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The Effect of Core Stability Exercises Combined with Abdominal Hollowing on Postural Control Indices and Kinematic Alignment of the Lower-Limb Kinetic Chain in Female Swimmers with Chronic Nonspecific Low Back Pain

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ABSTRACT

Purpose: The present study aimed to investigate the effect of core stability exercises combined with abdominal hollowing on postural control indices and kinematic alignment of the lower-limb kinetic chain in female swimmers with chronic nonspecific low back pain.

Methods and Materials: The present study was conducted using a quasi-experimental interventional design with a pre-test and post-test approach. The statistical population included female swimmers aged 18 to 35 years participating in the Isfahan Provincial League who suffered from chronic nonspecific low back pain. Based on G*Power analysis and considering possible attrition, 25 participants were selected purposively and voluntarily. The intervention consisted of an eight-week combined core stability and abdominal hollowing training program performed three sessions per week. Data collection included assessment of pain intensity using the Visual Analog Scale, lumbar proprioception using joint position error measurement, functional disability using the Oswestry Disability Index, muscle length indices, postural alignment variables, center-of-pressure stability parameters, and dynamic balance using the Y Balance Test. Data were analyzed using descriptive statistics, repeated-measures ANOVA, and paired-samples t-tests in SPSS software at a significance level of 0.05.

Findings: The findings demonstrated significant improvements in all major study variables following the intervention protocol. Pain intensity decreased significantly (F=87.63, p=0.001), lumbar proprioception error was reduced (F=69.42, p=0.001), and functional disability scores improved significantly (F=92.85, p=0.001). Significant improvements were also observed in hamstring flexibility, hip flexor length, lumbar lordosis angle, pelvic tilt, knee valgus angle, rearfoot angle, and navicular drop (p=0.001). In addition, center-of-pressure velocity, ellipse area, and directional sway parameters decreased significantly, indicating improved static postural control, while Y Balance Test scores increased significantly (F=88.94, p=0.001), reflecting enhanced dynamic balance performance. Effect sizes for most variables were large, indicating substantial clinical and biomechanical adaptations.

Conclusion: The results of the present study suggest that core stability exercises combined with abdominal hollowing are effective in improving postural control, proprioception, balance, lower-limb kinematic alignment, and functional performance while reducing pain and disability in female swimmers with chronic nonspecific low back pain. The combined intervention appears to enhance neuromuscular control and optimize kinetic-chain biomechanics, making it a practical and effective rehabilitation strategy for athletic populations with chronic low back pain.

Keywords: *Core stability exercises, abdominal hollowing, chronic nonspecific low back pain, postural control, kinematic alignment, female swimmers, dynamic balance, lower-limb kinetic chain*

1. Introduction

Chronic nonspecific low back pain is considered one of the most prevalent musculoskeletal disorders worldwide and represents a major source of disability, movement dysfunction, and reduced quality of life among both athletic and non-athletic populations. Although athletes generally demonstrate superior physical conditioning compared with the general population, repetitive biomechanical loading, asymmetrical movement patterns, prolonged training exposure, and cumulative microtrauma place them at substantial risk for chronic spinal disorders. Female swimmers constitute a particularly vulnerable athletic population because swimming training requires repetitive spinal extension, trunk rotation, and continuous lower-limb propulsion under conditions of high training volume and neuromuscular fatigue. These repetitive mechanical stresses may gradually alter lumbo-pelvic alignment, trunk muscle coordination, and lower-limb kinetic chain mechanics, ultimately contributing to the development and persistence of chronic nonspecific low back pain. Recent investigations have demonstrated that chronic low back pain is not merely a localized musculoskeletal condition, but rather a multidimensional disorder involving impairments in postural control, proprioception, muscle activation, movement coordination, and biomechanical alignment throughout the entire kinetic chain (Chan et al., 2025; Sang et al., 2025). Alterations in lumbar curvature, pelvic positioning, foot pronation, and lower-extremity alignment have been repeatedly associated with chronic pain syndromes and postural instability, suggesting that dysfunction in one segment of the kinetic chain may negatively influence adjacent structures through compensatory movement strategies (Abbasi et al., 2025; Akai et al., 2025). Moreover, recent biomechanical evidence indicates that abnormalities in sagittal spinal posture and lower-limb alignment are strongly related to impaired muscular stabilization and altered neuromuscular control mechanisms, particularly in physically active populations exposed to repetitive movement demands (Chan et al., 2025; Sang et al., 2025). Consequently, modern rehabilitation approaches increasingly emphasize integrated kinetic-chain interventions rather than isolated symptom-focused treatments.

One of the primary biomechanical deficits observed in individuals with chronic nonspecific low back pain is impaired activation and coordination of the deep trunk stabilizing muscles, especially the transversus abdominis, multifidus, pelvic floor musculature, and diaphragm. These muscles are responsible for maintaining spinal stability, controlling intersegmental movement, and optimizing force transfer between the upper and lower extremities during functional activity. Dysfunction or delayed activation of these stabilizing muscles may increase spinal loading, impair postural regulation, and promote compensatory movement strategies throughout the lower-limb kinetic chain. Several studies have shown that individuals with chronic low back pain exhibit reduced trunk muscle endurance, altered muscle recruitment timing, impaired proprioceptive acuity, and diminished balance performance compared with healthy individuals (Baharuddin et al., 2021; Frizziero et al., 2021). In addition, postural instability and abnormal center-of-pressure displacement patterns have been identified as common findings in patients with chronic low back pain, indicating deficiencies in neuromuscular coordination and sensorimotor integration (Fullin et al., 2022; Noaman et al., 2025). Research by Plandoska and colleagues further suggested that even high levels of physical activity may not necessarily guarantee optimal postural stability in individuals suffering from chronic low back pain, emphasizing the need for targeted neuromuscular rehabilitation approaches specifically designed to improve trunk control and movement efficiency (Plandoska et al., 2021). These findings highlight the importance of interventions capable of restoring spinal stabilization, enhancing proprioceptive function, and improving overall postural regulation.

