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Effects of Pain Neuroscience Education Combined with Dynamic Neuromuscular Stabilization on Movement Control and Clinical Outcomes in Individuals with Chronic Non-Specific Low Back Pain: A Three-Arm Randomized Controlled Trial

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ABSTRACT

Purpose: This study aimed to compare the effects of pain neuroscience education combined with dynamic neuromuscular stabilization, dynamic neuromuscular stabilization alone, and conventional core exercise on lumbar motor control, pain intensity, functional disability, and quality of life in individuals with chronic non-specific low back pain.

Methods and Materials: This three-arm randomized controlled trial included 54 adults aged 25–40 years with chronic non-specific low back pain who were randomly allocated to PNE + DNS, DNS, or conventional core exercise groups (n = 18 each). All groups completed an 8-week supervised intervention with three sessions per week. Outcomes were assessed at pre-test, post-test, and 2-month follow-up using a six-test lumbar movement-control battery, visual analogue scale, Roland–Morris Disability Questionnaire, and SF-36. Data were analyzed using 3 × 3 mixed-model repeated-measures ANOVA with Bonferroni-adjusted pairwise comparisons.

Findings: Significant Time × Group interactions were found for lumbar motor control, $F(3.156, 80.488) = 7.004, p < 0.001, \eta^2 = 0.215$; pain, $F(3.388, 86.388) = 53.282, p < 0.001, \eta^2 = 0.676$; disability, $F(4, 102) = 29.750, p < 0.001, \eta^2 = 0.538$; and quality of life, $F(3.383, 86.261) = 105.071, p < 0.001, \eta^2 = 0.805$. Bonferroni comparisons showed significant pre-test-to-post-test and pre-test-to-follow-up improvements in the PNE + DNS group across all outcomes (all $p < 0.001$), while the DNS group showed significant but generally smaller and less sustained improvements.

Conclusion: Combining pain neuroscience education with dynamic neuromuscular stabilization produced broader and more sustained improvements in movement control and clinical outcomes than DNS alone or conventional core exercise in individuals with chronic non-specific low back pain.

Keywords: Chronic non-specific low back pain; pain neuroscience education; dynamic neuromuscular stabilization; lumbar motor control; pain; disability; quality of life.

1. Introduction

Chronic low back pain is one of the most prevalent and disabling musculoskeletal conditions worldwide and represents a substantial challenge for patients, clinicians, and healthcare systems. It is associated with persistent pain, limitations in mobility and activities of daily living, reduced occupational participation, impaired psychological well-being, and deterioration in health-related quality of life. In many individuals, low back pain persists beyond the expected period of tissue healing and develops into a chronic condition characterized by recurrent symptoms, functional limitations, and complex interactions among biological, psychological, behavioral, and social factors. Chronic primary or non-specific low back pain constitutes a particularly important clinical category because symptoms cannot be attributed to a clearly identifiable structural pathology in most patients, despite substantial pain and disability. Consequently, contemporary clinical management has increasingly shifted away from purely pathoanatomical explanations and toward multidimensional approaches that address physical function, movement behavior, pain processing, beliefs, and self-management. International guidance similarly emphasizes non-surgical, non-pharmacological, person-centered interventions, including education and structured exercise, as core components of chronic low back pain management ([World Health, 2023](#)).

The clinical importance of chronic non-specific low back pain extends beyond pain intensity alone. Patients frequently experience reduced physical capacity, impaired trunk function, altered movement strategies, fear of movement, and limitations in everyday activities, all of which may contribute to the persistence of disability. The relationship among pain, disability, and quality of life is therefore multidimensional rather than linear, and patients with comparable pain intensities may demonstrate markedly different levels of functional restriction and perceived health status ([Wettstein et al., 2019](#)). Persistent pain can also alter the way individuals plan and execute movement, potentially reinforcing protective, rigid, or avoidant motor behaviors. Experimental work has shown that repeated exposure to movement can influence pain-related responses and movement behavior, underscoring the importance of addressing not only symptoms but also how patients perceive and perform movement in the presence of pain ([Trost et al., 2008](#)). These considerations support the use of

rehabilitation strategies that simultaneously target pain-related cognitions and physical movement-control deficits.

One of the clinically relevant features observed in individuals with non-specific low back pain is impaired lumbar movement control. Movement-control impairment refers to difficulty maintaining appropriate control of the lumbar spine and pelvis during functional or limb movements when excessive or poorly coordinated lumbar motion is not required for task performance. Individuals with low back pain have been shown to perform differently from healthy controls on standardized movement-control tests, suggesting that altered lumbopelvic control may represent an important component of the clinical presentation in at least a subgroup of patients ([Luomajoki et al., 2008](#)). Such deficits may reflect altered neuromuscular coordination, suboptimal recruitment strategies, reduced proprioceptive control, pain-related protective behaviors, or learned movement patterns. Because movement-control deficits may contribute to inefficient mechanical loading and reinforce pain-related apprehension, interventions specifically aimed at improving lumbopelvic stability and movement quality may have particular relevance for chronic non-specific low back pain.

