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Research Article

The Effect of Double Density Foot Orthoses on Lower Limb Muscular Co-contraction in Adults with Pronated Feet during Running

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Abstract

Introduction: Analyzing muscular co-contraction activity can help clinicians assess mechanical and motor control changes in individuals with pronated feet (PF) during rehabilitation. This study examines the impact of double-density foot orthoses (FO) on muscular co-contraction activity in adults with PF during running at a constant speed, compared with healthy controls.

Method: Twenty male adults with PF and twenty healthy male controls volunteered for this study. Muscle activity was recorded using an electromyography system (Biometric Ltd, UK). We measured two variables, directed co-contraction and general co-contraction, while participants ran along an 18-meter walkway, both with and without foot orthoses.

Result: We found lower general knee co-contraction ($p=0.017$; $\eta2=0.241$) during the loading phase (especially in the PF group) when running with FO than without. We observed decreased directed knee flexor/extensor co-contraction during mid-stance in the PF group when running with FO compared with running without it ($p=0.040$; $\eta^2=0.185$). This effect was not seen in the healthy group. Additionally, we found greater directed ankle co-contraction during the push-off phase in the PF group when running with FO compared with without ($p=0.006$; $\eta^2=0.305$), which was also not observed in the healthy group.

Conclusion : These findings suggest that FO use significantly reduces co-contraction during running, enhancing biomechanical efficiency and potentially mitigating the risk of joint dysfunction and related injuries. FO appears to improve movement mechanics, supporting better alignment and function in individuals with PF.

Keywords: Pronated feet, Foot orthoses, Co-contraction, Running.

Introduction

Running is one of the most popular physical activities globally because it requires minimal equipment and is time-efficient, making it beneficial for health [1]. The incidence of running-related injuries (RRIs) varies significantly across different populations, ranging from 3% to 85%, with an injury rate of 2.5–33 per 1000 hours of activity [2-4]. Foot posture is a major contributor to these injuries [4]. Approximately 70% of runners' experience lower limb injuries, with knee injuries being common. While the exact causes vary, pronated feet (PF) are often considered a contributing factor, among others [4]. The prevalence of PF is around 11% in individuals aged 18–25 [5].

Evidence suggests that individuals with PF exhibit increased activity in subtalar invertor muscles (tibialis posterior, tibialis anterior, and gastrocnemius) and decreased activation of subtalar evertor muscles compared to those with normal foot alignment during running [3]. As foot pronation and knee valgus are related deformities, PF can also contribute to abnormal internal rotation at the knee and hip [6]. Surface electromyography is used to assess the interaction between agonist and

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antagonist muscle activations [7]. Muscular co-contraction, the simultaneous contraction of agonist and antagonist muscles around a joint, is a neuromuscular strategy that enhances joint stiffness, postural stability, and movement precision in dynamic conditions [8]. Furthermore, excessive PF has been linked to conditions such as plantar fasciitis [9], medial tibial stress syndrome [10], and calcaneal tendinopathy [5]. Therefore, rehabilitation or treatment approaches for individuals with PF are crucial.

Foot orthoses (FOs) are commonly used as a conservative intervention to reduce overuse injury risks in individuals with PF [11,12]. FOs designed for PF aim to restore normal dynamic foot function, which can be assessed through joint kinematics, kinetics, and muscle activity during running [13]. These corrective effects are typically achieved through specific orthotic component configurations [12]. Thus, understanding the relationship between FO component features and the resulting biomechanical responses (e.g., dose-response effects) is essential for effective FO design and prescription. Medial wedge FOs are the most widely used orthoses to reduce foot pronation and modify lower limb biomechanics in individuals with PF [14]. Rearfoot posting is generally preferred, as forefoot posting can be challenging to fit inside the shoe and may cause discomfort [15]. Consequently, double-density FOs have been developed, incorporating a low-density lateral side and a high-density medial side (Figure 1). It remains unclear whether double-density FOs affect lower limb muscular co-contraction differently in adults with PF during running. Studies have shown that insole design and materials can either worsen or alleviate these conditions. For example, rigid insoles may restrict natural foot movement, potentially increasing tension in the ankle and knee joints. This stiffening effect can reinforce improper biomechanical patterns and potentially worsen contractures.[16,14]

Biomechanical variables such as lower limb muscular co-contraction (at the knee and ankle) are important in understanding the etiology of RRIs in individuals with PF. They should be explored to improve injury prevention strategies. To our knowledge, no studies have examined lower limb muscular co-contraction in adults with PF compared to healthy controls during running with double-density FOs. Therefore, this study aimed to compare knee and ankle co-contraction in adults with PF during the stance phase of running at a constant speed, with and without double-density FOs, versus healthy controls. Based on existing literature [14, 17–20], we hypothesized that muscle activity during running would differ between individuals with PF and healthy controls. We also expected double-density FOs to improve muscular co-contraction in adults with PF.