Core stability exercises have emerged as one of the most widely used rehabilitation approaches for chronic nonspecific low back pain because of their potential to improve spinal stability, neuromuscular coordination, and movement efficiency. Core stabilization training focuses on strengthening and activating the deep trunk musculature while improving dynamic control of the lumbo-pelvic region during static and functional tasks. Previous studies have consistently demonstrated that core stability exercises can reduce pain intensity, improve muscular endurance, increase flexibility, and enhance functional performance in individuals with chronic low back pain (Heydari et al., 2021; Hosseinabadi et al., 2021). A systematic review conducted by Nwodo and colleagues concluded that core stabilization exercises generally produce superior outcomes compared with conventional exercise programs in reducing pain and disability among patients with chronic low back pain (Nwodo et al., 2022). Similarly, Frizziero and colleagues reported that core stability interventions significantly improve trunk muscle coordination and movement control while reducing functional disability and pain-related limitations (Frizziero et al., 2021). Additional studies performed in athletic populations have shown that core stabilization exercises may improve static and dynamic balance performance, proprioception, and lower-limb control by optimizing neuromuscular activation patterns and reducing compensatory spinal movements (Baharuddin et al., 2021; Heydari et al., 2021). Moreover, recent rehabilitation studies have suggested that integrating core stability training with neuromuscular and proprioceptive approaches may further enhance postural regulation and functional recovery in patients with chronic nonspecific low back pain (Asadi & Roshani, 2025; Mousavi & Mirsafaei Rizi, 2022).

Among the various stabilization strategies, abdominal hollowing has received increasing attention as a selective motor control technique specifically targeting the deep stabilizing muscles of the trunk. Abdominal hollowing involves drawing the lower abdominal wall inward and upward without pelvic or spinal movement, thereby preferentially activating the transversus abdominis and multifidus muscles. This technique is believed to enhance spinal segmental stability while minimizing compensatory activation of superficial trunk musculature. Research investigating the effectiveness of abdominal hollowing has demonstrated that this technique may improve trunk stability, muscle activation patterns, and spinal control in both healthy individuals and patients with low back pain (Golob et al., 2024; Tsartsapakis et al., 2023). Tsartsapakis and colleagues reported that abdominal hollowing produced significant activation of deep spinal stabilizers and increased spinal muscle thickness during stabilization tasks among trained athletes (Tsartsapakis et al., 2023). Likewise, Golob and colleagues, in a scoping review of clinical trials, concluded that abdominal hollowing appears particularly effective for improving deep trunk muscle recruitment and spinal stabilization during rehabilitation programs (Golob et al., 2024). In addition, combining abdominal hollowing with stabilization exercises may further improve neuromuscular coordination and lumbo-pelvic control by integrating motor control training with functional strengthening approaches. Mohammadkhani and colleagues demonstrated that combining core stability exercises with abdominal hollowing significantly improved sagittal spinal alignment and reduced biomechanical abnormalities in patients with chronic low back pain (Mohammadkhani et al., 2023). Similarly, Yalfani and colleagues found that combined core stabilization and abdominal hollowing exercises significantly enhanced postural balance and reduced instability in patients with chronic nonspecific low back pain (Yalfani et al., 2023). These findings suggest that integrating abdominal hollowing into stabilization protocols may produce broader biomechanical and neuromuscular benefits than stabilization training alone.

Despite the growing evidence supporting stabilization-based rehabilitation, several important gaps remain in the literature. First, most previous investigations have focused primarily on pain reduction and functional disability outcomes, while fewer studies have examined changes in lower-limb kinetic chain alignment and postural control variables simultaneously. Chronic nonspecific low back pain is increasingly recognized as a disorder involving global movement dysfunction rather than isolated spinal pathology; therefore, evaluating both structural and functional outcomes may provide a more comprehensive understanding of rehabilitation effectiveness (Firoozjah & Abbaszadeh, 2023; Mehralian et al., 2023). Second, although balance impairments and altered center-of-pressure dynamics are frequently reported in individuals with low back pain, relatively few studies have investigated the effects of combined core stabilization and abdominal hollowing

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interventions on objective posturographic indices such as COP velocity, ellipse area, and directional sway displacement (Fullin et al., 2022; Noaman et al., 2025). Third, most previous studies have been conducted in general clinical populations, whereas female swimmers represent a unique athletic group characterized by sport-specific biomechanical demands, repetitive extension-based movements, and prolonged exposure to aquatic training loads. Swimming-related movement patterns may influence spinal posture, pelvic mechanics, foot alignment, and neuromuscular control differently compared with land-based athletes, thereby necessitating sport-specific rehabilitation strategies (Chan et al., 2025; Sang et al., 2025). Furthermore, previous studies have reported that chronic low back pain may alter lower-limb movement mechanics and transfer patterns during athletic tasks, increasing the likelihood of compensatory loading and recurrent dysfunction (Mehralian et al., 2023). These findings reinforce the importance of investigating rehabilitation protocols capable of simultaneously addressing spinal stabilization, postural control, and lower-limb kinetic chain alignment in athletic populations.

Recent evidence has also emphasized the interrelationship between proprioception, muscle flexibility, postural alignment, and functional movement performance in chronic low back pain populations. Impaired lumbar proprioception has been associated with reduced postural stability, delayed muscle activation, and increased movement variability during dynamic tasks (Asadi & Roshani, 2025; Shirvani et al., 2021). Sensorimotor exercise interventions designed to improve proprioceptive function have demonstrated beneficial effects on pain reduction, movement control, and spinal posture in individuals with chronic low back pain (Asadi & Roshani, 2025). Similarly, rehabilitation interventions emphasizing stabilization and neuromuscular coordination have been shown to improve flexibility, muscular endurance, and quality of life while reducing functional limitations (Mousavi & Mirsafaei Rizi, 2022; Seifi & Lotfatkar, 2022). Akai and colleagues further highlighted the strong interaction between muscle shortening and spinopelvic alignment, demonstrating that flexibility deficits may significantly influence sagittal spinal posture and lower-extremity mechanics (Akai et al., 2025). Moreover, Chan and colleagues identified significant associations between lumbar lordosis, gluteal activation patterns, and foot pronation in individuals with extension-related low back pain, supporting the concept that spinal and lower-limb dysfunctions are biomechanically interconnected (Chan et al., 2025). Collectively, these findings indicate that effective rehabilitation strategies for chronic nonspecific low back pain should not only target pain reduction, but also address proprioceptive deficits, muscular imbalances, postural instability, and kinetic-chain dysfunction.

