Research Paper

Comparison of Push-off Muscle Electromyography Mean Frequency Before and After Running-induced Fatigue in Pronated-foot Runners Wearing Carbon-plated or Cushioned Shoes

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ABSTRACT

Objectives: This study aimed to compare push-off lower-limb muscle electromyography (EMG) mean frequency (MNF) between recreational male runners with pronated feet using carbon-plated and highly cushioned non-plated footwear, with particular attention to muscles involved in late-stance stabilization and propulsion.

Methods: Thirty recreational male runners with pronated feet were randomly assigned to a carbon-plated advanced technology footwear (ATF) group (Nike ZoomX Vaporfly Next% 2; n=15) or a non-plated cushioned footwear group (Nike Invincible Run 3; n=15). A two-way mixed repeated-measures analysis of variance was used to examine footwear-group, fatigue, and footwear-group × fatigue interaction effects.

Results: Compared to the non-plated cushioned footwear group, the carbon-plated footwear group demonstrated higher overall push-off EMG-MNF values in the vastus medialis (VM) ($P<0.001$, $\eta^2p=0.291$), vastus lateralis ($P<0.001$, $\eta^2p=0.220$), and biceps femoris (BF) ($P<0.001$, $\eta^2p=0.251$). Across footwear groups, post-fatigue testing was associated with higher semitendinosus (ST) MNF ($P<0.001$, $\eta^2p=0.330$) and higher BF MNF ($P=0.001$, $\eta^2p=0.159$). A significant footwear-group×fatigue interaction was observed only for the medial gastrocnemius (MG) ($P=0.001$, $\eta^2p=0.163$), indicating that the pattern of pre- to post-fatigue change differed between footwear groups, with MNF increasing in the non-plated footwear group and decreasing in the carbon-plated footwear group.

Discussion: Carbon-plated footwear was associated with higher push-off EMGMNF in the VM, vastus lateralis, and BF. Fatigue increased MNF in the ST and BF, while the MG showed different fatigue-related responses between footwear conditions.

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Highlights

- Runners with pronated feet showed footwear-specific differences in push-off electromyography-MNF.
- Running-induced fatigue increased MNF in the ST and BF.
- The MG showed different fatigue responses between the two footwear conditions.

Plain Language Summary

This study examined whether two different running shoes changed leg muscle activity in runners with pronated feet, both before and after a tiring running protocol. One shoe was carbon-plated, whereas the other was highly cushioned and non-plated. We measured the electrical activity of several lower-limb muscles during the push-off phase of running, when the body moves forward before toe-off. The results showed that the carbon-plated shoe was associated with different muscle activity patterns in some thigh muscles compared to the cushioned shoe.

Introduction

Pronated foot (PF) is a common lower-extremity alignment characteristic with a prevalence of approximately one-third among physically active adults [1]. Excessive rearfoot eversion and its coupling with tibial internal rotation may alter lower-extremity mechanics and increase the muscular demands required to control foot motion and segmental stability during running [2-4]. The push-off phase is particularly relevant for examining neuromuscular responses because it requires coordinated muscle activity to stabilize the lower limb, transfer forces through the foot and ankle, and generate forward propulsion [5, 6]. In runners with a PF posture, prolonged rearfoot eversion and altered medial foot and forefoot mechanics may influence force transmission and the mechanical demands placed on the lower-limb musculature during propulsion [7-9]. However, it remains unclear how these demands are reflected in the frequency-domain characteristics of lower-limb muscle activity when runners with pronated feet use different footwear constructions.

Advanced technology footwear (ATF), particularly carbon-plated shoes, combines a relatively stiff curved plate with a compliant and resilient midsole, increasing longitudinal bending stiffness and altering forefoot deformation, rollover mechanics, and the effective lever function of the foot during push-off [6, 10]. Experimental studies have reported altered plantar-flexor muscle activity in carbon-plated footwear, including lower medial gastrocnemius (MG) activity during push-off in Vaporfly-type shoes compared to conventional running shoes, and plate geometry may further influence the magnitude and timing of muscle activation [6, 11, 12].