Exercise therapy is widely used in chronic low back pain, but the specific characteristics of exercise programs vary considerably. Conventional core stabilization programs typically focus on strengthening and endurance of the trunk musculature, with exercises such as bridging, planking, bird-dog variations, and abdominal stabilization. Progression is commonly based on increasing postural challenge and the demand placed on trunk control ([Vera-Garcia et al., 2020](#)). Core stabilization approaches have demonstrated beneficial effects in patients with chronic low back pain, although the magnitude and durability of response can vary according to the exercise protocol, participant characteristics, and outcomes examined. For example, core stability and traditional trunk exercise have both been investigated with respect to functional lumbopelvic stability and clinical symptoms, supporting the general role of exercise in the management of chronic low back pain ([Shamsi et al., 2015](#)). Nevertheless, conventional strengthening may not fully address the integration of respiration, intra-abdominal pressure regulation, postural control, developmental movement patterns, and sensorimotor coordination that may be relevant to impaired lumbar movement control.

Dynamic neuromuscular stabilization is a rehabilitation approach derived from developmental kinesiology and based on the concept that optimal postural stabilization patterns are established during early motor development.

DNS seeks to restore efficient stabilization strategies by integrating diaphragmatic breathing, intra-abdominal pressure regulation, trunk control, joint centration, and coordinated movement in developmentally derived positions (Frank et al., 2013). Rather than focusing primarily on isolated muscle strengthening, DNS emphasizes the integrated function of the neuromuscular system and the quality of movement under progressively demanding conditions. The diaphragm plays a central role in this model because it contributes not only to respiration but also to postural stabilization and regulation of intra-abdominal pressure. Evidence indicates that individuals with chronic low back pain may demonstrate alterations in the postural function of the diaphragm, providing a physiological basis for interventions that integrate breathing and trunk stabilization (Kolar et al., 2012).

The growing use of DNS in low back pain rehabilitation has been accompanied by increasing empirical investigation. Studies have suggested that DNS-based training may reduce pain, improve functional disability, and enhance quality of life in individuals with chronic or non-specific low back pain. In obese postpartum women with low back pain, DNS training produced favorable clinical changes, supporting the applicability of the method beyond athletic populations (Ghavipanje et al., 2022). More recently, an 8-week randomized clinical trial with a 2-month follow-up showed that DNS exercise could improve pain, functional disability, and quality of life in individuals with non-specific chronic low back pain, while also providing evidence regarding persistence of treatment effects after completion of the intervention (Rabieezadeh et al., 2024). A systematic review and meta-analysis examining DNS and related Vojta-based interventions further reported beneficial effects on pain intensity and physical function in individuals with low back pain, although variability among protocols and study populations remained evident (Kong et al., 2024).

Current evidence also suggests that the mechanisms through which DNS may benefit patients extend beyond symptom reduction. A recent randomized controlled trial found that DNS training could influence core muscle contractility and standing postural control in patients with chronic low back pain, indicating that the intervention may modify neuromuscular and postural mechanisms directly relevant to movement performance (Huang et al., 2025). Likewise, DNS has been associated with changes in lower-limb muscle activity as well as pain and disability, suggesting that its effects may extend across the broader kinetic chain rather than being restricted to local trunk

musculature (Rezazadeh et al., 2025). A scoping review specifically addressing the relationship between DNS and movement-control impairment in non-specific low back pain highlighted the theoretical compatibility between developmental stabilization principles and rehabilitation of movement-control dysfunction, while also emphasizing the need for more targeted clinical research using movement-control outcomes (Kaushik & Ahmad, 2024). Thus, although the clinical effects of DNS are increasingly supported, its specific influence on lumbar motor control and whether these effects can be enhanced through concurrent pain-focused education remain incompletely understood.

Pain neuroscience education represents another increasingly used intervention in chronic musculoskeletal pain rehabilitation. PNE aims to reconceptualize pain by explaining the neurophysiological processes underlying pain perception, including nociception, peripheral and central sensitization, neural signaling, modulation, and nervous-system plasticity. Its central purpose is to reduce the perceived threat associated with pain and replace inaccurate or overly structural interpretations of symptoms with a more contemporary understanding of pain as a protective output influenced by multiple contextual and neurobiological factors (Louw et al., 2016). This framework is consistent with contemporary pain models that distinguish nociception from pain and emphasize that pain intensity does not necessarily correspond directly to the extent of tissue damage. The imprecision hypothesis of chronic pain further proposes that persistent pain may involve altered protective prediction and broadening of pain-related responses beyond the original nociceptive context (Moseley & Vlaeyen, 2015). Such concepts are particularly relevant to chronic non-specific low back pain, where persistent symptoms often coexist with limited evidence of ongoing structural pathology sufficient to explain symptom severity.

