Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Effects of Physical Fatigue on Muscle Activities and Running Kinetics in Individuals with both Obesity and Pronated Feet

**Ehsan Fakhri Mirzanagh**
University of Mohaghegh Ardabili
**AmirAli Jafarnezhadgero**
amiralijafarnezhad@gmail.com
University of Mohaghegh Ardabili
**Mahrokh Dehghani**
University of Mohaghegh Ardabili
**Farhad Rezazadeh**
University of Mohaghegh Ardabili
**Elif Aydin**
Ardahan University
**Heidar Sajedi**
Düzce Üniversitesi
**Valdeci Carlos Dionisio**
Universidade Federal de Uberlândia

**Research Article**

**Keywords:** Obesity, Muscle activity, Ground reaction force, Fatigue

**Posted Date:** September 22nd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-10936704/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

**Additional Declarations:** No competing interests reported.

## Abstract

# Background and Purpose

Despite the known changes in ground reaction forces (GRFs) components in individuals with overweight and obesity, the effects of running-induced fatigue on GRFs and lower-limb electromyographic (EMG) activity remain unclear. This study aimed to investigate the impact of running-related fatigue on GRF components and lower-limb muscle activity in individuals with obesity and pronated feet during running.

# Methods

Thirty-one male participants were divided into two groups: a normal weight/normal foot group (body mass index [BMI] < 25 kg/m²; navicular drop: 4–10 mm) and an obesity/pronated foot group (BMI ≥ 30 kg/m²; navicular drop > 10 mm). Participants ran barefoot along an 18-m runway at a controlled speed of 3.3 m/s (± 5%) before and after completing a fatigue protocol. GRF components were collected using a force plate, and EMG activity of selected lower-limb muscles was recorded using a surface electromyography system.

# Results

Following fatigue, several GRF components increased significantly in both groups. Overall muscle activity decreased after fatigue; however, gluteus medius activity during the early stance phase was significantly affected (P = 0.004, d = 1.161). Specifically, gluteus medius activity increased in the normal weight/normal foot group but did not increase in the obesity/pronated foot group (P = 0.001, d = 0.959).

# Interpretation:

These findings suggest that running-related fatigue increases GRF components and reduces lower-limb muscle activity. Importantly, individuals with obesity and pronated feet exhibit insufficient compensatory increases in gluteus medius activity during fatigue, which may compromise pelvic stability and increase the risk of running-related musculoskeletal injury.

## Key Points

- Several GRF components increased significantly in both groups.
- Pairwise analysis indicated that LR was significantly greater following the fatigue protocol in the normal weight/normal foot group, but not in the obesity/pronated foot group.
- Paired comparisons showed decreased activity in TA, VL, AL, and ST after fatigue, with an increase in
- GL-M activity post-fatigue during the early stance phace.

## 1. Introduction

Running is widely recommended as an effective and accessible physical activity for weight loss [1] and the prevention of chronic diseases [2]. Because of its high energy expenditure, running is often chosen by individuals seeking to reduce body mass and improve cardiometabolic health [1, 2]. However, for people with overweight or obese, running also poses significant biomechanical challenges that may increase the risk of musculoskeletal injuries, especially in the lower limbs, and can negatively affect locomotion and quality of life [3, 4].

During running, the musculoskeletal system endures repeated high-impact loads, which can be intensified in those with excess body weight. The foot is crucial for movement, offering support, reducing impact and rotational forces, providing sensory feedback, and balancing flexibility with stability for forward motion [5]. However, foot problems are among the most common musculoskeletal issues in adults with obesity, likely due to increased mechanical stress from excess body mass [6]. A common biomechanical change in people with obesity is excessive foot pronation, which manifests as progressive distortion. Excess body weight causes greater subtalar joint eversion and collapse of the medial longitudinal arch. Long-term overpronation can cause cumulative stress throughout the kinetic chain, potentially leading to foot and ankle pain, as well as secondary issues in the knee and lower back [7].

When combined with running, excessive pronation can further change how loads and ground reaction forces (GRF) are distributed, raising the risk of overuse injuries. Gait and running biomechanics differ significantly between adults with obesity or overweight and those with a normal weight. Studies indicate that adults with obesity exhibit reduced knee flexion and hip extension moments at initial contact, while showing higher hip flexion moments during late stance than normal-weight individuals [8]. Moreover, those with overweight [9] and obesity [10] exhibit increased medio-lateral GRF components, which may act as biomechanical precursors to lower-limb injuries [9]. Recent research has expanded these insights into running biomechanics, showing specific kinetic adaptations among individuals with overweight and obesity. These individuals tend to produce lower peak vertical impact forces, reach peak impact more quickly, experience reduced vertical loading rates, and generate lower braking and propulsion forces. They also show decreased medio-lateral loading rates and increased free moments compared to normal-weight runners [11].

However, biomechanical adjustments can be substantially affected by fatigue, a common and unavoidable aspect of running. Fatigue is acknowledged as a significant risk factor for musculoskeletal injuries because it weakens movement control and neuromuscular function [12]. Running-related fatigue leads to higher muscle activation levels, likely indicating increased motor unit recruitment and firing rates [13]. Although this compensatory mechanism supports performance, it can also degrade proprioception and joint stability, raising the likelihood of injury [14].

Individuals with obesity frequently experience higher fatigue and reduced motor performance compared to those of normal weight. For instance, they exhibit greater quadriceps fatigability during voluntary contractions, even though electrically elicited fatigue levels are similar, indicating central rather than peripheral causes [15]. However, how obesity affects running-induced fatigue remains poorly understood.

This study aimed to explore how running-related fatigue influences ground reaction force components and lower-limb muscle activity in people with obesity and pronated feet. Gaining insights into these interactions could help improve injury prevention strategies and lead to safer exercise guidelines for this group.