However, most footwear studies have examined general running populations without specifically considering foot posture. Runners with PF may require different muscular strategies to control rearfoot motion, tibial rotation, and ankle stability than runners with neutral foot posture [1, 13]. Therefore, findings from neutral-footed runners cannot necessarily be generalized to runners with PF, particularly when comparing a carbon-plated racing shoe such as the Nike Vaporfly Next% 2 with a highly cushioned non-plated shoe such as the Nike Invincible Run 3.

Electromyography (EMG) is a non-invasive method for examining these neuromuscular responses. Mean frequency (MNF), the weighted average frequency of the EMG power spectrum, has been used to examine spectral changes during locomotor tasks [14]. EMG spectral characteristics may be influenced by motor-unit behavior, conduction properties, locomotor demands, and fatigue [14-16]. Running-induced fatigue may further modify these neuromuscular strategies. Experimental studies have reported reductions in EMG median or mean power frequency in several lower-limb muscles, including the MG, vastus lateralis (VL), rectus femoris, and tibialis anterior (TA), during prolonged or exhaustive running [15-18]. Despite increasing interest in carbon-plated footwear, limited evidence is available regarding its effects on EMG frequency-domain measures, particularly push-off MNF, in runners with PF. Accordingly, the present study investigated the effects of the Nike Vaporfly Next% 2 and Nike Invincible Run 3 on push-off lower-limb muscle EMG-MNF during running in runners with PF.

Table 1. Demographic and anthropometric characteristics of the participants

Characteristics	Mean±SD		P
	Control Shoe	Carbon-Plated Shoe	
Age (y)	22.93±2.52	22±2.95	0.360
Height (cm)	177.93±6.49	175.80±7.72	0.420
Mass (kg)	72.80±9.37	72.78±10.33	0.997
Body mass index (kg/m²)	22.93±2.11	23.52±3.03	0.544

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Between-group comparisons were performed using an independent-sample t-test. Statistical significance was set at P<0.05.

Materials and Methods

Study design

A randomized laboratory-based study was conducted to compare push-off lower-limb EMG-MNF between two footwear conditions in recreational male runners with PF. Participants were assigned to either an ATF condition (n=15) or a conventional running shoe condition (n=15).

Participants

Thirty male recreational runners with PF participated in this study (Table 1). Limb dominance was identified according to the leg preferred for kicking a ball; all enrolled participants were classified as right-leg dominant [19]. Electromyographic recordings were obtained from muscles of the dominant lower limb and used for all subsequent analyses. Participants were recruited from local running clubs and were required to have at least three years of recreational running experience, a minimum weekly frequency of three running sessions, and an average weekly running mileage of approximately 30 km. Their usual training was performed at a self-selected pace corresponding to their typical training intensity.

The inclusion criteria were age between 18 and 35 years, at least 3 years of recreational running experience, participation in running training at least three times per week, and PF posture confirmed by the foot posture index (FPI). The exclusion criteria included lower-extremity injury within the previous 12 months, previous lower-extremity surgery, severe trunk deformity, withdrawal from the study, or injury occurring during the testing session [20-23]. An a priori sample size calculation was conducted using G*Power software, version 3.1.9.7 for a mixed-model repeated-measures analysis of variance (ANOVA) (within-between interaction: two groups × two time points). Based on effect sizes reported in prior footwear and electromyographic fatigue investigations during running [20-23], a moderate-to-large effect size of Cohen's f=0.28 was assumed. All participants successfully completed the pre- and post-fatigue running protocols and were included in the final statistical analysis without any dropouts (Figure 1).

