ISSN: 2476-5279; International Journal of Musculoskeletal Pain Prevention. 2025;10(3):1281-1286

Intrinsic versus Extrinsic Muscle Fatigue on Spatiotemporal Gait Parameters in Women with Flexible Flatfoot

ARTICLEINFO

Article Type
Original Article

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How to cite this article

Mohammadi M, Piri H, Sheikhhoseini R, Ebrahimi E. Comparison of Intrinsic versus Extrinsic Muscle Fatigue on Spatiotemporal Gait Parameters in Women with Flexible Flatfoot. Int.J. Musculoskelet. Pain. Prev. 2025;10(3): 1281-1286.

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10.48311/ijmpp.2025.110575.0

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Article History
Received: Agu 27, 2025
Accepted: Oct 10, 2025
E Published: Oct 15, 2025

ABSTRACT

Aims: Flatfoot is associated with altered knee kinematics and knee pain. Yet, there is a lack of evidence about gait parameters after fatigue in flatfoot individuals. Therefore, this study aims to compare the effect of intrinsic and extrinsic muscles' fatigue on spatiotemporal parameters during walking in women with flexible flatfoot.

Method and Materials: This study included 20 women with flexible flatfoot. They were divided into intrinsic muscles fatigue (N=10) and extrinsic muscles fatigue groups (N=10). The Foot Posture Index and Zebris FDM-T Treadmill were used to assess flatfoot and spatiotemporal parameters, respectively. Also, fatigue was applied with paper grip and heel-rise endurance tests. Analysis of Covariance (ANCOVA) and Quade's tests were utilized for inferential statistics. Data analysis was conducted at a significance level of 0.05.

Findings: The findings showed there is no significant difference between intrinsic and extrinsic muscle fatigue on spatiotemporal gait parameters in women with flatfoot during treadmill walking (P>0.05).

Conclusion: This study suggests that intrinsic and extrinsic muscle fatigue may not significantly impact spatiotemporal parameters in individuals with flexible flatfoot. These findings highlight the robustness and adaptability of gait mechanics under fatigue, even in the presence of postural foot abnormalities.

Keywords: Muscle Fatigue, Spatiotemporal Parameters, Flexible Flatfoot, Walking

Introduction

The foot, a complex structure that supports various functions, provides a base of support during standing and must absorb shock and remain stable at foot strike and push off during walking[1]. Anatomically, it consists of the hindfoot, midfoot, and forefoot [2]. Passive and active tissues in the foot region form three arches: the medial and lateral longitudinal arches, and the transverse arch, which are essential for shock absorption, weight transfer, and propulsion [3]. The Medial Longitudinal Arch (MLA) is higher than the lateral longitudinal arch, and when bearing weight, its curvature may vary to variable degrees[4]. Pes planus, commonly referred to as flatfoot, is characterized by a reduced height of the MLA, resulting in the sole making near or complete contact with the ground[5]. This condition is typically categorized into two forms: flexible and rigid flatfoot [6, 7]. In a flexible flatfoot, the arch appears normal when the foot is not bearing weight (open kinetic chain) but flattens upon weight-bearing (closed kinetic chain)[8].

In contrast, a rigid flatfoot exhibits a consistently diminished arch, regardless of whether the kinematic chain is open or closed [9]. The prevalence of flatfoot among students aged 18–25 years was 11.25%, and all affected individuals had bilateral flatfoot [8]. It is also associated with several intricate structural alterations, including calcaneal valgus and adduction, forefoot abduction, increased forefoot pronation, subluxation of the talonavicular joint, and abduction and dorsiflexion of the first metatarsal [10, 11].

While ligaments and fascia contribute to the support of the MLA, muscles play a crucial role in maintaining its structure [12]. Intrinsic foot muscles like the Abductor Hallucis (ABH) and Flexor Digitorum Brevis(FDB) are situated with both origins and insertions near the foot bones [13].