Methods

Participants

Forty men aged 25–30 years, with or without PF, volunteered for this study. Participants were assigned to the PF (n=20) and 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. Descriptive characteristics of the participants are shown in Table 1. All participants were right-footed as determined by a kicking ball test. PF were defined using the Foot Posture Index (FPI), assessed by an experienced podiatrist. The FPI consists of six clinical observations, each scored from −2 to +2, resulting in a total score ranging from −12 (highly supinated) to +12 (highly pronated). Based on established criteria, participants with FPI scores between +6 and +10 were classified as having PF.

The inclusion criteria for the PF group were: (i) male gender; (ii) body mass index < 25 kg/m2; (iii) rearfoot eversion angle > 4° (6, 7); (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 foot posture index validity has been reported in a previous study [8]. The foot posture index consists of 6 items to classify foot posture [8, 9]. 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 [8, 9].

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 limb length asymmetry above 5 mm [10]; and (iv) strenuous physical activity for 48 hours

before the test. All participants provided written informed consent before the study began. Eligible participants provided written informed consent. The study conformed to the ethical guidelines of the latest version of the Declaration of Helsinki, and the Ethics Committee of Baqiyatallah Medical Sciences University, Iran (IR.BMSU.BAQ.REC.1403.066) approved the procedures, which were registered with the Iranian Registry of Clinical Trials (IRCT20220129053865N1).

Double density foot orthoses

Before the study began, participants were familiarized with the applied tests and instruments. All participants received the same double-density FOs, fitted to their foot size. All participants (PF and normal foot groups) used the same double-density FO model. The double density FOs were made of ethylene-vinyl acetate (EVA), with a medial stiffness of Shore A 60 and a lateral stiffness of Shore A 30. These stiffness values were selected based on previous studies showing that increased medial stiffness provides adequate support to control excessive pronation. In contrast, lower lateral stiffness preserves natural foot motion and comfort during running.

Overground running

Before testing, participants performed a standardized 10 min warm-up protocol consisting of jogging at low-to-moderate intensities for 7 min, followed by dynamic stretching for 3 min [11]. For the running trials, we used an 18 m walkway and a wireless EMG system (Biometrics Ltd., Nine Mile Point Ind. Est., Newport, United Kingdom) with eight pairs of bipolar Ag/AgCl surface electrodes to collect lower limb muscular co-contraction data. All participants ran at a controlled speed of 3.2 m/s (±5%) across the walkway. Running speed was monitored using a chronometer, and participants completed familiarization trials to ensure consistent pacing. Trials performed outside the predefined speed range were discarded and repeated. Three test trials were conducted per condition. Each subject completed three familiarization trials to ensure a constant speed. Objective criteria to discard a trial were: (i) if the data were incomplete or had noise; (ii) the participant lost balance during the trial; (iii) participants ran with a midfoot or forefoot strike pattern.

Muscular co-contraction

A wireless EMG system (Biometrics Ltd., Nine Mile Point Ind. Est., Newport, United Kingdom) with seven 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), and rectus femoris (RF) muscle activities of the dominant limb. Center-to-center electrode distance was 25 mm. 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 alcohol (70% Ethanol–C2H5OH) over the respective muscle bellies. The skin was then gently abraded before electrode placement. The surface electrodes were placed on the muscle belly, longitudinally to the muscle fibers [12]. Participants performed two familiarization trials before the actual tests were recorded. The raw EMG signals were digitized at 1000 Hz. EMG data were processed as in a previous study, and root mean square (RMS) values were calculated for all phases [12]. In brief, test trials were divided into the loading (0–15% of running cycle), mid-stance (15–25% of running cycle), and push-off (25–40% of running cycle) phases [13]. Maximum voluntary isometric contraction (MVIC) was assessed using a handheld dynamometer to normalize EMG during running to MVIC. For each participant, 3 running trials during each condition (with and without FOs) were recorded. A trial was considered successful if EMG signals were artifact-free upon visual examination of the online screen. MVIC tests were applied after the running trials for each muscle separately to normalize EMG data. For normalization, peak RMS values during running trials were divided by peak MVIC values and multiplied by 100. Muscle activity was reported as % MVIC. We sampled raw EMG signals at 1000 Hz and processed them using root mean square (RMS) calculations. EMG amplitudes were normalized to maximum voluntary isometric contraction (MVIC) values and expressed as a percentage of MVIC. We calculated directed and general co-contraction indices using previously established formulas, allowing reproducible quantification of agonist–antagonist muscle activity during each phase of the running stance. There are three characteristics of muscle co-contraction: (1) the ratio of the agonist to antagonist activation (directed co-contraction, DCC), (2) the total

