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ORIGINAL RESEARCH ARTICLE

Effects of an Eight-Week Neuromuscular Conditioning Program on Ground-Reaction Kinetics During Gait in Individuals With Piriformis Syndrome

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Abstract

Background Piriformis syndrome can lead to excessive internal rotation or adduction of the hip joint, thereby disrupting normal gait cycles. Accordingly, this study aimed to examine the effects of neuromuscular exercises on the frequency spectrum of ground reaction forces during walking in individuals with piriformis syndrome.

Methods This quasi-experimental study was conducted under controlled laboratory conditions. Based on calculations using G*Power software, the required sample size for each group was determined to be 15 participants. The study population comprised men aged 35–45 years who were clinically diagnosed with piriformis syndrome. Ground reaction forces were recorded during heel-to-toe walking at a self-selected speed. The time-domain signals were transformed into the frequency domain using MATLAB software. Statistical analysis was performed using a two-way repeated-measures ANOVA in SPSS version 26.

Results A significant main effect of time on cumulative signal power up to 99.5% was observed in the medial–lateral ($p < 0.001$; $\eta^2 = 0.874$), anterior–posterior ($p < 0.001$; $\eta^2 = 0.675$), and free moment ($p < 0.001$; $\eta^2 = 0.601$) components of the ground reaction force. A significant group effect was found for the median frequency of the vertical component ($p = 0.048$; $\eta^2 = 0.199$) and the free moment ($p = 0.028$; $\eta^2 = 0.240$). Furthermore, a significant time × group interaction effect on cumulative signal power up to 99.5% was identified in the anterior–posterior component ($p = 0.010$; $\eta^2 = 0.312$).

Conclusion Neuromuscular exercises improved the spectral characteristics of ground reaction forces across the vertical, anterior–posterior, medial–lateral, and free moment dimensions in individuals with piriformis syndrome. Increases in median frequency, 99.5% frequency, and bandwidth reflected enhanced signal organization and more efficient neuromuscular control, thereby reducing reliance on compensatory movement strategies.

Keywords Exercise Therapy, Piriformis Muscle Syndrome, Postural Balance, Spectrum Analysis

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1 Introduction

Walking is one of the most fundamental human activities, playing a crucial role in daily mobility and overall health. Previous studies have reported that individuals take between 5,000 and 15,000 steps per day.[1,2] During walking, the foot repeatedly strikes the ground, and as the heel contacts the surface, it is exposed to considerable forces and pressures.[3] From a biomechanical perspective, gait analysis and muscle performance assessments indicate that the mechanical efficiency of each muscle improves when it functions synergistically with others.[4] Consequently, dysfunction in one muscle can affect the overall gait pattern. The piriformis muscle is among the primary muscles involved in gait.[5] As the largest external rotator of the hip joint, it plays a critical role in maintaining dynamic hip stability during walking.[6] Repetitive activities, such as walking, can increase muscle tension in the piriformis, potentially compressing the nerves and blood vessels passing through it, which may lead to piriformis syndrome.[7,8]

In piriformis syndrome, dysfunction of the muscle often causes excessive internal rotation or adduction of the hip joint due to pain. Conversely, patients may compensate by maintaining the leg in a shortened, externally rotated position during gait.[5] Individuals with this condition frequently experience pain-related limitations in daily activities, resulting in restricted hip mobility. Moreover, compression of the sciatic nerve may lead to partial paralysis of the lower limb and subsequent motor impairments, including difficulties in walking and running.[9] Piriformis syndrome is considered one of the most common neuromuscular disorders in the general population.[10] Studies have estimated its annual global prevalence at approximately 2.4 million cases.[11] If left untreated, the condition can cause progressive damage to the sciatic nerve, leading to pain, paresthesia, hyperesthesia, and neuromuscular weakness.[12,13]

Altered neuromuscular control is recognized as a major risk factor for secondary injuries.[14] Neuromuscular exercises, a specialized form of training, aim to restore movement control by enhancing sensory feedback throughout the body, thereby improving functional performance.[15] These exercises depend on motor control responses mediated primarily by the brainstem.[16] Neuromuscular training facilitates improvements in motor control across multiple levels of the nervous system, forming a cornerstone of rehabilitation and balance enhancement. Proper motor control relies on spinal reflex responses, automatic postural and balance adjustments in the brainstem, and conscious control at the cortical level.[16] Chaitow and DeLany suggested that neuromuscular exercises may represent one of the most effective treatment strategies for piriformis syndrome.[17] Danazumi, Yakasai et al. and Mujawar, Lin et al. (2021) emphasized that to achieve optimal outcomes, these exercises must be performed in a coordinated and continuous manner.[12,18]