## 2. Methods

# 2.1. Participants

This study is both experimental and descriptive. It received ethical approval from the ethics committee of the University of Mohaghegh Ardabili (IR.UMA.REC.1403.062). Before starting, researchers explained the benefits and potential risks of participation, and all participants gave written informed consent. Data access was granted for research purposes on 2024-12-20. The authors did not have access to identifiable participant information during or after data collection. The study followed the Declaration of Helsinki.

Prior to recruiting volunteers, a sample size calculation was performed using previous data (e.g., peak vertical GRF) [16, 17] and G-Power 3 software (University of Kiel, Germany). This indicated that 15 participants per group were needed to achieve 80% statistical power at a 0.05 significance level. Thirty-one sedentary young adult males, aged 18 to 35, were divided into two groups (see Table 1). The first group (NN) comprised 16 individuals with a normal body mass index (20 ≤

BMI < 25 kg/m2) and normal foot posture (navicular drop 4–10 mm, foot posture index 0–6). The second group (OP) included 15 individuals with obesity (BMI ≥ 30 kg/m2) and plantar fasciitis (navicular drop > 10 mm, foot posture index 10–12). Detailed descriptions of the foot posture index are available elsewhere [18, 19]. Participants were recruited from Ardabil city via the internet and social media announcements. Previous research links increased sedentary behavior with overweight/obesity across ages [20, 21]. Therefore, only sedentary individuals were included, defined as walking fewer than 1000 steps daily (tracked via a pedometer app on participants' Exclusion criteria included: 2–3 weekly physical activity sessions; history of trunk or lower limb musculoskeletal surgery; cardiorespiratory, neuromuscular, or orthopedic disorders (except foot pronation in the OP group); and limb length differences over 5 mm.

## 2.2. Anthropometric and navicular drops measurement

Height and weight were measured using standardized clinical procedures across studies. Body mass index was calculated and categorized into normal and obese according to the WHO standards [22]. In this study, waist circumference (WC) was measured following WHO procedures [23]. The waist-to-height ratio (WHtR) was calculated as WC (cm) divided by height (cm), and the waist-to-hip ratio (WHR) was calculated as WC (cm) divided by hip circumference (cm). In this study, a modified navicular drop test, based on Brody's method, was used to assess sagittal plane displacement of the navicular between seated and standing on one leg positions [24]. During testing, participants sat on a chair with both feet on the ground and knees flexed at 90º. The medial aspect of the navicular was marked, and its height was measured with a ruler. The participant then stood on one leg with the opposite knee fixed, a position shown by McPoil and Cornwall to better reflect foot posture during mid-stance in walking [25]. The navicular height was measured again, and the difference between seated and standing measurements was recorded as navicular drop. The foot posture index, comprising six items, was used to quantify and classify foot posture [18, 19]. All participants were heel strikers, as determined by kinetic data.

Table 1
Anthropometric characteristics.

| Group | Normal weight/normal foot group (n = 16) | Obesity /pronated foot group (n = 15) | P-value |
|---|---|---|---|
| Height (m) | 1.77 ± 0.24 | 1.79 ± 0.04 | 0.106 |
| Mass (kg) | 76.94 ± 5.35 | 117.61 ± 16.69 | **< 0.001*** |
| Body mass index ($kg/m^2$) | 23.25 ± 1.41 | 34.69 ± 4.41 | **< 0.001*** |
| Age (year) | 23.40 ± 0.82 | 23.86 ± 0.91 | 0.154 |
| Navicular drop (mm) | 7.33 ± 0.61 | 11.06 ± 0.79 | **< 0.001*** |
| Waist circumference (cm) | 78.50 ± 4.21 | 122.60 ± 14.29 | **< 0.001*** |
| Waist-to-hip ratio (cm) | 0.84 ± 0.04 | 1.11 ± 0.07 | **< 0.001*** |
| Waist-to-height ratio (cm) | 0.44 ± 0.23 | 0.68 ± 0.08 | **< 0.001*** |
| *Significant level P < 0.05 | | | |

## 2.3. Experimental protocol

This study was conducted under two conditions: before and after fatigue. On the day of the test, the protocol began with a warm-up consisting of 4 minutes of dynamic stretching and 5 minutes of jogging. Participants then familiarized themselves with the 18-meter overground walkway, which included a force plate at its center. The task was for participants to run through the walkway in approximately 5.6 seconds, with an average speed of about 3.2 m/s [26], and to step with their dominant foot on the force plate [27]. We allowed several familiarization trials so participants could learn the target running speed and foot placement, with a 10% margin of variability. After familiarization, each participant completed 3 running trials during which ground reaction forces and moments were recorded. Trials were repeated if the participant did not fully place their dominant foot on the force plate, changed their running pattern to hit the plate, or if their running speed was outside 10% of the targeted speed. Participants used their preferred running shoes for the study.

## 2.4. Ground reaction force recording

We recorded three-dimensional ground reaction forces (GRFs) and moments using a Bertec force plate (Model 4060–07, Columbus, OH, United States) sampled at 1000 Hz. Kinetic data were analyzed during the stance phase of running, from ground contact (vertical GRF > 20 N) to toe-off (vertical GRF < 20 N). The data were filtered with a third-order low-pass Butterworth filter at a 50 Hz cutoff frequency. From the running data [23], we extracted the first vertical impact peak (FzHC), the braking force (FyHC), and the propulsion force (FyPO) from the anterior-posterior force curve. The medial-lateral force curve provided the positive (lateral) peak (FxHC), occurring shortly after heel contact, and the negative peak (FxPO), indicating weight transfer to the opposite limb. All GRF amplitudes were normalized to body weight (BW) and expressed as a percentage of BW (%BW). The time-to-peak (TTP) was the time from initial heel contact to the peak of each GRF component. Vertical loading rates (LR) were calculated as the average slope of the vertical GRF (Fz) between 20% and 80% at the relevant point [28]. The foot's free moment (FM) was obtained, with FM amplitudes normalized by BW times height. All running variables were averaged over three trials [29, 30]. Additionally, GRF data were normalized to 101 points across the stance phase for detailed analysis.

