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Comparison of Lower Limb Biomechanical Responses to Running-Induced Fatigue Between Rearfoot and Non-Rearfoot Strike Male Amateur Marathon Runners

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Abstract

Purpose: The purpose of this study was to investigate the effects of foot strike patterns and running-induced fatigue on the biomechanical responses of the knee and ankle joints in amateur marathon runners by analyzing the combined effects of these two factors on lower limb joint kinematics, kinetics, and muscle activation characteristics under different conditions. **Methods:** A total of 26 participants were recruited.13 male amateur marathon runners with habitual non-rearfoot strike and 13 with rearfoot strike patterns underwent mild, moderate, and severe running-induced fatigue interventions. Kinematic, ground reaction force, and electromyographic data were collected. A two-way analysis of variance was performed in SPSS for statistical analysis. **Results:** Fatigue level significantly affected knee joint range of motion ($p = 0.023$), peak joint moment ($p = 0.003$), and joint stiffness ($p = 0.040$). The non-rearfoot strike runners exhibited significantly greater ankle joint range of motion ($p < 0.001$), and lower peak joint moments ($p < 0.001$) compared to rearfoot strike runners. A significant interaction effect between fatigue and foot strike pattern was observed on the Root Mean Square amplitude of the medial gastrocnemius ($p = 0.017$) and biceps femoris ($p = 0.021$). **Conclusion:** A significant interaction effect between fatigue and foot strike patterns was observed in Root Mean Square. Given the impact of localized muscle fatigue on joint kinematics and kinetics, the non-rearfoot strike runners may demonstrate intense fatigue-related biomechanical alterations to the knee and ankle joints during the latter stages of long-distance running. These results suggest that understanding foot strike biomechanics under fatigue may inform training and injury prevention.

Keywords: Marathon, Foot strike pattern, Running-induced fatigue, Amateur runners, Lower Limb.

1 Introduction

In recent years, marathon running has experienced rapid global growth, with an increasing number of amateur runners actively participating in marathon training and competitions [38].

Although long-distance running can effectively improve cardiopulmonary function and physical fitness [12], it has also become a major contributing factor to musculoskeletal fatigue accumulation in the lower limbs, due to prolonged and high-intensity repetitive impact loading [9]. The average incidence of running-related musculoskeletal injuries has been reported to be 40.2%, with the knee and ankle identified as the most affected anatomical sites [21]. In the absence of professional guidance and biomechanical optimization the risk of running-related injuries (RRI) is significantly increased among amateur runners [32].

The foot strike pattern, in the context of running, has been identified as a key factor influencing lower limb shock absorption and load transmission. Studies have demonstrated significant differences in lower limb kinematic and kinetic characteristics between rearfoot strike (RFS) and non-rearfoot strike (NRFS) running patterns [40]. Runners habituated to RFS experience higher peak vertical ground reaction forces [25]. These high-load impact forces are rapidly transmitted through the lower limbs, constituting an important biomechanical mechanism that effects the risk of tibial stress fractures and plantar fasciitis [4],[28],[30]. Runners habituated to NRFS experience relatively lower impact loads upon initial ground contact; however, this process places greater functional demands on the ankle joint and calf muscles [23],[24]. These biomechanical differences suggest that varying foot strike patterns may exert distinct effects on joint loading.

Although biomechanical studies suggest potential benefits of NRFS running, epidemiological research has shown no significant difference in injury risk between the two patterns [1]. A potential contributing factor to this discrepancy may be running-induced fatigue (RIF). The onset of RIF not only weakens neuromuscular control and proprioception [27] but also alters joint movement patterns and compensatory mechanisms during running, this may increase the load on passive structures such as ligaments and cartilage [22]. RIF particularly affects the gastrocnemius, quadriceps, and hamstrings, and the functional decline of these muscles under fatigued conditions can lead to abnormal loading of the knee and ankle joints, thereby impacting the lower limb biomechanical responses [31]. Therefore, considering the dependence of NRFS on ankle function, running fatigue may interact with strike pattern, offsetting the biomechanical advantages of NRFS and resulting in no significant difference in injury risk between different running postures.

