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ORIGINAL RESEARCH

Frequency spectrum analysis of ground reaction forces during running in individuals with piriformis syndrome following an eight-week neuromuscular training program

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Abstract

Background: Piriformis syndrome, a neuromuscular condition associated with sciatic nerve irritation, can disrupt lower limb biomechanics and alter ground reaction force (GRF) profiles during running. Neuromuscular training may improve lumbopelvic stability and coordination, but its effects on GRF frequency characteristics remain underexplored. **Methods**: Thirty physically active males (aged 35–45 years) with piriformis syndrome were recruited and allocated to either an intervention group (n = 15) or a control group (n = 15) in this quasi-experimental study. The intervention group completed an eight-week neuromuscular training protocol designed to enhance lumbopelvic stability and coordination. Vertical and free moment GRF components were recorded during treadmill running before and after the intervention. Temporal and group effects were analyzed using a two-way repeated-measures Analysis of Variance (ANOVA). **Results**: The intervention group exhibited a significant reduction in the number of harmonics in the vertical GRF component (p = 0.003, d = 0.55) and a decrease in the 99.5% power frequency of the free moment component (p = 0.001, d = 0.92). These changes reflected diminished high-frequency oscillations, suggesting improved eccentric muscle function, lumbopelvic control, and neuromuscular coordination. **Conclusions**: Neuromuscular training resulted in favorable alterations in GRF frequency spectra among individuals with piriformis syndrome, aligning with reductions in pain and indicating more efficient force transfer and load attenuation. These findings support the application of neuromuscular training to optimize running biomechanics and reduce mechanical stress in this population. **Clinical Trial Registration**: https://trialsearch.who.int/Trial2.aspx?TrialID=IRCT20200912048696N2, IRCT20200912048696N2.

Keywords

Neuromuscular training; Piriformis syndrome; GRF; Frequency

1. Introduction

Running is a globally popular form of physical activity that provides numerous health benefits, including weight management and reduced cardiovascular risk [1]. However, repetitive running is also associated with a high incidence of musculoskeletal disorders and overuse injuries, with reported prevalence ranging from 2.3% to 84.9%, more than half involving the lower extremities [1]. Such injuries result from complex interactions among neuromuscular impairments, anatomical predispositions, and excessive training load [1]. The neuromuscular system plays a critical role in stabilizing the lower limb and pelvis by pre-activating muscles to control joint alignment and absorb impact forces during gait [2].

Despite this, pelvic injuries remain challenging among runners, particularly piriformis syndrome, a neuromuscular condition involving compression or irritation of the sciatic nerve by the piriformis muscle [3]. Piriformis syndrome can lead to buttock pain and altered muscle activation patterns during locomotion. Because the sciatic nerve innervates most of the lower limb, its involvement can significantly affect neuromuscular control and running biomechanics [4].

Frequency-domain analysis of ground reaction forces (GRFs) provides valuable insight into neuromechanical function and can detect subtle alterations in movement patterns associated with injury [5–7]. This approach offers a deeper understanding of the neuromuscular and mechanical adaptations that occur in pathological conditions, such as PS [8].

Various treatment modalities have been proposed for PS, ranging from pharmacological management with non-steroidal anti-inflammatory drugs (NSAIDs) to physiotherapy protocols focusing on inhibition, stretching, activation, and integration [9]. Neuromuscular training (NMT), which combines balance, plyometric, agility, and sport-specific exercises, has proven effective in enhancing proprioception, strength, and motor control in lower limb disorders [10, 11].

However, to date, no study has specifically examined the influence of neuromuscular training on GRF frequency spectrum during running in individuals with piriformis syndrome. To our knowledge, this study is the first to investigate frequency-domain adaptations of GRF following NMT in this population, providing a novel perspective on the neuromechanical effects of rehabilitation beyond traditional time-domain analysis. We hypothesized that NMT would reduce the high-frequency components of GRF signals, reflecting optimized mechanical loading, improved neuromuscular control, and better functional performance in runners with piriformis syndrome.

2. Methodology

2.1 Participants

This investigation was conducted as a quasi-experimental study in a controlled laboratory setting and was registered in the Iranian Registry of Clinical Trials (IRCT; registration number: IRCT20200912048696N2, 08 March 2024). Participant recruitment was carried out between 05 March 2024 and 04 July 2024.