## 2.5. Electromyography (EMG) recordings

During the running trial, EMG patterns were recorded using bipolar Ag/AgCl surface electrodes aligned parallel to the muscle fibers, with a 20-mm inter-electrode distance. Skin was prepared to achieve an impedance of ≤ 5000 Ω. EMG signals were captured at 1000 Hz using the Data LITE EMG system (Biometrics Ltd, England). Data were collected from eight major lower limb muscles—tibialis anterior (TA), soleus (Sol), vastus medialis (VM), rectus femoris (RF), vastus lateralis (VL), adductor longus (A-L), semitendinosus (ST), and gluteus medius (GL-M)—following SENIAM guidelines [38]. Signals were sampled at 1000 Hz with 16-bit resolution (amplitude range ± 5 V; band-pass filter 10–500 Hz; input impedance > 10 Ω; common-mode rejection > 110 dB) via a portable Wi-Fi transmitter. The run was segmented into two phases for EMG analysis: the first phase (0–50% stance) and the second half (50–100% stance) of the stance phase [31, 32]. A handheld device assessed each muscle's maximum voluntary isometric contraction (MVIC) to normalize root mean square (RMS) values to maximal voluntary activation [33].

## 2.6. Fatigue protocol

The fatigue-running protocol involved a motorized treadmill with no incline (Horizon Fitness, Omega GT, USA). Participants began walking at 6 km/h, with the treadmill speed increasing by 1 km/h every 2 minutes. Perceived exertion was recorded at the end of each stage using the 13–20 Borg scale [34]. When participants reported a perceived exertion of 13 or higher, the treadmill speed was maintained to allow steady-state running. During this phase, perceived exertion was monitored every 30 seconds, and the protocol was stopped if the Borg scale rating exceeded 17 or if heart rate reached ≥ 70% of maximum after two minutes of steady running [35].

## 2.7. Statistical analysis

We averaged all running variables across three trials for each participant, and the results are shown as group means and standard deviations. We used the Shapiro-Wilk test to assess data normality, and a mixed ANOVA with factors for time

(pre vs. post) and group (normal weight vs. obesity) to compare outcomes over time. We used the Bonferroni test as Post-hoc comparisons, and we converted partial eta-squared ($\eta^2p$) to Cohen's d for effect sizes, where $d < 0.50$ indicates small effects, $0.50 \leq d < 0.80$ medium effects, and $d \geq 0.80$ large effects. We carried out all analyses in SPSS version 24.0, with significance set at $p < 0.05$.

# 3. Results

Results for GRFs components showed a significant main effect of “Fatigue” on FxHC (P = 0.025, d = 0.876), FzHC (P = 0.004, d = 1.164), TTP FxHC (P = 0.032, d = 0.148), and TTP FxPO (P = 0.008, d = 0.834) during running. Paired comparisons revealed that FxHC, FzHC, and TTP FxPO were significantly higher after the fatigue protocol. Conversely, TTP FxHC was significantly lower post-fatigue (Table 2). Additionally, a significant main effect of “Group” was observed for FyHC (P < 0.001, d = 1.526), TTP FxHC (P = 0.028, d = 0.156), TTP FxPO (P = 0.026, d = 0.873), TTP FyPO (P = 0.036, d = 0.814), and TTP FzPO (P = 0.024, d = 0.886) during running. The obesity/pronated foot group showed significantly higher values in FyHC, TTP FxHC, TTP FxPO, TTP FyPO, and TTP FzPO compared to the normal weight/foot group (Table 2). No significant interactions between fatigue and group were found for other variables during running (P > 0.05).

**Table 2. Peak ground reaction forces (% BW) and their time-to-peak (ms) during the running stance phase.**

| RF | Normal weight/normal foot group Mean ± SD | | Obesity /pronated foot group Mean ± SD | | Fatigue Sig. (Cohen's d ) | Group Sig. (Cohen's d) | Fatigue-by-group Interactions Sig. (Cohen's d) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Before fatigue | After fatigue | Before fatigue | After fatigue | | | | | |
| $F_{XHC}$ | 8.77 ± 4.92 | 11.31 ± 6.98 | 7.13 ± 3.71 | 8.50 ± 4.69 | **0.025 (0.876)** | 0.199 (0.487) | 0.484 (0.263) | | |
| $F_{XPO}$ | -14.05 ± 5.26 | -13.97 ± 4.24 | -11.55 ± 2.66 | -11.01 ± 2.96 | 0.528 (0.238) | 0.050 (0.759) | 0.639 (0.180) | | |
| $F_{yHC}$ | | | -26.66 ± 8.32 | -29.70 ± 8.81 | -18.67 ± 5.85 | -18.58 ± 6.08 | 0.273 (0.414) | **< 0.001 (1.526)** | 0.243 (0.444) |
| $F_{yPO}$ | 23.64 ± 4.89 | 24.26 ± 4.01 | 17.06 ± 3.48 | 17.69 ± 2.8 | 0.329 (0.369) | 0.199 (0.487) | 0.988 (0.000) | | |
| $F_{ZHC}$ | 104.65 ± 50.44 | 141.06 ± 66.98 | 109.83 ± 41.39 | 135.08 ± 96.40 | **0.004 (1.164)** | 0.985 (0.000) | 0.575 (0.211) | | |
| $F_{ZPO}$ | 233.0 ± 26.70 | 236.02 ± 33.29 | 167.03 ± 21.55 | 192.3 ± 99.60 | 0.200 (0.487) | 0.002 (1.244) | 0.311 (0.381) | | |
| TTP $Fx_{HC}$ 33.73 ± 15.13 | 28.24 ± 14.24 | 43.52 ± 25.39 | 30.37 ± 18.45 | **0.032 (0.148)** | **0.028 (0.156)** | 0.821 (0.002) | | | |
| TTP $Fx_{PO}$ | 97.28 ± 64.72 | 96.39 ± 61.91 | 131.78 ± 61.32 | 181.63 ± 173.96 | **0.008 (1.053)** | **0.026 (0.873)** | 0.941 (0.000) | | |
| TTP $Fy_{HC}$ | | 62.45 ± 32.97 | 52.35 ± 17.63 | 57.36 ± 20.81 | 57.08 ± 22.30 | 0.245 (0.046) | 0.981 (0.000) | 0.271 (0.042) | |
| TTP $Fy_{PO}$ | 230.65 ± 41.12 | 232.75 ± 59.76 | 249.45 ± 61.71 | 313.90 ± 171.20 | 0.215 (0.468) | **0.036 (0.814)** | 0.245 (0.439) | | |
| TTP $Fz_{HC}$ | 15.54 ± 12.28 | 14.56 ± 9.97 | 18.70 ± 17.77 | 16.33 ± 10.14 | 0.455 (0.278) | 0.550 (0.220) | 0.757 (0.110) | | |
| TTP $Fz_{PO}$ | 118.85 ± 46.05 | 96.12 ± 39.05 | 131.70 ± 33.58 | 182.08 ± 166.71 | 0.575 (0.211) | **0.024 (0.886)** | 0.144 (0.557) | | |