Randomization and group allocation

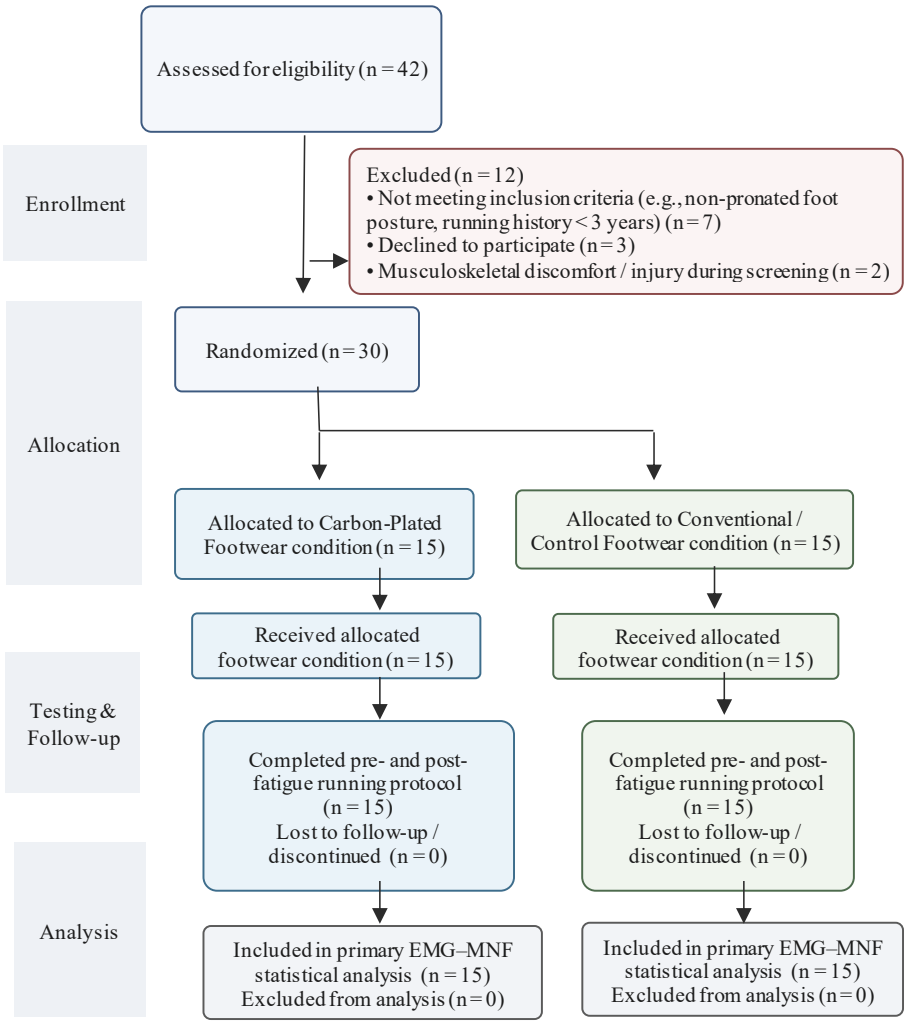
All footwear was supplied by the investigators, and prior experience with either shoe was not required. Electromyographic recordings were anonymized and stored using coded identifiers. Data processing and statistical analyses were performed on coded datasets without access to participant identities. Due to visible differences between shoe conditions, neither participants nor testing personnel were blinded to group allocation.

Foot pronation assessment

Foot posture was assessed before randomization using the FPI-6 by a trained specialist at the Health Center of the Faculty of Sports Sciences, University of Mohaghegh Ardabili. Each of the six FPI-6 items was scored from −2 to +2, resulting in a total score of −12 to +12. Participants were considered to have a PF posture when the dominant right foot scored ≥6. Because EMG measurements were obtained from the dominant right lower limb, eligibility was based on the right-foot score. The mean FPI-6 values were 8.3±1.4 for the right foot and 8.1±1.2 for the left foot, confirming PF posture at the group level.