To ascertain the requisite sample size, data derived from prior research endeavors were employed [6]. Based on computations executed using G*Power software (3.1, Heinrich-Heine Düsseldorf, Düsseldorf, NRW, Germany), a sample size of 15 participants per group was deemed necessary to attain a statistical power of 0.8 at a significance level of 0.05. Consequently, 15 middle-aged males diagnosed with piriformis syndrome were recruited as the experimental cohort, and an additional 15 middle-aged males exhibiting comparable characteristics were selected as the control cohort. The target statistical population for this study comprised males aged 35 to 45 years. Only male participants aged 35–45 years were included to reduce variability related to sex-based hormonal and biomechanical differences, as well as age-related changes in neuromuscular control that could influence ground reaction force parameters.

Participants with piriformis syndrome were identified through orthopedic and physiotherapy clinics in the local community. Orthopedic specialists diagnosed patients based on clinical examination and confirmatory nerve conduction studies, including tenderness over the greater sciatic notch and positive Pace and Freiberg tests [12]. Individuals who had received gluteal injections within the preceding month, had a history of lumbar disc surgery, or presented with electromyographic (EMG) or nerve conduction study (NCS) findings suggesting other diagnoses, such as radiculopathy or myopathy, were excluded [13].

Potential cases were identified consecutively during routine clinic visits and invited to participate voluntarily after eligibility assessment. Control participants were recruited through targeted announcements in the same orthopedic and physiotherapy clinics and via their official websites and social media pages. These announcements invited healthy adults with no history of lower back or sciatic pain to participate. Both groups were drawn from the same source population under comparable recruitment conditions to minimize the risk of selection bias.

Inclusion criteria: Participants were considered eligible if they had not received any rehabilitative intervention for the knee joint within the three months preceding the study [14, 15]. Individuals who did not actively participate in any specific sport and whose knee pain had developed gradually and persisted for at least eight weeks were included [1]. Eligible participants also had no history of lower limb or spinal surgery, no previous diagnosis of traumatic, inflammatory, or infectious conditions affecting the knee or lower extremities, absence of joint deformities or fractures, and no limitation in sagittal plane knee joint motion.

Exclusion criteria: Participants were excluded if they had a history of neurological, rheumatological, or other musculoskeletal disorders, experienced pain in regions other than the knee (such as dizziness, uncorrected visual impairments, or vestibular disorders), or had used corticosteroids in the past three months or any analgesic medication within 72 hours prior to testing. This revision avoids excluding patients with piriformis syndrome-related low back or buttock pain, ensuring that the study population accurately reflects the target condition.

Initially, the aims and methodology of the investigation were elucidated to the participants. Following their expression of voluntary consent to participate and the completion of the informed consent documentation, the research protocol commenced.

2.2 Experimental design and intervention

The neuromuscular training group participated in an eight-week exercise program consisting of three sessions per week, each incorporating a warm-up (see Table 1). The duration of each session ranged from 45 to 60 minutes. The intensity and volume of the exercises were progressively increased to mitigate the risk of overtraining and prevent injury among the participants. The neuromuscular training program included exercises targeting general strength, plyometrics, agility, speed, core stability, and balance (specifically dynamic balance and lumbopelvic control) [6]. Additionally, the fitness coach provided guidance to the players, emphasizing the importance of executing the exercises with proper movement technique, such as maintaining correct alignment of the lower limbs.

2.3 Data collection and measurement instruments

GRF data were recorded during running at a self-selected speed using a Bertec force plate system (Bertec Corporation, USA) operating at a sampling frequency of 1000 Hz. GRFs were captured in three orthogonal directions: vertical (Fz), anterior-posterior (Fy), and medial-lateral (Fx) as participants ran along a 20-meter walkway. Two force plates were installed in sequence with a 1 cm gap between them. To ensure natural

TABLE 1. Neuromuscular training program description.