PNE has been investigated as both a standalone educational strategy and as an adjunct to exercise-based rehabilitation. Randomized research has shown that combining PNE with lumbar stabilization exercise can improve pain-related and physical outcomes in patients with chronic low back pain, suggesting that educational reconceptualization may enhance engagement with active rehabilitation (Kim et al., 2022). Similarly, combining PNE with physiotherapy has been associated with improvements in chronic low back pain, fear of movement, and functional status (Lendraitienė et al., 2024). These effects may be clinically meaningful because fear, threat perception, and maladaptive beliefs can discourage movement and reduce

adherence to physical activity, thereby perpetuating deconditioning and protective movement patterns. By reducing the perceived danger associated with movement, PNE may enable patients to participate more confidently and effectively in exercise-based interventions.

Systematic reviews and meta-analyses provide further support for PNE in chronic low back pain, while also indicating that its effects depend on how it is delivered and combined with other interventions. A systematic review and meta-analysis found that PNE can improve short-term pain and disability outcomes in chronic low back pain (Ma et al., 2024). More recent evidence indicates beneficial effects not only on pain and disability but also on kinesiophobia and catastrophizing, reinforcing the relevance of PNE for both clinical and psychological dimensions of chronic pain (Medina-Viedma et al., 2025). An umbrella review with meta-analysis similarly concluded that PNE can be effective in individuals with chronic non-specific low back pain, particularly when embedded within multimodal rehabilitation rather than delivered as an isolated informational intervention (García Cancela et al., 2025). Long-term evidence is also emerging; a randomized controlled trial with a 12-month follow-up compared PNE with education focused on spinal physiology and ergonomics within multidisciplinary rehabilitation, contributing to understanding of the durability and specificity of educational effects in chronic low back pain (Adenis et al., 2026).

The effectiveness of PNE may also be influenced by individual characteristics and the way educational material is communicated. Educational level has been examined as a potential moderator of response to PNE, with evidence indicating that patients' capacity to engage with pain-related concepts may vary according to educational background (Bilteryx et al., 2022). This finding has methodological implications for randomized trials because imbalance in educational level could potentially influence responses to PNE independently of the intervention itself. Stratification according to educational status may therefore improve group comparability when investigating education-based rehabilitation. In addition, PNE is generally considered most clinically useful when complex neurophysiological concepts are communicated in accessible language and linked directly to patients' experiences, movement behavior, and rehabilitation goals rather than presented as abstract biomedical information.

The rationale for combining PNE with DNS is particularly compelling because the two interventions may

address complementary mechanisms. DNS primarily targets the motor and neuromuscular dimensions of chronic low back pain through improved stabilization, diaphragmatic function, postural control, and movement coordination, whereas PNE primarily targets pain-related knowledge, threat perception, maladaptive beliefs, and fear-related behavior. In patients who interpret movement as dangerous, even a technically well-designed stabilization program may be performed cautiously, rigidly, or inconsistently. Conversely, reducing fear and threat through education without providing a structured opportunity to practice efficient movement may not sufficiently address physical movement-control deficits. A combined intervention may therefore allow patients to reinterpret pain while simultaneously experiencing safe, progressively challenging movement, potentially reinforcing both cognitive and motor learning.

This integrated approach is supported by emerging research combining PNE with neuromuscular exercise. A randomized controlled trial protocol has specifically proposed evaluating PNE combined with neuromuscular exercises for pain, functional disability, and psychological factors in chronic low back pain, reflecting increasing interest in multimodal interventions that target both pain processing and physical function (Alvani et al., 2024). Clinical trials of combined exercise approaches have also emphasized the importance of evaluating whether adding complementary therapeutic components produces clinically relevant improvements beyond exercise alone (Blanco-Giménez et al., 2024). Nevertheless, direct evidence regarding the additional value of PNE when combined specifically with DNS remains limited, particularly when lumbar motor control is considered alongside pain, disability, and quality of life.

The need for such research is further reinforced by the heterogeneity of chronic non-specific low back pain. Clinical outcomes cannot be adequately characterized by pain intensity alone, and interventions should ideally be evaluated across multiple domains. Functional disability reflects the impact of symptoms on daily activities, whereas quality of life captures broader physical, social, and psychological consequences of the condition. Measures of movement control provide an additional functional dimension that may be especially relevant to DNS. The clinical relevance of treatment effects should therefore be interpreted through a combination of pain, disability, motor-control, and health-related quality-of-life outcomes. Previous research has demonstrated that combined exercise-

based interventions may produce meaningful clinical changes, although differences in treatment content and outcome selection complicate direct comparison across studies (Blanco-Giménez et al., 2024). Similarly, interpretation of changes in pain requires consideration of both statistical and clinical relevance, and validated pain measurement frameworks remain important when evaluating chronic pain interventions (Ferrer-Peña et al., 2016).