Evidence further indicates that neuromuscular exercises can reduce Ground Reaction Forces (GRFs) and effectively prevent sports-related injuries, particularly among individuals with chronic conditions.[19] The frequency spectrum of GRFs provides insight into the frequency-domain characteristics of anatomical structures such as joints, muscles, and nerves during locomotor activities like walking and running.[20] Since each anatomical component has its own characteristic frequency range, frequency-domain analysis allows researchers to identify these specific patterns. Examining GRFs in the frequency domain thus helps to clarify variations in loading conditions during daily movements.[20,21] McGrath et al. reported that frequency analysis of GRFs revealed significant differences between individuals with peripheral artery disease and healthy controls, even under pain-free conditions, highlighting the sensitivity of this method.[22] Similarly, frequency-domain analysis can identify high-frequency components in GRFs during painful walking, compared to pain-free gait, reflecting altered neuromuscular coordination.

Wurdeman et al., in their research on multiple sclerosis, suggested that frequency-domain analysis of GRFs may provide valuable insights into disease progression.[23] Moreover, it has been suggested that piriformis syndrome can alter the frequency spectrum of GRFs.[24] Various treatment strategies have been proposed to alleviate pain and improve function in patients with piriformis syndrome, which can be broadly categorized as invasive and non-invasive. Invasive interventions include surgery, local anesthetic injections, corticosteroid administration, and botulinum toxin therapy.[24] In contrast, non-invasive approaches remain the mainstay of management, focusing on correcting biomechanical abnormalities and releasing compressive factors in the gluteal region.[13,25]

Despite growing evidence supporting the effectiveness of neuromuscular exercises in improving motor control and reducing pain, no domestic study has yet examined their impact on the frequency spectrum of GRFs in individuals with piriformis syndrome. Addressing this research gap is crucial, as inadequate management may lead to adverse outcomes, including increased pain, motor disability, secondary neuromuscular complications, higher treatment costs, and reduced adherence to conservative interventions. Accordingly, the present study hypothesized that neuromuscular exercises would significantly improve the frequency spectrum of GRFs during walking in patients with piriformis syndrome, thereby enhancing motor performance and alleviating symptoms. The main research question, therefore, was whether neuromuscular exercises influence the frequency spectrum of GRFs during walking in individuals with piriformis syndrome.

2 Methods

This study employed a quasi-experimental, laboratory-based design. Based on data from previous research and calculations using G*Power software, a sample size of 15 participants per group was estimated to achieve a statistical power of 0.80 at a significance level of 0.05. Accordingly, 15 men diagnosed with piriformis syndrome were assigned to the experimental group, and 15 men were included in the control group. All participants were between 35 and 45 years of age and were recruited from individuals who had been diagnosed with piriformis syndrome at public clinics and private rehabilitation centers in Ardabil, Iran. Inclusion criteria comprised a diagnosis of unilateral piriformis syndrome and a history of buttock pain lasting at least three months.[26] The diagnosis was confirmed based on the presence of buttock pain and tenderness, along with positive findings in all five standard stress tests for piriformis syndrome.[26] (Figure 1). Participants were further examined for deep tenderness along the sciatic notch.[26] To complement clinical assessments, nerve conduction studies were performed to objectively evaluate sciatic nerve integrity and conduction velocity, thereby excluding other potential neuropathic or myopathic disorders. All diagnostic procedures were conducted under controlled clinical conditions by an experienced orthopedic specialist, ensuring the accuracy and reliability of the diagnosis.

Participants were excluded if they had a history of spinal or lower limb surgery, lumbar disc degeneration or herniation, neurological disorders, severe trauma, or musculoskeletal conditions such as ischio-gluteal bursitis, abnormal knee alignment, or marked gait abnormalities.[26–28] Additional exclusion criteria included a recent corticosteroid injection, use of analgesic or anti-inflammatory medication within the preceding 72 hours, or engagement in physiotherapy for the lower limbs during the past three months. Participants were also instructed to abstain from strenuous exercise or resistance training for at least eight weeks prior to the study. Those who missed more than two consecutive training sessions were excluded from the final analysis. Before data collection, the study objectives and procedures were clearly explained to all participants. Written informed consent was obtained from each individual before participation.