Exercise	Distance	Repetition/Time					
Warm-up (7′ and 10′)							
- Joint mobility (Spine, hip, knee, ankle)		2 × 15 s per joint					
- High knees, reps	10 m						
- Butt kicks, reps	10 m						
- Hip rotation, reps	10 m						
- Side skips, reps	10 m						
- Backward run, reps	10 m						
- Shuttle runs, reps	5–5 m						
Strength (10′ and 15′)							
- Half-squat, reps		2 × 15	3 × 15	4 × 15	3 × 15	3 ×15	1 × 15
- Forward lunge, reps	10 m	2	3	4	3	3	1
- Nordic hamstring, reps		4	6	8	6	6	4
- Copenhagen exercise (right side), s		2 × 15	2 × 20	2 × 30	2 × 30	2 × 20	1 × 15
- Copenhagen exercise (left side), s		2 × 15	2 × 20	2 × 30	2 × 30	2 × 20	1 × 15
- Calf extension, reps		2 × 15	3 × 15	4 × 15	4 × 15	3 × 15	1 × 15
- Hip thrust, reps		2 × 15	3 × 15	4 × 15	4 × 15	3 × 15	1 × 15
Plyometrics (7′ to 10′)							
- Forward leap over a 25 cm obstacle, reps		-	1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
- Side jump over a cone obstacle (right), reps		-	1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
- Side jump over a cone obstacle (left), reps		-	1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
- Forward leap over a 45 cm obstacle, reps		-	1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
- Side jump over 35 cm obstacle (right), reps			1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
- Side jump over 35 cm obstacle (left), reps			1 × 6	2 × 6	3 × 6	2 × 6	2 × 6
Change-of-direction speed (7′ to 10′)							
- Shuttle runs (angle 180°)	10 m	1	2	3	4	2	1
- Change-of-direction speed (angle 45°)	20 m	1	2	3	4	2	1
- Change-of-direction speed (angle 90°)	20 m	1	2	3	4	2	1
Core stability and balance (7′ to 15′)							
- Proprioceptive BOSU ball (right leg), s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Proprioceptive BOSU ball (left leg), s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Plank on Swiss ball, s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Side plank with legs apart (Right side), s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Side plank with legs apart (Left side), s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Crunch on Swiss ball, s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15
- Lumbar extension, s		2 × 15–15	3 × 20–10	3 × 30–10	2 × 45–15	2 × 45–15	1 × 45–15

Reps: repetitions; s: seconds; m: meter; BOSU: Both Sides Utilized.

running mechanics, participants completed at least six preparatory strides before contacting the first force plate. Calibration procedures were completed prior to data acquisition.

Each participant performed five familiarization trials, followed by five successful test trials at a consistent self-selected pace. Trials were repeated if instability, incorrect foot placement, or inadequate bilateral foot contact with the force plates occurred. Vertical GRF thresholds were set at greater than 20 N for heel strike and less than 20 N for toe-off [16, 17].

In the discrete spectrum, the frequency range was determined as a multiple of the fundamental frequency, and the sum of N harmonics is expressed as follows (Eqn. 1):

$$F(t) = \sum A_n \sin(n\omega_0 t + \theta_n) \tag{1}$$

A_n = Amplitude; ω_0 = Fundamental Frequency; n = Harmonic Coefficient; θ_n = Phase Angle.

To evaluate the frequency content of the force, the following indices are calculated (Eqn. 2) [18]:

$$\int_0^{f99.5} p(f)\,df = 0.995 \times \int_0^{f_{max}} p(f)\,df \tag{2}$$

p = calculated power, f_{max} = Maximum frequency of the signal, median frequency of the force, the median frequency is the frequency at which half of the signal's power is above it and half is below it (Eqn. 3).

$$\int_0^{f_{med}} p(f)\,df = \int_{f_{med}}^{f_{max}} p(f)\,df \tag{3}$$

f_{max} = Maximum Frequency of the Signal.
f_{med} = Median Frequency of the Signal.

The bandwidth of the force frequency is equal to the difference between the maximum and minimum frequencies. The signal power is considered to be the power of the harmonics greater than half of the maximum signal power (Eqn. 4).

$$f_{band} = f_{max} - f_{min}(when\, p > 1/2 \times p_{max}) \tag{4}$$

f_{max} = Maximum Frequency of the Signal.
f_{min} = Minimum Frequency of the Signal.
f_{band} = Bandwidth of the Signal.
p_{max} = Maximum Power of the Signal.