Despite increasing evidence supporting both DNS and PNE, several gaps remain. First, many DNS studies have concentrated primarily on pain and disability, with less emphasis on standardized lumbar movement-control outcomes. Second, studies of PNE often combine education with general physiotherapy or stabilization exercises rather than DNS specifically. Third, relatively few trials have directly compared a combined PNE + DNS intervention against DNS alone and an active conventional exercise control within the same randomized design. Such a three-arm comparison is methodologically valuable because it can help distinguish the effects associated with DNS from the potential added contribution of PNE while also accounting for the non-specific benefits of participation in a structured exercise program. Finally, follow-up assessment is necessary to determine whether improvements observed immediately after treatment are sustained after supervised intervention has ended, since short-term treatment response does not necessarily indicate persistence of clinical benefit.

Accordingly, the aim of this study was to compare the effects of pain neuroscience education combined with dynamic neuromuscular stabilization, dynamic neuromuscular stabilization alone, and conventional core exercise on lumbar movement control, pain intensity, functional disability, and quality of life in individuals with chronic non-specific low back pain (CLBP) across pre-intervention, post-intervention, and 2-month follow-up assessments.

2. Methods and Materials

2.1. Study Design and Participants

This applied experimental study was conducted as a three-arm randomized controlled trial with pre-test, post-test, and 2-month follow-up assessments to investigate the effects of pain neuroscience education (PNE) combined with dynamic neuromuscular stabilization (DNS) on lumbar movement control and clinical outcomes in individuals with chronic non-specific low back pain (CLBP). The study was conducted in Kerman, Iran, and participants were recruited

through referrals from physicians and physiotherapists as well as advertisements distributed through physiotherapy clinics and social media. Men and women aged 25–40 years with a clinical diagnosis of chronic non-specific low back pain were considered for participation. This age range was selected to minimize the potential influence of age-related degenerative changes and to achieve greater homogeneity in neuromuscular and core muscle function (Lendraitienė et al., 2024). The diagnosis of non-specific CLBP was confirmed by a neurologist following clinical examination and exclusion of identifiable specific spinal pathology. Participants were eligible if they had experienced low back pain for at least 3 months, were able to sit, stand, and walk independently without assistive devices, and were not engaged in regular structured exercise programs (Lendraitienė et al., 2024). Exclusion criteria included specific spinal disorders such as disc herniation requiring specific medical management, spinal cord injury, previous spinal surgery, neurological disorders, spinal tumors, osteoarthritis or rheumatoid arthritis affecting physical function, or any medical condition diagnosed by a physician that contraindicated participation in physical exercise. Participants were also excluded if they developed intolerable pain, were unable to perform the prescribed exercises safely, voluntarily withdrew, missed more than one-third of the intervention sessions, or were absent for three consecutive sessions (Rabieezadeh et al., 2024). Before enrollment, all participants received information regarding the study procedures and provided written informed consent. Educational level was recorded through self-report of the highest academic degree attained and categorized as below a bachelor's degree or bachelor's degree and higher for the purpose of stratified randomization, consistent with the approach described by Bilterys et al. (2022).

The required sample size was determined using G*Power software, version 3.1.9.4, based on repeated-measures analysis of variance and pain intensity as the principal outcome used for sample-size estimation (Blanco-Giménez et al., 2024). An effect size corresponding to Cohen's $d = 0.44$ was adopted on the basis of previous findings (Shamsi et al., 2015). With a significance level of 0.05, statistical power of 0.90, and three intervention groups, the minimum required sample was estimated as 45 participants, corresponding to 15 participants in each group. The selected effect magnitude was within the small-to-moderate range and was consistent with effect sizes previously reported in related research (Ferrer-Peña et al., 2016). To compensate for an anticipated attrition rate of approximately 15% during

the intervention and follow-up phases, the target sample was increased to 54 participants, with 18 participants assigned to each group. Following baseline assessment and confirmation of eligibility, participants were allocated in a 1:1:1 ratio to the PNE combined with DNS group, the DNS-only group, or the conventional core exercise control group. Stratified block randomization was performed according to educational level using variable block sizes of six and nine to reduce predictability of the sequence. The random allocation sequence was generated using Random Allocation Software by an independent researcher who was not involved in intervention delivery or outcome assessment. Allocation concealment was ensured through sequentially numbered, opaque, sealed envelopes prepared and retained by the independent researcher. Each envelope was opened only after completion of baseline assessments and confirmation of eligibility. The outcome assessor remained blinded to group allocation throughout the assessment process. All participants completed assessments at baseline, immediately after the 8-week intervention, and 2 months after the intervention. Assessments were generally conducted between 9:00 AM and 12:00 PM under comparable testing conditions, and the order of outcome assessments was randomized to minimize potential order effects. When necessary, physically demanding assessments were distributed across an additional testing day to minimize fatigue.