Some studies have supported the hypothesis that the biomechanical advantages of NRFS patterns are offset by RIF. It has been found that, under fatigued conditions, runners with NRFS patterns and high training volumes exhibit significantly smaller changes in ankle plantar flexion and hip external rotation moments compared to those with moderate training volumes [39]. Evidence has also shown that forefoot strike runners are able to maintain performance by compensating for decreased gastrocnemius activation through increased activation of the biceps femoris [19], indirectly indicating a significant decline in ankle joint function under fatigue in NRFS runners. A follow-up study on amateur competitive runners after completing a 12-kilometer race revealed that the relative pressure on the left foot decreased by 3.2%, while postural balance and plantar flexion strength were significantly reduced [29]. These fatigue-related biomechanical changes may exacerbate abnormal lower limb joint loading. Previous studies have investigated the independent effects of specific foot strike patterns and RIF on lower limb joint loading [26],[33], but mechanistic investigations into their combined effects remain limited, particularly due to the lack of systematic data in amateur runner populations. This research gap limits our understanding of the combined effects of injury risk factors; therefore, it is of significant scientific value and practical importance to investigate the combined effects of foot strike patterns and running fatigue on the kinematics, kinetics, and muscle activation characteristics of the lower limb joints in amateur marathon runners.

The purpose of this study was to investigate the effects of foot strike patterns and RIF on the biomechanical responses of the knee and ankle joints in amateur marathon runners by analyzing the combined effects of these two factors on lower limb joint kinematics, kinetics, and muscle activation characteristics under different conditions. It is hypothesized that, with increasing levels of fatigue, adaptive changes in lower limb muscle activation will occur to maintain locomotor function, and that runners with NRFS patterns will exhibit greater declines in peak knee moment compared to RFS runners.

2 Materials and Methods

2.1 Participants

A total of 26 male amateur marathon runners were recruited for this study, including 13 habitual RFS and 13 habitual NRFS. The inclusion criteria were a minimum of 2 years of long-distance running experience, right-leg dominance, a weekly running volume of no less than 40 km, a personal best half marathon time within 1 hour and 55 minutes (https://www.runchina.org.cn), and no lower limb injuries within the past 6 months. The participants' baseline characteristics are presented in Table 1. Results of the paired sample t-test indicated that there were no statistically significant differences between the two groups ($p > 0.05$). The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Ningbo University (TY20250210). All participants were informed of the experimental procedures and voluntarily signed an informed consent form prior to participation.

Table 1. Basic characteristics of the participants

Index	RFS(n=13)	NRFS(n=13)	P
Age (years)	23.1(2.75)	24.4(2.42)	0.888
Height (cm)	173.5(4.39)	174.4(4.70)	0.688
Body mass (kg)	64.3(5.92)	66.1(5.35)	0.728
BMI (kg·m^{-2})	20.3(1.58)	21.8(1.98)	0.786
Running experience (years)	4.1(1.73)	4.0(1.58)	0.603
Weekly mileage (km)	61.0(17.40)	62.7(16.9)	0.826
Half marathon PB (min)	92.1(12.18)	90.5(11.05)	0.798

RFS: Rear-foot strikers; NRFS: Non-rearfoot strikers; BMI: Body Mass Index; PB: Personal Best.

2.2 Experimental protocol

The experiment was conducted in a biomechanics laboratory, and the experimental setup and protocol illustrated in Figure 1. During the experiment, participants remained shirtless and wore standardized tight-fitting shorts and carbon-plated running shoes (C202 6th Generation, ANTA Sports, Jinjiang, China). Before each trial, participants performed a 10-minute self-paced warm-up run on a treadmill, followed by the researchers' preparation procedures, which included skin preparation on the dominant lower limb (removal of leg hair and cleaning of superficial debris with alcohol wipes), and the placement of wireless surface electromyography (sEMG) sensors. Using ultrasound imaging(Mindray M7, Mindray Bio-Medical Electronics Co., Shenzhen, China), the muscle bellies of the rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), medial gastrocnemius (MG), and lateral gastrocnemius (LG) were identified, and the electrodes were attached along the direction of the muscle fibers (Delsys, Natick, MA, United States). 38 spherical reflective markers, each 10 mm in diameter, were attached to bony landmarks according to previous established protocol [5],[14],[35]. The placement of the reflective markers and EMG electrodes is shown in Figure 1(A).