The fourth index quantified the requisite number of harmonics in each axis. In accordance with the Schneider method, the necessary harmonic count for reconstructing 95% of the data was defined as the point at which the cumulative summation of the relative amplitudes of each harmonic, normalized by the total amplitude, was less than or equal to 0.95 (Eqn. 5) [19].

$$\sum_{n=1}^{n_e} \frac{\sqrt{A_n^2 + B_n^2}}{\sum_{n=1}^{m} \sqrt{A_n^2 + B_n^2}} \leq 0.95 \tag{5}$$

2.4 Data analysis

Raw GRF data were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 50 Hz. Following signal conditioning, harmonic analysis was conducted by transforming the time-domain signals into the frequency domain using MATLAB software (version 2016, MathWorks Inc., Natick, MA, USA).

All statistical analyses were carried out in accordance with the Checklist for Statistical Assessment of Medical Papers (CHAMP) guidelines [20]. The Shapiro-Wilk test was used to confirm the normality of data distributions. A two-way repeated-measures analysis of variance (ANOVA) was employed to examine the main and interaction effects of Group (Exercise *vs.* Control) and Time (Pre-test *vs.* Post-test). Where significant interaction or main effects were detected, Bonferroni-adjusted paired *t*-tests were applied for *post-hoc* comparisons to control the family-wise error rate.

Effect sizes for between-group comparisons were calculated by converting partial eta-squared values to Cohen's d. Interpretation of within-group effect sizes was as follows: $d < 0.50$ = small, $0.50 \leq d < 0.80$ = moderate, and $d \geq 0.80$ = large [21]. Statistical significance was set at $p \leq 0.05$.

All analyses were conducted using SPSS software, version 24 (IBM Corp., Armonk, NY, USA). No deviations were made from the pre-specified primary or secondary outcomes, and no interim analyses or formal stopping rules were implemented during the study.

3. Results

Table 2 outlines the initial demographic and clinical profiles of the study participants, demonstrating no statistically significant disparities between the exercise and control groups for any of the assessed parameters ($p > 0.05$).

Based on the findings of this investigation, the influence of the temporal factor on the requisite number of harmonics of the vertical component of the GRF was statistically significant ($p = 0.003$; $d = 0.55$). *Post-hoc* pairwise comparisons revealed a statistically significant reduction in the requisite number of harmonics of the vertical component of the GRF in the post-intervention assessment compared with the pre-intervention assessment. Moreover, a statistically significant influence of the temporal factor was observed on the frequency values associated with 99.5% power in the free moment component ($p = 0.001$; $d = 0.92$). *Post-hoc* pairwise comparisons demonstrated that the frequency values associated with 99.5% power in the free moment component were significantly lower in the post-intervention assessment compared with the pre-intervention assessment. Consistent with the findings presented in Table 3, no statistically significant differences were observed in the remaining components (Table 3, Fig. 1).

4. Discussion

The primary objective of this study was to investigate the impact of neuromuscular exercises on the GRF frequency spectrum during running in individuals diagnosed with piriformis syndrome. The results demonstrated a statistically significant effect of the temporal factor on the number of required harmon-

TABLE 2. Participants' baseline demographic and clinical characteristics.

Variable	Control (n = 15)	Exercise (n = 15)	Significance (*p*-value)
Age (yr)	41.20 ± 3.32	42.11 ± 4.51	0.580
Weight (kg)	77.76 ± 3.88	76.54 ± 3.53	0.293
Height (cm)	176.91 ± 5.36	177.18 ± 2.84	0.918
BMI ($kg \cdot m^{-2}$)	24.20 ± 3.25	24.93 ± 3.47	0.648
Right Dominant Side, n (%)	13 (82%)	15 (88%)	0.239
Symptom Duration (mon)	6.3 (0.9)	7.6 (1.8)	0.062
VAS Score (0–10) Sitting	6.1 (0.9)	6.7 (1.4)	0.288
VAS Score (0–10) Walking	1.6 (0.9)	1.6 (0.5)	0.773
ODI Score (0–100)	35.9 (5.8)	39.3 (3.8)	0.143
IPAQ Score (METs)	3430 (268.1)	3767 (440.5)	0.056

Data are expressed as mean ± standard deviation, with statistical significance set at $p < 0.05$. No notable differences were observed between the exercise and control groups in any of the demographic or anthropometric measurements.
BMI: Body Mass Index; VAS: Visual Analog Scale; ODI: Oswestry Disability Index; IPAQ: International Physical Activity Questionnaire; METs: Metabolic Equivalents.

ics in the vertical component of the GRF. *Post-hoc* analyses confirmed a significant reduction in the number of harmonics following the intervention. Moreover, the temporal factor had a statistically significant effect on the frequency associated with 99.5 percent of the power in the free moment component, indicating meaningful changes in frequency-domain parameters of locomotion post-intervention.