activation of the agonist and antagonist muscles (general co-contraction, GCC), and (3) determination of which agonists or antagonists are the dominant co-contractors. Directed co-contraction ratios (DCCR) were calculated for the medial (semitendinosus and vastus medialis)/lateral (biceps femoris and vastus lateralis) muscles (MLDCCR), and the knee flexors (semitendinosus, biceps femoris, and medial gastrocnemius)/extensors (vastus lateralis, vastus medialis, and rectus femoris) (FEDCCR). The DCCRs were calculated as follows:

If agonist mean EMG > antagonist mean EMG;

DCCR = 1 - antagonist mean EMG / agonist mean EMG

Else

DCCR = agonist mean EMG / antagonist mean EMG – 1

In these equations, if agonists (e.g., extensors or medial muscles) are more active than antagonists (e.g., flexors or lateral muscles), DCCR is above zero, and vice versa. Maximum co-contraction is represented by a DCCR of zero, while minimum co-contraction is indicated by a DCCR of 1 or -1. In directed co-contraction, as the numerical value approaches zero, co-contraction intensifies. Conversely, when the value approaches either 1 or -1, the degree of co-contraction diminishes [14].

Statistical analyses

The normality of data distribution was verified using Shapiro–Wilk tests. We used a two-way repeated-measures ANOVA for statistical analysis. We performed post-hoc testing with Bonferroni correction using a paired-samples t-test. Effect sizes in the form of Cohen's d were used to describe effect size values [15,16]. Effect sizes (η^2) were interpreted as small (< 0.06), medium (0.06–0.14), and large (> 0.14), indicating that most statistically significant findings demonstrated medium to large practical effects. The significance level was set at $P < 0.05$. Statistical analysis was conducted with SPSS (Version 26).

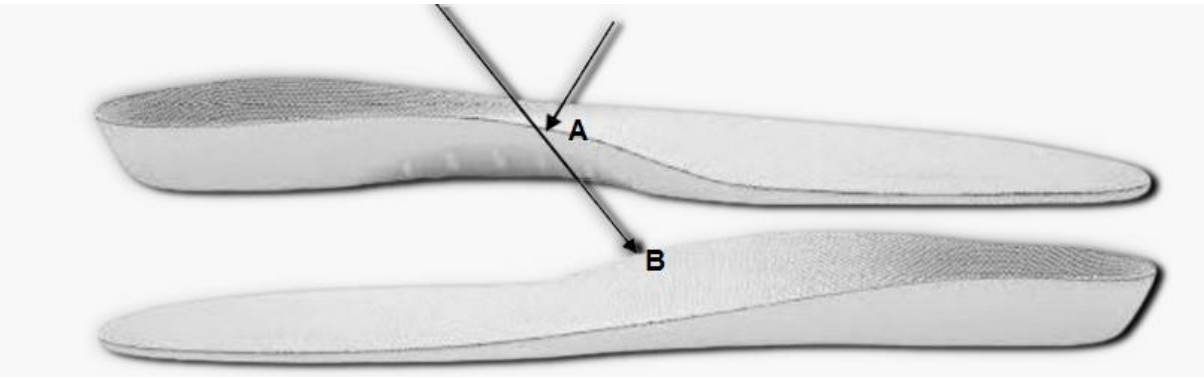


Figure 1: Double density FO design. (A): Increasing the longitudinal arc medial part as much as 12 mm; (B): Increasing the stiffness of the medial part as much as 60 shore A, and 30 shore A in lateral part.