2.2. Data Collection Tools

Lumbar motor control was evaluated using the six-test movement control battery developed by Luomajoki et al. (2007, 2008). The battery assesses the ability of an individual to control the lumbar spine and pelvis during specific movements and consists of the Waiter's Bow, Pelvic Tilt, One-Leg Stance, Seated Knee Extension, Quadruped Position, and Prone Lying Active Knee Flexion tests. Each test was scored dichotomously according to established performance criteria, with a score of 0 indicating correct movement control and a score of 1 indicating the presence of a movement-control deficit. The total score therefore ranged from 0 to 6, with higher scores indicating poorer lumbar motor control and a greater number of movement-control impairments (Luomajoki et al., 2007, 2008). Each test was performed in three trials. Participants wore tight-fitting sports clothing to permit clear observation of the lumbar spine, pelvis, and lower extremities. Performances were recorded using a Xiaomi Poco X3 smartphone camera,

and the recorded trials were subsequently evaluated independently by a corrective exercise specialist according to the predefined criteria.

Pain intensity was measured using a 100-mm visual analogue scale (VAS), which is widely used to quantify subjective pain intensity (Hawker et al., 2011). Participants were asked to indicate the intensity of their current low back pain by placing a mark along a 100-mm horizontal line anchored by "no pain" at the left endpoint and "worst imaginable pain" at the right endpoint. The distance in millimetres between the zero anchor and the participant's mark was measured and recorded as the pain-intensity score, with higher scores indicating greater perceived pain (Hawker et al., 2011). For descriptive interpretation, scores of 0–4 mm were considered indicative of no pain, 5–44 mm of mild pain, 45–74 mm of moderate pain, and 75–100 mm of severe pain, based on previously proposed classification thresholds (Jensen et al., 2003).

Functional disability associated with chronic low back pain was assessed using the Persian version of the 24-item Roland–Morris Disability Questionnaire (RMDQ) (Troost et al., 2008). The RMDQ is a self-report instrument designed to evaluate limitations in everyday activities attributable to low back pain. Participants indicated whether each of the 24 statements described their functional condition on the day of assessment (Roland & Fairbank, 2000). Each endorsed item contributed one point to the total score, producing a possible score ranging from 0 to 24. Higher scores indicated greater disability and a greater adverse effect of low back pain on activities of daily living, whereas lower scores represented better functional status (Roland & Fairbank, 2000).

Health-related quality of life was measured using the 36-Item Short Form Health Survey (SF-36), a standardized questionnaire designed to assess perceived physical and mental health status (Moseley & Vlaeyen, 2015; Wettstein et al., 2019). The instrument contains 36 items organized into eight dimensions comprising physical functioning, role limitations due to physical health, bodily pain, general health, vitality, social functioning, role limitations resulting from emotional problems, and mental health. Responses were scored according to the standard SF-36 scoring procedure, with higher scores representing better perceived health-related quality of life. The Persian version of the SF-36 has previously demonstrated appropriate validity and reliability for use among Iranian populations (Montazeri et al., 2005).

2.3. Intervention

All three groups participated in supervised exercise programs for 8 weeks, with three sessions conducted each week. The intervention duration and subsequent 2-month follow-up were selected in accordance with previous research investigating DNS-based interventions among individuals with low back pain (Huang et al., 2025; Rabieezadeh et al., 2024). Each session was supervised by a corrective exercise specialist and consisted of approximately 5–7 min of warm-up, the group-specific intervention, and approximately 5–7 min of cool-down. Exercise intensity and progression were individualized according to each participant's functional ability while preserving appropriate movement quality, trunk control, and breathing patterns. Participants allocated to the DNS group performed exercises based on developmental kinesiology principles, emphasizing coordinated diaphragmatic breathing, regulation of intra-abdominal pressure, postural stabilization, trunk control, and restoration of developmental movement patterns (Frank et al., 2013; Kolar, 2014). The program incorporated diaphragmatic breathing, the supine 90°–90° position with baby rocking, prone positioning and rolling, side-lying exercises, oblique sitting, tripod and kneeling positions, squatting, and the Czech Get-Up, consistent with exercises previously used in DNS interventions for low back pain (Frank et al., 2013; Ghavipanje et al., 2022; Huang et al., 2025; Rabieezadeh et al., 2024; Alvani et al., 2021). Progression occurred systematically across the 8 weeks, with early sessions emphasizing isometric stabilization and mastery of basic developmental positions, followed by isotonic exercises and increasingly demanding functional tasks, while later sessions emphasized transitional movements such as the Czech Get-Up (Rabieezadeh et al., 2024). Depending on participants' ability to preserve correct breathing and movement control, exercises were generally performed for one to three sets using approximately 10-second isometric holds or 10–15 repetitions, with 90–120 s of rest between sets. Light resistance using equipment such as kettlebells or dumbbells was introduced when adequate movement quality and stabilization could be maintained. Participants allocated to the PNE + DNS group performed the identical DNS protocol but additionally received face-to-face pain neuroscience education immediately before each exercise session. PNE sessions lasted approximately 10–20 min, were delivered three times per week throughout the 8-week period, and were conducted by the corrective exercise