In contrast, extrinsic muscles such as the Tibialis Anterior (TA), Tibialis Posterior (TP), and Flexor Digit rum Longus (FDL) play a significant role in reinforcing the MLA due to their mechanical advantage and capacity to generate movement and propulsion during gait[1]. It has been demonstrated that the early activation of intrinsic foot muscles may help stabilize the foot, allowing the extrinsic muscles to generate torque more effectively. Additionally, intrinsic muscles may assist in the final phase of push-off, continuing to function after the extrinsic muscles have been deactivated[14].

Fatigue is a common condition characterized by depleted physical and mental energy levels. It impairs motor performance and can negatively impact an individual's gait [15]. A study indicated that fatigue diminishes the body's capacity to absorb impact forces during walking, which can lead to discomfort in the lower limb muscles and joints [16]. Previous study showed that fatigue resulted in a decrease in the knee flexion and abduction moments and an increase in knee ROM in sagittal and frontal planes in the flatfoot group [17]. Another study by previous study demonstrated that calf muscle fatigue caused medialization of the maximum force, and the midfoot was affected differently by fatigue in flexible flatfoot and normal feet [18]. In addition, previous study demonstrated that fatigue changes ankle plantar flexor moment and spatiotemporal gait variables [19]. Although fatigue is known to affect gait mechanics and motor performance, there is a notable lack of research comparing the specific effects of intrinsic and extrinsic muscle fatigue on spatiotemporal parameters during walking, particularly in individuals with flexible flatfoot. Given the importance of walking for functional mobility and the potential for increased injury risk in this population, examining how fatigue in these two muscle groups specifically influences walking dynamics and spatiotemporal parameters is crucial. This research could offer critical insights for targeted rehabilitation and injury prevention strategies for women with flexible flatfoot.

Method and Materials

This study included 20 women with flexible flatfoot. They were selected using convenience sampling and divided into intrinsic muscles (N=10) and extrinsic muscles' fatigue groups (N=10). According to a previous study [20] and considering an effect size of 0.68, a statistical power of 0.80, and a significance level of 0.05, as determined using G*Power Ver. 3.1 software, the sample size was calculated to be 10 in each group. The inclusion criteria for the study were as follows: being female, aged between 20 and 35 years, having flatfoot, and having a score of six or higher based on the Foot Posture Index (FPI)[21]. Also, flatfoot was considered flexible if the MLA height was restored and hind foot valgus was correctable with standing on toes (tiptoe test) [22]. Exclusion criteria included any clinical condition that restricted physical activity, failure to complete the test, a previous history of lower extremity surgery, experiencing any lower limb pain at the time of the test, and taking medication that may affect vigilance and attention. At first, for ethical considerations based on the Declaration of Helsinki, all stages of the study were discussed with the subjects. Then, written informed consent was obtained. Additionally, individuals were informed that in the event of any issues during the tests, the examiner would take all necessary actions to address them. The subjects were instructed on how to perform each test. All steps were explained to the participants. Before starting the tests, the procedure was presented to them. It is worth mentioning that all tests were conducted in the Sport Sciences Research Institute laboratory in Tehran, Iran. Approval was granted by the Ethics Committee of the Research Institute of Movement Science of Kharazmi University in Iran (No. IR-KHU.KRC.1000.273).

Foot posture was evaluated by measuring the FPI. At the same time, subjects were barefoot and in a relaxed standing position, allowing for visual and manual inspection. The FPI comprises six components about the positioning of the forefoot, midfoot, and hindfoot across three planes of motion. This index includes: 1) Palpation of the talar head; 2) Assessment of symmetry in the supra and infra lateral malleolar curvature; 3) Evaluation of inversion and eversion of the calcaneus; 4) Identification of prominence in the talonavicular joint region; 5) Measurement of the height of the MLA; 6) Analysis of forefoot abduction and adduction. The obtained FPI ranges from -12, indicating high supination, to +12, indicating high pronation [23]. A greater positive value indicates a more pronated foot [21]. Inter-observer reliability was found to be good, with an Intraclass Correlation Coefficient (ICC) ranging from 0.852 to 0.895 [24, 25].