Table 1: Demographic characteristics of the participants.

Characteristics	Healthy group	PF group	Sig.
Age (years)	25.4±0.3	26.4±1.0	0.091
Height (cm)	177.3±7.2	181.7±6.4	0.883
Mass (kg)	73.2±14.8	79.6±13.2	0.407
BMI (kg/m2)	23.3±1.2	24.0±0.7	0.501
Navicular drop (mm)	7.5±1.2	13.4±1.5	<0.001

Notes: PF, pronated feet. Stand for significant level $p<0.05$

Results

A significant main effect of “group” was found for general knee co-contraction ($p<0.001$; $\eta2=0.747$) and general ankle co-contraction ($p<0.001$; $\eta2=0.682$) during the loading phase, and for general ankle co-contraction ($p=0.003$; $\eta2=0.352$) during the push-off phase. Pairwise comparisons showed greater general knee co-contraction, general ankle co-contraction during the loading phase, and general ankle co-contraction during the push-off phase in the PF group than in the healthy group (Table 2). A significant main effect of “FO” was found for general knee co-contraction ($p<0.001$; $\eta2=0.799$) and general ankle co-contraction ($p<0.001$; $\eta2=0.639$) during the loading phase. Pairwise comparisons showed reduced general knee and ankle co-contraction during the loading phase when running with foot orthoses compared to running without them (Table 2). Significant “group-by-FO” interactions were found for general knee co-contraction ($p=0.017$; $\eta2=0.241$) during the loading phase. Post hoc analysis indicated reduced general knee co-contraction in both groups, particularly in the PF group, when running with foot orthoses compared to running without them (Table 2). In directed co-contraction analyses, positive and negative values indicate dominance of agonist and antagonist muscle activity, respectively. Values closer to zero represent higher levels of muscular co-contraction.

A significant main effect of "group" was found for directed knee flexor/extensor co-contraction ($p=0.016$; $\eta2=0.246$) and directed knee vastus medialis/vastus lateralis co-contraction ($p=0.008$; $\eta2=0.294$) during mid-stance. Paired-wise comparisons showed lower directed knee flexor/extensor co-contraction and directed knee vastus medialis/vastus lateralis co-contraction (mid-stance phase) in the PF group than in the healthy group (Table 3).

A significant main effect of "FO" was found for directed ankle co-contraction ($p=0.012$; $\eta2=0.265$) and directed knee medio/lateral co-contraction ($p=0.043$; $\eta2=0.180$) during the loading phase. Pairwise comparisons showed that directed ankle co-contraction during running was greater with the foot orthosis (FO) than without it. Conversely, directed knee medio-lateral co-contraction during running was lower with FO than without it. A significant main effect of "FO" was found for directed ankle co-contraction ($p=0.017$, $\eta2=0.241$) and for directed knee co-contraction involving the vastus medialis and vastus lateralis muscles ($p=0.042$, $\eta2=0.923$) during mid-stance. Paired-wise comparisons further demonstrated that directed ankle co-contraction during mid-stance was greater with FO than without it. In contrast, directed knee co-contraction involving the vastus medialis and vastus lateralis was lower with FO than without it. A significant main effect of "FO" was found for directed knee medio/lateral co-contraction ($p=0.044$; $\eta2=0.179$) and directed knee vastus medialis/vastus lateralis co-contraction ($p=0.018$; $\eta2=0.238$) during push-off. Pairwise comparisons showed that directed knee medio-lateral co-contraction and directed knee vastus medialis/vastus lateralis co-contraction during the push-off phase were greater with the foot orthosis (FO) than without it (see Table 3). Significant "group-by-FO" interactions were found for directed ankle co-contraction ($p=0.006$, $\eta2=0.308$) during the loading phase. Post hoc analysis showed greater directed ankle co-contraction in the PF group

(but not in the healthy group) during the loading phase while running with FO than without. Significant "group-by-FO" interactions were found for directed knee flexor/extensor co-contraction (p=0.040, η2=0.185) during the mid-stance phase. Post hoc analysis showed that directed knee flexor/extensor co-contraction was lower in the PF group (but not in the healthy group) during mid-stance while running with the FO than without it. Significant "group-by-FO" interactions were found for directed ankle co-contraction (p=0.006; η2=0.305) during the push-off phase. Post hoc analysis demonstrated greater directed ankle co-contraction in the PF group (but not in the healthy group) during push-off while running with FO than without it (Table 3).