Notes: GRF, Ground reaction force; $Fx_{HC}$, Peak lateral ground reaction force at heel contact; Fxpo Peak medial ground reaction force during push-off; $Fy_{HC}$, Braking reaction force; $Fy_{PO}$, Propulsion force; $Fz_{HC}$; First peak of vertical ground reaction force at heel contact; $Fz_{PO}$, vertical ground reaction force during push-off; TTP, Time to Peak; SD, standard deviation.

A notable main effect of "Fatigue" was also identified in LR during running (P = 0.0001, d = 1.442). Paired comparisons revealed a significantly higher LR after fatigue. Additionally, a significant interaction between fatigue and group was observed for LR (P = 0.024, d = 1.034). Pairwise analysis indicated that LR was significantly greater following the fatigue protocol in the normal weight/normal foot group, but not in the obesity/pronated foot group. No significant main effects of fatigue or group were detected for other GRFs, such as the peak positive and negative components during running (P > 0.05) (Table 3).

Table 3
Free moment (body weight*height), loading rate (BW/S), and stance time (ms) during the stance phase.

| GRF | Normal weight/normal foot group Mean ± SD | | Obesity /pronated foot group Mean ± SD | | Fatigue Sig. (Cohen's d ) | Group Sig. (Cohen's d) | Fatigue-by-group Interactions Sig. (Cohen's d) |
|---|---|---|---|---|---|---|---|
| | Before fatigue | After fatigue | Before fatigue | After fatigue | | | |
| FM Positive | 20.32 ± 12.94 | 23.98 ± 12.01 | 30.44 ± 15.35 | 28.60 ± 13.19 | 0.614 (0.191) | 0.110 (0.613) | 0.135 (0.574) |
| FM Negative | -10.40 ± 8.85 | -13.06 ± 9.62 | -8.66 ± 4.77 | -8.50 ± 7.60 | 0.346 (0.358) | 0.228 (0.459) | 0.290 (0.403) |
| LR | 97.40 ± 67.35 | 136.10 ± 92.46 | 78.03 ± 33.12 | 84.40 ± 36.15 | **< 0.001 (1.442)** | 0.132 (0.602) | **0.027 (1.034)** |

Notes: GRF, Ground reaction force; FM, Free moment; LR, Loading rate; SD, standard deviation.

During the early stance phase, muscle activity results revealed a significant main effect of “Fatigue” for VL (P = 0.001, d = 1.334), AL (P = 0.023, d = 0.889), ST (P = 0.043, d = 0.783), and GL-M (P < 0.001, d = 1.54). Paired comparisons showed decreased activity in TA, VL, AL, and ST after fatigue, with an increase in GL-M activity post-fatigue during the same phase (Table 2). A significant main effect of “Group” was observed for GL-M muscle activity (P = 0.001, d = 1.385), with lower activity in the obesity/pronated foot group compared to the normal weight/normal foot group (Table 4). Additionally, a significant “Fatigue-by-group interaction” was found for GL-M activity (P = 0.004, d = 1.161). Paired comparisons indicated that GL-M activity increased after fatigue in the normal weight/normal foot group but remained unchanged in the obesity/pronated foot group during early stance (P = 0.001, d = 0.959; Table 4).