Spatiotemporal gait parameters were obtained using the Zebris FDM-T Treadmill (Zebris Medical GmbH, Germany) fitted with an electronic mat of 10,240 miniature force sensors, each approximately 0.85 cm × 0.85 cm, embedded underneath the belt. The treadmill's contact surface measures 150 cm x 50 cm, and its speed can be adjusted from 0.2 to 22 km/h at 0.1 km/h intervals. When the subject walked on the treadmill, the force exerted by her feet was recorded by the sensors at a sampling rate of 120 Hz [26]. Due to the high density of the sensors, the foot is mapped with a high resolution, facilitating even the most subtle changes in force distribution. Primary spatiotemporal data, including stride time (s), right and left step time (s), right and left single support phases (% of gait cycle), double support phases (% of gait cycle), and stride width, were evaluated during a barefoot gait cycle in this study. Participants walked on a treadmill for five minutes to ensure familiarization and warm-up. Gait data were collected one minute before and immediately after the fatigue protocol. To minimize the influence of potential noise, the first and last 10 seconds of each recording were excluded from statistical analysis, and the middle 40 seconds were used for further evaluation. The treadmill speed for gait parameter measurement was set at 5 km/h. A study reported that the Zebris treadmill had excellent reliability for most gait characteristics (ICC: .91–1.00) [27].

The Borg scale assessed localized perceived fatigue [28]. At the beginning and end of the fatigue protocol, participants were asked to rate their perceived exertion of the activity using the Borg scale to ensure fatigue was achieved. For this, participants were instructed to rate the level of fatigue in their muscles on a scale from 0 to 10. A score of 0 indicated no fatigue, while a score of 10 represented the maximum imaginable fatigue. In this study, a score of 8 or above indicated muscle fatigue. Also, a fatigue protocol involving a heel-rise endurance test (targeting extrinsic foot muscles) and a paper-grip endurance test (targeting intrinsic foot muscles) was employed. Each participant performed a minimum of five consecutive repetitions[29]. The rationale for using this protocol was that these tests effectively induced fatigue in intrinsic and extrinsic foot muscles while representing functional activities.

This research used descriptive statistics to describe the variables and inferential statistics for data analysis. The normality of the data distribution was assessed using the Shapiro-Wilk test. If the data were normally distributed, the Analysis of Covariance (ANCOVA) was used for inferential statistics. Also, the Quade's test was utilized for non-parametric data analysis. Data analysis was conducted using SPSS software version 27, with a significance level of 0.05 (corresponding to a 95% confidence level).

Findings

Table 1 displays the demographic characteristics of participants in both groups. The results of the independent t-test showed no significant difference between the groups (Table 1).

Table 1) Demographic characteristics of participants

Variable	Intrinsic Mean ± SD	Extrinsic Mean ±SD	p-value
Age (year)	29.20±4.49	27.30±4.11	0.33
Weight (kg)	69±7.87	65.50±6.94	0.30
Height (m)	1.63±0.07	1.67±0.10	0.32
BMI (Kg/m^2)	25.94±3.84	22.97±3.14	0.07

BMI: Body Mass Index; SD: Standard Deviation

Table 2) Quade's test results

Variable	Stage	Intrinsic Mean ± SD	Extrinsic Mean ± SD	F	Mean square	P-value
Left step time (sec)	Pre-test	0.47±0.02	0.46±0.03	0.067	0.697	0.79
	Post-test	0.48±0.03	0.48±0.02			
Stride time (sec)	Pre-test	0.94±0.05	0.92±0.07	2.196	9.474	0.15
	Post-test	0.96±0.07	0.95±0.04			
Right single support phase (%)	Pre-test	38.90±1.44	39.13±1.35	1.843	43.117	0.19
	Post-test	38.84±1.24	39.76±1.29			
Left single support phase (%)	Pre-test	39.06±0.87	39.58±1.86	0.036	0.448	0.85
	Post-test	38.41±1.21	39.42±1.58			
double support phase (%)	Pre-test	22.06±1.69	21.26±3.20	2.82	26.406	0.11
	Post-test	22.78±1.96	20.84±2.67			
Stride Width (cm)	Pre-test	20.70±3.56	16.00±2.44	1.22	25.01	0.28
	Post-test	17.50±3.34	16.44±2.40			
Right step time (sec) +	Pre-test	0.47±0.02	0.46±0.03	0.148	7.83	0.70
	Post-test	0.48±0.03	0.47±0.02			

sec: Seconds; cm: Centimeter; SD: Standard Deviation

+ Analysis of Covariance was used.

