TA and PL. Only channels with stable envelopes and consistent timing across gait cycles were retained for analysis (Campanini et al., 2007; Papagiannis et al., 2019).

Signal processing

A wireless Trigno IMU sensor (Delsys, MA, USA) was securely attached to the lateral aspect of each shank using elastic bands. Initial contact (IC) and toe-off (TO) were detected from the shank's sagittal-plane angular velocity using a validated, rule-based algorithm (Fadillioglu et al., 2020). Specifically, IC was identified as the first zero-crossing following the mid-swing angular velocity peak. TO was then determined as the negative peak occurring just before the subsequent mid-swing peak, effectively capturing the high-frequency components of the stance phase. EMG and IMU data were imported into Visual3D software (HAS motion, Canada) for further processing. Successful trials were defined as those where surface EMG signals showed no visible movement artifacts or technical errors, a signal-to-noise ratio (SNR) ≥ 20 dB, and baseline noise ≤ 2% of the maximum EMG amplitude for that muscle (De Luca et al., 2010); any contaminated trials were rejected and repeated. The EMG signals were band-pass filtered (20-450 Hz), full-wave rectified, and then filtered with a 6 Hz low-pass filter. Peak and average EMG muscle activity were recorded for each stance phase and averaged over the three successful trials which were then normalized to the maximum observed signal for each muscle across all walking conditions. To enable direct comparisons of muscle activation across the different orthotic conditions within each participant, these values were subsequently normalized to the highest signal recorded for each muscle across all tested conditions. This normalization approach is consistent with accepted task-based strategies, which aim to reduce variability and enhance the comparability of data across different experimental conditions (Burden, 2010; Yang & Winter, 1984).

Statistical analysis

Primary analyses and all subsequent post-hoc comparisons used Benjamini-Hochberg False Discovery Rate (FDR)-adjusted p-values (q-value). Pre-specified primary variables included comfort score during testing in each condition, step length, step time, % stance phase, % double support phase, stride length, stride time, step width, cadence, velocity, and peak and mean normalized EMG amplitudes for TA, MG, PL, BF, and RF during the stance phase. To manage the extensive number of potential outcomes and mitigate the risk of Type I error from multiple comparisons, the primary analysis focused solely on data collected from the more symptomatic limb of each participant. Normality of data distribution was assessed via the Kolmogorov-Smirnov test, guiding the selection of appropriate statistical tests.

For normally distributed data, a repeated-measures ANOVA was used to explore differences between orthotic conditions. Sphericity was assessed using Mauchly's Test of Sphericity, with sphericity confirmed, no adjustments to the degrees of freedom were necessary. For data that were not normally distributed, the non-parametric equivalent, the Friedman test, was used. To account for multiplicity across these variables, p-values from the primary omnibus tests were corrected using the FDR adjustment (at a 0.05 significance threshold), performed in R statistical software (version 4.5.3).

When a significant main effect was found, exploratory post-hoc pairwise comparisons were conducted and evaluated using FDR-adjusted p-values. For non-parametric data, post-hoc analysis utilized the automated pairwise comparisons built into the Friedman procedure in SPSS (based on mean ranks), where ties are assigned the average rank. All effect sizes were expressed using Cohen’s d to facilitate comparison across analyses, with partial eta-squared from ANOVA and Kendall’s W from Friedman tests converted to an approximate Cohen’s d. Values of approximately 0.15, 0.36, and 0.67 were labeled small, medium, and large, respectively (Kinney et al., 2020). All other statistical analyses were performed using SPSS (Version 30.0), with the level of significance set at $p < 0.05$.

RESULTS

A total of 45 participants with a mean age of 44.35 (SD 10.54) years and a mean BMI of 24.57 (SD 3.52) kg/m² were recruited, reporting chronic symptoms with a median heel pain duration of 13.50 weeks. Detailed participant characteristics, including specific measurements for foot progression angle, dorsiflexion lunge test, hallux valgus angle, 1st MTP joint dorsiflexion, FPI, and the LSD test, are presented in Table 1.

A highly significant main effect for comfort scores was found across the four conditions (unadjusted $p < 0.001$ and $q < 0.001$) (Table 2). Post-hoc analysis, based on this robust significance, confirmed that all three orthotic conditions (CFOs without wedge, CFO W1, and CFO W2) resulted in significantly higher comfort scores compared to the shod condition (Table 3, Figure 2a).