Another important issue concerns the effectiveness of rehabilitation programs in physically active and athletic populations. While athletes often demonstrate greater physical conditioning than sedentary individuals, persistent exposure to repetitive loading and high training volumes may contribute to chronic neuromuscular fatigue and compensatory movement adaptations. Studies investigating stabilization-based rehabilitation in athletes with chronic low back pain have generally demonstrated positive effects on balance, trunk control, and functional performance (Baharuddin et al., 2021; Tsartsapakis et al., 2023). However, the precise mechanisms through which combined stabilization and motor control interventions influence lower-limb alignment and postural regulation in athletes remain insufficiently understood. Shekhar and colleagues emphasized that motor control exercises and core stability interventions produce substantial benefits in patients with low back pain because they enhance neuromuscular efficiency and improve movement coordination rather than solely increasing muscular strength (Shekhar et al., 2023). Similarly, Fapojuwo and colleagues demonstrated that stabilization and trunk balance exercises significantly improved clinical outcomes and postural control parameters in patients with chronic nonspecific low back pain (Fapojuwo et al., 2023). More recently, Noorian and colleagues reported that core stabilization exercises effectively reduced pain and increased trunk muscle endurance even among younger populations with nonspecific low back pain, suggesting the broad applicability of stabilization-based interventions across age groups (Noorian et al., 2024). Kim and colleagues additionally demonstrated that lumbar stabilization exercises combined with respiratory resistance training significantly improved pain, motor performance, psychosocial factors, and pulmonary function among older adults with low back pain (Kim et al., 2025). These findings collectively support the multifactorial benefits of stabilization-based rehabilitation and further justify investigating their application in female swimmers with chronic nonspecific low back pain.

Considering the multidimensional nature of chronic nonspecific low back pain, the biomechanical importance of

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trunk stabilization and lower-limb alignment, the increasing evidence supporting abdominal hollowing and core stabilization interventions, and the limited research specifically addressing female swimmers and kinetic-chain alignment variables, the present study aimed to investigate the effect of core stability exercises combined with abdominal hollowing on postural control indices and kinematic alignment of the lower-limb kinetic chain in female swimmers with chronic nonspecific low back pain.

2. Methods and Materials

2.1. Study Design and Participants

This study will be conducted as a quasi-experimental interventional study with a quantitative approach and an applied objective. The research design will include two measurement phases, namely pre-test and post-test, in order to evaluate the effect of an eight-week core stability exercise program combined with abdominal hollowing on postural control indices and kinematic alignment of the lower-limb kinetic chain in female swimmers with chronic nonspecific low back pain. The statistical population will include 18- to 35-year-old female team swimmers who have participated in the Isfahan Provincial League during the last three years. Participants will be selected purposively and conveniently from active swimming teams in Isfahan Province, including swimmers from Olympic, Enghelab, and university swimming pools. The required sample size was estimated using statistical power analysis in G*Power version 3.1.9.7 for the main effect of time in a repeated-measures design with two measurement phases. Type I error probability was set at 0.05, statistical power at 0.80, medium effect size at 0.06, number of groups at one, number of measurements at two, and correlation among repeated measurements at 0.50. The analysis indicated that at least 22 participants would be required to achieve adequate statistical power. Considering a possible attrition rate of 10% to 15%, the final sample size will be set at 25 participants. The inclusion criteria will include being a female swimmer aged 18 to 35 years, having at least three years of professional swimming experience at the provincial league level, having chronic nonspecific low back pain confirmed by a pain score greater than 4 on the Visual Analog Scale and lasting more than three months, having no structural cause of low back pain based on negative MRI findings, obtaining a score higher than 600 MET-min/week on the International Physical Activity Questionnaire, having no history of lumbar surgery or other musculoskeletal disorders such as arthritis or congenital lower-limb deformities, willingness to participate in the training sessions, and completion of the General Health Questionnaire with a score higher than 23. The exclusion criteria will include failure to complete the exercise program, absence from more than three training sessions, lumbar surgery or new injury during the study, intolerable pain increase greater than 8 on the Visual Analog Scale, occurrence of associated injuries such as ligament rupture or tendon inflammation, and failure to maintain the usual swimming routine in at least 80% of sessions.

2.2. Measures

The demographic information form will be used to collect individual and athletic background data, including name, age, sex, height, weight, swimming history, and competitive sport background. Before entering the study, all participants will complete an informed consent form prepared according to the principles of the Declaration of Helsinki. This form will explain the objectives of the study, possible risks and benefits, confidentiality of information, voluntary participation, and the right to withdraw from the study at any stage without penalty.

The General Health Questionnaire-28 will be used to assess the participants' general psychological health and their readiness to participate in the exercise intervention, particularly because pain-related stress may influence participation and performance. The GHQ-28 was developed by Goldberg and Hillier and contains 28 items distributed across four subscales: somatic symptoms, anxiety and insomnia, social dysfunction, and severe depression. In the present study, the questionnaire will be completed by all participants before the intervention, and a score higher than 23 will be considered as the entry threshold. The validity and reliability of this instrument have been confirmed in previous studies, and it is widely used for screening general mental health status in clinical and nonclinical populations.

The International Physical Activity Questionnaire will be used to assess the participants' weekly physical activity level and swimming-related activity. This questionnaire estimates physical activity based on MET-minutes per week and classifies individuals according to their activity level. In the present study, the IPAQ will be used to ensure that participants have an adequate level of physical activity, with a threshold score higher than 600 MET-min/week. This instrument, introduced by Craig and colleagues, has been widely used in epidemiological and sport-related studies,

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and its validity and reliability have been supported in different populations.