The following section focuses on the interpretation of the present study's findings before comparing them with previous research. The frequency characteristics of GRF are influenced by all components of the movement system, including bones, muscles, nerves, and connective tissues, which work together to enable effective force transmission during motion [18]. A reduction in the number of harmonics has been previously linked to a decrease in perceived pain [22]. Neuromuscular exercises may enhance the stretch reflex mechanism and improve intramuscular coordination, which could explain the observed reduction in high-frequency oscillations and the lower number of harmonics detected in the GRF spectrum following the intervention. However, this interpretation remains theoretical, as no direct muscle activation data (*e.g.*, EMG) were collected in the present study. This reflex acts as a primary neuromuscular response by facilitating the recruitment of a greater number of motor units during dynamic movements, such as those found in plyometric activities. These neuromuscular improvements likely contributed to the observed reduction in the number of harmonics within the vertical GRF component, reflecting smoother and more coordinated force application during running. As a result, there may be more rapid and synchronous motor unit activation, particularly in the lumbopelvic region. This improvement could contribute to better weight transfer mechanics during running, ultimately reducing pain and improving performance.

In addition, researchers suggest that the effect of neuromuscular exercises may involve changes at the neuromuscular junction. The increased load introduced through such exercises may reduce synaptic transmission latency and enhance the storage and release of elastic potential energy in muscle tissues, leading to faster muscle fiber recruitment and more effective intermuscular coordination between agonist and antagonist muscles [23]. This mechanism may underlie the lower 99.5% power frequency values observed in the free moment component after training, indicating enhanced control of rotational stability and reduced mechanical oscillation. This improvement in neuromuscular recruitment becomes particularly significant when neuromuscular control is impaired due to fatigue or neuromuscular dysfunction [24, 25].

Neuromuscular training also induces a stretch in muscle fibers due to external forces. This stretch activates muscle spindles, which in turn generate a dynamic reflex response. Afferent neurons from these spindles transmit signals to the spinal cord, where they synapse with alpha motor neurons. This leads to a strong efferent response that triggers a more forceful muscle contraction [23, 25]. Therefore, the reduction in the number of required harmonics in the GRF after neuromuscular training may indicate improved control mechanisms during running in individuals with piriformis syndrome.

The frequency corresponding to 99.5 percent of the power in GRF serves as an indicator of movement tremor and postural instability. Higher values are often associated with more unstable motor patterns. For example, Worden found that individuals with multiple sclerosis displayed higher frequency values than healthy participants, which was interpreted as a compensatory mechanism to maintain balance [26]. In contrast, the significant decrease in this frequency parameter following neuromuscular training in the current study suggests improved muscular tone and reduced activation of oscillatory neuromuscular components, contributing to a more stable movement pattern.

TABLE 3. Mean and standard deviation of the frequency spectrum components of ground reaction force and free moment.