Gait and Spatiotemporal Parameters

While stance phase duration showed a significant main effect based on its unadjusted p-value of 0.017 (medium effect size), this effect became non-significant after Benjamini-Hochberg FDR adjustment ($q = 0.085$) (Table 2). Nevertheless, exploratory post-hoc analysis, justified by the unadjusted significance, indicated the CFO W1 condition significantly increased stance phase duration compared to the shod condition (Table 3, Figure 2b).

Conversely, a significant main effect with a large effect size was consistently found for the double support phase (unadjusted $p = 0.004$; $q = 0.040$), where the CFO W1 condition significantly lengthened this phase compared to both shod and CFO W2 conditions (Table 2 and 3, Figure 2c). Other spatiotemporal parameters—step length ($q = 0.988$), step time ($q = 0.861$), stride length ($q = 0.864$), stride time ($q = 0.918$), step width ($q = 0.861$), cadence ($q = 0.988$), and walking velocity ($q = 0.988$)—showed no significant main effects (Table 2).

Muscle activity during stance phase

Analysis of the peak relative muscle activation profiles during the stance phase revealed distinct neuromuscular demands (Table 2). Across all conditions, MG was consistently the most active muscle. Peak BF activity showed a significant main effect with medium effect size (unadjusted $p = 0.006$; $q = 0.040$). Post-hoc tests indicated that both CFOs without wedge and CFO W1 resulted in significantly lower BF activity compared to CFO W2 (Table 3, Figure 2d), suggesting increased BF activity with CFO W2. Peak TA activity initially had a significant main effect with medium effect size (unadjusted $p = 0.026$) but became non-significant after FDR adjustment ($q = 0.104$) (Table 2). Exploratory post-hoc analysis, based on the unadjusted result, suggested the CFO W1 condition produced the highest TA activity, while CFO W2 resulted in the lowest (Table 3, Figure 2e). Given these findings of significant differences, the muscle activity patterns of BF and TA across the four conditions during the entire stance phase are further illustrated in Figure 3a and 3b. No significant main effects were observed for peak RF ($q = 0.861$), MG ($q = 0.716$), or PL ($q = 0.269$) activity, nor for the average activity of all muscles across conditions ($q > 0.05$ for all) (Table 2).

DISCUSSION

This study examined the effects of three types of CFOs on comfort, gait parameters, and lower-limb muscle activity in individuals with PF. The results demonstrated that all CFO conditions significantly increased comfort compared to the shod condition, aligning with previous research showing that CFOs are effective for pain reduction and functional improvement in individuals with PF (Coheña-Jiménez et al., 2020; Harutaichun et al., 2022; Thong-On & Harutaichun, 2023).

Summary of key findings

Gait and Spatiotemporal Parameters

CFO W1 significantly increased stance phase duration compared to the shod condition, and also prolonged the double support phase relative to both the shod and CFO W2 conditions. These observed temporal alterations may reflect a more cautious gait pattern or altered temporal coordination. Based on prior research, it is theorized that CFO W1, through combined varus rearfoot and forefoot posting, improves rearfoot control and mitigates compensatory midfoot movement and overpronation, potentially reducing plantar fascia strain and contributing to the extended stance and double support times (Hajizadeh et al., 2019; Harutaichun et al., 2022).

Conversely, interpretations of CFO W2's effects are more cautious and presented as hypotheses. It is proposed that CFO W2 primarily functions as an alignment intervention at the forefoot and knee, consistent with prior findings that varus forefoot posting can induce lateral load shifting and reduce forefoot abduction (Harutaichun et al., 2022). This intervention modifies segmental kinematics and resulted in shorter stance and double support durations. While both CFO designs are hypothesized to alter plantar fascia strain and foot kinematics through differing mechanisms and effects on gait parameters (Harutaichun et al., 2022; Zhang & Vanwanseele, 2023), these mechanistic explanations remain speculative and are hypothesis-generating rather than directly established outcomes from the present measurements. The lack of significant changes in step length, stride length, cadence, and walking velocity across conditions aligns with previous work indicating that orthoses primarily influence temporal rather than spatial aspects of gait in individuals with PF (Harutaichun et al., 2022; Harutaichun et al., 2023; Zhang & Vanwanseele, 2023).