**Table 4. Muscle activities (%MVIC) at the early stance phase.**

| | Normal weight/normal foot group Mean ± SD | | Obesity /pronated foot group Mean ± SD | | Fatigue Sig. (Cohen's d) | Group Sig. (Cohen's d) | Fatigue-by-group Interactions Sig. (Cohen's d) | |
|---|---|---|---|---|---|---|---|---|
| | Before fatigue | After fatigue | Before fatigue | After fatigue | | | | |
| TA | 44.3 ± 27.2 | 36.1 ± 20.3 | 49.5 ± 27.4 | 38.7 ± 23.1 | 0.052 (0.756) | 0.606 (0.191) | 0.777 (0.110) | |
| Sol | 21.1 ± 11.3 | 20.1 ± 18.3 | 14.6 ± 9.0 | 19.4 ± 15.0 | 0.472 (0.271) | 0.404 (0.314) | 0.289 (0.403) | |
| VM | 18.6 ± 10.9 | 17.7 ± 14.8 | 26.4 ± 21.0 | 21.2 ± 14.8 | 0.059 (0.732) | 0.537 (0.230) | 0.462 (0.278) | |
| RF | 15.4 ± 10.9 | 11.8 ± 6.4 | 12.6 ± 7.6 | 11.4 ± 8.6 | 0.290 (0.403) | 0.456 (0.278) | 0.585 (0.667) | |
| VL | 8.14 ± 6.56 | 5.99 ± 2.56 | 11.2 ± 6.32 | 7.55 ± 4.06 | **0.001 (1.334)** | 0.166 (0.527) | 0.340 (0.358) | |
| AL | | 11.8 ± 6.5 | 10.9 ± 9.1 | 13.8 ± 9.7 | 8.46 ± 5.89 | **0.023 (0.889)** | 0.935 (0.000) | 0.094 (0.644) |
| ST | 6.5 ± 2.4 | 6.9 ± 4.2 | 9.02 ± 3.8 | 7.6 ± 3.4 | **0.043 (0.783)** | 0.642 (0.180) | 0.237 (0.449) | |
| GL-M | 7.8 ± 3.9 | 16.4 ± 9.1 | 5.2 ± 2.5 | 6.2 ± 4.3 | **< 0.001 (1.549)** | **0.001 (1.385)** | **0.004 (1.161)** | |

Notes: TA, Tibialis anterior; Sol, Soleus; VM, Vastus medialis; RF, Rectus femoris; VL, Vastus lateralis; AL, Adductor longus; ST, semitendinosus; GL-M, Gluteus-Medius ; SD, standard deviation.

During the late stance phase, muscle activity results showed significant main effects of “Fatigue” on VM (P = 0.006, d = 1.099) and ST (P = 0.049, d = 0.763) muscles (Table 5). The paired comparisons revealed notably higher VM and ST activity levels after fatigue. Additionally, a significant main effect of group was observed for GL-M muscle activity (P = 0.011, d = 1.009). The pairwise analysis indicated that the obesity/pronated foot group exhibited significantly lower GL-M muscle activity than the normal weight/normal foot group. No other muscles showed significant group effects or fatigue-by-group interactions during this phase (P > 0.05).

**Table 5. Mean and standard deviation of the muscle activities (%MVIC) at the late stance phase.**

| Muscles | Normal weight/normal foot group<br>Mean ± SD | | Obesity /pronated foot group<br>Mean ± SD | | Fatigue<br>Sig. (Cohen's d) | Group<br>Sig. (Cohen's d) | Fatigue-by-group Interactions<br>Sig. (Cohen's d) | |
|---|---|---|---|---|---|---|---|---|
| | Before fatigue | After fatigue | Before fatigue | After fatigue | | | | |
| TA | 45.1 ± 23.2 | 50.7 ± 37.8 | 45.8 ± 25.7 | 45.4 ± 32.1 | 0.716 (0.142) | 0.773 (0.110) | 0.636 (0.180) | |
| Sol | 54.2 ± 22.3 | 50.3 ± 35.1 | 50.6 ± 24.5 | 69.3 ± 51.7 | 0.300 (0.392) | 0.474 (0.271) | 0.118 (0.598) | |
| VM | 24.1 ± 15.8 | 46.4 ± 37.1 | 24.6 ± 10.5 | 37.1 ± 26.4 | **0.006 (1.099)** | 0.519 (0.238) | 0.406 (0.314) | |
| RF | 14.5 ± 6.2 | 21.5 ± 13.3 | 23.4 ± 13.3 | 18.6 ± 10.7 | 0.690 (0.155) | 0.336 (0.364) | 0.035 (0.820) | |
| VL | 13.1 ± 11.9 | 10.09 ± 7.1 | 15.3 ± 10.9 | 12.3 ± 7.3 | 0.112 (0.610) | 0.474 (0.271) | 0.949 (0.000) | |
| AL | | 12.1 ± 9.18 | 19.4 ± 16.1 | 13.6 ± 9.1 | 12.8 ± 11.3 | 0.315 (0.381) | 0.414 (0.307) | 0.119 (0.598) |
| ST | 11.9 ± 8.5 | 14.1 ± 11.9 | 8.3 ± 3.8 | 13.6 ± 9.4 | **0.049 (0.763)** | 0.451 (0.286) | 0.392 (0.320) | |
| GL-M | 22.2 ± 21.7 | 20.2 ± 13.6 | 10.4 ± 11.4 | 7.1 ± 4.4 | 0.261 (0.424) | **0.011 (1.009)** | 0.793 (0.090) | |

Notes: TA, Tibialis anterior; Sol, Soleus muscle; VM, Vastus medialis; RF, Rectus femoris; VL, Vastus lateralis; AL, Adductor longus; ST, semitendinosus; GL-M, Gluteus-Medius; ; SD, standard deviation.

# 4. Discussion

This study investigated the effects of running-related fatigue on ground reaction force (GRF) components and lower-limb muscle activity in runners with obesity and pronated feet. The GRF results indicated that fatigue increased FxHC, FzHC, TTP FxPO, and loading rate (LR), while TTP FxHC decreased.

Previous studies have reported inconsistent findings regarding the influence of fatigue on GRF variables. Some authors suggested that fatigue has minimal or negligible effects on GRF patterns and does not substantially alter force profiles during prolonged running [36–38]. Nonetheless, fatigue is widely recognized as a contributing factor to musculoskeletal injuries during sports participation [39]. The vertical loading rate reflects how rapidly the vertical GRF increases during foot-ground contact, and elevated loading rates have been consistently associated with running-related injuries [40, 41], including plantar fasciitis [42], tibial bone stress injuries [43], and patellofemoral pain [44].