specialist (Alvani et al., 2024). Educational content addressed action potentials, neurons and synaptic transmission, spinal inhibition and facilitation, pain neurophysiology, nociception, nociceptive pathways, sensitization, and nervous-system plasticity (Kim et al., 2022). The intervention emphasized the distinction between nociception and pain, the contribution of nervous-system sensitivity and contextual factors to pain experience, and the concept that pain does not necessarily provide a direct measure of tissue damage. The material was based on established PNE principles and concepts presented in *Explain Pain* and was intended to reduce pain-related threat perceptions, modify maladaptive beliefs, decrease fear avoidance and kinesiophobia, enhance self-efficacy, and promote active participation in movement and rehabilitation (Louw et al., 2016; Moseley & Vlaeyen, 2015). Educational material was delivered verbally and supplemented by a booklet containing written explanations, summaries, diagrams, figures, and other visual materials. Each week emphasized one of the eight principal PNE topics, and sessions generally began with a brief review of previously presented concepts before introducing and discussing new material. Participants who missed educational sessions were provided with opportunities to complete the missed content whenever feasible to preserve continuity of the educational program. Participants in the conventional core exercise control group completed an exercise program of the same overall duration and weekly frequency that included commonly prescribed trunk-strengthening exercises such as single-leg and double-leg bridging, side bridging, abdominal crunches, prone planks, and bird-dog exercises (Vera-Garcia et al., 2020). These exercises were performed slowly and under controlled conditions for two sets of 10 repetitions, with approximately 2 min of rest between exercises. Participants were instructed to maintain natural rhythmic breathing and avoid the Valsalva maneuver. Immediately after the 8-week intervention, all groups underwent post-test assessment using the same procedures as at baseline, followed by an additional assessment 2 months later. During the follow-up period, no structured DNS or PNE intervention was provided as part of the study protocol, although participants were contacted periodically to maintain communication and monitor adherence to study requirements. The same outcome measures and assessment procedures were applied at all three measurement occasions.

2.4. Data Analysis

Data were analyzed using a 3×3 mixed-model repeated-measures analysis of variance (ANOVA), in which Group, comprising PNE + DNS, DNS, and conventional core exercise groups, was entered as the between-subjects factor and Time, comprising pre-test, post-test, and 2-month follow-up, was entered as the within-subjects factor. The analysis examined the main effects of Group and Time as well as the Group $\times$ Time interaction. The interaction effect was considered particularly relevant because it determined whether changes in lumbar motor control, pain intensity, functional disability, and quality of life across the three measurement occasions differed according to intervention group. Prior to conducting the main analyses, the relevant statistical assumptions were evaluated. Normality of the outcome distributions was assessed using the Shapiro–Wilk test, homogeneity of variance across groups was evaluated using Levene's test, and the assumption of sphericity for repeated measurements was examined using Mauchly's test. When Mauchly's test was statistically significant at $p < 0.05$, indicating violation of the sphericity assumption, the Greenhouse–Geisser correction was applied and the corresponding adjusted degrees of freedom were reported. Because Box's test indicated heterogeneity of covariance matrices between groups, multivariate findings were interpreted cautiously, and corrected univariate repeated-measures results were considered the primary inferential findings. Greenhouse–Geisser corrections were therefore applied to lumbar motor control, pain intensity, and quality of life when sphericity was violated, whereas uncorrected degrees of freedom were retained for functional disability when the assumption of sphericity was satisfied. When statistically significant effects were identified, Bonferroni-adjusted pairwise comparisons were conducted to determine differences between specific measurement occasions and,

where appropriate, between intervention groups. Mean differences and corresponding p values were reported for pairwise comparisons. Partial eta squared (η^2) was calculated as the measure of effect size for repeated-measures ANOVA effects. Statistical significance was established at $p < 0.05$, and all multiple pairwise comparisons were adjusted using the Bonferroni procedure to control inflation of the type I error rate.

3. Findings and Results

A total of 54 participants with chronic non-specific low back pain completed the baseline assessment and were equally allocated to the PNE + DNS, DNS, and conventional core exercise (CONT) groups, with 18 participants in each group. The participants were aged 25–40 years, with a mean age of 33.42 ± 4.21 years; 30 participants (55.6%) were female and 24 (44.4%) were male. The mean height, weight, and body mass index (BMI) of the total sample were 169.35 ± 7.84 cm, 72.18 ± 9.65 kg, and 25.12 ± 2.45 kg/m², respectively. Regarding educational level, 24 participants (44.4%) had an educational level below a bachelor's degree and 30 (55.6%) had a bachelor's degree or higher. The mean duration of low back pain symptoms was 11.48 ± 5.12 months. The demographic characteristics were comparable across the three groups, with mean ages of 33.78 ± 4.15 , 32.89 ± 4.47 , and 33.61 ± 4.19 years in the PNE + DNS, DNS, and CONT groups, respectively. Sex distribution, height, weight, BMI, educational level, and symptom duration were also similar across the study groups. One-way ANOVA and Pearson's chi-square tests showed no statistically significant baseline differences among the groups in demographic and clinical characteristics ($p > 0.05$), indicating satisfactory comparability of the groups before initiation of the interventions.