Footwear conditions

The ATF condition consisted of a Nike ZoomX Vaporfly Next% 2 (Nike Inc., Beaverton, OR, USA) featuring a full-length curved carbon-fiber plate embedded in a Pebax-based ZoomX midsole. The shoe also incorpo-



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Figure 1. Flowchart of participant screening, experimental footwear allocation, and completion of the fatigue protocol

EMG: Electromyography; MNF: Mean frequency.

rates a rocker-shaped sole and increased longitudinal bending stiffness, which may modify forefoot mechanics and propulsion during running. Heel and forefoot stack heights were approximately 39 and 31 mm, respectively, with an 8-mm heel-to-toe drop (Figure 2). The comparison condition was the Nike Invincible Run 3 (Nike Inc., Beaverton, OR, USA), a highly cushioned neutral daily-training shoe that uses a full-length ZoomX foam midsole but does not contain a carbon-fiber plate. Thus, the two footwear conditions differed in several shoe-level characteristics, including the presence or absence of a full-length carbon-fiber plate, shoe mass, stack height, heel-to-toe drop, rocker geometry, and longitudinal bending stiffness. Accordingly, the present study compared two distinct footwear constructions rather than isolating the effect of the carbon-fiber plate. Therefore, any differences observed between the footwear conditions should be interpreted as responses to the overall biomechanical characteristics of the two shoe constructions and cannot be attributed solely to the carbon-fiber plate (Figure 3).

To minimize footwear-fit effects on neuromuscular measurements, shoe size was individually matched to foot dimensions, with equivalent European sizes (EU 41–42.5) used across both models. Table 2 summarizes the main technical and biomechanically relevant characteristics. Before testing, footwear was inspected for visible wear or structural defects, and participants completed a standardized 5-min familiarization run on the laboratory runway to become accustomed to the assigned shoe and overground running protocol [24].



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Figure 2. Photo of the carbon shoe



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Figure 3. Photo of the control shoe

Fatigue protocol

Running-induced fatigue was induced using a standardized treadmill protocol while participants wore their assigned footwear. The treadmill (Horizon Fitness, Omega GT, USA) was set at 0% incline and 4.0 m/s, following a brief familiarization period. Perceived exertion was monitored using the Borg 6–20 rating of perceived exertion (RPE) scale [25], with participants reporting RPE at regular intervals. Fatigue was defined as RPE≥17 combined with inability to maintain the prescribed speed despite standardized verbal encouragement. Heart rate (HR) was continuously monitored using a telemetry chest strap (Polar H10, Polar Electro Oy, Kempele, Finland). The average duration to reach the fatigue criterion was 14.8±3.2 minutes. At the cessation of the protocol, the participants attained a mean terminal HR of 184.5±6.8 bpm (corresponding to approximately 94.2±3.1% of their age-predicted maximal HR), objectively confirming high physiological strain alongside the subjective RPE threshold.

Data collection

Testing was conducted under standardized laboratory conditions. Surface EMG was recorded during shod overground running using a wireless system (Biometrics Ltd., Newport, UK) at 1000 Hz. Bipolar Ag/AgCl surface electrodes (11-mm diameter, 25-mm inter-electrode distance) were placed over the selected lower-limb muscle bellies according to standardized recommendations (Table 3). Figure 4 shows the experimental setup, including sEMG electrode placements on the selected lower extremity muscles according to surface EMG for the non-invasive assessment of muscles (SENIAM) guidelines. The participants performed running trials



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Figure 4. Experimental test setup and electrode placement, schematic and photographic illustration of surface electromyography bipolar electrode placements on the eight target lower limb muscles (TA, MG, VM, VL, RF, ST, BF, and GM) Adhering to SENIAM recommendations

Abbreviation: TA: Tibialis anterior; VM: Vastus medialis; VL: Vastus lateralis; RF: Rectus femoris; ST: Semitendinosus; GM: Gluteus medius; SENIAM: Surface electromyography for non-invasive assessment of muscles.