Table 2: Mean and standard deviation of the general knee and ankle muscular co-contraction (% maximum isometric voluntary contraction) during running stance phase.

Muscles		Healthy group		PF group		Main effect of Group: P value (η^2)	Main effect of FO: P value (η^2)	Group-by-FO interaction: P value (η^2)
		Without FO Mean± SD	With FO Mean± SD	Without FO Mean± SD	With FO Mean± SD			
Loading phase	General knee co-contraction	512.52±118.74	257.80±45.33	868.42±181.16	412.42±106.48	<0.001 (0.747)	<0.001 (0.799)	0.017 (0.241)
	General ankle co-contraction	211.13±64.29	122.19±25.25	342.48±76.98	204.54±57.43	<0.001 (0.682)	<0.001 (0.639)	0.202(0.076)
Mid-stance phase	General knee co-contraction	476.14±164.37	432.28±162.41	397.69±209.48	348.97±98.18	0.118(0.112)	0.334(0.044)	0.959(0.001)
	General ankle co-contraction	166.72±68.33	177.48±75.67	150.03±62.95	194.58±62.64	0.992(0.001)	0.160(0.092)	0.383(0.036)
Push-off phase	General knee co-contraction	283.71±125.95	418.56±175.40	452.39±211.72	402.78±87.44	0.127(0.108)	0.351(0.042)	0.052(0.169)
	General ankle co-contraction	116.92±46.20	140.74±47.69	190.74±69.11	184.32±40.70	0.003 (0.352)	0.508(0.021)	0.254(0.061)

Legends: PF, Pronated feet; FO, Foot orthoses. Stand for p<0.05.

Table 3: Mean and standard deviation of the knee and ankle directed muscular co-contraction during running stance phase.

Muscles		Healthy group		PF group		Main effect of Group: P value (η^2)	Main effect of FO: P value (η^2)	Group-by-FO interaction: P value (η^2)
		Without FO Mean± SD	With FO Mean± SD	Without FO Mean± SD	With FO Mean± SD			
Loading phase	Directed ankle co-contraction	-0.03 ±0.40	-0.05 ±0.34	-0.36 ±0.46	0.09±0.19	0.508(0.021)	0.012 (0.265)	0.006 (0.308)
	Directed knee flexor/extensor co-contraction	-0.02 ±0.33	-0.02 ±0.04	-0.05 ±0.21	-0.05±0.11	0.645(0.010)	0.941(0.000)	0.964(0.000)
	Directed knee medio/lateral co-contraction	0.06±0.25	-0.08 ±0.04	-0.01 ±0.08	-0.05±0.08	0.557(0.017)	0.043 (0.180)	0.252(0.062)
	Directed knee vastus medialis/ vastus lateralis co-contraction	0.11±0.38	-0.13 ±0.09	-0.04 ±0.15	-0.04±0.15	0.629(0.011)	0.067(0.151)	0.085(0.134)
Mid-stance phase	Directed ankle co-contraction	-0.09 ±0.24	-0.02 ±0.29	-0.25 ±0.61	0.23±0.09	0.639(0.011)	0.017 (0.241)	0.070(0.148)
	Directed knee flexor/extensor co-contraction	-0.01 ±0.14	0.07±0.12	-0.002 ±0.09	-0.08±0.08	0.016 (0.246)	0.976(0.000)	0.040 (0.185)
	Directed knee medio/lateral co-contraction	-0.05 ±0.06	-0.05 ±0.05	-0.08 ±0.04	-0.09±0.07	0.099(0.125)	0.796(0.003)	0.830(0.002)
	Directed knee vastus medialis/ vastus lateralis co-contraction	-0.05 ±0.11	-0.08 ±0.09	-0.12 ±0.08	-0.17±0.12	0.008 (0.294)	0.042 (0.923)	0.764(0.004)
Push-off phase	Directed ankle co-contraction	-0.11 ±0.43	0.10±0.24	0.18±0.26	-0.15±0.18	0.856(0.002)	0.527(0.019)	0.006 (0.305)
	Directed knee flexor/extensor co-contraction	0.00±0.05	0.04±0.09	-0.01 ±0.07	-0.01±0.06	0.112(0.116)	0.268(0.058)	0.296(0.052)
	Directed knee medio/lateral co-contraction	-0.10 ±0.03	-0.001 ±0.09	-0.03 ±0.11	-0.01±0.11	0.424(0.031)	0.044 (0.179)	0.157(0.093)
	Directed knee vastus medialis/ vastus lateralis co-contraction	-0.15 ±0.05	0.03±0.18	-0.08 ±0.22	-0.01±0.20	0.915(0.001)	0.0 18(0.238)	0.268(0.058)

Legends: PF, Pronated feet; FO, Foot orthoses. Stand for $p<0.05$.