In the group comparisons, runners with obesity and pronated feet exhibited significantly higher FyHC, TTP FxHC, TTP FxPO, TTP FyPO, and TTP FzPO than runners with normal body weight and neutral foot posture. These findings are consistent with earlier research reporting greater braking and propulsive impulses during the stance phase in overweight and obese runners compared with their healthy-weight counterparts[45]. Additionally, overweight and obese individuals have been shown to experience greater vertical and horizontal loading when absolute GRF values are considered [45]. Further biomechanical differences have also been reported in runners with obesity, including reduced vertical center-of-mass excursion (15%), wider step width (18%), and longer stance durations (3%) compared with nonobese runners [46].

Although normalized peak GRFs were higher in nonobese runners, GRF impulse was greater in runners with obesity, likely reflecting prolonged stance times [46]. High lateral GRFs have been associated with increased foot pronation during running [47, 48], which may further exacerbate injury risk in this population. Supporting this notion, Lerner et al. demonstrated that obese children generate greater vertical GRFs during walking than nonobese children [49], and elevated vertical GRFs have been linked to an increased risk of injury and joint degeneration [50].

Regarding muscle activity, the primary findings indicated that following the fatigue protocol, activation of the tibialis anterior (TA), vastus lateralis (VL), adductor longus (AL), and semitendinosus (ST) muscles decreased during the early stance phase of running. In contrast, the activity of the gluteus medius (GL-M) increased during this phase after fatigue. Furthermore, GL-M activation was regularly lower in the obesity/pronated foot group compared with the normal weight/normal foot group during both the early and late stance phases.

Previous research has consistently demonstrated reductions in lower-limb muscle activity following fatigue during hopping [51], walking [52, 53], and running [53, 54]. For example, Chaparro et al. [52] reported decreased electromyographic (EMG) amplitudes in the rectus femoris, biceps femoris, gastrocnemius lateralis, and TA muscles following walking with a knee brace. Similarly, diminished activation of the gastrocnemius medialis has been observed during both walking and running tasks after fatigue [53]. Such reductions in muscle activity may partially explain the increased kinetic variables observed after fatigue in the present study, as fatigue compromises the musculoskeletal system's capacity to attenuate impact forces, sustain mechanical loads, and efficiently return stored elastic energy [55]. Nevertheless, the central nervous system may compensate by redistributing muscle activity and adopting alternative muscle synergies to maintain performance and reduce the risk of injury [54]. These adaptive synergies may influence vertical center-of-mass displacement and modulate vertical stiffness, serving as compensatory attenuation strategies in response to neuromuscular deficits [56].

The current findings also demonstrated significantly lower GL-M activity in the obesity/pronated foot group than in the normal weight/normal foot group during both the early and late stance phases. The role of the GL-M during running and other weight-bearing activities is well established [57]. Among the hip musculature, the GL-M generates the greatest peak muscle force during running, particularly in early stance, where it contributes substantially to controlling lateral pelvic tilt [58]. Its large physiological cross-sectional area and favorable moment arm enable the production of an effective hip abduction moment, which is essential for maintaining pelvic stability and proper lower-limb alignment during stance [59]. Insufficient GL-M activation can result in excessive pelvic drop, altered lower-extremity kinematics, and increased injury risk [60]. Adequate GL-M control has therefore been implicated in reducing the incidence of musculoskeletal conditions such as patellofemoral pain syndrome, low back pain, Achilles tendinopathy, and gluteal tendinopathy [60, 61].

Interestingly, increased GL-M activity following fatigue was observed only in the normal weight/normal foot group during the early stance phase. In contrast, no such adaptation occurred in the obesity/pronated foot group. Fatigue or weakness of the gluteal musculature has been linked to altered lower-extremity mechanics, including increased knee valgus, which can elevate joint loading and injury risk [62]. Moreover, hip muscle fatigue protocols have been shown to disrupt force production, proprioception, and intermuscular coordination, potentially affecting distal joints such as the ankle and increasing susceptibility to sprain injuries [63].

Finally, significantly greater activity of the vastus medialis (VM) and ST muscles was observed during the late stance phase following fatigue. In contrast, Avela and Komi [55] reported that fatigue-induced reductions in EMG activity of the soleus and VM were more pronounced during pre-activation and eccentric phases than during concentric muscle actions after a marathon run. This discrepancy may reflect task-specific or phase-dependent neuromuscular control strategies. It has been suggested that pre-activation is strongly preprogrammed and regulated by supraspinal centers, underscoring the importance of central control mechanisms in maintaining locomotor stability under fatigued conditions [64].

## 4.1. Limitations

Several limitations of this study should be acknowledged. First, kinematic data were not collected; therefore, differences in joint range of motion, segment alignment, and movement patterns could not be evaluated. Future studies incorporating three-dimensional kinematic analyses are recommended to provide a more comprehensive understanding of running biomechanics in this population. Second, all participants were male, which limits the generalizability of the findings. Caution should be exercised when extrapolating these results to female runners, given known sex-related differences in running biomechanics and neuromuscular function.

## 5. Conclusions

The findings of this study indicate that running-induced fatigue is associated with increased GRF components and reduced lower-limb muscle activity. Notably, runners with obesity and pronated feet demonstrated insufficient increases in gluteus medius activity following fatigue, which may compromise pelvic stability and increase the risk of running-related musculoskeletal injuries. These results highlight the importance of considering both fatigue and individual biomechanical characteristics when developing injury prevention and training strategies.

## Abbreviations

GRF
ground reaction forces
body mass index
BMI
WC
waist circumference
WHR
waist-to-hip ratio
TA
Tibialis anterior
Sol
Soleus
VM
Vastus medialis
RF
Rectus femoris
VL
Vastus lateralis
AL
Adductor longus
ST
semitendinosus
GL-M
Gluteus-Medius
$Fx_{HC}$
Peak lateral ground reaction force at heel contact
Fxpo Peak medial ground reaction force during push-off
$Fy_{HC}$

Braking reaction force
$Fy_{PO}$
Propulsion force
$Fz_{HC}$
First peak of vertical ground reaction force at heel contact
$Fz_{PO}$
vertical ground reaction force during push-off
TTP
Time to Peak
SD
standard deviation
FM
Free moment
LR
Loading rate.