Table 2. Technical specifications and biomechanical characteristics of the experimental footwear

Characteristic	Nike ZoomX Vaporfly Next% 2 (Carbon-Plated)	Nike Invincible Run 3 (Control)
Manufacturer	Nike Inc., Beaverton, OR, USA	Nike Inc. Beaverton, OR, USA
Shoe category	Racing shoe	Cushioned neutral running shoe
Midsole foam	ZoomX (Pebax-based)	ZoomX
Carbon-fiber plate	Full-length curved plate	None
Longitudinal bending stiffness	Increased	Lower (relative to CPS)
Rocker geometry	Pronounced forefoot rocker	Mild rocker
Heel stack height	39 mm	35.2 mm
Forefoot stack height	31 mm	25.6 mm
Heel-to-toe drop	8 mm	9 mm
Approximate weight (US Men's 9)	~232 g	~310 g
Intended use	Competitive road racing	Daily training

CPS: Carbon plated shoes.

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Both footwear models were manufactured by the same company and incorporated ZoomX midsole foam; however, they also differed in carbon-fiber plate presence, longitudinal bending stiffness, shoe mass, stack height, heel-to-toe drop, and rocker geometry. Therefore, the comparison should be interpreted as a carbon-plated racing shoe versus a highly cushioned non-plated running shoe, rather than as an isolated effect of the carbon-fiber plate.

along an 18-m runway while wearing their assigned footwear. Running speed was standardized at 4.5 m/s and was monitored by timing each participant over the 18-m runway; running speed was calculated by dividing the runway distance by the recorded time. Because running speed can influence lower-limb kinematics and kinetics, standardized speed across footwear conditions was used to minimize speed-related variability and ensure that observed differences were examined under the same running-speed condition. Trials were accepted when running speed remained within ±5% of the target, and three valid trials were collected for both pre- and post-fatigue conditions.

Outcome variables

The primary outcome variable was the MNF of the surface EMG signals during the push-off phase of running, calculated from the EMG power spectrum for eight muscles of the dominant lower limb: Vastus medialis (VM), VL, RF, BF, semitendinosus (ST), MG, TA, and gluteus medius (GM). Raw sEMG signals were bandpass filtered using a zero-lag fourth-order Butterworth filter at 20–450 Hz to eliminate motion artifacts and high-frequency noise. The push-off phase was operationalized as the terminal 40% of the stance phase (60–100% of stance duration, immediately prior to toe-off) identified via synchronized vertical ground reaction force from the force plate. The EMG power spectrum and MNF were derived using a FFT with a 256-ms Hamming window and 50% overlap [26, 27]. For each participant and testing condition (pre-fatigue and post-fatigue), MNF values were obtained from three valid running trials and averaged for statistical analysis.

Statistical analysis

The distribution of all outcome variables was assessed using the Shapiro–Wilk test, and no significant departures from normality were observed ($P>0.05$). To examine the effects of footwear and fatigue on EMG-MNF, a two-way mixed repeated-measures ANOVA was performed for each analyzed muscle. Footwear condition (ATF vs non-plated cushioned footwear) was treated as the between-subjects factor, whereas fatigue condition (pre-fatigue vs post-fatigue) was considered the within-subjects factor. Equality of variances between groups was checked using Levene's test. When significant main effects or interaction effects were identified, Bonferroni-adjusted pairwise comparisons were applied to determine the locations of differences. The magnitude of ANOVA effects was expressed as partial eta squared

Table 3. Electrode placement sites according to the SENIAM protocol

Muscle	Electrode Placement Site
TA	Upper 30% of the line connecting the tip of the fibula to the medial malleolus of the ankle
MG	Most prominent region of the medial muscle belly
GM	50% of the distance along the line connecting the anterior superior iliac spine to the greater trochanter
BF	50% of the line connecting the lateral condyle of the tibia to the ischial tuberosity
ST	50% of the line connecting the medial condyle of the tibia to the ischial tuberosity
RF	50% of the distance along the line connecting the anterior superior iliac spine to the superior border of the patella
VM	Distal 80% of the line connecting the anterior superior iliac spine to the patella at approximately 55° relative to the longitudinal axis of the thigh
VL	Upper 35% of the distance along the line connecting the anterior superior iliac spine to the lateral border of the patella

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Abbreviations: TA: Tibialis anterior; MG: Medial gastrocnemius; GM: Gluteus medius; BF: Biceps femoris; ST: Semitendinosus; RF: Rectus femoris; VM: Vastus medialis; VL: Vastus lateralis; SENIAM: Surface electromyography for non-invasive assessment of muscles.