Flexion, Adduction, and Internal Rotation (FAIR) Test

Because piriformis syndrome involves both physical and functional impingement, it has been suggested that positioning the lower limb in the FAIR posture may exacerbate symptoms by increasing the pressure exerted by the piriformis muscle on the sciatic nerve, or on a portion of the nerve passing between the tendinous or muscular segments of the piriformis.[29] Therefore, in the present study, the FAIR test was employed as a diagnostic aid for confirming piriformis syndrome.

a) PaceTest:
The patient sits on the edge of the examination table and attempts to perform hip adduction, while the examiner applies resistance against this movement. A positive result is indicated by pain or weakness during the test.[27,28]

b) HipExternal Rotation Test:
The patient lies supine in a relaxed position.
A positive test result is indicated by the
presence of pain or discomfort during external rotation of the hip joint.[27,28]

c) FAIR Test:
In this test, the examiner positions the patient supine with the hip and knee flexed at 90°. The lower limb is then moved into hip adduction and internal rotation. A positive result is indicated by pain or discomfort during the maneuver.[27,28]

d) Beatty Test:
The patient lies on their side on the unaffected side, with the hip and knee of the affected side flexed. The flexed hip is then held in abduction against gravity. The patient is asked to perform lateral rotation and abduction of the hip against manual resistance applied by the examiner. A positive result is indicated by pain or weakness during the movement.[27,28]

E) Heel–Contralateral Knee (HCLK) Maneuver:
In this test, the patient places the heel of the affected leg on the opposite knee, positioning the painful thigh in marked flexion and external rotation, while the examiner flexes the contralateral hip.[27,28]

Figure 1 Diagnostic tests for piriformis syndrome used in the present study

GRF data were collected using a Bertec force plate (Bertec Corporation, Columbus, OH, USA) at a sampling rate of 1000 Hz. The force plate was embedded at the midpoint of a 20-meter walkway, ensuring that participants took at least six natural steps before contacting the plate. The system was calibrated before each data collection session. Prior to formal testing, each participant performed five familiarization trials of heel-to-toe walking to ensure consistent foot placement on the force plate. GRF data were then recorded during five successful trials of barefoot walking at a self-selected speed of approximately 1.5 m/s. Trials were repeated if participants lost balance, stepped on the plate edge, contacted the plate with both feet simultaneously, or failed to comply with the testing protocol.

The experimental group subsequently participated in an eight-week corrective exercise program consisting of three sessions per week, whereas the control group did not perform any structured exercise during this period. Both groups were reassessed after eight weeks. Participants were instructed to refrain from any additional physical activity throughout the intervention period.

The training program comprised two phases:

1. Educational phase: A two-hour theoretical session covering the principles of functional movement.
2. Practical phase: A series of 21 exercises.[30–32] including self-administered myofascial release, static stretching, activation, and integration exercises (Table 1).

Exercise intensity was individualized and prescribed by a Corrective Exercise Specialist (CES) based on each participant's maximal voluntary contraction. Each session lasted approximately 60 minutes, including a 10-minute warm-up, 10 minutes of inhibition techniques, 35 minutes of stretching, strengthening, and integration exercises, and a 5-minute cool-down. All sessions were supervised by a certified CES to ensure both safety and adherence to the intervention protocol.[30–32] Participants in the control group were monitored weekly through phone follow-ups and activity logs. During the eight-week intervention, one participant from each group withdrew, while all remaining participants completed the study protocol.

To minimize noise and smooth the force signals, a fourth-order Butterworth low-pass filter with a cutoff frequency of 20 Hz was applied.[33] The parameters selected for further analysis included GRFs in the mediolateral (internal–external), anteroposterior, and vertical directions, as well as the free moment.

After filtering, harmonic analysis was performed in MATLAB (version 2016) using the following equation, which converted the time-domain signal into its frequency-domain representation. In the discrete spectrum, each frequency amplitude is expressed as a multiple of the fundamental frequency, and the cumulative contribution of n harmonics was calculated as:

Equation (1)

$$F(t) = \sum A_n \sin(n\omega_0 t + \theta_n)$$

A = Amplitude, ω_0 = Fundamental frequency, n = Harmonic number, nΘ = Phase angle.

