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Research Paper

Effects of Motor Control Exercises in Aquatic and Land-based Environments on Vertical Ground Reaction Force in Women With Chronic Nonspecific Low Back Pain: A Randomized Clinical Trial

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ABSTRACT

Background: Impaired motor control in individuals with nonspecific chronic low back pain (NSCLBP) may alter gait mechanics and contribute to altered spinal loading.

Objectives: This study aimed to investigate the effects of motor control exercises (MCE) performed in aquatic and land-based environments on vertical ground reaction force (vGRF) parameters and psychological variables in women with NSCLBP.

Methods: In this randomized clinical trial, 60 women with NSCLBP were recruited through convenience sampling in 2022 at Bu-Ali Sina University, Hamadan, Iran, and randomly allocated to the experimental group (n=30) and control group (n=30). The experimental group participated in an 8-week MCE program performed in aquatic and land-based environments, whereas the control group received no intervention. Pain intensity, disability, and kinesiophobia were assessed as clinical and psychological outcomes, while vGRF parameters during walking were evaluated as biomechanical outcomes. Data were analyzed using repeated-measures analysis of variance (ANOVA).

Results: Compared with the control group, the MCE group demonstrated significantly greater improvements in pain intensity, disability, and kinesiophobia (all $P<0.001$). Significant between-group differences were also observed in vGRF parameters following the intervention (all $P<0.001$).

Conclusion: An 8-week MCE program performed in aquatic and land-based environments improved pain, disability, and kinesiophobia and altered vGRF parameters during walking in women with NSCLBP. These findings suggest that MCE may have beneficial clinical and biomechanical effects in this population.

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Introduction

Low back pain (LBP) is commonly defined as pain, muscle tension, or stiffness localized between the lower costal margin and the inferior gluteal folds, with or without referred pain into the legs [1]. LBP affects approximately 49–90% of individuals during their lifetime [2]. Nonspecific chronic low back pain (NSCLBP) is one of the most prevalent musculoskeletal conditions worldwide, accounting for approximately 85% of LBP cases [2].

Previous studies have shown that individuals with LBP may exhibit impaired motor control and altered movement patterns, which can compromise walking capacity, an essential component of daily living [3]. Alterations in gait mechanics in individuals with LBP may reflect compensatory strategies aimed at reducing mechanical loading and protecting painful or sensitive tissues [3]. These compensatory strategies may involve changes in spatiotemporal parameters, interjoint and intersegmental coordination, and kinetic variables, including ground reaction forces and joint moments, as well as alterations in muscle activation patterns [3]. Such kinematic, kinetic, and neuromuscular adaptations may influence lower-limb function and the characteristics of vertical ground reaction force (vGRF) during walking, potentially limiting excessive hip and spinal motion and attenuating increased forces and joint moments [4]. In a gait analysis study, individuals with LBP demonstrated significant reductions in several vGRF parameters during self-selected walking speed, with the exception of the first force peak, compared with asymptomatic individuals [5].

Trunk muscles play a crucial role in controlling whole-body mechanics and ground reaction forces during walking [6]. Impaired coordination of the trunk stabilizing musculature has been reported in individuals with chronic LBP [7]. For example, delayed or reduced activation of the multifidus and transversus abdominis, along with altered activation of other trunk muscles, has been identified as a characteristic neuromuscular adaptation in individuals with LBP [8]. The multifidus and transversus abdominis, in particular, contribute substantially to lumbopelvic stability, and impaired function of these muscles may be associated with reduced spinal stability, altered postural control, and changes in plantar pressure distribution and shock attenuation during gait [9, 10]. Ghamkhar et al. (2015) reported altered activation of the lumbar erector spinae in individuals with LBP compared with healthy controls [11]. Similarly, van der Hulst et al. (2010) observed increased rectus abdominis activity during both phases of gait in individuals with chronic LBP. These altered trunk muscle activation patterns may contribute to changes in gait mechanics and ground reaction force characteristics [12]. Pakzad et al. (2016) reported positive associations between trunk muscle activity, kinesiophobia, and pain catastrophizing during walking. Specifically, greater pain catastrophizing was associated with increased erector spinae and rectus abdominis activity and reduced activation of the transversus abdominis and multifidus [13]. Collectively, these findings suggest that appropriate coordination and activation of trunk musculature may be important for maintaining efficient trunk control and optimal gait mechanics [14].