Discussion

The findings suggest that double-density foot orthoses may alter lower limb muscle co-contraction in individuals with PF during running. We found lower general knee co-contraction in both groups when running with FO than without. We observed decreased directed knee flexor/extensor co-contraction during mid-stance in the PF group when running with FO compared with running without them. This effect was not seen in the healthy group. Additionally, we found greater directed ankle co-contraction during push-off in the PF group when running with FO compared to without it, which was also not observed in the healthy group.

4-1: General muscular co-contraction

Results demonstrated greater general knee co-contraction, general ankle co-contraction (at loading phase), and general ankle co-contraction (at push-off phase) in the PF group than in the healthy group. In general, co-contraction involves equal activation of agonist and antagonist muscles at the knee, which may affect articular loading [17]. Notably, our research showed a significant increase in general knee and ankle co-contraction (during the loading and push-off phases) in the PF group compared with the healthy group. Previous studies indicate that increased general knee muscle co-contraction elevates joint load [25] and is also associated with greater impact forces. Our results showed lower general knee and ankle co-contraction in both groups (especially in the PF group) during the loading phase while running with FO than without it. Consistent with our findings, several authors have advocated using FO to reduce co-contraction and minimize joint load, given its potential adverse effects on knee load [18, 19]. This reduction may indicate improved neuromuscular efficiency and a potential reduction in excessive stress on lower limb joints, allowing individuals with PF to achieve a more biomechanically optimal running form. Moreover, the pronounced decrease in knee co-contraction in the PF group when using foot orthoses highlights the orthoses' capacity to support improved movement biomechanics. Reduced muscular co-contraction may decrease excessive joint compressive forces, thereby lowering mechanical stress on the knee and ankle joints. Double-density foot orthoses likely contribute to these effects by providing enhanced medial support, reducing excessive pronation, improving lower limb alignment, and consequently decreasing the need for compensatory muscle activation. These findings are consistent with previous studies reporting beneficial effects of foot orthoses on muscle activation patterns and injury prevention.

.4-2Directed muscular co-contraction

Results showed lower directed knee flexor/extensor co-contraction and vastus medialis/vastus lateralis co-contraction during mid-stance in the PF group compared to the healthy group. These observations suggest compromised neuromuscular control and stability in individuals with PF during functional tasks. Co-contraction plays a vital role in joint stability, as it ensures that antagonistic muscle groups provide the support needed to maintain proper knee joint alignment and function. The reduced co-contraction in the PF group may impair joint mechanics, potentially exacerbating patellar deformity and dysfunction during transitional movements [19]. Previous research has shown that, in healthy individuals compared with those with patellofemoral pain syndrome, two muscular mechanisms prevent additional lateral displacement of the patella. The first is early activation of the vastus medialis compared with the vastus lateralis [20], and the second is greater vastus medialis activity in healthy people than in patients with patellofemoral pain syndrome [21]. This reduced directed knee vastus medialis/vastus lateralis co-contraction during the mid-stance phase in the PF group, compared with the healthy group, may contribute to patellofemoral pain syndrome in PF individuals.

Findings demonstrated greater directed ankle co-contraction during the loading and mid-stance phases while running with FO than that without it. Previous findings indicate that increased directed ankle co-contraction reduces the risk of lower limb injuries and ankle instability in individuals with PF [42]. Results also showed lower directed knee medio/lateral co-contraction during running with FO than without it during the loading phase. In medio-lateral directed co-contraction, medial agonists are activated to support knee abduction moments and lateral muscles for knee adduction moments [22]. Also, medial knee muscle co-contraction has been reported to lead to faster progression of medial knee OA [23]. An increased duration of lateral muscle co-contraction could protect against medial cartilage loss [23]. Nonetheless, longitudinal studies should be done to investigate whether bias towards medial muscle co-contraction is

related to greater cartilage loss .