To evaluate the frequency content of the force, the following indices were calculated.[22,23]

Equation (2)

$$\int_0^{f99.5} p(f)df = 0.995 \times \int_0^{f_{max}} p(f)df$$

P = Calculated power, fmax = Maximum signal frequency, Median Frequency of Force, which occurs at the point where half of the signal power lies above and half below.

Equation (3)

$$\int_0^{f_{med}} p(f)df = \int_{f_{med}}^{f_{max}} p(f)\,df$$

f_{max} = Maximum Signal Frequency

f_{med} = Median signal frequency

The force frequency bandwidth is defined as the difference between the maximum and minimum frequencies. The signal power is considered as the power of harmonics exceeding half of the maximum signal power.

Equation (4)

$$f_{band} = f_{max} - f_{min}(when\, p > 1/2 \times p_{max})$$

f_{max} = Maximum signal frequency

f_{min} = Minimum signal frequency

f_{band} = Signal bandwidth

P_{max} = Maximum signal power

The fourth index determined the number of required harmonics in each direction. According to Schneider's method, the number of necessary harmonics (n_e) to reconstruct 95% of the data was considered as the number of harmonics whose cumulative relative amplitudes accounted for 95% or less of the total amplitude.[34]

Equation (5)

$$\sum_{n=1}^{n_e} \frac{\sqrt{A_n^2 + B_n^2}}{\sum_{n=1}^{m} \sqrt{A_n^2 + B_n^2}} \leq 0.95$$

The Shapiro–Wilk test was used to assess the normality of data distribution, confirming that the data were normally distributed. Levene's test was applied to evaluate the homogeneity of variances, and the results indicated that the data met this assumption. To control for Type I error across multiple comparisons, the Bonferroni correction was applied. An independent-samples t-test was first performed to compare the two groups at baseline (pre-test). Since no significant differences were observed between the groups at baseline, a two-way repeated-measures ANOVA was subsequently conducted to analyze the effects of time, group, and their interaction. All statistical analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA).

Table 1 Neuromuscular exercise protocol used in the present study

Exercise goal	Muscles	Set	Repetition	Number	Rest	Duration	Type of exercise
				Self-myofascial release			
Inhibition	Gastrocnemius / soleus	1	1	-	-	30 seconds	Foam roller (gastrocnemius / soleus muscles)
Inhibition	Biceps femoris, short head	1	1	-	-	30 seconds	Foam roller (biceps femoris, short head)
Inhibition	Iliotibial band / tensor fasciae latae	1	1	-	-	30 seconds	Foam roller (iliotibial band / tensor fasciae latae)
Inhibition	Adductor / hip flexor muscles	1	1	-	-	30 seconds	Foam roller (adductor / hip flexor muscles)
Inhibition	Gracilis	1	1	-	-	30 seconds	Foam roller (gracilis muscle)
				Static stretching (lengthening)			
Lengthening	Gastrocnemius (with internal foot rotation)	1	1	-	-	30 seconds	Stretch (gastrocnemius – internal foot rotation)
Lengthening	Soleus	1	1	-	-	30 seconds	Stretch (soleus)
Lengthening	Biceps femoris (short head)	1	1	-	-	30 seconds	Stretch (biceps femoris, short head)
Lengthening	Iliotibial band / tensor fasciae latae (standing, external foot rotation)	1	1	-	-	30 seconds	Stretch (iliotibial band / tensor fasciae latae)
Lengthening	Adductor / hip flexor muscles	1	1	-	-	30 seconds	Stretch (adductor / hip flexor muscles)
Lengthening	Gracilis	1	1	-	-	30 seconds	Stretch (gracilis)
				Activation exercises (isolated strengthening)			
Strengthening	Dorsiflexion of the ankle against resistance	2-1	15-10	4/2/2	-	-	Tibialis anterior
Strengthening	Plantar flexion and internal rotation against resistance	2-1	15-10	4/2/2	-	-	Tibialis posterior
Strengthening	Single-leg heel raise	2-1	15-10	4/2/2	-	-	Medial gastrocnemius
Strengthening	Knee flexion with internal rotation against resistance	2-1	15-10	4/2/2	-	-	Middle hamstring muscles
Strengthening	Towel curl with toes	2-1	15-10	4/2/2	-	-	Hip flexor / hip adductor muscles
Strengthening	Hip abduction and external rotation against resistance	2-1	15-10	4/2/2	-	-	Hip abductor / external rotator muscles
Isometric	Supine position, against hand resistance, knees flexed at 90°	1	4	25/50/75/100	-	-	Internal hamstrings (isometric, positional)
Positional isometrics	Supine with straight knees, against hand resistance, knee flexion”	1	4	25/50/75/100	-	-	Tibialis anterior