Clinical practice guidelines for the management of NSCLBP recommend exercise therapy as the first-line intervention. Among the available exercise approaches, motor control exercise (MCE) has been extensively investigated [15, 16]. MCE is based on principles of motor learning and aims to improve the control of intersegmental spinal movement and coordination between the spine and pelvis [17]. One of the principal strategies used in MCE is the activation and retraining of the deep trunk musculature, particularly the transversus abdominis and multifidus, with the aim of restoring appropriate muscle control and coordination. During MCE, therapists seek to facilitate appropriate patterns of trunk muscle recruitment while integrating these patterns with other functional systems, including respiration and pelvic floor muscle control.

Given the pain and functional limitations frequently experienced by individuals with LBP, aquatic exercise may represent an alternative or complementary rehabilitation approach [18]. The physical properties of water, including buoyancy, reduced gravitational loading, viscosity, and hydrostatic pressure, can decrease mechanical loading on the musculoskeletal system during exercise compared to land-based exercise. Aquatic exercise may also facilitate movement and potentially improve range of motion, muscular strength and endurance, and pain-related outcomes [18]. Furnari et al. (2014) reported that aquatic exercise may be beneficial for individuals with chronic LBP and impaired postural balance, with improvements in balance and selected gait-related variables [19].

Despite the established clinical benefits of MCE for individuals with NSCLBP and documented alterations in gait mechanics and vGRF associated with LBP, evidence regarding the effects of MCE performed in aquatic and land-based environments on gait biomechanics remains limited. To our knowledge, no clinical trial has directly

investigated whether an MCE-based rehabilitation program incorporating aquatic and land-based exercises can modify gait-related vGRF parameters in women with NSCLBP. Therefore, this study aimed to determine the effects of an 8-week MCE program performed in aquatic and land-based environments on gait-related vGRF parameters in women with NSCLBP.

Methods

Study design and participants

This randomized controlled clinical trial used a two-group, pre-test–post-test design and was conducted at the Rehabilitation Laboratory of Bu-Ali Sina University, Hamadan, Iran. This study was approved by the Research Ethics Committee of Bu-Ali Sina University and was registered with the Iranian Registry of Clinical Trials (IRCT).

All participants provided written informed consent before participation. The study population comprised women aged 30–50 years with NSCLBP. The participants were initially examined by an orthopedic specialist and were referred to the research team after meeting the clinical criteria for NSCLBP and demonstrating at least two impairments on standardized lumbar motor control tests. A researcher subsequently screened participants according to the predefined eligibility criteria. The required sample size was estimated using G*Power software, version 3.1.9.2 based on an F-test within the repeated-measures analysis of variance framework, assuming two groups and two measurement occasions, with an alpha level of 0.05, a statistical power of 0.80, and the anticipated effect size derived from previous research. The estimated sample size was 54 participants. Considering a potential dropout rate of 10%, the target sample size was increased to 60 participants, with 30 participants allocated to each group (Figure 1).

The inclusion criteria included a history of LBP lasting more than 12 weeks, age between 30 and 50 years, pain intensity of at least 3/10 on the visual analog scale (VAS), at least two impairments on the lumbar motor control tests described by Luomajoki et al. [20], and no history of spinal surgery or hip joint replacement. The exclusion criteria were pain in other body regions; severe upper- or lower-extremity deformities; use of analgesic medication during the previous 6 months; participation in physiotherapy during the previous year; regular participation in structured exercise; sciatic or radicular pain; spondylolysis; neuromuscular, neurological, or respiratory disorders; muscle spasm; and vertebral fractures. The study was designed and reported in accordance with the consolidated standards of reporting trials (CONSORT) 2010 statement.

Randomization and blinding

Participants were randomly allocated using Random Allocation Software version 1.0, with block sizes of 4 and 6. Centralized allocation concealment was achieved through sequentially numbered, sealed envelopes, which were opened in consecutive order by a researcher not involved in outcome data collection. As a result, 30 participants were assigned to receive a combined aquatic and land-based MCE intervention, while the remaining 30 constituted the no-intervention control group. Assessors of outcomes were blinded to allocation, and participants were requested not to communicate their group to the assessors.