The results of Table 2 showed there is no significant difference between intrinsic and extrinsic muscle fatigue on spatiotemporal gait parameters in women with flatfoot during treadmill walking (P>0.05).

Discussion

This study found no significant effect of intrinsic and extrinsic muscle fatigue on spatiotemporal gait parameters during walking in women with flexible flatfoot. Previous studies exploring fatigue-related gait changes have yielded mixed findings. For instance, Sanjari et al. (2016) reported fatigue may not alter the biomechanical behavior of individuals with flatfoot compared to those with normal arches [30], a finding that is consistent with our results. In contrast, a study by Dorrtaj et al. (2020) reported that fatigue may affect several spatial–temporal parameters in normal and flatfooted adolescents, increasing step width and various temporal parameters, with strong interaction effects in the flatfoot group [31]. However, their study induced lower-limb fatigue using intensive protocols, rather than focusing on intrinsic versus extrinsic foot muscles, which may explain the discrepancy with our findings. Barbieri et al. (2013) demonstrated that fatigue appears to modulate spatiotemporal gait parameters; however, the effects of fatigue seem to be dependent on the muscles that are fatigued [32]. In another study by Keklicek et al. (2023), it was demonstrated that extrinsic and intrinsic foot core fatigue led to increases in the single support and terminal stance durations [33]. A key difference lies in the methodology that they studied general adult volunteers, whereas ours focused on female flexible flatfoot subjects.

Furthermore, a review supports that flexible flatfoot primarily affects joint kinematics and gait speed, but not necessarily in relation to fatigue states [34]. Our findings offer reassuring insight for clinicians and physical therapists: individuals with flexible flatfoot may maintain stable walking patterns even when fatigued. This suggests that standardized walking tasks may not reveal functional deficits under fatigue, and more challenging or varied environments may be needed in rehabilitation to detect or isolate impairments. Given that interventions like intrinsic muscle strengthening have proven to bolster arch morphology and reduce navicular drop [35], future research might explore whether improved muscle endurance translates into gait resilience under variable conditions. This study has several limitations. Firstly, our protocol may not have induced sufficient fatigue in target muscle groups to affect spatiotemporal parameters. Validating fatigue with electromyography or dynamometry could provide deeper insights. Secondly, the study focused on women with flexible flatfoot. Moreover, it appears difficult to distinctly separate the fatigue effects of intrinsic and extrinsic foot muscles, as both groups often work synergistically during gait and postural control. Results may not generalize to men, rigid flatfoot cases, or individuals with symptomatic flatfoot pain. Lastly, our focus was limited to basic spatiotemporal variables. Additionally, a small sample size was another limitation that should be taken into consideration. Future work should include muscle activation patterns (via EMG) and measures of dynamic stability or balance.

Conclusion

This study indicated that fatigue may not affect the spatiotemporal parameters of gait in individuals with flexible flatfoot. These findings highlight the robustness and adaptability of gait mechanics under fatigue, even in the presence of postural foot abnormalities. For both researchers and clinicians, this suggests that assessing gait under more demanding conditions may be necessary to make evident the influence of muscle fatigue on foot posture and movement control.

Acknowledgments

We thank all the participants who participated in this study.

Authors' Contribution

All authors contributed to the conceptualization, methodology, project administration, resources, and formal analysis. All authors helped in the investigation. All authors contributed to data curation. All authors approved the final version of the manuscript.

Conflicts of Interest

The authors have no conflicts of interest.

Ethical Permission

This research was approved by the Ethics Committee of the Research Institute of Movement Science at Kharazmi University in Iran (No. IR-KHU.KRC.1000.273).

Funding/Supports

No funding

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