## Declarations

**Ethics approval and consent to participate**

This study is both experimental and descriptive. It received ethical approval from the ethics committee of the University of Mohaghegh Ardabili (IR.UMA.REC.1403.062).

**Consent for publication**

Not applicable.

# Competing interests

The authors declare that they have no competing interests.

# Funding

No funding was acquired for this research.

# Author Contribution

EFM collected the data, analyzed the data, and wrote the manuscript; AAJ analyzed the data and wrote the manuscript; MD and FR collected the data and wrote the manuscript; EA,VCD and HS contributed to the study design and wrote the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

# Acknowledgments

We gratefully thank all participants for volunteering for this study.

# Availability of data and material

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

## References


1. Williams PT (2013) Greater weight loss from running than walking during 6.2-yr prospective follow-up. Med Sci Sports Exerc 45(4):706
2. Lee D-c et al (2017) Running as a key lifestyle medicine for longevity. Prog Cardiovasc Dis 60(1):45–55
3. Tukker A, Visscher T, Picavet H (2009) Overweight and health problems of the lower extremities: osteoarthritis, pain and disability. Public Health Nutr 12(3):359–368
4. Calenzani G et al (2017) Prevalence of musculoskeletal symptoms in obese patients candidates for bariatric surgery and its impact on health related quality of life. Archives Endocrinol metabolism 61:319–325
5. McKeon PO et al (2015) The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med 49(5):290–290
6. Sarkar A, Sawhney AJMA, Physiol (2017) Eff body mass index Biomech adult female foot 4(1):232–236
7. Stovitz SD, J.C.J.T P, Coetzee, Sportsmedicine (2004) Hyperpronation and foot pain: steps toward pain-free feet. 32(8):19–26
8. McMillan A et al (2010) Sagittal and frontal plane joint mechanics throughout the stance phase of walking in adolescents who are obese. 32(2):263–268
9. Kim HK et al (2022) Discriminating features of ground reaction forces in overweight old and young adults during walking using functional principal component analysis. 94:166–172
10. Browning RC, Kram R (2007) Effects of obesity on the biomechanics of walking at different speeds. Med Sci Sports Exerc 39(9):1632–1641
11. Jafarnezhadgero AA et al (2023) The impact of excessive body weight and foot pronation on running kinetics: a cross-sectional study. Sports medicine-open 9(1):116
12. Farahpour N et al (2016) Gait ground reaction force characteristics of low back pain patients with pronated foot and able-bodied individuals with and without foot pronation. J Biomech 49(9):1705–1710
13. Bergstrom HC et al (2020) Neuromuscular responses of the superficial quadriceps femoris muscles: muscle specific fatigue and inter-individual variability during severe intensity treadmill running. 20(1):77
14. Green B et al (2020) Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. 54(18):1081–1088
15. Maffiuletti NA et al (2007) Differences in quadriceps muscle strength and fatigue between lean and obese subjects. Eur J Appl Physiol 101:51–59
16. Villarrasa-Sapiña I et al (2017) Relationship between body composition and vertical ground reaction forces in obese children when walking. Clin Biomech Elsevier Ltd 41:77–81
17. Frederick EC, Hagy JL (1986) Factors affecting peak vertical ground reaction forces in running. J Appl Biomech 2(1):41–49
18. Redmond AC, Crosbie J, Ouvrier RA (2006) Development and validation of a novel rating system for scoring standing foot posture: the Foot Posture Index. Clin Biomech Elsevier Ltd 21(1):89–98
19. Gijon-Nogueron G et al (2015) Normal values of the Foot Posture Index in a young adult Spanish population: a cross-sectional study. J Am Podiatr Med Assoc 105(1):42–46