Laboratory assessments

Pain intensity, disability, kinesiophobia, and vGRF parameters were assessed at baseline and immediately after the intervention. Demographic characteristics, including age, height, weight, and body mass index (BMI), were recorded at baseline. Height, weight, and BMI were measured with participants wearing minimal clothing and standing upright using a digital stadiometer and scale (BMS370; InBody, USA).

Pain intensity

Pain intensity was assessed using a 10-cm VAS, ranging from 0 (no pain) to 10 (worst imaginable pain). The VAS is a widely used measure for the quantitative assessment of pain intensity and has demonstrated good reliability, with an intraclass correlation coefficient (ICC) of 0.91 [21].

Kinesiophobia

Kinesiophobia was assessed using the 11-item tampa scale for kinesiophobia. The questionnaire assessed fear of movement and reinjury, including beliefs related to injury and activity avoidance. Each item is rated on a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree), yielding a total score ranging from 11 to 44 [22]. Higher scores indicate greater fear of movement or reinjury. The validity and reliability of the questionnaire have been established in previous research [23]. In the present study, internal consistency was assessed using Cronbach's α, which yielded a coefficient of 0.86.

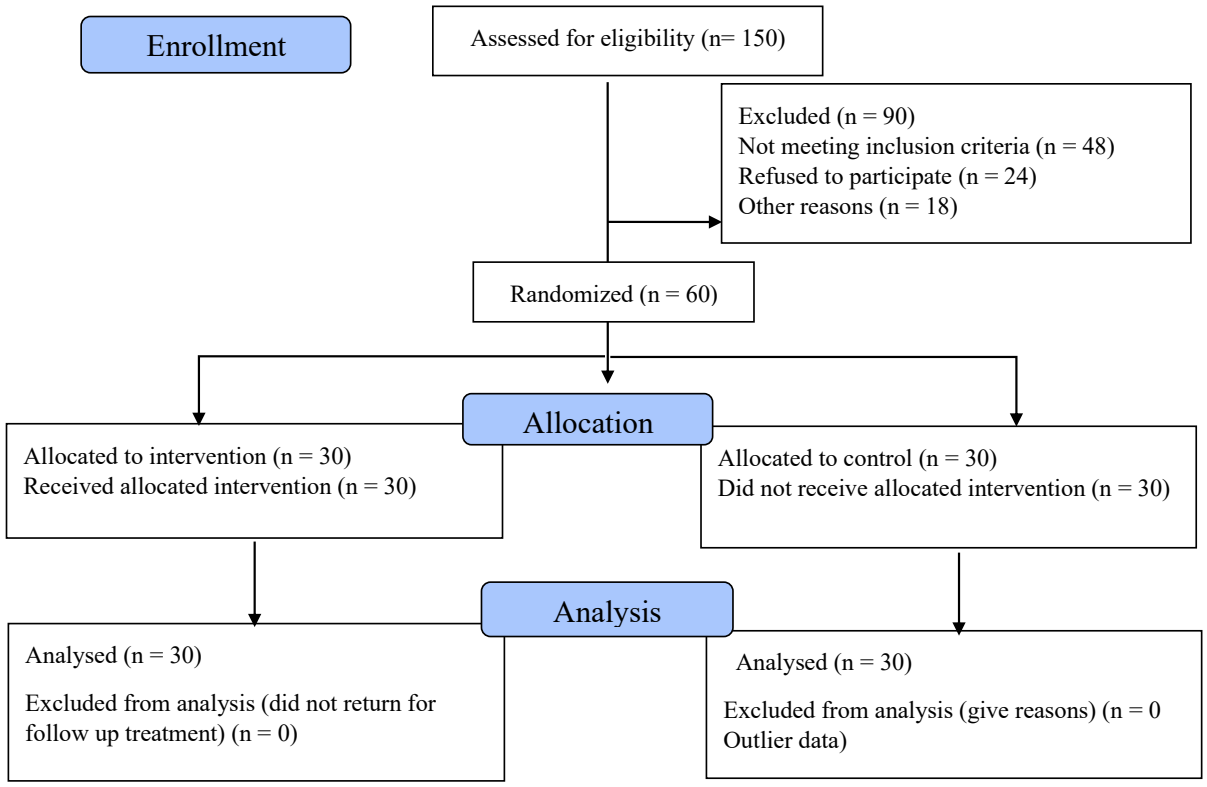


Figure 1. TheCONSORT flow diagram of the randomized controlled trial

Disability

The severity of disability attributable to LBP was quantified using the Oswestry disability index (ODI) [24]. This instrument consists of 10 distinct domains measuring pain intensity and functional limitations in activities of daily living, including personal care, lifting, walking, sitting, standing, sleeping, social life, and travel. Each item is rated on a 0-5 scale, with higher aggregate scores denoting more severe disability. The total score is converted to a percentage, with higher percentages indicating greater functional disability. The ODI has demonstrated good reliability in individuals with LBP (ICC=0.84) [25].

VGRF parameters

The FDM-S Plantar Pressures device manufactured by Zebris Germany was used to evaluate the vGRF (ICC=0.91) [26]. This device has a platform with dimensions of 54×34 cm and 2560 active sensors with high sensitivity. We evaluated vGRF parameters based on the study by Ahmad et al. (1996) [27]. After identifying patients' dominant leg, we assessed vGRF parameters. The walking test was carried out in such a way that the device was located in the center of a ten-meter-long corridor, and the subject walked the path five times at their normal walking speed. Of the five performances, the mean scores of three correct attempts were recorded for analysis. The condition of performing a correct step effort included the full impact of the foot on the middle part of the device. Data were extracted during the support phase of walking. The walking support phase was defined as heel contact with the ground until toe-off. The vGRF parameters were defined as follows:

FzHC: peak vGRF during heel contact phase (peak force 1). FzMS: peak vGRF during mid-stance phase (peak force 2). FzPO: peak vGRF during push-off phase (peak force 3).

The recorded data were smoothed with a 4th-order Butterworth low-pass filter without phase difference with a cutoff frequency of 20 Hz.

MCE intervention

Participants in the experimental group completed an 8-week MCE program, consisting of four weeks of aquatic-based exercises followed by four weeks of land-based exercises, with three sessions per week. Each session lasted 45 min. The intervention was conducted at the Rehabilitation Center and swimming pool of Bu-Ali Sina University. The same MCE exercises were performed in both aquatic and land-based environments, with the exer-

cise setting being the primary difference between the two conditions.

The intervention consisted of two main stages. During the first stage, participants were instructed to selectively activate the deep spinal stabilizing muscles, particularly the transversus abdominis and multifidus. Diaphragmatic breathing and pelvic floor muscle activation were progressively incorporated into the exercises. Participants were also instructed on appropriate breathing patterns during the exercise [28, 29]. Progression to the subsequent stage occurred when participants were able to maintain an isolated contraction for 10 s across 10 repetitions [30]. During the second stage, activation of the deep and superficial trunk musculature was integrated into dynamic and functional movements. Exercises progressively incorporated combined movements of the trunk and extremities, with continued emphasis on appropriate activation of the deep and superficial spinal musculature. The training load was progressively increased according to the participants' ability to perform the exercises correctly, to improve intermuscular coordination, postural alignment, and lumbopelvic stability [29].

During the intervention, the therapist provided feedback to facilitate appropriate movement patterns and muscle activation. As the participants demonstrated improved motor control and proficiency in performing the exercises, the amount of external feedback was progressively reduced.

Statistical analysis

Statistical analyses were conducted using SPSS software, version 26.0; (IBM Corp., Armonk, NY, USA). Continuous data were checked for normality using the Shapiro–Wilk test, and descriptive results are expressed as means and standard deviations. To examine the impact of the intervention on outcome measures, repeated-measures analysis of variance (ANOVA) was implemented, featuring time as the within-subjects factor and group as the between-subjects factor. The interaction effect (time×group) was analyzed to establish whether the longitudinal trajectories differed between the experimental and control cohorts. Effect sizes were determined using partial eta squared (η_p^2), with statistical significance set at $P<0.05$.

Results

Table 1 summarizes the demographic characteristics of the groups. No differences were observed between the groups in age, height, weight, and BMI. Therefore, the data distribution was normal ($P>0.05$).