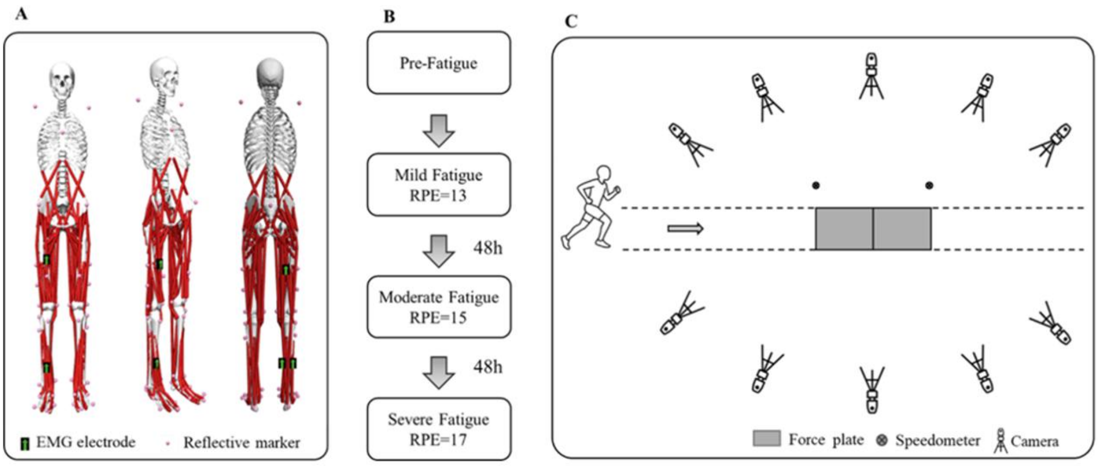

Figure 1. Experimental setup and protocol overview. (A) Schematic diagram of reflective marker and EMG electrode placement. (B) Flowchart of the fatigue intervention protocol. PRE indicates baseline data collection before fatigue; MF refers to the mild fatigue intervention; MOF represents the moderate fatigue intervention; and SF denotes the severe fatigue intervention. (C) Schematic representation of the laboratory setup.

Three treadmill-based fatigue interventions were conducted on a treadmill (h/p/cosmos, Nussdorf-Traunstein, Germany), following a protocol adapted from previous research [16]. To simulate air resistance during outdoor running, the treadmill incline was set to 1°. Participants began running at 6 km/h, with the speed increased by 1 km/h every 2 minutes. Throughout the fatigue intervention, the Borg Rating of Perceived Exertion (RPE) Scale was used to assess perceived exertion [3], with participants asked to report their RPE every minute. Fatigue levels were classified based on Borg scale scores: an RPE of 13 indicated Mild Fatigue (MF), 15 denoted Moderate Fatigue (MOF), and 17 corresponded to Severe Fatigue (SF). Once an RPE of 13 was reached, the speed was maintained as the steady-state pace, and participants continued running until the target fatigue level was achieved, followed by a 2-minute countdown to conclude the intervention. Participants visited the laboratory 3 times, with each session involving MF, MOF, and SF interventions in sequence. Data was collected after each trial, with three valid datasets obtained under each fatigue condition for analysis, and a washout period of no less than 48 hours was enforced between sessions. Total running distance was monitored using the treadmill's built-in distance measurement function and recorded upon completion of each intervention.

2.3 Data collection

The sequence of data collection and the laboratory environment schematic are depicted in Figure 1(B) and Figure 1(C), respectively. Baseline data were collected prior to the first fatigue intervention.

Prior to dynamic data collection, participants stood at the center of the experimental environment to get static standing data. Subsequently, participants ran naturally at a comfortable pace and with their habitual running style along an 18-meter indoor track. At the same time, a photoelectric gate measured the speed as participants passed over the force plate. A 3D motion capture system with 10 cameras (Vicon Metrics Ltd., Oxford, United Kingdom) recorded kinematic data at a frequency of 200 Hz. 2 force plates (Kistler, Winterthur, Switzerland) collected ground reaction forces (GRF) during the running support phase at a frequency of 2000 Hz. Delsys wireless sEMG equipment recorded muscle activity signals at a frequency of 2000 Hz. A valid data collection was defined as when the participant naturally ran along the track, with their right foot fully landing on a force plate and no reflective markers or EMG electrodes falling off. 3 valid data sets were collected for each condition.

2.4 Data analysis

Data from the dominant leg was analyzed. Vicon Nexus (version 2.15.0 x64, Vicon Motion Systems, Oxford, UK) was used to extract the running stance phase, with a GRF threshold of

10 N, generating c3d files. Custom-written MATLAB (R2022a, The MathWorks Inc., Natick, MA, USA) code was employed to export marker trajectory files, ground reaction force files, and EMG signal files from the c3d files.