(η^2p), and Cohen's d was calculated for pairwise comparisons to facilitate interpretation of effect magnitude. Partial eta squared values of 0.01, 0.06, and 0.14 were interpreted as small, medium, and large effects, respectively [28]. The Bonferroni-adjusted significance threshold was 0.05/8=0.0062. Statistical analyses were conducted using SPSS software, version 26.0 (IBM Corp., Armonk, NY, USA).

Results

No significant between-group differences were observed at baseline for age, body mass, height, body mass index, or FPI-6 scores (all P>0.05), confirming successful randomization and baseline homogeneity between the two footwear groups. The mixed-design ANOVA revealed significant between-group main effects for the VM (P<0.001, η^2p=0.291, large effect size), VL (P<0.001, η^2p=0.220, large effect size), and biceps femoris (BF) (P<0.001, η^2p=0.251, large effect size) (Table 4). Pairwise comparisons demonstrated that the carbon-plated footwear group exhibited significantly higher overall push-off MNF values compared with the non-plated cushioned footwear group for the VM (mean difference=13.06 Hz, P<0.001) and the VL (mean difference=14.47 Hz, P<0.001). Similarly, overall BF MNF was significantly greater in the carbon-plated footwear group than in the non-plated cushioned footwear group (mean difference=11.07 Hz, P<0.001).

Regarding the main effect of running-induced fatigue, significant differences were observed for the ST (P<0.001, η^2p=0.330, large effect size) and BF (P=0.001, η^2p=0.159, large effect size) (Table 4). Pairwise comparisons showed that the fatigue protocol significantly increased ST MNF from pre- to post-fatigue conditions, with post-fatigue values exceeding pre-fatigue values by an average of 10.58 Hz (P<0.001). Fatigue also significantly increased BF MNF, with post-fatigue values being 8.96 Hz greater than pre-fatigue baseline values (P<0.001). No significant main effects of fatigue were detected for the TA (P=0.123, η^2p=0.083), MG (P=0.891, η^2p=0.001), VM (P=0.792, η^2p=0.003), VL (P=0.601, η^2p=0.010), RF (P = 0.969, η^2p=0.000), and GM (P=0.172, η^2p=0.066).

A significant footwear group×fatigue interaction was observed exclusively for the MG (P=0.001, η^2p=0.163, large effect size) (Table 4). Subsequent post-hoc simple main effects analysis (with Bonferroni adjustment) revealed that within the carbon-plated footwear group, the pre-to-post decrease in MG MNF (100.19±7.49 Hz to 93.44±12.01 Hz) reached statistical significance (P=0.038), whereas the increase observed in the non-plated cushioned footwear group (98.03±10.86 Hz to 104.02±17.41 Hz) did not reach statistical significance (P=0.086). Furthermore, between-group comparisons showed no significant differences at pre-fatigue baseline (P=0.609) or at post-fatigue (P=0.088), confirming that the observed significance was primarily driven by the crossover interaction effect and the selective decrease within the carbon-plated group. No significant footwear

Table 4. Mean±SD of EMG-MNF values of lower extremity muscles during running under two footwear conditions (Hz)