Pain

Repeated-measures analysis of variance showed a significant main effect of time on pain, with a large effect size ($F=90.429$, $\eta_p^2=0.609$, $P<0.001$), indicating a significant change in pain over time. The main effect of group was also significant, with a large effect size ($F=13.857$, $\eta_p^2=0.193$, $P<0.001$), indicating an overall difference in pain between the two groups. In addition, the time×group interaction was significant and associated with a large effect size ($F=208.282$, $\eta_p^2=0.782$, $P<0.001$), indicating different patterns of change in pain over time between the groups (Tables 2 and 3). Pairwise comparisons showed a significant between-group difference in pain at post-test ($P<0.001$). Descriptively, pain decreased by 51% in the experimental group compared to a 12% reduction in the control group (Table 4).

Disability

Repeated-measures analysis of variance showed a significant main effect of time on disability, with a large effect size ($F=9.425$, $\eta_p^2=0.140$, $P=0.003$), indicating a significant change in disability over time. The main effect of group was also significant, with a moderate effect size ($F=8.982$, $\eta_p^2=0.134$, $P=0.004$), indicating an overall difference in disability between the two groups. Furthermore, the time×group interaction was significant and associated

Table 1. Demographic characteristics of participants at baseline

Variables	Experimental Group (n=30)	Control Group (n=30)	P*
Age (y)	42.00±3.56	42.00±6.41	0.110
Height (cm)	164.51±4.96	163.82±5.66	0.267
Weight (kg)	64.08±5.04	65.49±5.69	0.658
BMI (kg/m²)	23.69±1.80	24.42±2.10	0.508

BMI: Body mass index.

*P values (P), based Shapiro-Wilk.

Table 2. Results of repeated measures analysis of variance (ANOVA) test

Variablea	Source	Mean Square	F Value	Eta Squared (η^2)	P
Pain	Time	60.208	90.429	0.609	0.001*
	Group	63.075	13.857	0.193	0.001*
	Time×group	138.675	208.282	0.782	0.001*
Disability	Time	546.133	9.425	0.140	0.003*
	Group	842.700	8.982	0.134	0.004*
	Time×group	6992.133	120.671	0.675	0.001*
Kinesiophobia	Time	842.700	158.040	0.732	0.001*
	Group	2253.333	128.450	0.689	0.001*
	Time×group	1216.033	228.055	0.797	0.001*

*Significant difference.

Journal of Research in Orthopedic Science

with a large effect size (F=120.671, η_p^2=0.675, P<0.001), indicating different patterns of change in disability over time between the groups (Table 2). Pairwise comparisons showed a significant between-group difference in disability at post-test (P<0.001). Descriptively, disability decreased by 38% in the experimental group compared with a 26% reduction in the control group (Table 4).

Kinesiophobia

Repeated-measures analysis of variance showed a significant main effect of time on kinesiophobia, with a large effect size (F=158.040, η_p^2=0.732, P<0.001), indicating a significant change in kinesiophobia over time. The main effect of group was also significant, with a large effect size (F=128.450, η_p^2=0.689, P<0.001), indicating an overall difference in kinesiophobia between the two groups. In addition, the time×group interaction was significant and associated with a large effect size (F=228.055, η_p^2=0.797, P<0.001), indicating different patterns of change in kinesiophobia over time between the groups (Table 2). Pairwise comparisons showed a significant between-group difference in kinesiophobia at post-test (P<0.001). Kinesiophobia decreased by 33.92% in the experimental group compared to a 2.88% reduction in the control group (Table 4).

Table 3. Results of repeated measures ANOVA test

Variables	Source	Mean Square	F Value	Eta Squared (η^2)	P
FzHC	Time	2048.580	62.517	0.519	0.001*
	Group	1186.817	15.843	0.215	0.001*
	Time×group	5557.601	169.519	0.745	0.001*
FzMS	Time	2410.106	33.140	0.364	0.001*
	Group	3395.277	28.043	0.326	0.001*
	Time×group	5866.218	80.663	0.582	0.001*
FzPO	Time	2528.904	81.632	0.585	0.001*
	Group	14220.606	42.659	0.424	0.001*
	Time×group	880.640	28.427	0.329	0.001*

Journal of Research in Orthopedic Science

Abbreviations: FzHC: Peak vGRF during heel contact; FzMS: Peak vGRF during mid-stance; FzPO: Peak vGRF during push-off.
*Significant difference.