Kinematic and kinetic analyses: Model was scaled in OpenSim 4.3 (SimTK, Stanford University, CA, USA) using static trial data. Inverse kinematics tools in OpenSim were used to estimate sagittal plane kinematics of the knee and ankle joints, while inverse dynamics tools, incorporating kinematics data (filtered using OpenSim's built-in 4th-order Butterworth low-pass filter with a 6 Hz cutoff frequency) and GRF, were employed to obtain sagittal plane kinetics [6],[34],[36]. Custom Python scripts were developed to normalize the kinetic data by participant body weight. Joint stiffness (k_{joint})was defined as the ratio of change in joint moment (ΔM) to change in joint angle (Δθ) during the stance phase. Joint stiffness was calculated using the following formula [15]:

$$k_{joint} = \frac{\Delta M}{\Delta \theta} \tag{1}$$

EMG signal: Custom Python scripts were developed to preprocess raw EMG signals. First, a high-pass filter with a cutoff frequency of 20 Hz was applied to remove Direct Current offset, followed by a 4th-order Butterworth band-pass filter (20-450 Hz) to eliminate low-frequency motion artifacts and high-frequency noise. The filtered EMG signals were then full-wave rectified and normalized to the maximum amplitude value across all channels under each experimental condition. This normalization method focuses on capturing the within-muscle changes across different experimental conditions. To evaluate muscle activation intensity, root mean square (RMS) values were calculated [7]. The RMS was computed using the following equation:

$$RMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[x_k]^2 \; k = 1, 2 \ldots\ldots, N} \tag{2}$$

N: number of samples; x_k: the k-sample

2.5 Statistical Analysis

Data analysis was conducted using IBM SPSS Statistics 26 (Version 26.0, IBM Corp., Armonk, New York, United States). All continuous variables are expressed as mean ± standard deviation (SD). First, the normality of the dependent variables was assessed using the Shapiro-Wilk test. For data that followed a normal distribution, a two-way repeated measures ANOVA was conducted to assess the main effects and interactions of foot strike pattern (2 levels) × fatigue level (4 levels). Mauchly's test was used to assess the sphericity assumption, and if violated, the Greenhouse-Geisser correction was applied. If the interaction was significant, simple effects analysis was performed, followed by pairwise comparisons with Bonferroni correction. The statistical significance threshold was set at $p < 0.05$, and partial η^2 was reported to quantify effect size.

3 Results

3.1 Running-related parameters

As shown in Table 2, statistical analysis revealed a significant increase in running distance with increasing fatigue levels ($p < 0.001$, $\eta^2 = 0.878$), as well as a significant increase in running duration ($p < 0.001$, $\eta^2 = 0.999$). During the intervention, foot strike pattern did not exhibit a significant main effect on either running distance or running duration. Neither foot strike pattern, fatigue level, nor their interaction had a significant main effect on post-fatigue running speed ($p > 0.05$). Under the eight experimental conditions, running speed did not show significant changes, thereby ruling out the influence of speed on the significance of kinematic and kinetic outcomes.

Table 2. Mean (SD) of distance results from the running fatigue intervention and speed under experimental conditions

	RFS				NRFS				Statistical indices		
	PRE	MF	MOF	SF	PRE	MF	MOF	SF	Foot strike	Fatigue level	Interaction
Running distance (km)	/	4.45 (0.63)	5.72 (0.85)	6.97 (1.28)	/	4.02 (0.78)	5.92 (0.91)	7.94 (1.04)	p=0.442; η^2=0.025	p<0.001; η^2=0.878	p=0.006; η^2=0.254
Running duration (min)	/	22.28(2.65)	28.75(2.72)	36.75 (2.09)	/	23.31(3.63)	28.53 (2.11)	37.40(3.73)	p=0.110; η^2=0.162	p<0.001; η^2=0.999	p<0.001; η^2=0.723
Speed(km/h)	14.92 (1.05)	15.63 (1.00)	15.39 (1.01)	15.13 (1.74)	15.97 (1.80)	16.68 (2.02)	16.36 (1.46)	16.18 (2.32)	p=0.770; η^2=0.124	p=0.069; η^2=0.110	p=0.981; η^2=0.000

RFS: Rear-foot strikers; NRFS: Non-rearfoot strikers; PRE: Pre-Fatigue; MF: Mild Fatigue; MOF: Moderate Fatigue; SF: Severe Fatigue.