Variables	Parameters	Control Group		95% Confidence Interval	Intervention Group		95% Confidence Interval	Significance Level		
		Pre-test (mean ± SD)	Post-test (mean ± SD)		Pre-test (mean ± SD)	Post-test (mean ± SD)		Time	Group	Time × Group
Medial-Lateral Component of GRF										
	Frequency with 99.5% Power	11.90 ± 2.87	13.40 ± 2.72	−0.315 (−2.93, 2.3)	12.22 ± 4.01	13.90 ± 2.70	−0.5 (−2.53, 1.53)	0.077 (0.21)	0.586 (0.02)	0.916 (0.00)
	Number of Necessary Harmonics	14.57 ± 3.09	14.66 ± 3.48	−0.33 (−2.56, 1.9)	14.90 ± 2.85	14.22 ± 2.46	0.43 (−1.83, 2.69)	0.731 (0.08)	0.940 (0.00)	0.653 (0.01)
	Median Frequency	1.98 ± 0.14	2.02 ± 0.13	0.035 (−0.08, 0.15)	1.95 ± 0.16	2.02 ± 0.21	0 (−0.14, 0.14)	0.110 (0.17)	0.757 (0.00)	0.587 (0.02)
	Frequency Bandwidth	1.02 ± 0.05	1.04 ± 0.09	0.01 (−0.03, 0.05)	1.01 ± 0.04	1.00 ± 0.00	0.045 (−0.01, 0.1)	0.739 (0.00)	0.068 (0.22)	0.332 (0.06)
Anterior-Posterior Component of GRF										
	Frequency with 99.5% Power	11.65 ± 2.99	13.25 ± 3.48	1.085 (−1.16, 3.33)	10.57 ± 3.00	11.27 ± 1.34	1.985 (0.01, 3.96)	0.074 (0.21)	0.073 (0.22)	0.475 (0.03)
	Number of Necessary Harmonics	15.82 ± 3.11	15.64 ± 3.31	1.215 (−0.86, 3.29)	14.61 ± 2.38	14.87 ± 2.22	0.77 (−1.34, 2.88)	0.959 (0.00)	0.156 (0.14)	0.771 (0.00)
	Median Frequency	2.02 ± 0.10	2.07 ± 0.16	0.03 (−0.04, 0.1)	1.98 ± 0.07	2 ± 0.06	0.075 (−0.02, 0.17)	0.184 (0.12)	0.090 (0.19)	0.374 (0.05)
	Frequency Bandwidth	1.00 ± 0.00	1.01 ± 0.05	0.025 (−0.03, 0.08)	1.00 ± 0.00	1.01 ± 0.05	0.075 (−0.01, 0.16)	0.174 (0.14)	1.000 (0.00)	1.000 (0.00)
Vertical Component of GRF										
	Frequency with 99.5% Power	9.35 ± 2.59	9.68 ± 1.91	0.655 (−0.79, 2.1)	8.69 ± 0.84	8.26 ± 1.25	1.43 (0.22, 2.64)	0.903 (0.00)	0.044 (0.27)	0.366 (0.05)
	Number of Necessary Harmonics	15.24 ± 2.82	14.16 ± 2.69	−0.355 (−2.53, 1.82)	15.59 ± 2.99	13.04 ± 1.79	1.11 (−0.6, 2.82)	0.003* (0.55)	0.627 (0.01)	0.206 (0.11)
	Median Frequency	2.03 ± 0.12	2.05 ± 0.17	0.1 (−0.01, 0.21)	1.93 ± 0.15	1.97 ± 0.08	0.075 (−0.03, 0.18)	0.228 (0.10)	0.051 (0.26)	0.684 (0.01)
	Frequency Bandwidth	1.04 ± 0.09	1.07 ± 0.14	0.035 (−0.02, 0.09)	1.01 ± 0.04	1.01 ± 0.04	0.06 (−0.02, 0.14)	0.534 (0.26)	0.074 (0.21)	0.537 (0.02)

TABLE 3. Continued.

Variables	Parameters	Control Group		95% Confidence Interval	Intervention Group		95% Confidence Interval	Significance Level		
		Pre-test (mean ± SD)	Post-test (mean ± SD)		Pre-test (mean ± SD)	Post-test (mean ± SD)		Time	Group	Time × Group
Components of Free Moment										
	Frequency with 99.5% Power	10.18 ± 3.77	13.95 ± 2.73	−0.725 (−2.95, 1.5)	10.91 ± 1.85	13.60 ± 1.76	0.355 (−1.37, 2.08)	0.001* (0.92)	0.777 (0.00)	0.457 (0.03)
	Number of Necessary Harmonics	13.71 ± 3.64	13.5 ± 2.64	−0.58 (−3.02, 1.86)	14.28 ± 2.82	14.55 ± 2.13	−1.05 (−2.85, 0.75)	0.962 (0.00)	0.331 (0.06)	0.717 (0.00)
	Median Frequency	2.05 ± 0.15	2.06 ± 0.13	0.095 (−0.03, 0.22)	1.95 ± 0.18	2.00 ± 0.14	0.06 (−0.05, 0.17)	0.275 (0.92)	0.119 (0.16)	0.52 (0.02)
	Frequency Bandwidth	1.06 ± 0.14	1.06 ± 0.13	0.05 (−0.03, 0.13)	1.01 ± 0.04	1.00 ± 0.00	0.065 (−0.01, 0.14)	0.843 (0.00)	0.056 (0.24)	0.761 (0.00)