			Integrated exercises (dynamic movement integration)				
Integration (balance)	Single-leg balance in multiple directions	2-1	15-10	Slow	30 seconds	-	Single-leg multi-directional balance
Integration (functional movement)	Step-ups and step-downs	2-1	15-10	Slow	30 seconds	-	Step
Integration (functional movement)	Forward and backward lunge	2-1	15-10	Slow	30 seconds	-	Lunge
Integration (balance and stability)	Single-leg balance and stability	2-1	15-10	Slow	30 seconds	-	Single-leg exercises

3 Results

According to the results, the effect of time was statistically significant for the cumulative signal power up to 99.5% in the mediolateral (internal–external) GRF component ($p < 0.001$; $\eta^2 = 0.874$), anteroposterior component ($p < 0.001$; $\eta^2 = 0.675$), and free moment ($p < 0.001$; $\eta^2 = 0.601$). Pairwise comparisons indicated that the cumulative signal power up to 99.5% in all three components, mediolateral, anteroposterior GRFs, and free moment, was higher in the post-test compared to the pre-test.

The effect of time was also statistically significant for the median frequency in the mediolateral component of the GRF ($p = 0.006$; $\eta^2 = 0.353$). Pairwise comparisons showed that the median frequency in the mediolateral component increased in the post-test relative to the pre-test (Table 2).

According to the results, the effect of group was statistically significant for the 99.5% frequency in the vertical GRF component ($p = 0.017$; $\eta^2 = 0.279$). Pairwise comparisons indicated that the cumulative signal power up to 99.5% in the vertical component was higher in the control group compared to the intervention group. The effect of group was also statistically significant for the median frequency in the vertical GRF component ($p = 0.048$; $\eta^2 = 0.199$) and free moment ($p = 0.028$; $\eta^2 = 0.240$). Pairwise comparisons showed that the median frequency in the vertical component and free moment was higher in the control group compared to the intervention group. The effect of group was statistically significant for the frequency bandwidth in the anteroposterior GRF component ($p = 0.008$; $\eta^2 = 0.329$) and free moment ($p = 0.004$; $\eta^2 = 0.240$). The differences were statistically significant. Pairwise comparisons indicated that the frequency bandwidth in the anteroposterior GRF component and free moment was higher in the control group compared to the intervention group (Table 2).

According to the results, the time × group interaction was statistically significant for the cumulative signal power up to 99.5% in the anteroposterior GRF component ($p = 0.010$; $\eta^2 = 0.312$). Post-hoc analysis showed that the cumulative signal power up to 99.5% in the anteroposterior component increased by 15.78% in the post-test of the control group compared to its pre-test. The time × group interaction was also statistically significant for the cumulative signal power up to 99.5% in the free moment component ($p = 0.014$; $\eta^2 = 0.293$). Post-hoc analysis indicated that the cumulative signal power up to 99.5% in the free moment increased by 38.66% in the post-test of the control group compared to its pre-test (Table 2, Figure 2).

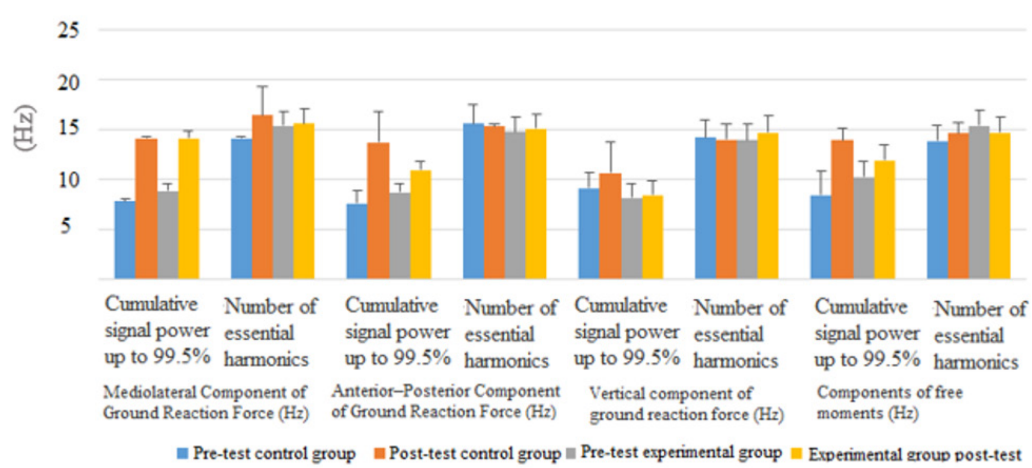

Figure 2 Mean and standard deviation of frequency spectrum components of GRF and free moment