EMG	Mean±SD				P (η^2p)		
	Control Shoe		Carbon-Plated Shoe				
	Pre-test	Post-test	Pre-test	Post-test	Main Effect of Fatigue	Main Effect of Group	Main Effect of Fatigue Group*
TA	85.79±8.66	80.80±19.04	90.54±23.63	82.75±9.74	0.123 (0.083)	0.463 (0.019)	0.729 (0.004)
MG	98.03±10.86	104.02±17.41	100.19±7.49	93.44±12.01	0.891 (0.001)	0.258 (0.045)	0.001 (0.163)
VM	61.45±8.02	56.46±20.41	70.80±13.53	73.23±21.89	0.792 (0.003)	<0.001 (0.291)	0.448 (0.021)
VL	64.97±18.10	57.42±24.96	74.64±16.76	76.69±19.41	0.601 (0.010)	<0.001 (0.220)	0.365 (0.029)
RF	67.14±15.73	60.74±19.92	65.27±11.54	71.34±17.56	0.969 (0.000)	0.311 (0.037)	0.157 (0.070)
ST	92.25±17.40	100.88±9.27	87.76±11.16	100.28±9.40	<0.001 (0.330)	0.468 (0.019)	0.500 (0.016)
BF	75.57±14.84	80.16±17.01	82.26±16.11	95.60±8.72	0.001 (0.159)	<0.001 (0.251)	0.271 (0.043)
GM	73.75±14.20	78.25±11.99	78.23±18.17	84.86±13.97	0.172 (0.066)	0.140 (0.076)	0.791 (0.003)

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Abbreviations: EMG: Electromyography; MNF: Mean frequency; CPS: Carbon plated shoes; TA: Tibialis anterior; MG: Medial gastrocnemius; GM: Gluteus medius; BF: Biceps femoris; ST: Semitendinosus; RF: Rectus femoris; VM: Vastus medialis; VL: Vastus lateralis.

group×fatigue interactions were observed for the TA (P=0.729, η^2p=0.004), VM (P=0.448, η^2p=0.021), VL (P=0.365, η^2p=0.029), RF (P=0.157, η^2p=0.070), ST (P=0.500, η^2p=0.016), BF (P=0.271, η^2p=0.043), or GM (P=0.791, η^2p=0.003).

Decomposition of the significant interaction for MG: Pre-to-post change in the carbon-plated shoe group: Mean difference=-6.75 Hz (95% confidence interval [CI], -13.12%, -0.38%, P=0.038); Pre-to-post change in the control shoe group: Mean difference=+5.99 Hz (95% CI, -0.85%, 12.83%, P=0.086). Between-group difference at post-test: Mean difference=-10.58 Hz (95% CI, -22.80%, 1.64%, P=0.088). *P<0.05.

Discussion

The main findings were that the carbon-plated shoe was associated with higher push-off MNF in the VM, VL, and BF; fatigue increased ST and BF-MNF; and a significant footwear×fatigue interaction was observed only for the MG, with opposite post-fatigue changes between footwear conditions. The higher quadriceps and BF-MNF observed in the carbon-plated condition is biomechanically plausible, although the underlying mechanisms cannot be directly confirmed. The tested carbon-plated footwear model likely differed from the non-plated cushioned footwear model in longitudinal bending stiffness, rocker geometry, mass, and forefoot mechanics, which may have contributed to the observed differences in neuromuscular demands during late stance [29, 30]. In runners with pronated feet, these footwear-related mechanical differences may also be associated with altered knee and hip stabilization demands during push-off. Importantly, MNF reflects the spectral organization of muscle activity and neuromuscular function rather than providing a direct measure of muscle fiber type or motor-unit recruitment alone [31, 32].

Consistent with previous literature [33-35], our findings indicate that carbon-plated footwear modulates neuromuscular demands. Unlike prior studies often focused on EMG amplitude [11, 34], we observed significant footwear effects on push-off MNF specifically in the VM, VL, and BF, whereas the TA and MG remained unaffected. Differences in participant characteristics, including the presence of a PF posture in the present sample, may also have contributed to the different findings.

With respect to fatigue, MNF increased significantly following the fatigue protocol in the ST and BF, whereas no significant main effect of fatigue was observed for the quadriceps, TA, MG, or GM. This finding differs from the spectral slowing commonly reported during pro-

longed or exhaustive exercise, in which a reduction in EMG spectral frequency has frequently been interpreted as a consequence of fatigue-related changes in neuromuscular function [15-18, 31, 36]. One possible explanation is that the present post-fatigue measurement represented a task-specific neuromuscular response during a brief push-off phase immediately following treadmill running to the predefined fatigue criterion, rather than the sustained contraction conditions commonly used in fatigue studies. The mechanical and temporal demands of push-off may require rapid modulation of motor-unit activity to maintain lower-limb stability and propulsion after fatigue.