**Significance level is less than or equal to 0.5 ($p \leq 0.5$). GRF: Ground Reaction Force; SD: standard deviation.*

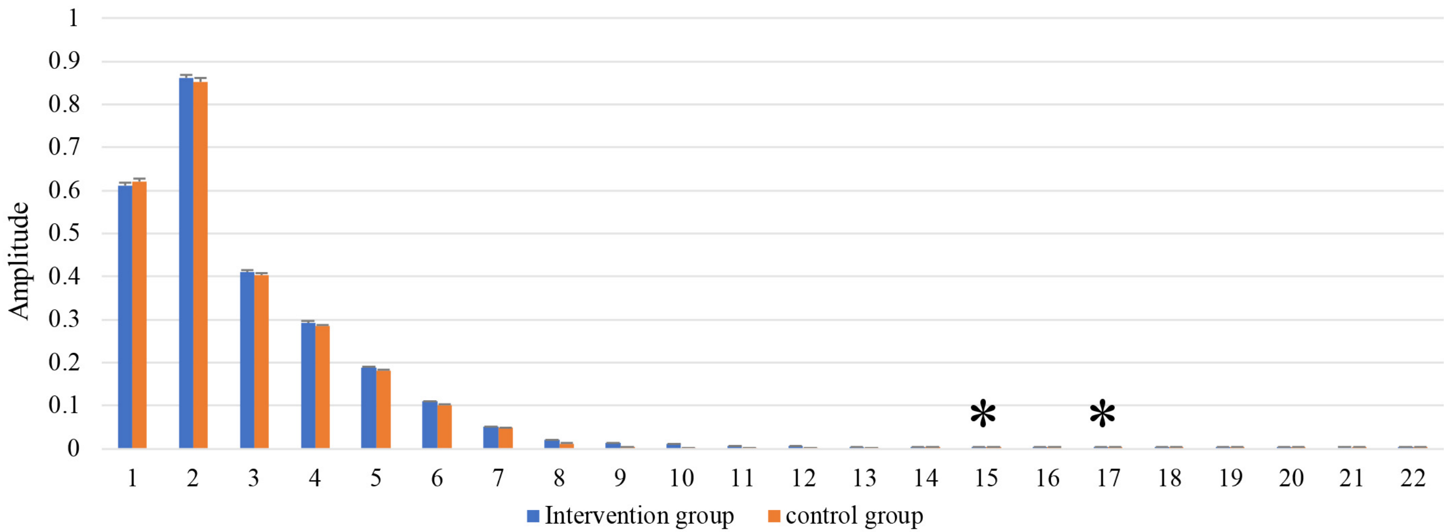

FIGURE 1. Amplitude versus harmonic number plot of the vertical ground reaction force for the control group (Red) and Intervention group (Blue) limbs. The red bar represents data of the control group whereas the blue bar represents data of the Intervention group. *Significance level is less than or equal to 0.5 ($p \leq 0.5$).

Additional support for this interpretation comes from the work of Giovanelli, who reported that at high running speeds, the step frequency that minimized mechanical power was lower than participants' preferred step frequency. This indicates that optimizing frequency may reduce mechanical energy expenditure [27]. Furthermore, Allison demonstrated that even in non-rearfoot running patterns, frequency components related to initial contact are present in the GRF signal, showing that frequency-domain information persists even when impact peaks are absent in the time domain [6]. Therefore, the reduction in power frequency in the current study likely reflects a more efficient muscle response with reduced reliance on mechanical compensatory strategies during the stance phase.

In order to contextualize these results within the broader literature, the following section compares our findings with those of previous studies on neuromuscular training and GRF characteristics. These improvements are important in optimizing neuromuscular coordination and reducing the risk of musculoskeletal injuries [28]. It is important to emphasize that even in the absence of significant changes in some time-domain biomechanical variables, functional benefits from such training should not be overlooked.