Muscle activity during stance phase

The present findings reveal selective, rather than widespread, neuromuscular adaptations across different orthotic conditions, with only peak TA and BF activity showing significant differences, thus warranting cautious interpretation. Specifically, the dual forefoot and rearfoot posting from CFO W1 was linked to higher peak TA activity compared to CFO W2. This could be attributed to the additional rearfoot posting, which might alter initial contact mechanics and rearfoot stability, thereby increasing TA's role in controlling foot placement and deceleration during early stance, a notion supported by previous research (Harutaichun et al., 2022; Schmitt et al., 2022; Zhang & Vanwanseele, 2023).

Conversely, both the CFOs without wedge and CFO W1 exhibited lower peak BF activity than CFO W2. As CFO W2 only provides forefoot posting, it may offer less rearfoot control, potentially necessitating greater compensatory hamstring (BF) activation to stabilize the knee and hip. The added rearfoot support of W1 might, therefore, reduce this need for compensatory BF activity (Abiko et al., 2020; Harutaichun et al., 2022; Zhang & Vanwanseele, 2023). However, it is possible that these differences in BF activity reflect other changes in joint kinematics or altered muscle synergies not directly related to compensatory demand. These mechanistic explanations are acknowledged as speculative hypotheses requiring further confirmation through more comprehensive EMG studies. While the previous study (Piri et al., 2025) explored double-density orthoses in individuals with pronated feet, the precise effects on muscle activities during dynamic tasks in individuals with plantar fasciitis remain an unresolved area, underscoring the need for further investigation in this specific patient population.

Finally, spatial data further indicated that CFO W1 extended both stance and double-support durations compared to other conditions. This prolonged foot contact might lessen the need for proximal hamstring activation to maintain limb stability, while simultaneously, altered foot mechanics and enhanced rearfoot control could increase the demand for dorsiflexion control, aligning with the observed higher TA activity. Given the limited number of EMG variables showing significant differences, these potential relationships between spatial gait changes and muscle activity are considered tentative and hypothesis-generating rather than definitive conclusions.

Clinical Implications

Overall, these findings emphasize that lower limb muscle activity is responsive to orthotic modifications, underscoring the importance of individualized considerations in orthotic prescriptions to potentially optimize gait mechanics and stability. The selection among interventions —CFO without wedge, CFO W1 (dual posting), or CFO W2 (forefoot posting only) —could be informed by a comprehensive gait assessment and the patient’s unique biomechanical requirements. Specifically, given its association with increased peak TA activity, prolonged stance and double support durations, and significantly lowers peak BF activity compared to CFO W2 in this acute laboratory setting, CFO W1 may be considered for further study in individuals requiring rearfoot control, but clinical recommendations require longitudinal evidence. Similarly, while CFO W2 offers forefoot-specific modifications and the CFO without wedge provides neutral support, clinical superiority cannot be claimed for any of these designs based solely on immediate, laboratory-based responses without long-term outcomes.

Strengths of the study

The present findings have several important clinical implications. This study directly addresses a common clinical dilemma: which orthotic posting design to choose for patients with PF. A significant strength of this study is its direct addressal of clinically relevant orthotic prescription strategies for PF, contributing valuable insights for individualized treatment approaches. Furthermore, this study contributes significantly to a relatively limited body of literature examining immediate neuromuscular responses to different orthotic posting strategies. To our knowledge, this is the first study to integrate subjective comfort scores with objective spatiotemporal gait parameters and multi-muscle EMG, providing a holistic and comprehensive assessment of orthotic effects. This multimodal approach yields comprehensive insights into both biomechanical and neuromuscular functional adaptations, thereby filling a critical knowledge gap identified in previous research that has largely focused on kinematic or pain outcomes, or reported inconsistent EMG findings. The randomized, within-subject design is a critical strength of this study, as it inherently and significantly reduces inter-individual variability, thereby strengthening the validity and precision of our comparisons. The inclusion of multiple distinct orthotic designs (CFO without wedge, CFO W1, and CFO W2) within the same cohort is a major contribution, allowing for the direct comparison of different prescription approaches under controlled conditions. By directly comparing the shod condition with each CFO design, this protocol allowed for the isolation of specific biomechanical and neuromuscular effects unique to each design. An additional strength is the assessment of intra-rater reliability for both Root and Monaghan orthotic measurement methods, a detail rarely reported in orthotic studies. Notably, the standardized experimental setup, employing controlled walking conditions, a standardized footwear protocol (which addresses shoe type as a major confounder), and an instrumented walkway, enhanced the reliability and precision of the measurements.