Table 2 Mean and standard deviation of GRF frequency spectrum components and free moment

Variables	Parameters	Control group		Intervention group		P-value (effect size Cohen's d)		
		Pre-test	Post-test	Pre-test	Post-test	Main effect: Fatigue	Main effect: Group	Interaction: group × Fatigue
Mediolateral component of GRF (Hz)	Cumulative signal power up to 99.5%	.890 ± 7.88	2.11 ± 14.14	1.29 ± 8.85	2.57 ± 14.12	0.001 > p* ((0.847	0.426 (0.035)	0.405 (0.039)
	Number of necessary harmonics	2.72 ± 14.18	2.96 ± 16.44	2.49 ± 15.41	2.43 ± 15.60	0.178 (0.098)	0.806 (0.003)	0.252 (0.072)
	Median frequency	0.13 ± 2.00	0.17 ± 2.20	25/0 ± 1.97	0.21 ± 2.03	0.006* (0/353)	0.251 (0.073)	0.095 (0.147)
	Frequency bandwidth	0.08 ± 1.05	0.17± 1.20	0.14 ± 1.06	0.09 ± 1.05	0.058 (0.186)	0.158 (0.108)	0.051 (0.195)
Anterior–posterior component of GRF (Hz)	Cumulative power (99.5%)	1.30± 7.69	3.54± 13.70	1.34 ± 8.79	1.24± 10.97	0.001 > p* (0.675)	0.230 (0.079)	0.010* (0.312)
	Essential harmonics	2.93 ± 15.65	2.33 ± 15.35	3.44 ± 14.77	2.30 ± 15.15	0/963 (0.000)	0.591 (0.016)	0.655 (0.011)
	Median frequency	0.14± 2.10	0.17 ± 2.21	0.17 ± 2.07	0.09 ± 2.04	0.323 (0.054)	0.064 (0.178)	0.103 (0.141)
	Frequency bandwidth	0.17 ± 1.13	0.17 ± 1.21	0.15 ± 1.08	0.05± 1.01	0.909 (0.001)	0.008* (0.329)	0.153 (0.110)
Vertical component of GRF (Hz)	Cumulative signal power up to 99.5%	3.04 ± 9.16	1.51 ± 10.66	1.25 ± 8.19	1.10 ± 8.39	0.163 (0.105)	0.017* (0.279)	0.281 (0.064)
	Number of essential harmonics	2.57 ± 14.28	3.19 ± 14.2	2.24 ± 13.92	2.48 ± 14.72	0.769 (0.005)	0.823 (0.003)	0.568 (0.018)
	Median frequency	0.11 ± 2.06	0.18 ± 2.18	0.20± 1.96	0.14 ± 2.02	0.073 (0.168)	0.048* (0.199)	0.550 (0.020)
	Frequency bandwidth	0.11 ± 1.06	0.18 ± 1.18	0.11 ± 1.05	0.11 ± 1.06	0.159 (0.107)	0.134 (0.120)	0.233 (0.078)
Components of free moments (Hz)	Cumulative signal power up to 99.5%	2.30 ± 8.39	1.43 ± 13.96	2.82 ± 10.19	1.65 ± 11.93	0.001 > p* (0.601)	0.859 (0.002)	0.014* (0.293)
	Number of essential harmonics	2.78 ± 13.83	2.76 ± 14.69	3.95 ± 15.49	3.19 ± 14.70	0.972 (0.000)	0.416 (0.037)	0.433 (0.035)
	Median frequency	0.21 ± 2.06	0.21 ± 2.23	0.25 ± 1.97	0.10 ± 1.96	0.160 (0.106)	0.028* (0.240)	0.115 (0.132)
	Frequency bandwidth	0.16 ± 1.09	0.21 ± 1.23	0.10 ± 1.06	0.00 ± 1.00	0.452 (0.032)	0.004* (0.372)	0.063 (0.180)

The significance level is less than or equal to 0.05 ($p < 0.05$)
GRF: Ground Reaction Forces
Hz: Hertz

4 Discussion

The aim of this study was to examine the effects of neuromuscular training on the frequency spectrum of GRFs during walking in individuals with piriformis syndrome. The main effect of time was statistically significant for the cumulative signal power up to 99.5% in the mediolateral, anteroposterior, and free moment components of the GRF. Pairwise comparisons revealed that the cumulative signal power up to 99.5% in all three components was significantly higher in the post-test compared with the pre-test.