3.2 Kinematics and Kinetics

As shown in Table 3, the statistical analysis of knee and ankle joint range of motion (ROM), peak joint moment, and joint stiffness was conducted. Fatigue level showed significant main effects on knee joint ROM ($p = 0.023$, $\eta^2 = 0.123$), peak knee joint moment ($p = 0.003$, $\eta^2 = 0.178$), and knee joint stiffness ($p = 0.040$, $\eta^2 = 0.135$). Post hoc comparisons with Bonferroni correction revealed that, in both RNS and NRFS groups, knee joint ROM significantly increased at the MF compared to the PRE ($p = 0.025$, 95% CI [0.147, 3.057]), and the peak knee joint moment in the MF was significantly greater than in the MOF ($p = 0.004$, 95% CI [0.084, 0.539]). No significant differences in knee joint stiffness were found among the different fatigue levels ($p > 0.05$). Neither foot strike pattern nor its interaction with fatigue showed significant effects on knee joint ROM, peak joint moment, or joint stiffness.

A significant main effect of foot strike pattern was found on ankle joint ROM ($p < 0.001$, $\eta^2 = 0.677$) and peak ankle joint moment ($p < 0.001$, $\eta^2 = 0.721$). Post hoc comparisons with Bonferroni correction revealed that ankle joint ROM in the NRFS group was significantly higher than that in the RFS group ($p < 0.001$, 95% CI [10.379, 18.900]). Additionally, the peak ankle joint moment in the NRFS group was significantly lower than that in the RFS group ($p < 0.001$, 95% CI [1.270, 0.742]). A significant main effect of fatigue level was observed on ankle joint stiffness ($p = 0.007$, $\eta^2 = 0.154$). In both RFS and NRFS groups, ankle joint stiffness at the MF was significantly greater than that at the SF ($p = 0.043$, 95% CI [0.006, 0.026]). No significant interaction effects were found for ankle joint ROM, peak joint moment, or joint stiffness.

Table 3. Statistical analysis results of kinematic and kinetic parameters of the knee and ankle joints under eight experimental conditions

	RFS				NRFS				Statistical indices		
Variables	PRE	MF	MOF	SF	PRE	MF	MOF	SF	Foot strike	Fatigue level	Interaction
Knee ROM (°)	24.67 (2.44)	26.79 (3.25)	26.32 (2.04)	26.21 (3.29)	25.23 (5.75)	26.32 (4.83)	26.69 (5.25)	25.86 (3.08)	$p=0.984$; $\eta^2=0.000$	***p=0.023;*** $\eta^2=0.123$	$p=0.747$; $\eta^2=0.016$
Peak Knee Moment (Nm/kg)	2.87 (0.76)	2.99 (0.83)	2.77 (0.95)	2.78 (0.72)	2.74 (0.71)	2.83 (0.71)	2.43 (0.98)	2.44 (0.73)	$p=0.407$; $\eta^2=0.029$	***p=0.003;*** $\eta^2=0.178$	$p=0.549$; $\eta^2=0.029$

Knee Joint Stiffness (Nm/kg/°)	0.13 (0.01)	0.12 (0.02)	0.12 (0.02)	0.12 (0.02)	0.11 (0.01)	0.13 (0.03)	0.11 (0.02)	0.11 (0.02)	p=0.466; η²=0.022	***p=0.040;*** η²=0.135	p=0.147; η²=0.072
Ankle ROM (°)	23.14 (4.56)	27.88 (8.99)	23.63 (5.54)	25.22 (4.20)	38.93 (7.36)	39.70 (7.61)	40.08 (9.19)	39.71 (3.68)	***p<0.001;*** η²=0.677	p=0.218; η²=0.059	p=0.325; η²=0.047
Peak Ankle Moment(N/kg)	-3.02 (0.37)	-2.83 (0.43)	-2.74 (0.38)	-2.93 (0.53)	-3.91 (0.42)	-3.91 (0.37)	-3.77 (0.42)	-3.94 (0.42)	***p<0.001;*** η²=0.721	p=0.097; η²=0.088	p=0.711; η²=0.017
Ankle Joint Stiffness (Nm/kg/°)	0.13 (0.03)	0.11 (0.03)	0.13 (0.02)	0.11 (0.01)	0.10 (0.03)	0.10 (0.02)	0.10 (0.03)	0.09 (0.01)	p=0.060; η²=0.140	***p=0.007;*** η²=0.154	p=0.719; η²=0.018

RFS: Rear-foot strikers; NRFS: Non-rearfoot strikers; PRE: Pre-Fatigue; MF: Mild Fatigue; MOF: Moderate Fatigue; SF: Severe Fatigue. Bold italics indicate statistical significance.