Limitations of the study

This study has several limitations that should be acknowledged. First, and crucially, we only investigated the immediate, "first-fit" effects of the orthoses. Therefore, our findings reflect acute, condition-specific responses and cannot be generalized to long-term clinical outcomes, as neuromuscular and gait adaptations may change significantly with prolonged orthotic use. Long-term adaptations in gait patterns and muscle activity may differ as the neuromuscular system learns and adjusts to the new sensory input, a phenomenon noted in other insole studies (Murley et al., 2010; Yi et al., 2018). Second, the study included a predominantly female sample (82.2%), which may limit the generalizability of these findings to broader populations. Third, the EMG analysis was limited to surface electrodes on a selection of muscles and may not fully capture the activity of deeper musculature (e.g., tibialis posterior, flexor hallucis longus) or the complexity of overall neuromuscular coordination. Fourth, the EMG normalization method, which involved normalizing to the maximum observed signal across all conditions, is a methodological limitation that may influence the comparability and interpretation of muscle activation levels, particularly when comparing with studies that utilize isometric reference contractions. As the study primarily focused on spatiotemporal gait parameters without direct measurement of joint kinematics or kinetics, interpretations concerning underlying biomechanical mechanisms (e.g., rearfoot motion, pronation, or plantar fascia loading) are therefore speculative. Fifth, the extensive number of outcome variables increased the risk of Type I error; while corrected with the Benjamini–Hochberg procedure, some main effects lacked significance. Therefore, post-hoc comparisons are presented as exploratory, hypothesis-generating analyses, requiring cautious interpretation (Rubin & Donkin, 2022). Finally, the study did not include comprehensive patient-reported functional outcomes, such as validated functional scales like the Foot Function Index or the Foot and Ankle Mobility Measure, beyond comfort scores, such as validated functional scales or quality-of-life measures, which limits the clinical interpretation of the findings regarding overall functional improvement. The study was conducted in a controlled laboratory environment with standardized footwear, specifically a single model (CROCS). While this setup ensured high internal validity, it may not fully reflect the variability in terrain, speeds, and activities encountered in real-world walking conditions. Crucially, the potential interaction between these orthotic designs and various types of footwear (e.g., work boots, athletic shoes, casual shoes) is a significant unaddressed factor, as different shoe characteristics could substantially alter the observed biomechanical and neuromuscular effects.

Future Directions

The present findings offer insights with implications for future research. The results after FDR adjustment highlight those different orthotic designs elicit distinct immediate biomechanical and neuromuscular responses. For example, CFO W1 demonstrated a significantly prolonged double support phase compared to the shod, which may reflect a more cautious gait pattern or altered temporal coordination. Although specific neuromuscular responses were observed—particularly concerning peak BF function when comparing CFO W2 to the CFO without a wedge—clinical recommendations for individualized orthotic prescriptions require longitudinal evidence. Future work is essential to determine if these immediate biomechanical and neuromuscular changes persist over time, how adaptation occurs, and which initial gait modification strategy best correlates with long-term clinical success.

CONCLUSION

This study has demonstrated that different CFO designs provide immediate discomfort relief for individuals with PF. Specifically, CFO W1 was associated with increased double support time, which may reflect a more cautious gait pattern or altered temporal coordination. Furthermore, CFO W1 and CFOs without wedge elicited less peak BF activity compared to the CFO W2 design. These findings are exploratory and hypothesis-generating, requiring confirmation in longer-term studies with direct stability measurements.

ACKNOWLEDGEMENTS

This research project is supported by Mahidol University (MU’s Strategic Research Fund: 2023). The authors would like to express our sincere gratitude to the research assistants, Ms. Neelubon Amonvuttikai and Ms. Narana Onsri, for their valuable supports in the data collection process, and to the Rubber Technology Research Center at the Faculty of Science, Mahidol University for their supports in the production of customized foot orthoses.

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Table 1 Participant characteristics (n = 45). Data are shown as mean (SD) / median (IQR), minimum and maximum.