Furthermore, a significant main effect of time was observed for the median frequency of the mediolateral GRF component, with post-test values exceeding those of the pre-test. The main effect of the group was statistically significant for the cumulative signal power up to 99.5% in the vertical GRF component, where the control group demonstrated higher values than the intervention group. In addition, the group factor showed a significant effect on the median frequency in both the vertical GRF component and the free moment, with higher values observed in the control group compared to the intervention group.

The group factor also exerted a statistically significant effect on the frequency bandwidth of the anteroposterior GRF component and the free moment, again showing greater values in the control group relative to the intervention group. Finally, a significant time × group interaction was found for the cumulative signal power up to 99.5% in the anteroposterior GRF component. Follow-up analysis indicated that, within the control group, cumulative signal power in this component increased by 15.78% from pre-test to post-test.

The time × group interaction also exerted a statistically significant effect on the cumulative signal power up to 99.5% in the free moment component. Follow-up analysis revealed that, within the control group, cumulative signal power in the free moment increased by 38.66% from pre-test to post-test. Previous studies have demonstrated that the median GRFs is closely related to the oscillatory behavior of the neuromuscular system, which plays a pivotal role in generating and transmitting forces to the ground during both walking and running.[22] The findings of the present study are generally consistent with earlier investigations analyzing the frequency-domain characteristics of GRFs. For example, Nicholas et al. reported that older women exhibited higher frequencies in the anteroposterior GRF component compared to younger women, a pattern associated with reduced walking speed and compromised balance among older adults.[35] In the current study, significant changes were also observed in the anteroposterior component. However, contrary to the findings of James, Nicholas et al., the intervention group exhibited a decrease in this component following neuromuscular training.[36] This reduction may reflect the beneficial effects of the intervention in enhancing neuromuscular control and reducing compensatory loading in the anteroposterior direction. Consequently, neuromuscular training may optimize the frequency characteristics of gait by improving movement efficiency and minimizing reliance on compensatory mechanisms.

McGrath et al. examined the GRF frequency spectrum in patients with peripheral arterial disease (PAD) and found that the median frequency in both the vertical and anteroposterior components was significantly lower in PAD patients, under both pain-free and painful conditions, compared with healthy controls. This reduction reflects decreased neuromuscular efficiency and slower motor system activity in these individuals. Moreover, the authors observed that the frequency spectrum in the anteroposterior direction was reduced even in pain-free PAD patients relative to healthy subjects. Although no significant differences were found between the pain and pain-free conditions for median frequency or frequency bandwidth, under painful conditions, the cumulative signal power up to 99.5% increased, possibly reflecting more irregular propulsive forces during gait.[22] In contrast, the present study demonstrated that, following neuromuscular training, the median frequency, cumulative signal power up to 99.5%, and frequency bandwidth in the vertical and anteroposterior GRF components increased significantly. These improvements likely represent the positive effects of neuromuscular training on optimizing force organization and enhancing motor control strategies. In PAD patients, however, the similar increases reported by McGrath et al. appear to stem from compensatory mechanisms and impaired neuromuscular function, rather than genuine improvements in coordination. Taken together, these findings suggest that frequency-domain analysis is a valuable approach not only for identifying pathological gait differences across various clinical populations but also for evaluating the effectiveness of rehabilitation interventions.

The present results are further supported by previous research on the frequency-domain analysis of GRFs in neurological disorders. For instance, Shang et al. found that patients with multiple sclerosis exhibited significant reductions in both median frequency and 99.5% frequency in the vertical GRF component compared with healthy controls. This reduction may indicate decreased center-of-mass oscillations, leading to restricted vertical movement patterns during walking.[23] Srebisto's study demonstrated that the sequence of strength and endurance exercises can influence biomechanical parameters of gait, including GRFs, step length, and step frequency. These findings underscore the importance of the exercise type and sequencing logic in improving movement patterns. Accordingly, in the present study, neuromuscular interventions were designed within this conceptual framework. This suggests that the observed changes in the frequency spectrum of GRFs following training may, similar to the effects reported in Srebisto's work, result from an optimized exercise organization. Therefore, referencing this source is essential to emphasize the influence of exercise sequencing on motor performance and its connection to the intervention protocol implemented in this research.[37]