Similar observations have been made in studies examining the effects of fatigue following high-intensity running. For example, after a 400-meter sprint, runners showed reduced force production during the stance phase, which was attributed to decreased muscle stiffness and a diminished capacity to absorb shock [29]. In cases of muscle dysfunction or fatigue, such as piriformis syndrome, this impaired ability to regulate impact forces can result in increased high-frequency components in the GRF [30]. Therefore, the post-training reduction in these frequency values may represent improved eccentric muscle function, restored stiffness in the musculoskeletal system, and lower transmitted forces.

In conclusion, the findings of the present study suggest that neuromuscular training can lead to significant improvements in frequency-domain characteristics of GRFs during running. These improvements likely reflect enhanced motor control, reduced pain, and more efficient force transmission through the lower limb and pelvic structures. The decrease in both the number of harmonics and the frequency associated with 99.5 percent power in GRF components points to improved neuromuscular coordination and reduced mechanical loading. These adaptations support the use of neuromuscular training as a non-invasive and effective approach to enhance biomechanical efficiency and minimize injury risk in individuals suffering from piriformis syndrome. Overall, this structured approach to discussion highlights that the observed frequency-domain adaptations are consistent with prior evidence while providing novel insight specific to individuals with piriformis syndrome.

These findings suggest that neuromuscular training may serve as an effective non-invasive intervention for improving lumbopelvic stability and reducing pain in runners with piriformis syndrome. Clinically, this approach could be incorporated into rehabilitation programs targeting neuromuscular control and movement efficiency.

5. Limitations

Despite the promising findings, this study has several limitations that should be acknowledged. First, although the sample size was calculated using G*Power to ensure sufficient statistical power, the number of cases was relatively small. Therefore, caution should be taken when generalizing the findings, and future studies with larger and more diverse populations—including females, other age groups, and individuals with different severities of the condition—are recommended to confirm and extend these results. Second, this study relied solely on force plate data, and electromyography (EMG) was not used to record direct muscle activation patterns. We acknowledge that this is one of the main limitations of the current research, as frequency-based GRF analysis provides only indirect evidence of neuromuscular adaptations. Future studies are encouraged to incorporate EMG together with integrated kinetic–kinematic analyses to directly examine muscle activation patterns and confirm the mechanisms underlying the frequency-domain adaptations observed in this study.

6. Conclusions

The findings of this study suggest that neuromuscular training effectively improves the mechanical behavior of the lower limbs during running in individuals with piriformis syndrome. Significant reductions in both the number of harmonics and the 99.5% power frequency of the GRF components reflect enhanced neuromuscular control, improved eccentric muscle function, and reduced mechanical instability. These spectral changes may be linked to decreased pain and better movement coordination. Overall, the results support the application of neuromuscular exercise as a targeted intervention to restore functional movement patterns and reduce mechanical load among middle-aged male runners with piriformis syndrome. However, the conclusions are limited to the studied population, and further research with larger sample sizes including females and other age groups is needed to confirm the generalizability of these findings. Future studies should also include long-term follow-up assessments and integrate EMG and kinematic analyses to validate the underlying mechanisms.

AVAILABILITY OF DATA AND MATERIALS

The data will be made available by the authors through sending email to the corresponding author at email address: georgian.badicu@unitbv.ro.

AUTHOR CONTRIBUTIONS

SA—Conceptualization, Methodology, Investigation, Data curation, Writing–original draft, Visualization. FR—Formal analysis, Software, Validation, Writing–review & editing, Supervision. HS—Methodology, Resources, Data curation, Writing–review & editing. MQ—Investigation, Software, Validation, Writing–review & editing. GB—Project administration, Supervision, Writing–review & editing. OA—Methodology, Resources, Data curation.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was conducted in accordance with the ethical standards of the Declaration of Helsinki and approved by the Research Ethics Committee of University of Mohaghegh Ardabili (Approval Number: IR.UMA.REC.1402.051). All participants were thoroughly informed about the purpose, procedures, and potential risks of the study and provided written informed consent prior to participation. Participation was entirely voluntary, and participants were assured of their right to withdraw at any stage without any consequence. Confidentiality and anonymity of the data were strictly maintained throughout the research process.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflict of interest. Georgian Badicu is serving as one of the Editorial Board members of this journal. We declare that Georgian Badicu had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to GG.

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