Findings showed lower directed knee vastus medialis/vastus lateralis co-contraction during mid-stance while running with FO than without it. VM and VL co-contraction is a critical factor in knee stability and function. The observed reduction in co-contraction with FO suggests these devices may facilitate a more efficient muscular strategy, allowing improved coordination and reduced strain on the knee joint. The decreased co-contraction of the VM and VL during mid-stance in runners using FO underscores the potential benefits of these devices in optimizing knee function. By improving the coordination and efficiency of muscle activation, FO may play a pivotal role in enhancing athletic performance and mitigating the risk of running-related injuries.[24]

Findings showed greater directed knee medio/lateral co-contraction and directed knee vastus medialis/vastus lateralis co-contraction during the push-off phase while running with FO than without it. The interplay between the medio-lateral stability and quadriceps muscle coordination is crucial for effective push-off during running. The increased medio-lateral co-contraction observed with FO suggests a stabilization mechanism, where greater muscle engagement may mitigate lateral forces that typically accompany high-impact activities [25]. This stabilization is vital for maintaining alignment and balance and may reduce the risk of knee injuries, which are common among runners.

Our results show a difference in directed ankle co-contraction between the groups while running with FO than without. The difference was more profound in the PF group. Our results demonstrated lower directed knee flexor/extensor co-contraction in the PF group (but not in the healthy group) during mid-stance while running with FO than without. Our findings indicate a significant decrease in directed knee medio-lateral co-contraction during running with FO compared with without it. However, to the best of our knowledge, no study has examined lower limb muscular co-contraction during running in adults with PF versus healthy controls while using double-density FOs.

This study included only male participants, which limits the generalizability of the findings to female populations. Additionally, the present study examined only the acute effects of foot orthoses; therefore, the long-term influence of double-density foot orthoses on muscular co-contraction remains unknown.

Clinical Implications

These findings may help trauma specialists, physiotherapists, and podiatrists prescribe double-density foot orthoses for runners with pronated feet. By reducing excessive muscular co-contraction and improving neuromuscular efficiency, these orthoses may help optimize running biomechanics and potentially reduce the risk of lower limb injuries.

Conclusion

In conclusion, the study found that individuals with PF exhibited lower co-contraction of knee flexor/extensor and vastus medialis/vastus lateralis muscles, indicating compromised neuromuscular control and stability. Running with FO enhanced directed ankle co-contraction and reduced knee co-contraction, suggesting improved muscle coordination and joint function. While these devices could reduce injury risk and enhance performance, further research is needed to validate this hypothesis and explore their long-term effects, particularly in females, as well as their influence on running kinematics. Moreover, the pronounced decrease in knee co-contraction in the PF group when using foot orthoses highlights the orthoses' capacity to support improved movement biomechanics.

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Conflict of Interest Disclosures

The authors declare that there are no conflicts of interest.

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Authors' Contributions

E. P: Writing, Analysis, Conceptualization. AA. J: Data curation, Conceptualization. A. S: Review & editing, Conceptualization. V. S, E.A: Supervision, Methodology, Investigation. A. SH, M.J.A and F.R: Review & editing, Conceptualization.

Ethical Statement

The study conformed to the ethical guidelines of the latest version of 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).

Declaration of Generative AI and AI-assisted technologies

The authors declare that generative artificial intelligence (AI) and AI-assisted technologies were used solely for linguistic and grammatical editing of the manuscript, and no AI tools were used for writing, data analysis, figure preparation, or generating any text, images, or tables.

References

1. Van Hooren B, Plasqui G, Meijer K. The effect of Wearable-based real-time feedback on running injuries and running performance: a randomized controlled trial. The American Journal of Sports Medicine. 2024;52(3):750-65.

.2 Jafarnezhadgero A, Givi AM, Hamlabadi MP, Sajedi H, Zago M. Muscle activation while running on the ground compared to artificial turf in males with pronated and supinated feet. Gait & Posture. 2024;107:306-11.

.3 Bovens A, Janssen G, Vermeer H, Hoeberigs J, Janssen M, Verstappen F. Occurrence of running injuries in adults following a supervised training program. International Journal of Sports Medicine. 1989;10(S 3):S186-S90.

.4 Lysholm J, Wiklander J. Injuries in runners. The American journal of sports medicine. 1987;15(2):168-71.