Neuromuscular training interventions may enhance the coordination and organization of force generation, thereby improving gait patterns in individuals with piriformis syndrome through enhanced neuromuscular control. Supporting this interpretation, a related study demonstrated that corrective interventions, such as the use of orthopedic insoles, can reduce specific frequency components of GRFs, particularly in the mediolateral direction, without altering walking speed.[35] This finding suggests that interventions improving joint mechanics and shock absorption capacity may decrease high-load frequency content, potentially serving as a protective mechanism against lower-limb injuries. Furthermore, the results concerning the number of harmonic components required to accurately reconstruct GRF signals at 99.5% precision indicate that the mediolateral direction consistently represents the most complex frequency component, necessitating a greater number of harmonics.[38] In the present study, despite the changes observed in frequency values, the overall structure of the frequency spectrum across all three GRF components remained stable, consistent with previous reports on the relative invariance of dynamic gait characteristics.[39] Taken together, these findings suggest that the alterations in the frequency spectrum of GRFs observed following neuromuscular training are both clinically meaningful and biomechanically significant. They reflect improvements in movement quality and reductions in oscillatory components that may predispose individuals with neuromuscular disorders, such as piriformis syndrome, to injury. These adaptations likely represent an optimization of neuromuscular system performance in response to the dynamic demands of walking, highlighting the potential of frequency-domain analysis as a sensitive and quantitative tool for evaluating the effects of corrective exercise interventions.

5 Conclusion

The findings of this study demonstrated that an eight-week course of neuromuscular training in individuals with piriformis syndrome led to significant improvements in the spectral indices of GRFs across the vertical, anteroposterior, and mediolateral components, as well as in the free moment. Increases in median frequency, 99.5% frequency, and frequency bandwidth in the intervention group indicate improved organization of GRF signals, reduced reliance on compensatory mechanisms in the anteroposterior direction, and enhanced neuromuscular control. In contrast, the control group, receiving no intervention, exhibited increases in certain high-frequency components, potentially reflecting compensatory loading and reduced motor efficiency.

The significant time × group interaction further confirms that the observed changes, particularly within the anteroposterior component and the free moment, were attributable to the training intervention rather than the passage of time. These findings are consistent with previous research involving neuromuscular disorders and older adults, reinforcing that frequency-domain analysis of GRFs not only differentiates pathological gait patterns but also serves as a sensitive and quantitative method for evaluating the effectiveness of rehabilitation interventions. From a clinical perspective, improvements in frequency indices following neuromuscular training may help to attenuate injurious oscillatory forces, enhance trunk and pelvic stability, and optimize gait mechanics in patients with piriformis syndrome. Therefore, it is recommended that rehabilitation programs for these patients incorporate targeted neuromuscular exercises as a fundamental component and utilize frequency-based GRF assessments to monitor treatment progress.

Future research should aim to conduct longitudinal studies with larger and more diverse samples, assess the effects of neuromuscular interventions on higher-level functional activities (e.g., running or directional changes), and compare their outcomes with other rehabilitation approaches to strengthen the evidence base and inform clinical practice guidelines. The present study had several limitations. First, the sample was restricted to men aged 35–45 years, which limits the generalizability of the findings to other age groups and women. Second, walking trials at self-selected speeds may have introduced variability and reduced experimental control. Third, the relatively small sample size limits the robustness and external validity of the results. Finally, the lack of a follow-up assessment prevented evaluation of the long-term retention of training effects.

Declarations

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Artificial Intelligence Disclosure

The authors confirm that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

Authors' Contributions

All authors contributed to the initial conceptualization, study design, data collection, and drafting of the manuscript. All authors have read and approved the final version of the manuscript and declare that they have no conflicts or disagreements regarding its content.

Availability of Data and Materials

The datasets generated and analyzed during the current study are not publicly available due to participant privacy but are available from the corresponding author on reasonable request.

Conflict of Interest

The authors of this study declare that this work was conducted independently and that there are no conflicts of interest with any organizations or individuals.

Consent for Publication

Not applicable.

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Ethical Considerations

This study was conducted in accordance with ethical principles and approved by the Ethics Committee of Mohaghegh Ardabili University, with the Ethical Code IR.UMA.REC.1402.051.

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