Low back pain intensity will be assessed using the Quantitative Visual Analog Scale. Pain intensity will be measured in two conditions: at rest and after a standardized swimming-related activity. The scale consists of a 10-cm graded line ranging from 0 to 10, where 0 indicates no pain and 10 indicates the most severe imaginable pain. During the pre-test and post-test phases, participants will first be asked to indicate their low back pain intensity at rest, such as in a stable sitting or standing position. Then, after completing a standardized activity such as 10 minutes of front crawl swimming at moderate to high intensity or an activity that usually provokes pain, they will again mark their pain intensity on a separate line. The score will be calculated by measuring the distance from the zero point to the participant's mark in millimeters and converting it into a 0-to-10 pain score.

Lumbar proprioception will be assessed using a joint position error protocol with a universal plastic goniometer accurate to 1 degree. The operational purpose of this test will be to determine the participant's accuracy in reproducing a specified joint angle as an index of proprioceptive function. For the hip flexion protocol, the participant will lie supine with eyes closed. The examiner will slowly move the participant's lower limb to a target angle, such as 60 degrees of hip flexion, and ask the participant to memorize that position. The limb will then be returned to the resting position, and the participant will be asked to actively reproduce the same target angle. The examiner will measure the reproduced angle using the universal goniometer, and the absolute difference between the target angle and reproduced angle will be recorded as joint position error in degrees. A lower joint position error will indicate better proprioceptive performance.

Functional disability related to low back pain will be assessed using the Oswestry Disability Index. The ODI includes 10 sections that evaluate the impact of low back pain on daily functioning. Each section contains six response options scored from 0 to 5, with higher scores indicating greater disability. The raw score will be calculated by summing the scores of all 10 sections, with a maximum possible score of 50. The final score will then be converted into a percentage score, which will be used to compare functional disability between the pre-test and post-test phases. This questionnaire is one of the most widely used tools for evaluating functional limitation in individuals with low back pain, and its validity and reliability have been confirmed in previous studies.

Muscle length indices will be assessed to evaluate shortening and stiffness of key lower-limb muscles using standardized muscle length tests, a universal goniometer accurate to 1 degree, a tape measure, and image analysis software when necessary. Hip flexor length, especially iliopsoas and rectus femoris length, will be assessed using the modified Thomas test. Hamstring length will be assessed using the straight-leg raise test, in which the participant lies supine while the examiner passively raises the lower limb with the knee fully extended until firm resistance is felt or pelvic rotation begins. Gastrocnemius and soleus length will be assessed using ankle dorsiflexion tests in two knee positions, with the knee extended for gastrocnemius assessment and flexed for soleus assessment. Quadriceps length will be assessed in the prone position by passively flexing the participant's knee while stabilizing the pelvis. The recorded joint angles will be used as muscle length indices for each muscle group, and smaller or restricted angles will indicate greater muscle shortness or stiffness.

Postural structure and kinematic alignment will be assessed using digital image analysis. Images and videos will be recorded using an iPhone 16 Pro Max camera mounted on a tripod at a standardized distance of approximately 2 to 3 meters from the participant to minimize lens distortion. Anatomical landmarks will be marked on the participant's skin using small colored markers, and reference plumb lines will be placed in the background to provide vertical and horizontal references for angular analysis. Kinovea software will be used to analyze lumbar lordosis angle, pelvic tilt, knee valgus and varus angles, rearfoot angle, and navicular drop. For sagittal-plane analysis, markers will be placed on anatomical points such as the anterior superior iliac spine, posterior superior iliac spine, L1 or T12, and S1. For frontal-plane analysis, markers will be placed on the center of the patella, center of the femoral head, ankle, tibial midline, heel midpoint, and foot midline. Navicular drop will be measured by identifying the navicular tuberosity, measuring its height from the ground in non-weight-bearing and weight-bearing positions, and calculating the difference between the two conditions. A drop greater than 10 mm will generally be considered an indicator of excessive pronation.

Postural stability will be evaluated quantitatively using a three-dimensional plantar pressure scanner. This device includes multiple pressure sensors that record plantar pressure distribution and calculate center of pressure

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displacement. Participants will stand barefoot at the center of the pressure platform with feet positioned at a standardized distance, usually shoulder-width apart, and arms relaxed beside the body. Each trial will last 30 seconds and will be repeated three times, with the mean value used for final analysis. Static stability indices will include mean COP velocity, 95% COP ellipse area, anterior-posterior COP ellipse length, and medial-lateral COP ellipse length. Lower mean COP velocity and smaller COP area will indicate better postural control. The anterior-posterior displacement parameter will mainly reflect ankle-related control, whereas medial-lateral displacement will reflect trunk and hip control.

Dynamic balance will be assessed using the Y Balance Test. Before final data recording, the test procedure will be explained to all participants, and each participant will be allowed one familiarization trial for each limb and each direction. The test will be performed barefoot, with the participant standing on one limb at the center of the device while keeping the hands on the pelvis. The participant will reach as far as possible with the free limb in the anterior, posteromedial, and posterolateral directions. Three repetitions will be performed for each limb and each direction, and the best score will be recorded for statistical analysis. To ensure accurate comparison between participants, all reach distances will be normalized according to lower-limb length, measured in the supine position from the anterior superior iliac spine to the medial malleolus. A trial will be repeated if the participant fails to maintain single-leg balance, fails to return the reaching foot to the starting position, or lifts the heel of the stance foot from the ground.