Table 1

Descriptive Statistics for Study Outcomes Across Groups and Measurement Time Points

Outcome	Time	PNE + DNS (n = 18)	DNS (n = 18)	CONT (n = 18)
LMC	Pre-test	3.11 ± 1.02	3.00 ± 1.14	3.17 ± 0.99
	Post-test	1.00 ± 0.69	1.94 ± 0.73	3.00 ± 0.84
	Follow-up	1.50 ± 0.51	2.50 ± 0.51	3.00 ± 0.84
Pain	Pre-test	43.46 ± 3.51	43.18 ± 3.27	43.41 ± 3.62
	Post-test	17.16 ± 4.26	30.08 ± 2.95	44.03 ± 8.40
	Follow-up	19.63 ± 4.85	36.80 ± 2.68	41.35 ± 6.25
Disability	Pre-test	18.00 ± 1.53	18.17 ± 1.69	18.17 ± 1.69
	Post-test	7.67 ± 1.65	11.00 ± 2.66	18.61 ± 2.30
	Follow-up	10.50 ± 1.76	14.22 ± 2.32	16.56 ± 3.96

QoL	Pre-test	66.35 ± 1.08	66.24 ± 0.97	65.42 ± 1.67
	Post-test	79.61 ± 1.91	73.00 ± 2.99	64.00 ± 1.19
	Follow-up	78.11 ± 1.32	69.00 ± 2.06	66.17 ± 1.69

As shown in Table 1, the three groups had highly similar mean values for all study outcomes at pre-test, whereas distinct patterns of change emerged after the interventions. The PNE + DNS group demonstrated the greatest descriptive improvement in lumbar motor control, with the mean LMC score decreasing from 3.11 ± 1.02 at pre-test to 1.00 ± 0.69 at post-test and remaining below baseline at 1.50 ± 0.51 at follow-up. Pain intensity similarly decreased markedly in this group from 43.46 ± 3.51 to 17.16 ± 4.26 at post-test and 19.63 ± 4.85 at follow-up. Functional disability declined from 18.00 ± 1.53 at baseline to 7.67 ± 1.65 immediately after the intervention and 10.50 ± 1.76 at follow-up, while quality of life increased from 66.35 ± 1.08 to 79.61 ± 1.91 and remained elevated at 78.11 ± 1.32 at follow-up. The DNS group also demonstrated improvement from pre-test to post-test across all four outcomes, although the magnitude of change was descriptively smaller than that observed in the PNE + DNS group and some attenuation was apparent at follow-up. In contrast, the CONT group showed relatively limited change over time, particularly for LMC and pain. Overall, the descriptive findings suggest greater and more sustained improvements in the PNE + DNS group than in the DNS and CONT groups.

Table 2

Mixed-Model Repeated-Measures ANOVA for Study Outcomes

Outcome	Effect	F	df	p	η^2
LMC	Time	25.201	1.578, 80.488	<0.001	0.331
	Group	27.068	2, 51	<0.001	0.515
	Time × Group	7.004	3.156, 80.488	<0.001	0.215
Pain	Time	136.651	1.694, 86.388	<0.001	0.728
	Group	120.324	2, 51	<0.001	0.825
	Time × Group	53.282	3.388, 86.388	<0.001	0.676
Disability	Time	98.346	2, 102	<0.001	0.659
	Group	73.747	2, 51	<0.001	0.743
	Time × Group	29.750	4, 102	<0.001	0.538
QoL	Time	210.680	1.691, 86.261	<0.001	0.805
	Group	335.302	2, 51	<0.001	0.929
	Time × Group	105.071	3.383, 86.261	<0.001	0.805

The mixed-model repeated-measures ANOVA demonstrated statistically significant Time, Group, and Time × Group effects for all four study outcomes (Table 2). For LMC, significant effects were observed for Time, $F(1.578, 80.488) = 25.201$, $p < 0.001$, $\eta^2 = 0.331$, Group, $F(2, 51) = 27.068$, $p < 0.001$, $\eta^2 = 0.515$, and the Time ×

Before conducting the mixed-model repeated-measures ANOVA, the relevant statistical assumptions were examined. The Shapiro–Wilk test was used to evaluate the normality of the outcome distributions, and Levene's test was used to assess homogeneity of variance across groups at each measurement occasion. Some evidence of heterogeneity of variance was observed at individual measurement points, particularly for post-test pain, follow-up disability, and post-test quality of life. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for LMC, pain, and QoL ($p < 0.05$); therefore, Greenhouse–Geisser-corrected degrees of freedom were used for these outcomes. Sphericity was not violated for disability (Mauchly's test, $p = 0.242$), and the uncorrected degrees of freedom were consequently retained. Box's test of equality of covariance matrices was statistically significant, indicating heterogeneity of the covariance matrices across the three groups. Accordingly, the multivariate results were interpreted cautiously, and the Greenhouse–Geisser-corrected univariate repeated-measures results were considered the primary inferential findings.