	Mean (SD) / Median (IQR)	Minimum	Maximum
Age, years	44.35 (10.54)	20.0	60.0
Females, number (%)	37 (82.2 %)	-	-
BMI, kg/m^2	24.57 (3.52)	17.24	29.87
Weight-bearing duration, hours/day	5.00 [3.00, 8.00]	1.0	15.0
Heel pain duration, weeks	13.50 [8.00, 33.00]	10.0	120.0
Tibiofemoral angle, degrees	9.00 [6.00, 13.00]	5.0	32.0
Foot progression angle, degrees	6.48 (5.05)	-3.0	18.0
Dorsiflexion lunge test, cm	11.27 (3.45)	4.0	18.5
Hallux valgus angle, degrees	11.95 (7.40)	0.0	29.0
1st MTP joint dorsiflexion angle, degrees	52.35 (8.35)	34.0	75.0
Foot posture index, scores	3.43 (4.07)	-5	12
Lateral step-down test, scores	3.00 [2.00, 4.00]	1	4

Table 2 Comparison of the mean (SD) or median (IQR) of comfort score, gait parameters, peak and average EMG of each muscle among each condition (n=45).

	Shod	CFOs without Wedge	CFO W1	CFO W2	95% Confidence i	
					Lower bound	Upp
Comfort score, cm	4.60 [2.93, 6.73]	6.60 [5.58, 7.83]	6.50 [4.58, 8.30]	6.80 [5.08, 8.50]	5.362	6
Step length, cm	57.00 [52.42, 59.50]	57.50 [51.17, 60.13]	55.17 [52.00, 59.92]	56.33 [52.50, 58.67]	54.626	5
Step time, s	0.59 (0.05)	0.59 (0.05)	0.59 (0.04)	0.59 (0.04)	0.576	(
Stance phase, %	66.31 (1.96)	66.76 (2.12)	67.08 (1.86)	66.25 (2.46)	66.021	6
Double support phase, %	32.02 (2.88)	32.77 (3.05)	33.35 (2.94)	32.33 (3.20)	31.686	3
Stride length, cm	110.84 (9.05)	110.76 (10.75)	110.60 (7.82)	111.66 (8.24)	108.098	11
Stride time, s	1.18 (0.09)	1.19 (0.09)	1.18 (0.10)	1.19 (0.09)	1.154	1
Step width, cm	12.62 (3.08)	12.46 (3.52)	12.26 (2.95)	12.35 (3.52)	11.446	1
Cadence, steps/minute	100.60 (7.80)	100.62 (8.06)	100.33 (8.59)	100.50 (7.56)	98.136	10
Velocity, km/h	3.36 (0.38)	3.34 (0.45)	3.34 (0.45)	3.34 (0.46)	3.221	3
Peak Rectus Femoris	0.453 (0.138)	0.472 (0.150)	0.458 (0.132)	0.447 (0.124)	0.422	(
Peak Medial Gastrocnemius	0.535 (0.086)	0.511 (0.100)	0.514 (0.092)	0.513 (0.107)	0.492	(
Peak Biceps Femoris	0.349 (0.135)	0.334 (0.138)	0.352 (0.132)	0.403 (0.114)	0.326	(
Peak Tibialis Anterior	0.355 (0.125)	0.337 (0.112)	0.372 (0.110)	0.327 (0.104)	0.316	(

Peak Peroneus Longus	0.421 (0.116)	0.456 (0.111)	0.460 (0.102)	0.449 (0.116)	0.417
Average Rectus Femoris	0.187 (0.051)	0.186 (0.048)	0.178 (0.043)	0.183 (0.047)	0.170
Average Medial Gastrocnemius	0.250 (0.054)	0.247 (0.060)	0.249 (0.051)	0.255 (0.069)	0.233
Average Biceps Femoris	0.145 (0.076)	0.136 (0.072)	0.147 (0.069)	0.151 (0.062)	0.124
Average Tibialis Anterior	0.127 (0.054)	0.122 (0.055)	0.127 (0.061)	0.123 (0.047)	0.109
Average Peroneus Longus	0.219 (0.057)	0.228 (0.057)	0.236 (0.051)	0.226 (0.058)	0.206