3.3 RMS of the EMG

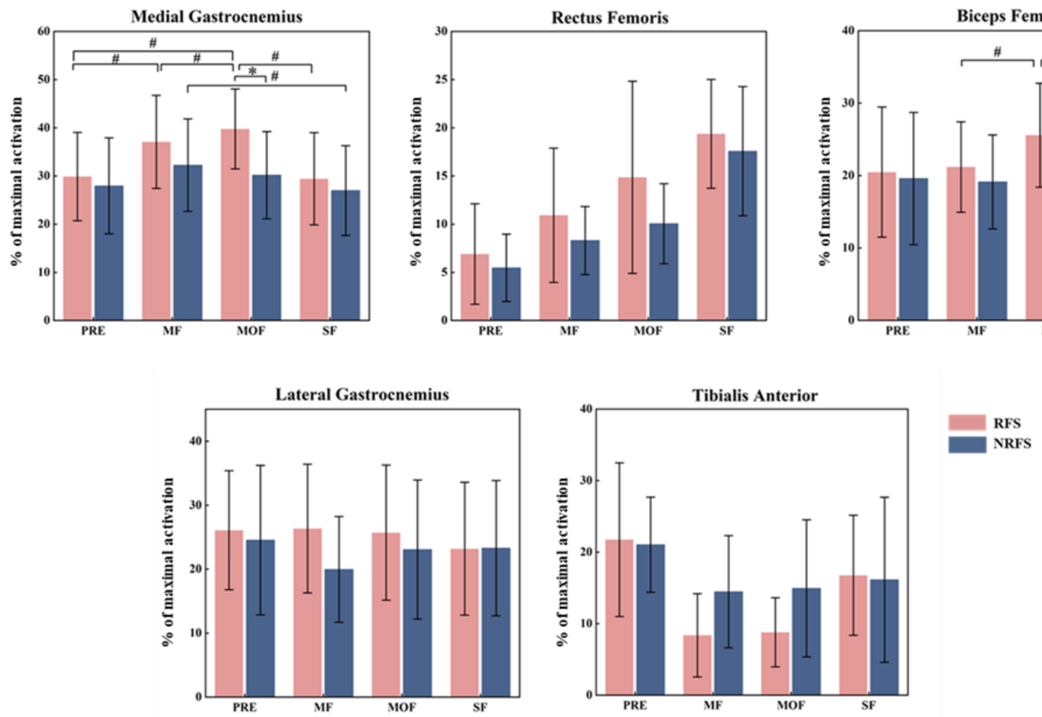

Figure 2. Bar chart of RMS values of lower limb EMG signal. * indicates a significant main effect of foot strike pattern; # indicates a significant main effect of fatigue level. RFS: Rear-foot strikers; NRFS: Non-rearfoot strikers; PRE: Pre-Fatigue; MF: Mild Fatigue; MOF: Moderate Fatigue; SF: Severe Fatigue.

Figure 2 presents the statistical results of RMS for the MG, LG, TA, RF, and BF. No significant main effects of foot strike pattern were observed for any of the muscles, including MG ($p = 0.187$, $\eta^2 = 0.071$), LG ($p = 0.507$, $\eta^2 = 0.019$), TA ($p = 0.228$, $\eta^2 = 0.060$), RF ($p = 0.130$, $\eta^2 = 0.093$), and BF ($p = 0.090$, $\eta^2 = 0.115$).

No significant main effects of fatigue level were found for LG ($p = 0.290$, $\eta^2 = 0.050$) and BF ($p = 0.537$, $\eta^2 = 0.024$). However, significant main effects of fatigue level were observed for MG ($p < 0.001$, $\eta^2 = 0.393$), TA ($p < 0.001$, $\eta^2 = 0.278$), and RF ($p < 0.001$, $\eta^2 = 0.365$). Post hoc comparisons with Bonferroni correction revealed that the RMS of MG was significantly lower in the PRE compared to MF ($p = 0.004$, 95% CI [1.512, 9.994]) and MOF ($p < 0.001$, 95% CI [2.822, 9.270]), while it was also significantly lower in SF than in MF ($p < 0.001$, 95% CI [3.117, 9.815]) and MOF ($p < 0.001$, 95% CI [3.012, 10.506]). For TA, significant differences in RMS were found between PRE and MF ($p < 0.001$, 95% CI [5.309, 14.643]) and between PRE and MOF ($p = 0.001$, 95% CI [3.681, 15.387]), with RMS significantly lower in both fatigues compared to PRE. Regarding RF, the RMS was significantly lower in PRE than in MOF ($p = 0.041$, 95% CI [0.175, 12.375]) and SF ($p < 0.001$, 95% CI [8.211, 16.371]), and significantly lower in MF compared to SF ($p < 0.001$, 95% CI [4.516, 13.200]).