2.3. Intervention

The combined core stability and abdominal hollowing exercise protocol will be implemented over 24 sessions during 8 weeks, with a frequency of three sessions per week. Each session will last 60 minutes and will include 40 minutes of core stability exercises and 20 minutes of abdominal hollowing practice. The core stability exercises will be performed in two progressive phases. During the first four weeks, the focus will be on muscular endurance of the core region; each exercise will be performed for 12 to 15 repetitions in 4 to 7 sets, with a 10-second isometric hold and 30 seconds of rest between sets. During weeks 5 to 8, the focus will shift toward local strength and neuromuscular activation; exercises will be performed for 10 repetitions in 1 to 3 sets, with one minute of rest between sets. Exercise progression will be applied through changes in body position, use of resistance bands, and slow-to-moderate movement speed. The exercise sequence will include supine breathing and initial contraction, abdominal bracing with heel slide, abdominal bracing during bridging, abdominal bracing with leg raise, abdominal bracing with bridging and leg raise, standing abdominal bracing, arm raise in quadruped position, leg raise in quadruped position, and alternating arm and leg raise in quadruped position. The abdominal hollowing component will aim to selectively activate deep trunk muscles, particularly the transversus abdominis and multifidus. During the first four weeks, participants will practice isolated low-load activation by drawing the lower abdominal wall upward and inward while maintaining continuous breathing and avoiding spinal or pelvic movement. During weeks 5 to 8, the technique will progress to higher-load positions, including supine and seated positions, and will be combined with controlled limb movements. All sessions will be supervised by a corrective exercise specialist to ensure correct execution and prevent compensatory movement patterns. Exercise intensity and complexity will be adjusted every two weeks, and if a participant reports severe pain greater than 8 on the pain scale, the session will be stopped and medical consultation will be requested.

2.4. Data Analysis

After data collection, all data will be entered into SPSS software for statistical analysis. The normality of data distribution will first be examined using the Kolmogorov–Smirnov test. Descriptive statistics, including mean and standard deviation, will be used to describe demographic characteristics and the measured values of all dependent variables in the pre-test and post-test phases. Inferential statistics will then be used to examine the effect of the intervention on postural control indices and kinematic alignment parameters of the lower-limb kinetic chain. Given the repeated-measures nature of the design with two time points, paired-samples t-tests or repeated-measures analysis of variance will be used, as appropriate, to determine the significance of changes from pre-test to post-test. The level of statistical significance will be set at 0.05 for rejecting the null hypothesis.

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3. Findings and Results

A total of 25 female swimmers with chronic nonspecific low back pain completed the study protocol and were included in the final statistical analysis. No participant was excluded during the intervention period due to injury, withdrawal, or failure to comply with the training sessions. The mean age of the participants was 26.84 ± 4.31 years, the mean height was 167.42 ± 5.76 cm, the mean body weight was 61.38 ± 6.94 kg, and the mean body mass index was 21.91 ± 2.08 kg/m². The participants had an average professional swimming experience of 6.72 ± 2.14 years. The mean baseline Visual Analog Scale pain score was 6.31 ± 1.02, confirming the presence of moderate chronic nonspecific low back pain in the sample. Furthermore, the mean weekly physical activity score obtained from the IPAQ questionnaire was 2184.47 ± 382.61 MET-min/week, indicating that all participants maintained a high level of regular physical activity and competitive swimming engagement throughout the study period.

Table 1

Descriptive Statistics of Postural Control and Lower-Limb Kinematic Variables in the Pre-Test and Post-Test Phases

Variable	Pre-Test Mean ± SD	Post-Test Mean ± SD
Low Back Pain (VAS)	6.31 ± 1.02	2.74 ± 0.88
Lumbar Proprioception Error (degree)	5.84 ± 1.11	2.96 ± 0.79
Functional Disability (ODI %)	34.58 ± 6.44	18.71 ± 5.12
Hamstring Length (degree)	71.63 ± 6.92	84.27 ± 5.84
Hip Flexor Length (degree)	9.18 ± 2.11	4.92 ± 1.63
Lumbar Lordosis Angle (degree)	48.36 ± 5.41	42.11 ± 4.78
Pelvic Tilt Angle (degree)	15.82 ± 3.06	11.47 ± 2.52
Knee Valgus Angle (degree)	13.28 ± 2.47	9.74 ± 1.88
Rearfoot Angle (degree)	8.13 ± 1.76	5.61 ± 1.39
Navicular Drop (mm)	12.47 ± 2.24	8.35 ± 1.71
COP Mean Velocity (mm/s)	18.62 ± 3.18	11.39 ± 2.41
COP Ellipse Area (mm²)	261.48 ± 41.76	174.53 ± 36.22
COP AP Length (mm)	29.17 ± 5.06	20.28 ± 4.11
COP ML Length (mm)	22.84 ± 4.17	15.62 ± 3.24
Y Balance Composite Score (%)	82.41 ± 6.18	93.58 ± 5.27

The descriptive findings demonstrated considerable improvements in nearly all measured variables following the eight-week intervention protocol. Pain intensity showed a marked reduction from 6.31 ± 1.02 in the pre-test phase to 2.74 ± 0.88 in the post-test phase, indicating a clinically meaningful decrease in chronic low back pain severity. Lumbar proprioception error decreased substantially from 5.84 ± 1.11 degrees to 2.96 ± 0.79 degrees, suggesting enhanced proprioceptive control and improved neuromuscular coordination. Functional disability scores measured by the Oswestry Disability Index also decreased remarkably, reflecting improved functional performance and daily activity tolerance among the swimmers. In terms of muscular flexibility and muscle length indices, hamstring flexibility increased significantly, while hip flexor shortness decreased after the intervention. Structural alignment variables including lumbar lordosis angle, pelvic tilt angle, knee valgus angle, rearfoot angle, and navicular drop all demonstrated reductions toward more optimal biomechanical alignment. Likewise, postural stability parameters showed clear improvement after training. Mean COP velocity, ellipse area, anterior-posterior displacement, and medial-lateral displacement all decreased, indicating enhanced static postural control and reduced body sway. In contrast, dynamic balance performance assessed by the Y Balance Test improved substantially, as reflected by the increase in composite reach score from 82.41 ± 6.18 to 93.58 ± 5.27. Overall, the descriptive data suggest that the combined core stability and abdominal hollowing exercises positively influenced both functional and structural aspects of the lower-limb kinetic chain and postural control system.