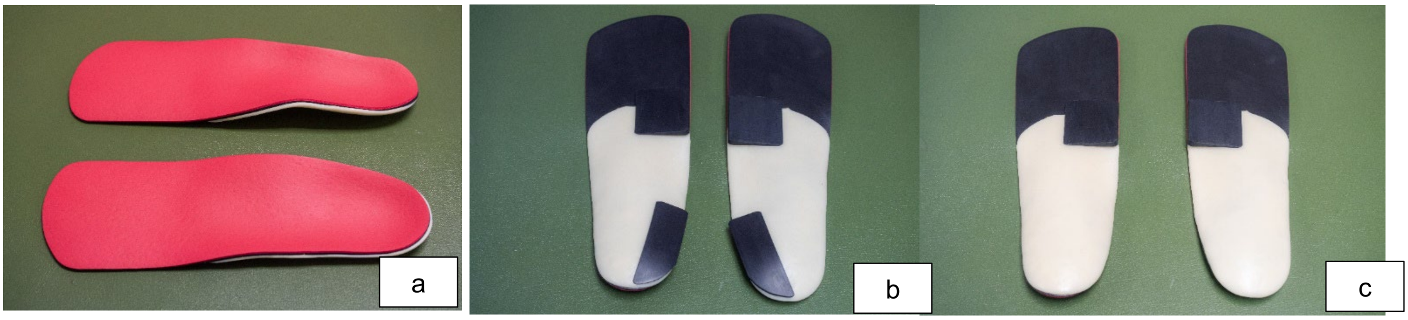
* Significant difference among conditions
† Effect sizes are expressed as Cohen's d, with partial eta-squared from ANOVA and Kendall's W from Friedman tests converted to an approximate Cohen's d.

Table 3 Post-hoc comparisons of the outcomes with a significant main effect.

Comparisons		Mean / Median Difference	*P*	95% Confidence interval of differences	
				Lower bound	Upper bound
Comfort scores					
Shod	CFOs without wedge	-2.058	**< 0.001***	-2.675	-1.442
Shod	CFO W1	-1.686	**< 0.001***	-2.229	-1.142
Shod	CFO W2	-1.932	**< 0.001***	-2.703	-1.162
CFOs without wedge	CFO W1	0.373	0.767	-0.260	1.005
CFOs without wedge	CFO W2	0.126	0.800	-0.410	0.663
CFO W1	CFO W2	-0.246	0.966	-0.902	0.409
Stance phase duration					
Shod	CFOs without wedge	-0.451	0.452	-1.137	0.235
Shod	CFO W1	-0.773	**0.020***	-1.460	-0.087
Shod	CFO W2	0.062	1.000	-0.856	0.980
CFOs without wedge	CFO W1	-0.323	1.000	-1.136	0.491
CFOs without wedge	CFO W2	0.513	0.813	-0.423	1.449
CFO W1	CFO W2	0.836	0.075	-0.051	1.723
Double support phase					
Shod	CFOs without wedge	-0.744	0.187	-1.670	0.182
Shod	CFO W1	-1.327	**0.001***	-2.205	-0.449
Shod	CFO W2	-0.310	1.000	-1.212	0.593
CFOs without wedge	CFO W1	-0.583	0.443	-1.466	0.301
CFOs without wedge	CFO W2	0.435	0.800	-0.355	1.225
CFO W1	CFO W2	1.017	**0.005***	0.236	1.799
Peak Biceps Femoris					
Shod	CFOs without wedge	0.015	1.000	-0.036	0.066
Shod	CFO W1	-0.003	1.000	-0.065	0.060
Shod	CFO W2	-0.054	0.139	-0.117	0.009
CFOs without wedge	CFO W1	-0.017	1.000	-0.076	0.041
CFOs without wedge	CFO W2	-0.069	**0.005***	-0.121	-0.016
CFO W1	CFO W2	-0.051	**0.043***	-0.101	-0.001
Peak Tibialis Anterior					
Shod	CFOs without wedge	0.018	1.000	-0.029	0.065
Shod	CFO W1	-0.017	0.913	-0.051	0.016
Shod	CFO W2	0.028	0.795	-0.023	0.080
CFOs without wedge	CFO W1	-0.035	0.075	-0.072	0.002
CFOs without wedge	CFO W2	0.011	1.000	-0.040	0.062
CFO W1	CFO W2	0.046	**0.030***	0.003	0.089