There were no significant interaction effects between foot strike pattern and fatigue level for the RMS of LG ($p = 0.107$, $\eta^2 = 0.087$), TA ($p = 0.190$, $\eta^2 = 0.064$), and RF ($p = 0.831$, $\eta^2 = 0.012$). However, there were significant interaction effects for MG ($p = 0.017$, $\eta^2 = 0.131$) and BF ($p = 0.021$, $\eta^2 = 0.146$). Post hoc comparisons with Bonferroni correction revealed that, at the MOF fatigue level, NRFS runners exhibited significantly higher RMS of MG compared to RFS ($p = 0.012$, 95% CI [2.289, 16.907]). Among NRFS runners, MG RMS in the PRE was significantly lower than in both MF ($p = 0.012$, 95% CI [1.214, 13.210]) and MOF ($p < 0.001$, 95% CI [5.321, 14.439]). Furthermore, RMS of MG in MF ($p = 0.001$, 95% CI [2.929, 12.403]) and MOF ($p < 0.001$, 95% CI [5.034, 15.633]) were significantly higher than those in SF. In RFS runners, MG at MF was significantly higher than at SF ($p = 0.023$, 95% CI [0.529, 10.003]). For BF, RMS at the MOF level were significantly higher in NRFS runners than in RFS runners ($p = 0.007$, 95% CI [2.441, 14.191]). Additionally, among NRFS runners, BF RMS at MF was significantly lower than at MOF ($p = 0.009$, 95% CI [0.885, 7.886]).

4 Discussion

This study aimed to investigate the interactive effects of foot strike pattern and fatigue level on lower limb biomechanical responses, specifically by analyzing the changes in lower limb biomechanics and muscle activation characteristics of amateur marathon runners with habitual NRFS and RFS patterns under 4 fatigue conditions: non-fatigued, MF, MOF, and SF. The main findings revealed that fatigue significantly affected knee joint ROM ($p = 0.023$), peak moment ($p = 0.003$), and joint stiffness ($p = 0.040$), and induced adaptive changes in the muscle activation intensity of the MG, TA, and RF. Compared to RFS runners, NRFS runners exhibited significantly greater ankle ROM ($p < 0.001$) and reduced peak ankle moment ($p < 0.001$). A significant interaction between fatigue and foot strike pattern was observed for the RMS of MG ($p = 0.017$) and BF ($p = 0.021$), with post hoc analysis showing that NRFS runners had significantly higher MG and BF RMS than RFS runners at the MOF fatigue level. These findings suggest that runners with different habitual foot strike patterns exhibit distinct biomechanical adaptations under specific fatigue conditions.

The results of this study regarding the effects of RIF on the participants are consistent with previous research. Johannsen suggested that long-distance running induces relaxation of the knee joint in the sagittal plane [20]. This study further found that, under three different fatigue conditions, both NRFS and RFS runners exhibited a significant increase in knee joint ROM compared to PRE levels. Notably, the effect of increasing fatigue on peak knee joint moment follows a nonlinear decay pattern, and peak knee joint moment is highest during the MF compared to the other three fatigue conditions. This may be due to the activation compensation state of the muscles during MF, where the muscles temporarily enhance output to maintain performance [13]. Under the MF condition, runners with RFS patterns exhibited relatively higher activation in the LG, whereas runners with NRFS patterns showed relatively higher activation in the MG and BF. However, as fatigue deepened, LG activation in RFS runners gradually decreased, and BF activation in NRFS runners progressively declined, whereas RF activation increased in both foot strike patterns. Muscle function progressively deteriorated, leading to diminished moment compensation ability and reduced joint shock absorption capacity [10],[11]. Foot strike pattern primarily has a significant impact on ankle joint movement patterns, with NRFS runners exhibiting a 58.60% increase in ankle joint ROM compared to RFS. This result is further supported by the significant reduction in peak ankle joint moment for NRFS runners ($p<0.001$). The occurrence of this phenomenon may be attributed to the NRFS pattern, which increases the ankle joint's range of dorsiflexion and plantarflexion, thereby more effectively absorbing shock, thereby reducing the instantaneous load on the joint; however, this characteristic may increase the risk of repetitive strain on the plantar fascia [8]. In this experiment, an increase in running fatigue did not significantly alter knee joint stiffness, which may be due to the reliance of knee joint stability on the dynamic regulation mechanisms of soft tissues during the fatigued phase [2],[17]. Ankle joint stiffness in the MF was significantly greater than in the SF, which may be attributed to the body's compensation for the reduced control capacity caused by fatigue through joint stability. However, as fatigue increases, this compensatory mechanism gradually fails, leading to a reduction in joint stiffness, which may increase ankle joint instability during the stance phase [18]. Contrary to the hypothesis of this study, we did not observe significant interactive effects of foot strike pattern and running fatigue on lower limb kinematics and dynamics in runners, which may be since, under the fatigue reached in this experiment, amateur marathon runners still possessed sufficient functional redundancy to maintain their physical activity.