Table 4. Descriptive statistics

Variables	Group	Mean±SD		95% CI (Post-test)		Δ (%)
		Pre	Post	Lower	Upper	
Pain	Experimental	6.86±1.47	3.30±1.05	2.75	3.84	-51
	Control	6.16±1.96	6.90±1.80	6.35	7.44	12
Disability	Experimental	50.76±10.23	31.23±6.31	28.73	33.72	- 38
	Control	40.80±10.27	51.80±7.29	49.30	54.29	26
Kinesiophobia	Experimental	34.40±1.24	22.73±3.75	21.32	24.14	-33.92
	Control	36.70±3.77	37.76±3.97	36.35	39.18	2.88
FzHC	Experimental	101.15±8.22	106.50±6.95	104.38	108.62	5.28
	Control	108.48±8.97	86.60±4.33	84.48	88.72	-20.16
FzMS	Experimental	104.98±5.65	99.96±11.45	96.38	103.54	- 4.78
	Control	101.63±12.80	124.58±7.77	121.00	128.16	22.58
FzPO	Experimental	107.27±15.03	121.87±15.38	117.04	126.70	13.61
	Control	90.91±12.36	94.68±10.63	89.85	99.51	4.14

Journal of Research in
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Abbreviations: FzHC: Peak vGRF during heel contact; FzMS: Peak vGRF during mid-stance; FzPO: Peak vGRF during push-off; CI: Confidence interval.

Ground reaction force

Repeated-measures analysis of variance (ANOVA) showed a significant main effect of time on the first peak vGRF, with a large effect size ($F=62.517$, $\eta_p^2=0.519$, $P<0.001$), indicating a significant change over time. The main effect of group was also significant, with a large effect size ($F=15.843$, $\eta_p^2=0.215$, $P<0.001$). In addition, the time×group interaction was significant and associated with a large effect size ($F=169.519$, $\eta_p^2=0.745$, $P<0.001$), indicating different patterns of change between the groups over time (Table 3). Pairwise comparisons showed a significant between-group difference in the first peak vGRF at post-test ($P<0.001$). The first peak vGRF increased by 5.28% in the experimental group and decreased by 20.16% in the control group (Table 4).

For the second peak vGRF, the main effect of time was significant, with a large effect size ($F=33.140$, $\eta_p^2=0.364$, $P<0.001$). The main effect of group was also significant, with a large effect size ($F=28.043$, $\eta_p^2=0.326$, $P<0.001$). Moreover, the time×group interaction was significant and associated with a large effect size ($F=80.663$, $\eta_p^2=0.582$, $P<0.001$), indicating different patterns of change between the groups over time (Table 3). Pairwise comparisons showed a significant between-group difference in the second peak vGRF at post-test ($P<0.001$). The second peak vGRF decreased by 4.78% in the experimental group, whereas it increased by 22.58% in the control group (Table 4).

For the third peak vGRF, the main effect of time was significant, with a large effect size ($F=81.632$, $\eta_p^2=0.585$, $P<0.001$). The main effect of group was also significant, with a large effect size ($F=42.659$, $\eta_p^2=0.424$, $P<0.001$). The time×group interaction was significant and associated with a large effect size ($F=28.427$, $\eta_p^2=0.329$, $P<0.001$), indicating different patterns of change between the groups over time (Table 3). Pairwise comparisons showed a significant between-group difference in the third peak vGRF at post-test ($P<0.001$). Descriptively, the third peak vGRF increased by 13.61% in the experimental group and by 4.14% in the control group (Table 4).

Discussion

This clinical trial investigated the effects of eight weeks of MCE performed in aquatic and land-based environments on vGRF during walking in women with NSCLBP. The findings showed that, compared with the control condition, MCE was associated with significant

improvements in pain, disability, and kinesiophobia, together with significant changes in the vGRF parameters during walking. Specifically, the intervention increased the first and third peaks of vGRF and decreased the second peak in the experimental group. These findings suggest that MCEs may influence not only clinical outcomes but also functional and biomechanical aspects of gait in women with NSCLBP.