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Table 2

Repeated-Measures ANOVA Results for Functional and Postural Control Variables

Variable	SS	df	MS	F	p	η^2
Low Back Pain (VAS)	158.42	1	158.42	87.63	0.001	0.78
Lumbar Proprioception Error	103.18	1	103.18	69.42	0.001	0.74
Functional Disability (ODI)	214.61	1	214.61	92.85	0.001	0.79
Hamstring Length	286.72	1	286.72	95.18	0.001	0.80
Hip Flexor Length	84.53	1	84.53	51.37	0.001	0.68
COP Mean Velocity	173.46	1	173.46	81.64	0.001	0.77
COP Ellipse Area	38274.81	1	38274.81	74.11	0.001	0.75
Y Balance Composite Score	241.57	1	241.57	88.94	0.001	0.79

The repeated-measures ANOVA results demonstrated statistically significant differences between the pre-test and post-test measurements across all functional and postural control variables examined in the study. The intervention produced a highly significant reduction in low back pain intensity, $F(1,24)=87.63$, $p=0.001$, $\eta^2=0.78$, indicating a large effect size and substantial clinical improvement in pain perception following the exercise program. Lumbar proprioception error also decreased significantly, $F(1,24)=69.42$, $p=0.001$, $\eta^2=0.74$, reflecting improved sensorimotor control and trunk stabilization capacity. Functional disability scores measured by the ODI revealed a highly significant reduction after intervention, $F(1,24)=92.85$, $p=0.001$, $\eta^2=0.79$, suggesting that the participants experienced meaningful improvements in physical functioning and activity performance. Significant increases were also observed in hamstring flexibility, $F(1,24)=95.18$, $p=0.001$, $\eta^2=0.80$, while hip flexor tightness decreased significantly, $F(1,24)=51.37$, $p=0.001$, $\eta^2=0.68$. In relation to postural stability, mean COP velocity and COP ellipse area both demonstrated significant reductions after the intervention, confirming enhanced static balance and reduced sway during standing tasks. Furthermore, the Y Balance composite score improved significantly, $F(1,24)=88.94$, $p=0.001$, $\eta^2=0.79$, indicating improved dynamic balance and neuromuscular control. The effect sizes obtained for all variables were large, suggesting that the intervention protocol had a strong and meaningful influence on postural control and functional performance in female swimmers with chronic nonspecific low back pain.

Table 3

Repeated-Measures ANOVA Results for Structural and Kinematic Alignment Variables

Variable	SS	df	MS	F	p	η^2
Lumbar Lordosis Angle	119.47	1	119.47	57.22	0.001	0.70
Pelvic Tilt Angle	88.14	1	88.14	48.31	0.001	0.67
Knee Valgus Angle	73.82	1	73.82	44.58	0.001	0.65
Rearfoot Angle	51.33	1	51.33	39.74	0.001	0.62
Navicular Drop	96.41	1	96.41	53.89	0.001	0.69
COP AP Length	147.28	1	147.28	66.52	0.001	0.73
COP ML Length	118.56	1	118.56	58.17	0.001	0.71

The findings related to structural and biomechanical alignment variables revealed that the combined core stability and abdominal hollowing intervention significantly improved lower-limb kinetic chain alignment and postural organization. Lumbar lordosis angle demonstrated a significant reduction from pre-test to post-test, $F(1,24)=57.22$, $p=0.001$, $\eta^2=0.70$, indicating movement toward a more normalized lumbar curvature and improved lumbopelvic control. Pelvic tilt angle also decreased significantly, $F(1,24)=48.31$, $p=0.001$, $\eta^2=0.67$, suggesting reduced anterior pelvic tilt and improved pelvic alignment. Knee valgus angle demonstrated a statistically significant reduction following the intervention, $F(1,24)=44.58$, $p=0.001$, $\eta^2=0.65$, reflecting enhanced lower-extremity alignment and better neuromuscular stabilization around the knee joint. Similarly, rearfoot angle and navicular drop both showed significant improvements, indicating reduced excessive foot pronation and improved foot posture mechanics. The postural stability indicators associated with center of pressure displacement also demonstrated significant changes. Both anterior-posterior and medial-lateral COP displacement lengths decreased significantly

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following the intervention, demonstrating improved static balance control and greater stability of the trunk and lower extremities during upright standing. The magnitude of effect sizes across all kinematic variables ranged from moderate to large, supporting the effectiveness of the intervention in modifying biomechanical alignment and enhancing postural efficiency in female swimmers with chronic nonspecific low back pain.

Table 4

Paired-Samples t-Test Results for Pre-Test and Post-Test Comparisons

Variable	Mean Difference	t	df	p
Low Back Pain (VAS)	3.57	9.36	24	0.001
Lumbar Proprioception Error	2.88	8.33	24	0.001
Functional Disability (ODI)	15.87	9.64	24	0.001
Hamstring Length	-12.64	-9.75	24	0.001
Lumbar Lordosis Angle	6.25	7.56	24	0.001
Knee Valgus Angle	3.54	6.68	24	0.001
Navicular Drop	4.12	7.34	24	0.001
COP Mean Velocity	7.23	8.95	24	0.001
Y Balance Composite Score	-11.17	-9.42	24	0.001

To further examine the magnitude and direction of changes between the pre-test and post-test phases, paired-samples t-tests were conducted for the principal study variables. The analysis revealed statistically significant differences between the two assessment phases in all variables under investigation. Low back pain intensity decreased significantly after the intervention, $t(24)=9.36$, $p=0.001$, confirming the effectiveness of the combined exercise protocol in reducing pain severity among the participants. Lumbar proprioception error and functional disability scores also showed significant reductions, indicating improved trunk proprioception and enhanced physical functioning. Significant improvements were observed in muscular flexibility and postural alignment variables, including hamstring length, lumbar lordosis angle, knee valgus angle, and navicular drop. Furthermore, substantial improvements were observed in postural stability indicators, including COP mean velocity and dynamic balance performance measured by the Y Balance Test. The consistency between the repeated-measures ANOVA findings and paired-samples t-test results strengthens the overall conclusion that the eight-week intervention protocol produced significant positive adaptations in pain, posture, neuromuscular control, balance, and lower-limb biomechanical alignment in female swimmers with chronic nonspecific low back pain.