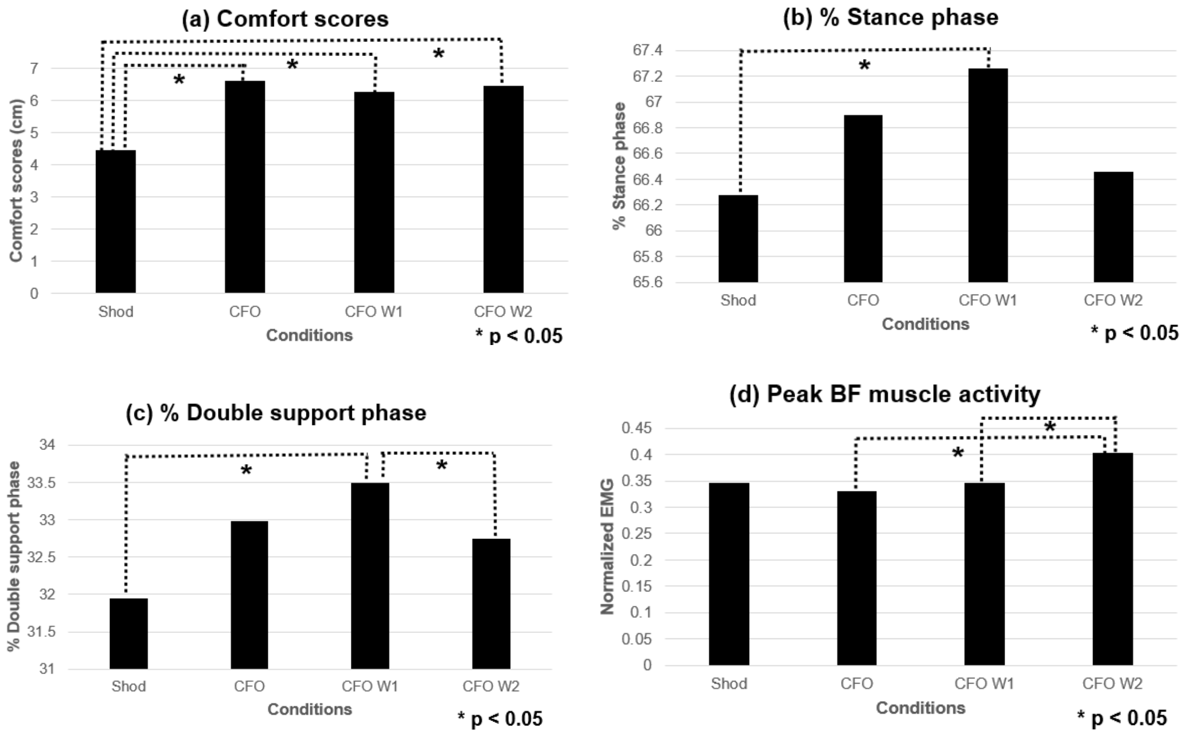
* Significant difference between conditions

Figure 1*: CFOs used in the present study: (a) CFOs without orthotic wedge, (b) CFO W1, (c) CFO W2



* Figure 1: Schematic Orthotic Designs
Figure 1a: CFOs without wedges: CFOs without forefoot or rearfoot posting.
Figure 1b: CFO W1 (Root Method): CFOs with forefoot varus post at 60% (max 8°) and rearfoot varus post at 50% (max 6%) of measured forefoot angle.
Figure 1c: CFO W2 (Monaghan et al. Method): CFOs with forefoot varus post at 50% of measured forefoot angle; no rearfoot varus post applied due to calculation.

Figure 2: Comparison of outcomes illustrating significant differences across conditions: (a) Comfort score, (b) % Stance phase, (c) % Double support phase, (d) Peak BF muscle activity, (e) Peak TA muscle activity.



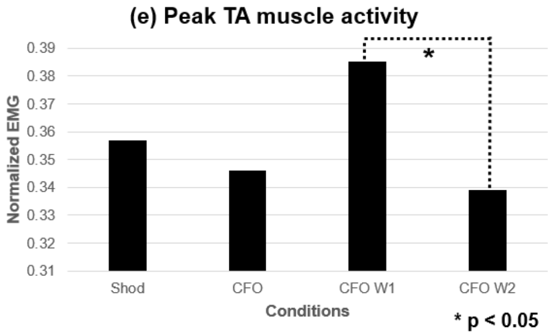


Figure 3: The muscle activity patterns of BF (a) and TA (b) muscle activity across the four conditions during the entire stance phase.