The reduction in pain observed in the present study may be related to improvements in neuromuscular control and trunk stabilization. Previous electromyographic studies have reported altered activation of the multifidus and impaired recruitment of trunk musculature in individuals with NSCLBP. Such alterations may compromise spinal stability and movement control and contribute to persistent symptoms. Accordingly, restoration of the coordinated function of the deep trunk musculature is an important component of rehabilitation in individuals with chronic LBP [31].

In the present study, MCEs emphasized selective and coordinated activation of the transversus abdominis and multifidus muscles [9]. These muscles play important roles in lumbopelvic stabilization, proprioceptive control, and regulation of spinal movement. Persistent pain may contribute to a maladaptive cycle involving reduced physical activity, impaired trunk muscle function, altered proprioception, and reduced neuromuscular coordination. These changes may subsequently affect spinal movement control and contribute to symptom persistence [20]. MCEs may help interrupt this cycle by improving the activation and coordination of trunk stabilizing muscles and enhancing sensorimotor control. Improvements in deep trunk muscle function may, in turn, contribute to greater lumbopelvic stability and more efficient mechanical loading during functional activities [32]. The reduction in pain may also have contributed to the observed improvements in disability and kinesiophobia, as pain intensity is an important factor associated with activity limitation and fear of movement in individuals with chronic LBP [33]. The clinical findings of the present study are consistent with previous research. Studies by Streicher et al. (2014) and Luomajoki et al. (2010) have reported beneficial effects of MCEs on pain and disability in individuals with NSCLBP, potentially through improvements in proprioception, neuromuscular coordination, and trunk muscle function [20, 34]. Similarly, Patricio et al. (2020) suggested that MCE may improve functional performance by addressing maladaptive movement patterns and reducing mechanically provoked symptoms [16]. The present findings extend this evidence by demonstrating concurrent changes in the objective biomechanical measures of gait.

Changes in vGRF

A major finding of the present study was the significant modification of vGRF parameters following the eight-week intervention. The experimental group demonstrated an increase in the first and third peaks of vGRF and a reduction in the second peak. These changes may reflect a modification of the loading strategy during stance and a reduction in compensatory gait strategies associated with chronic pain.

Individuals with chronic LBP may adopt protective movement strategies because of persistent pain, reduced confidence in movement, and fear of symptom exacerbation. Such strategies may alter muscle activation, trunk stabilization, and the distribution of mechanical loads during walking [35]. Consequently, patients may modify their weight-transfer strategy to avoid potentially painful loading conditions [36]. Therefore, the changes in vGRF observed after the intervention may reflect a shift toward a more efficient and less protective gait strategy.

Specifically, the increase in the first FzHC following MCE may indicate improved weight acceptance capacity during the initial foot-contact phase of gait. Individuals with chronic LBP may reduce loading during this phase because of pain or fear of movement in an attempt to avoid increasing mechanical stress on spinal structures. Although this adaptation may serve as a protective mechanism in the short term, it may contribute to alterations in the normal gait pattern over the long term [37]. Therefore, the increase in FzHC observed in the present study may indicate reduced pain-related avoidance behavior and an improved ability to transfer body weight more naturally during the initial stance phase. Similarly, da Fonseca et al. (2009) reported that a Pilates-based intervention in individuals with chronic LBP increased the first and third peaks of vGRF while reducing the second peak [38]. These findings are consistent with those of the present study.

Regarding the second FzMS, the findings showed a significant reduction following eight weeks of intervention in the experimental group. Because individuals with chronic LBP may reduce the first peak vGRF (FzHC) to decrease pain associated with ground reaction forces during walking [37], a greater proportion of body weight support may consequently be transferred to the mid-stance phase. This may have contributed to an increase in the second peak vGRF in individuals with chronic LBP. Following the therapeutic exercise intervention, the increase in the first and third peaks of vGRF may have reduced the loading demand during mid-stance, resulting in a reduction in the second peak vGRF.