20. Sallis JF, Glanz K (2006) *The role of built environments in physical activity, eating, and obesity in childhood.* The future of children, : pp. 89–108
21. da SILVA KS, da Silva Lopes A, SILVA FM (2007) *Comportamentos sedentários associados ao excesso de peso corporal.* Revista Brasileira de Educação Física e Esporte, 21(2): pp. 135–141
22. Who (2007) Growth reference data for 5–19 years. World Health Organization Geneva, Switzerland
23. Sardinha LB et al (2016) A comparison between BMI, waist circumference, and waist-to-height ratio for identifying cardio-metabolic risk in children and adolescents. PLoS ONE 11(2):e0149351
24. Brody DM (1982) Techniques in the evaluation and treatment of the injured runner. Qld Gov Min J 13(3):541–558
25. McPoil TG, Cornwall MW (1996) Relationship between three static angles of the rearfoot and the pattern of rearfoot motion during walking. J Orthop Sports Phys Therapy 23(6):370–375
26. Anbarian M, Esmaeili H (2016) Effects of running-induced fatigue on plantar pressure distribution in novice runners with different foot types. Gait Posture 48:52–56
27. Jafarnezhadgero AA, Sorkhe E, Oliveira AS (2019) Motion-control shoes help maintaining low loading rate levels during fatiguing running in pronated female runners. Gait Posture 73:65–70
28. Lafortune M, Hennig E (1992) Cushioning properties of footwear during walking: accelerometer and force platform measurements. Clin Biomech Elsevier Ltd 7(3):181–184
29. Mafi M et al (2023) Investigating the effect of sand training on running mechanics in individuals with anterior cruciate ligament reconstruction and pronated feet. Gait Posture 104:129–134
30. Jafarnezhadgero A et al (2019) Ground reaction forces and muscle activity while walking on sand versus stable ground in individuals with pronated feet compared with healthy controls. 14(9):e0223219
31. Dugan SA, Bhat KP (2005) Biomechanics and analysis of running gait. Phys Med Rehabilitation Clin 16(3):603–621
32. Jafarnezhadgero AA et al (2021) Analysis of ground reaction forces and muscle activity in individuals with anterior cruciate ligament reconstruction during different running strike patterns, vol 90. Gait & Posture, pp 204–209
33. Farahpour N et al (2018) Muscle activity and kinetics of lower limbs during walking in pronated feet individuals with and without low back pain. J Electromyogr Kinesiol 39:35–41
34. Milot M-H et al (2019) Using the Borg rating of perceived exertion scale to grade the intensity of a functional training program of the affected upper limb after a stroke: a feasibility study. : p. 9–16
35. Koblbauer IF et al (2014) Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. J Sci Med sport 17(4):419–424
36. Nikooyan AA, Zadpoor AA (2011) Effects of muscle fatigue on the ground reaction force and soft-tissue vibrations during running: a model study. IEEE Trans Biomed Eng 59(3):797–804
37. Luo Z et al (2019) Changes in ground reaction forces, joint mechanics, and stiffness during treadmill running to fatigue. Appl Sci 9(24):5493
38. Zadpoor AA, Nikooyan AA (2012) *The effects of lower-extremity muscle fatigue on the vertical ground reaction force: a meta-analysis.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 226(8): pp. 579–588
39. Jonkers I et al (2004) Muscular effort in multiple sclerosis patients during powered wheelchair manoeuvres. Clin Biomech Elsevier Ltd 19(9):929–938
40. Davis IS, Bowser BJ, Mullineaux DR (2016) Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. Br J Sports Med 50(14):887–892
41. Futrell EE et al (2018) Relationships between habitual cadence, footstrike, and vertical load rates in runners. Med Sci Sports Exerc 50(9):1837–1841

42. Prince HE (2019) Changes in outdoor learning in primary schools in England, 1995 and 2017: Lessons for good practice. J Adventure Educ Outdoor Learn 19(4):329–342
43. Pohl MB et al (2008) Biomechanical predictors of retrospective tibial stress fractures in runners. J Biomech 41(6):1160–1165
44. Davis IS, Bowser BJ, Hamill J (2010) *Vertical impact loading in runners with a history of patellofemoral pain syndrome: 2597: Board# 205 June 4 9: 00 AM-10: 30 AM.* Medicine & Science in Sports & Exercise, 42(5): p. 682
45. Roles K (2016) *Differences in Running Mechanics Between Overweight/Obese and Healthy Weight Children.*
46. Vincent HK et al (2020) Impact of body mass index on biomechanics of recreational runners, vol 12. PM&R, pp 1106–1112. 11
47. Rodrigues P, TenBroek T, Hamill J (2013) Runners with anterior knee pain use a greater percentage of their available pronation range of motion. J Appl Biomech 29(2):141–146
48. Willems TM et al (2006) A prospective study of gait related risk factors for exercise-related lower leg pain. Gait Posture 23(1):91–98
49. Messier SP et al (1995) Etiology of iliotibial band friction syndrome in distance runners. Med Sci Sports Exerc 27(7):951–960
50. Butler RJ, Crowell HP III, Davis IM (2003) Lower extremity stiffness: implications for performance and injury. Clin Biomech Elsevier Ltd 18(6):511–517
51. Padua DA et al (2006) Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. J Athl Train 41(3):294
52. Chaparro-Cárdenas SL et al (2021) Characterization of muscle fatigue in the lower limb by sEMG and angular position using the WFD protocol. Biocybernetics Biomedical Eng 41(3):933–943
53. Schlink BR et al (2021) Fatigue induces altered spatial myoelectric activation patterns in the medial gastrocnemius during locomotion. J Neurophysiol 125(5):2013–2023
54. Hajiloo B et al (2020) The effects of fatigue on synergy of selected lower limb muscles during running. J Biomech 103:109692
55. Avela J, Komi PV (1998) Reduced stretch reflex sensitivity and muscle stiffness after long-lasting stretch-shortening cycle exercise in humans. Eur J Appl Physiol Occup Physiol 78:403–410
56. Apte S et al (2021) Biomechanical response of the lower extremity to running-induced acute fatigue: a systematic review. Front Physiol 12:646042
57. Brinkman H, Yanchek A, Thorton E (2018) *Barefoot Training: Effect on Lateral Pelvic Drop and EMG Activity of Gluteus Medius and TFL.*
58. Lenhart R, Thelen D, Heiderscheit B (2014) Hip muscle loads during running at various step rates. J Orthop sports Phys therapy 44(10):766–A4
59. WF D (1986) Actions of hip muscles. Phys Ther 66:351–361
60. Allison K et al (2016) Hip Abductor Muscle Weakness in Individuals with Gluteal Tendinopathy. Med Sci Sports Exerc 48(3):346–352
61. Sims K, Richardson C, Brauer S (2002) Investigation of hip abductor activation in subjects with clinical unilateral hip osteoarthritis. Ann Rheum Dis 61(8):687–692
62. Yalfani A, Gandomi F, Kohboomi M (2017) The effect of g-max and g-med muscles fatigue on functional performance and balance in athletes with and without chronic ankle instability. Asian J Sports Med, 8(3)
63. Carcia C, Eggen J, Shultz S (2005) Hip-abductor fatigue, frontal-plane landing angle, and excursion during a drop jump. J Sport Rehabilitation 14(4):321–331

64. Avela J, Komi P, Santos P (1996) Effects of differently induced stretch loads on neuromuscular control in drop jump exercise. Eur J Appl Physiol Occup Physiol 72:553–562
65. Appendix 1 Tests for the assessment of maximum voluntary isometric contraction

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix1.docx