The increase in MNF may potentially reflect changes in motor-unit recruitment, discharge behavior, and action-potential conduction properties. The recruitment of higher-threshold motor units can contribute to changes in EMG spectral characteristics, partly because larger motor units generally have higher conduction velocities [37, 38]. Fatigue may also alter motor-unit recruitment and discharge strategies as the neuromuscular system attempts to maintain force production despite changes in the force-generating capacity of active motor units [38, 39]. However, MNF derived from conventional surface EMG is influenced by multiple physiological and methodological factors and cannot be considered a specific marker of motor-unit recruitment or muscle-fiber type [37, 40]. Therefore, the present increase in MNF should not be interpreted as direct evidence of selective recruitment of fast-twitch motor units.

Motor-unit synchronization may provide an additional consideration when interpreting fatigue-related changes in MNF. Experimental studies have shown that fatigue can increase synchronization or coherence among simultaneously active motor units [39], while greater synchronization has generally been associated with increased low-frequency spectral content [40]. Consequently, increased synchronization alone would not be expected to explain the increase in MNF observed in the present study. Rather, the observed increase may represent the combined influence of changes in motor-unit recruitment, discharge characteristics, synchronization, and action-potential conduction properties. Because the present study used conventional bipolar surface EMG rather than motor-unit decomposition techniques, the relative contribution of these mechanisms cannot be distinguished. Accordingly, the increased MNF observed in the ST and BF should be interpreted as a protocol-specific change in the frequency-domain characteristics of muscle activity following running-induced fatigue, rather than as evidence that fatigue universally increases MNF. The only significant interaction occurred in the MG, whose MNF increased after fatigue in the non-plated shoe but decreased in the carbon-plated shoe. This finding suggests that footwear construction may influence plantarflexor spectral responses to fatigue. Differences in plate, rocker, and midsole construction may have altered forefoot bending behavior and terminal-stance mechanics, thereby changing the role of the MG under fatigued conditions [6, 29, 35]. Because similar interactions have not been consistently reported, this finding should be interpreted cautiously and not as evidence of superiority or injury protection [6, 16].

This study has several limitations. The controlled laboratory setting and relatively small sample of recreational male runners with pronated feet limit generalizability to women, elite runners, and neutral-foot populations. The two footwear models differed in several characteristics beyond the presence of a carbon plate; therefore, the findings represent comparisons between footwear constructions rather than isolated carbon-plate effects. No kinematic, plantar-pressure, or internal loading measurements were obtained; therefore, the proposed biomechanical mechanisms cannot be confirmed directly. Finally, only acute responses before and immediately after fatigue were examined, precluding conclusions regarding long-term adaptations or injury risk.

Conclusion

This study aimed to compare push-off lower-limb EMG-MNF between carbon-plated and non-plated cushioned footwear in recreational male runners with pronated feet before and after running-induced fatigue. Compared with non-plated footwear, carbon-plated footwear was associated with higher push-off EMG-MNF in the VM, VL, and BF. Fatigue was associated with increases in ST and BF MNF, while a significant footwear-by-fatigue interaction was observed only for the MG, indicating different post-fatigue spectral responses between footwear conditions.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Ethics Committee of University of Mohaghegh Ardabili, Ardabil, Iran (Code: IR.UMA.REC.1401.081). All procedures involving human participants complied with institutional ethical standards and the 1964 Declaration of Helsinki and its subsequent amendments.

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Authors' contributions

Conceptualization, methodology, supervision, review and editing: Mohsen Barghamadi; Data curation, formal analysis, investigation, writing, original draft: Ladan Barzegarfar and Ebrahim Piri.

Conflict of interest

The authors declared no conflicts of interest.

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