However, the increase in the third FzPO following MCE may indicate improved function during the terminal stance phase and an enhanced capacity to generate propulsive force during walking. Chronic pain and associated movement limitations may reduce active lower-limb participation and impair the efficiency of the terminal push-off phase. Improvements in neuromuscular control, increased trunk stability, and reduced pain following the intervention may have allowed participants to adopt a more efficient movement pattern during terminal stance.

One potential mechanism underlying these changes may be improved central motor control following exercise. These exercises emphasize coordinated activation of the deep trunk muscles, improved co-contraction of the core musculature, and retraining of appropriate movement patterns, which may enhance lumbopelvic stability and improve the ability to control the body in response to external forces. Improved trunk control may facilitate force transmission across different segments of the kinetic chain and enhance the capacity of the neuromuscular system to regulate externally applied forces during walking [29]. Mohammadi et al. (2016) demonstrated that MCE can modify movement-control strategies in individuals with nonspecific LBP and movement-control impairment. In that study, improvements in biomechanical parameters following the intervention were attributed to enhanced activation of the deep trunk muscles and retraining of motor coordination [28]. Similarly, Ekstrom et al. (2007) reported that MCEs increased the activity and endurance of trunk-stabilizing muscles, including the multifidus, rectus abdominis, and internal oblique muscles. Improved function of these muscles may contribute to greater trunk stability, reduced compensatory movements, and more efficient force transmission along the kinetic chain [6]. The consistency of these findings with those of the present study suggests that interventions aimed at improving motor control may enhance the distribution of mechanical forces during walking by improving trunk muscle function and reducing pain-related compensatory movement patterns.

Strengths, limitations, and future directions

A major strength of this study was the simultaneous assessment of clinical and biomechanical outcomes following MCEs in women with NSCLBP. In addition to commonly used clinical measures such as pain, disability, and kinesiophobia, this study assessed vGRF during walking, providing an objective biomechanical perspective on functional changes associated with the intervention.

Several limitations should be considered when interpreting these findings. First, walking speed could not be precisely controlled because of technical and practical constraints. Because walking speed can substantially influence vGRF parameters, future studies should standardize walking speed or include it as a covariate in the statistical analysis. Second, biomechanical assessment was limited to walking. Although walking is an important functional activity, more demanding tasks such as stair negotiation, running, turning, or sport-specific movements may provide additional information about the functional effects of MCE. Third, the sample consisted exclusively of women with NSCLBP, which limits the generalizability of the findings to men and other populations. Fourth, only the short-term effects of the intervention were assessed. Long-term follow-up studies are therefore needed to determine whether the observed clinical and biomechanical changes are maintained after completion of the intervention. Finally, future studies incorporating electromyography, three-dimensional motion analysis, and additional kinetic variables could provide greater insight into the neuromuscular and biomechanical mechanisms underlying the observed changes in vGRF.

Conclusion

Eight weeks of MCE resulted in significant improvements in pain, disability, and kinesiophobia and was accompanied by significant changes in the vGRF parameters during walking in women with NSCLBP. The increase in the first and third peaks, together with the reduction in the second peak of vGRF in the experimental group, suggests a redistribution of vertical loading across the stance phase. These findings may reflect improved movement control and reduced pain-related protective gait strategies. MCEs may therefore represent a useful rehabilitation approach for addressing both clinical symptoms and functional biomechanical outcomes in women with NSCLBP. Further studies using direct measures of muscle activation, kinematics, and long-term follow-up are warranted to clarify the mechanisms and durability of these effects.

Ethical Considerations

Compliance with ethical guidelines

This randomized controlled clinical trial used a two-group, pre-test–post-test design and was conducted at the Rehabilitation Laboratory of Bu-Ali Sina University, Hamadan, Iran. This study was approved by the Research Ethics Committee of Bu-Ali Sina University Hamadan, Iran (Code: IR.BASU.REC.1402.095) and was registered with the Iranian Registry of Clinical Trials (IRCT), Tehran, Iran (Code: IRCT20240311061249N1).

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Authors' contributions

Conceptualization, writing and final approval: All authors; Study design: Fatemeh Souri; Data collection: Fatemeh Souri and Azadeh Asgarpoor; Data analysis: Fatemeh Souri, Azadeh Asgarpoor, and Mohammadreza Ahmadi.

Conflict of interest

The authors declared no conflict of interest.

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