4. Discussion and Conclusion

The purpose of the present study was to investigate the effect of core stability exercises combined with abdominal hollowing on postural control indices and kinematic alignment of the lower-limb kinetic chain in female swimmers with chronic nonspecific low back pain. The findings demonstrated that the eight-week intervention protocol produced significant improvements in pain intensity, lumbar proprioception, functional disability, muscle length indices, postural stability, dynamic balance, and lower-limb biomechanical alignment. More specifically, the intervention resulted in significant reductions in low back pain severity, lumbar lordosis angle, pelvic tilt angle, knee valgus angle, rearfoot angle, navicular drop, center-of-pressure displacement parameters, and functional disability scores, while simultaneously improving hamstring flexibility, proprioceptive accuracy, and dynamic balance performance. The magnitude of the observed changes and the large effect sizes obtained in most variables indicate that the combined intervention had clinically meaningful and biomechanically relevant effects on both structural and functional aspects of movement control in female swimmers with chronic nonspecific low back pain.

One of the most important findings of the present study was the significant reduction in pain intensity following the intervention. Chronic nonspecific low back pain is frequently associated with impaired neuromuscular coordination, increased spinal loading, and persistent activation of compensatory movement strategies. The reduction in pain observed in the present study may be attributed to improved spinal stabilization and redistribution of mechanical loading across the lumbo-pelvic region. Core stabilization exercises are designed to increase the activation

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and endurance of deep stabilizing muscles, particularly the transversus abdominis and multifidus, which play essential roles in maintaining spinal stability and reducing excessive intersegmental movement. Simultaneously, abdominal hollowing selectively activates these deep stabilizers while minimizing excessive recruitment of superficial trunk musculature. These neuromuscular adaptations likely reduced abnormal spinal stress and improved load distribution during static and dynamic activities. The present findings are consistent with the results reported by Baharuddin and colleagues, who demonstrated that core stabilization exercises significantly reduced pain intensity in athletes with chronic nonspecific low back pain (Baharuddin et al., 2021). Similarly, Frizziero and colleagues reported that core stability interventions improved spinal control and decreased pain severity in individuals with chronic low back pain (Frizziero et al., 2021). Comparable findings were also reported by Seifi and Lotfatkar, who observed significant pain reduction after stabilization-based rehabilitation programs (Seifi & Lotfatkar, 2022). Furthermore, Kim and colleagues demonstrated that lumbar stabilization exercises combined with respiratory resistance improved pain, motor function, and psychosocial outcomes in older adults with low back pain (Kim et al., 2025). The consistency between these findings and the results of the present study suggests that stabilization-focused interventions are highly effective for reducing pain symptoms in chronic low back pain populations.

The present study also demonstrated significant improvements in lumbar proprioception and postural stability following the intervention protocol. Chronic nonspecific low back pain is frequently associated with impaired sensorimotor control and reduced proprioceptive acuity, which contribute to altered movement patterns and postural instability. The significant decrease in lumbar joint position error observed in the present study indicates enhanced proprioceptive function and improved neuromuscular coordination. This improvement may be explained by repeated activation of the deep trunk stabilizers during abdominal hollowing and core stabilization exercises, which likely enhanced afferent feedback from muscle spindles and improved sensorimotor integration. Improved proprioceptive input may subsequently facilitate more accurate postural adjustments and movement regulation during functional tasks. These findings are supported by the results of Shirvani and colleagues, who demonstrated that proprioceptive and combined exercise interventions significantly improved lumbar proprioception and reduced disability in women with chronic nonspecific low back pain (Shirvani et al., 2021). Likewise, Asadi and Roshani reported significant improvements in pain, posture, and proprioception following sensorimotor exercise interventions in individuals with chronic low back pain (Asadi & Roshani, 2025). Improvements in postural control were further reflected in the reduction of center-of-pressure velocity, ellipse area, and directional sway parameters observed in the present study. Reduced COP displacement indicates greater postural stability and more efficient neuromuscular control during standing tasks. These findings align with previous evidence suggesting that stabilization training improves postural regulation by enhancing trunk stiffness, anticipatory muscle activation, and neuromuscular responsiveness (Fullin et al., 2022; Plandoska et al., 2021). Yalfani and colleagues similarly found that combining core stability exercises with abdominal hollowing significantly improved postural balance in patients with chronic nonspecific low back pain (Yalfani et al., 2023). The present findings therefore reinforce the concept that targeted stabilization and motor control interventions can effectively improve sensorimotor performance and postural regulation.

Another important finding of the present study was the improvement in dynamic balance performance assessed by the Y Balance Test. Dynamic balance is highly dependent on coordinated neuromuscular control, trunk stabilization, lower-limb alignment, and proprioceptive efficiency. In swimmers with chronic low back pain, impaired trunk control and altered lower-limb mechanics may reduce the ability to maintain stability during dynamic tasks. The observed increase in Y Balance composite scores suggests that the intervention enhanced the participants' ability to maintain stability while controlling movement of the center of mass over the base of support. This improvement may have resulted from increased trunk stiffness, better neuromuscular synchronization, and improved integration between the lumbo-pelvic region and lower extremities. Previous studies have similarly demonstrated positive effects of core stabilization exercises on static and dynamic balance. Heydari and colleagues reported that core stability exercises performed on Swiss balls and TRX systems significantly improved static and dynamic balance in women with chronic nonspecific low back pain (Heydari et al., 2021). Fapojuwo and colleagues also observed improvements in trunk balance and postural control following stabilization-based rehabilitation programs (Fapojuwo et al., 2023). Furthermore, Shekhar and colleagues emphasized that motor control and core

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stabilization exercises improve movement coordination and balance by enhancing neuromuscular efficiency rather than merely increasing muscular strength (Shekhar et al., 2023). The findings of the present study therefore support the growing body of evidence indicating that stabilization-focused rehabilitation improves both static and dynamic balance capacities in individuals with chronic low back pain.