.5 Klein M, Patterson C, Karim A, Cuddeford T. Running biomechanical and isokinetic strength differences in masters runners with and without Achilles tendinopathy. Sports Biomechanics. 2024:1-14.

.6 Root ML. Normal and abnormal function of the foot. Clinical biomechanics. 1977:457-9.

.7 Bok S-K, Kim B-O, Lim J-H, Ahn S-Y. Effects of custom-made rigid foot orthosis on pes planus in children over 6 years old. Annals of rehabilitation medicine. 2014;38(3):369-75.

.8 Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: the Foot Posture Index. Clinical biomechanics. 2006;21(1):89-98.

.9 Gijon-Nogueron G, Sanchez-Rodriguez R, Lopezosa-Reca E, Cervera-Marin JA, Martinez-Quintana R, Martinez-Nova A. Normal values of the Foot Posture Index in a young adult Spanish population: a cross-sectional study. Journal of the American Podiatric Medical Association. 2015;105(1):42-6.

.10 Woerman AL, Binder-Macleod SA. Leg length discrepancy assessment: accuracy and precision in five clinical methods of evaluation. Journal of Orthopaedic & Sports Physical Therapy. 1984;5(5):230-9.

.11 Jafarnezhadgero AA, Fakhri E, Granacher U. Effects of nail softness and stiffness with distance running shoes on ground reaction forces and vertical loading rates in male elite long-distance runners with pronated feet. BMC Sports Science, Medicine and Rehabilitation. 2021;13:1-9.

.12 Farahpour N, Jafarnezhadgero A, Allard P, Majlesi M. Muscle activity and kinetics of lower limbs during walking in pronated feet individuals with and without low back pain. Journal of Electromyography and Kinesiology. 2018;39:35-41.

.13 Dugan SA, Bhat KP. Biomechanics and analysis of running gait. Physical Medicine and Rehabilitation Clinics. 2005;16(3):603-21.

.14 Heiden TL, Lloyd DG, Ackland TR. Knee joint kinematics, kinetics and muscle co-contraction in knee osteoarthritis patient gait. Clin Biomech (Bristol, Avon). 2009;24(10):833-41.

.15 Cohen J. Statistical power analysis: LAWRENCE ERLBURN; 1989.

.16 Cohen J. Statistical power analysis for the behavioral sciences: routledge; 2013.

.17 ZHANG L-Q, Xu D, Wang G, HENDRIX RW. Muscle strength in knee varus and valgus. Medicine & Science in Sports & Exercise. 2001;33(7):1194-9.

.18 Anbarian M, Ghasemi MH, Sedighi AR, Jalalvand A. Immediate effects of various foot orthoses on lower limb muscles co-contraction during single-leg drop jump. Journal of Advanced Sport Technology. 2019;3(2):32-41.

.19 Lucy Hatton A, Dixon J, Rome K, Martin D. Effect of foot orthoses on lower limb muscle activation: a critical review. Physical Therapy Reviews. 2008;13(4):280-93.

.20 Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Simultaneous feedforward recruitment of the vasti in untrained postural tasks can be restored by physical therapy. Journal of Orthopaedic Research. 2003;21(3):553-8.

.21 Makhsous M, Lin F, Koh JL, Nuber GW, Zhang L-Q. In vivo and noninvasive load sharing among the vasti in patellar malalignment. Medicine & Science in Sports & Exercise. 2004;36(10):1768-75.

.22 Schipplein O, Andriacchi TJJoor. Interaction between active and passive knee stabilizers during level walking. 1991;9(1):113-9.

.23 Hodges PW, van den Hoorn W, Wrigley TV, Hinman RS, Bowles K-A, Cicuttini F, et al. Increased duration of co-contraction of medial knee muscles is associated with greater progression of knee osteoarthritis. 2016;21:151-8.

.24 Preece SJ, Jones RK, Brown CA, Cacciatore TW, Jones AK. Reductions in co-contraction following neuromuscular re-education in people with knee osteoarthritis. BMC musculoskeletal disorders. 2016;17:1-12.

25. Khandha A, Manal K, Capin J, Wellsandt E, Marmon A, Snyder- Mackler L, et al. High muscle co- contraction does not result in high joint forces during gait in anterior cruciate ligament deficient knees. Journal of Orthopaedic Research®. 2019;37(1):104-12.