Although no significant differences were observed in external performance between the two foot strike patterns with increasing fatigue, notable changes were observed in the sEMG signals. The EMG results indicated that the RMS of the MG was significantly higher in the MF and MOF compared to PRE but decreased in the SF. This may be due to neural compensation maintaining muscle activation during the MF and MOF, whereas metabolic fatigue dominated in the SF, leading to a significant reduction in the RMS of the MG. The results indicate that the RMS of the RF continuously increased with fatigue progression. As the primary extensor of the knee joint, the RF recruits more high-threshold motor units and increases firing frequency to maintain extension force as fatigue intensifies. Additionally, knee joint stiffness exhibited a decreasing trend with deepening fatigue [37]. It is noteworthy that there is a significant interaction effect between fatigue and landing pattern on the sEMG signals of the MG and BF.

In the MOF, NRFS runners exhibited higher MG activation intensity compared to the RFS group, and MG activation followed a trend of initially increasing and then decreasing with increasing fatigue. This suggests that NRFS runners maintain joint stability by increasing calf muscle force during the MOF, but the compensatory capacity of the muscles is exhausted during the SF. Additionally, NRFS runners exhibited higher BF activation in the MOF compared to the RFS group, suggesting that they limit excessive joint movement by increasing the force of the hamstring group, but this may increase muscle load. These results indicate that NRFS runners are more prone to localized muscle fatigue compared to RFS runners. Furthermore, in the SF, no significant difference was observed in RMS between NRFS and RFS runners, suggesting that muscles may be completely fatigued, leading to a decline in athletic performance. Given the high demand for the MG and BF in NRFS runners [24], the NRFS runners may exhibit a greater extent of lower limb biomechanical responses under fatigued conditions.

This study has several limitations. First, the participants in this study were amateur male marathon runners, and the diversity of gender and athletic levels was not addressed, which limits the generalizability and applicability of the study's conclusions. Second, although the fatigue intervention process was conducted in a controlled laboratory environment, it was difficult to fully replicate the complex fatigue responses induced by the combined effects of psychological, physiological, and environmental factors in an outdoor running setting, which may limit the external validity of the findings when applied to real-world long-distance running scenarios. Finally, this study only analyzed lower limb biomechanics in the sagittal plane and did not include an analysis of multi-plane kinematics, and the use of this EMG normalization method may result in the loss of information regarding the relative force contribution of each muscle. Future studies could expand the sample size to include female runners and athletes with varying training levels (e.g., beginners, elite athletes) to enhance the generalizability of the results. Additionally, the fatigue intervention could be conducted on outdoor marathon routes or training settings to increase the practical applicability of the results. Finally, future research could broaden the scope of analysis by incorporating three-dimensional joint motion and plantar pressure data, as well as adopting a more comprehensive EMG normalization approach, enabling a more in-depth investigation of the mechanisms through which foot strike patterns and fatigue affect lower limb function.

5 Conclusions

In this experiment, significant main effects were observed for both foot strike pattern and fatigue level on lower limb kinematic and kinetic parameters. Foot strike pattern significantly affected ankle joint ROM, with NRFS runners showing greater mobility than RFS, while fatigue was primarily evident in changes to knee joint ROM, peak moment, and joint stiffness before and after fatigue. However, a significant interaction effect between fatigue and foot strike patterns was observed in the EMG signals, with significant differences in MG and BF muscle activation between the foot strike patterns in the MOF, indicating that different foot strike patterns lead to varying degrees of local muscle fatigue. Given the impact of localized muscle fatigue on joint kinematics and kinetics, NRFS runners may demonstrate intense fatigue-related biomechanical alterations to the knee and ankle joints during the latter stages of long-distance running. These results further reflect the complex effects of foot strike patterns and fatigue levels on lower limb kinematics and kinetics.

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