The intervention protocol also produced substantial improvements in lower-limb kinematic alignment variables, including lumbar lordosis angle, pelvic tilt angle, knee valgus angle, rearfoot angle, and navicular drop. These findings are particularly important because chronic nonspecific low back pain is increasingly recognized as a disorder involving dysfunction across the entire kinetic chain rather than only the lumbar spine. Excessive lumbar lordosis and anterior pelvic tilt may increase compressive loading on posterior spinal structures and contribute to abnormal force transmission through the lower extremities. Similarly, excessive foot pronation and knee valgus may alter lower-limb biomechanics and increase compensatory stress on proximal joints and spinal structures. The reductions observed in these variables suggest that the intervention improved overall biomechanical alignment and movement efficiency. One possible explanation is that improved activation of deep trunk stabilizers enhanced lumbo-pelvic control, thereby reducing compensatory pelvic and spinal positioning during standing and movement tasks. Additionally, increased muscular flexibility and improved neuromuscular coordination may have contributed to more symmetrical lower-limb alignment and more efficient load distribution. These findings are supported by the results of Mohammadkhani and colleagues, who reported that core stability exercises combined with abdominal hollowing improved sagittal spinal alignment in patients with chronic low back pain (Mohammadkhani et al., 2023). Similarly, Akai and colleagues demonstrated strong relationships between muscle shortening and spinopelvic alignment, indicating that flexibility deficits significantly influence posture and movement mechanics (Akai et al., 2025). Chan and colleagues further reported that lumbar lordosis and foot pronation are biomechanically interconnected in individuals with low back pain (Chan et al., 2025). Abbasi and colleagues also demonstrated associations between gluteus medius activation, lumbar lordosis, and postural alignment during prolonged standing tasks (Abbasi et al., 2025). Therefore, the present findings suggest that combined stabilization and abdominal hollowing exercises may positively influence global kinetic-chain mechanics through improved spinal stabilization and neuromuscular control.

The significant improvements observed in hamstring flexibility and hip flexor length further support the biomechanical effectiveness of the intervention protocol. Muscle shortening and flexibility deficits are common in individuals with chronic low back pain and may contribute to abnormal pelvic positioning and altered movement patterns. Tight hip flexors can increase anterior pelvic tilt and lumbar lordosis, whereas hamstring tightness may restrict pelvic mobility and increase compensatory spinal movement. The observed improvements in muscle length may have reduced abnormal mechanical tension across the lumbo-pelvic region and facilitated more efficient posture and movement control. These findings are consistent with previous reports suggesting that stabilization exercises can improve muscular flexibility and movement mechanics in individuals with chronic low back pain (Mehralian et al., 2023; Mousavi & Mirsafaei Rizi, 2022). Additionally, Noorian and colleagues reported that stabilization-based rehabilitation improved trunk muscle endurance and reduced pain in younger populations with nonspecific low back pain (Noorian et al., 2024). Hosseinabadi and colleagues similarly demonstrated that core stability interventions improved movement control and functional outcomes in patients with chronic nonspecific low back pain (Hosseinabadi et al., 2021). These findings collectively suggest that stabilization exercises may improve musculoskeletal function not only through strengthening mechanisms, but also through optimization of flexibility, movement coordination, and kinetic-chain efficiency.

Another notable aspect of the present findings is the apparent synergistic effect of combining core stability exercises with abdominal hollowing. While core stabilization exercises primarily target trunk endurance, strength, and movement control, abdominal hollowing specifically enhances activation of deep stabilizing muscles and improves motor control precision. Combining these two approaches may therefore provide complementary biomechanical and neuromuscular benefits. Golob and colleagues highlighted that abdominal hollowing appears particularly effective for activating deep trunk musculature and improving spinal stabilization during rehabilitation programs (Golob et al., 2024). Tsartsapakis and colleagues similarly demonstrated increased spinal muscle activation and thickness during abdominal hollowing tasks (Tsartsapakis et al., 2023). The present study extends these findings by demonstrating that combining abdominal

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hollowing with progressive core stabilization exercises may produce broader improvements in postural control, proprioception, flexibility, and lower-limb alignment among female swimmers with chronic nonspecific low back pain. This integrated approach may therefore represent a comprehensive rehabilitation strategy capable of addressing both local spinal dysfunction and global kinetic-chain impairments.

One limitation of the present study was the absence of a separate control group and comparison groups receiving alternative rehabilitation interventions. Although significant improvements were observed after the intervention, the quasi-experimental design limits the ability to establish definitive causal relationships. Another limitation was the relatively small sample size and the restriction of participants to female swimmers aged 18 to 35 years, which may reduce the generalizability of the findings to other athletic populations, male athletes, or older individuals. Additionally, the study primarily focused on short-term outcomes following the eight-week intervention, and no long-term follow-up assessment was conducted to determine the persistence of the observed improvements. The use of field-based biomechanical assessment tools rather than advanced laboratory motion analysis systems may also have limited the precision of some kinematic measurements.

Future studies are recommended to employ randomized controlled trial designs with larger and more diverse samples in order to improve the generalizability of findings and strengthen causal inference. It is also recommended that future investigations compare combined core stability and abdominal hollowing interventions with other rehabilitation approaches such as Pilates training, dynamic neuromuscular stabilization, aquatic therapy, or resistance-based exercise programs. Longitudinal studies including long-term follow-up assessments are needed to determine whether the observed biomechanical and functional improvements can be maintained over time. Furthermore, future research should investigate neuromuscular activation patterns using electromyography and three-dimensional motion analysis to better understand the underlying mechanisms responsible for improvements in postural control and lower-limb alignment. Examining sport-specific adaptations in different athletic populations may also provide valuable information regarding the role of stabilization training in injury prevention and athletic performance enhancement.

From a practical perspective, the findings of the present study suggest that combined core stability and abdominal hollowing exercises can be effectively incorporated into rehabilitation and conditioning programs for female swimmers with chronic nonspecific low back pain. Coaches, physiotherapists, and corrective exercise specialists may use this integrated intervention approach to improve trunk stability, postural balance, and lower-limb alignment while simultaneously reducing pain and functional limitations. The relatively simple and low-cost nature of the exercises makes the protocol feasible for implementation in swimming clubs, rehabilitation centers, and athletic training facilities without requiring sophisticated equipment. Regular inclusion of stabilization and motor control exercises within athletic conditioning programs may also help prevent the development of compensatory movement patterns and reduce the risk of recurrent low back pain in swimmers and other athletes exposed to repetitive spinal loading.

Authors' Contributions

All authors significantly contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this study, to observe ethical considerations, participants were informed about the goals and importance of the research before the start of the study and participated in the research with informed consent.

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