Group interaction, $F(3.156, 80.488) = 7.004$, $p < 0.001$, $\eta^2 = 0.215$. Pain intensity also demonstrated significant Time, $F(1.694, 86.388) = 136.651$, $p < 0.001$, $\eta^2 = 0.728$, Group, $F(2, 51) = 120.324$, $p < 0.001$, $\eta^2 = 0.825$, and Time × Group effects, $F(3.388, 86.388) = 53.282$, $p < 0.001$, $\eta^2 = 0.676$. For functional disability, the effects of Time, $F(2,$

102) = 98.346, $p < 0.001$, $\eta^2 = 0.659$, Group, $F(2, 51) = 73.747$, $p < 0.001$, $\eta^2 = 0.743$, and Time $\times$ Group, $F(4, 102) = 29.750$, $p < 0.001$, $\eta^2 = 0.538$, were significant. Likewise, QoL showed significant effects of Time, $F(1.691, 86.261) = 210.680$, $p < 0.001$, $\eta^2 = 0.805$, Group, $F(2, 51) = 335.302$, $p < 0.001$, $\eta^2 = 0.929$, and Time $\times$ Group, $F(3.383, 86.261) = 105.071$, $p < 0.001$, $\eta^2 = 0.805$. The significant interaction

effects indicate that the trajectories of change across pre-test, post-test, and follow-up differed significantly among the three groups. Among the interaction effects, the largest effect was observed for QoL ($\eta^2 = 0.805$), followed by pain ($\eta^2 = 0.676$), disability ($\eta^2 = 0.538$), and LMC ($\eta^2 = 0.215$). The η^2 value of 0.929 for QoL represents the main effect of Group rather than the Time $\times$ Group interaction.

Table 3

Bonferroni-Corrected Within-Group Pairwise Comparisons Across Measurement Time Points

Outcome	Group	Pre-test $\rightarrow$ Post-test, MD (p)	Pre-test $\rightarrow$ Follow-up, MD (p)	Post-test $\rightarrow$ Follow-up, MD (p)
LMC	PNE + DNS	2.111 (<0.001)	1.611 (<0.001)	-0.500 (0.040)
	DNS	1.056 (0.006)	0.500 (0.297)	-0.556 (0.019)
	CONT	0.167 (1.000)	0.167 (1.000)	0.000 (1.000)
Pain	PNE + DNS	26.300 (<0.001)	23.828 (<0.001)	-2.472 (0.106)
	DNS	13.094 (<0.001)	6.378 (<0.001)	-6.717 (<0.001)
	CONT	-0.622 (1.000)	2.061 (0.498)	2.683 (0.068)
Disability	PNE + DNS	10.333 (<0.001)	7.500 (<0.001)	-2.833 (0.002)
	DNS	7.167 (<0.001)	3.944 (<0.001)	-3.222 (<0.001)
	CONT	-0.444 (1.000)	1.611 (0.126)	2.056 (0.033)
QoL	PNE + DNS	-13.261 (<0.001)	-11.761 (<0.001)	1.500 (0.066)
	DNS	-6.756 (<0.001)	-2.756 (<0.001)	4.000 (<0.001)
	CONT	1.417 (0.060)	-0.750 (0.255)	-2.167 (0.004)

Bonferroni-adjusted pairwise comparisons further clarified the significant Time $\times$ Group interactions (Table 3). In the PNE + DNS group, LMC improved significantly from pre-test to post-test (MD = 2.111, $p < 0.001$) and from pre-test to follow-up (MD = 1.611, $p < 0.001$). A significant increase in LMC score occurred between post-test and follow-up (MD = -0.500, $p = 0.040$), indicating partial attenuation of the initial improvement, although follow-up performance remained significantly better than baseline. Pain intensity decreased significantly from pre-test to post-test (MD = 26.300, $p < 0.001$) and from pre-test to follow-up (MD = 23.828, $p < 0.001$), while the post-test-to-follow-up difference was not significant (MD = -2.472, $p = 0.106$), indicating relative maintenance of the reduction in pain. Disability also decreased significantly from pre-test to post-test (MD = 10.333, $p < 0.001$) and from pre-test to follow-up (MD = 7.500, $p < 0.001$), although a significant increase in disability was observed between post-test and follow-up (MD = -2.833, $p = 0.002$). Quality of life increased significantly from pre-test to post-test (MD = -13.261, $p < 0.001$) and from pre-test to follow-up (MD = -11.761, $p < 0.001$), whereas the relatively small decline between post-test and follow-up was not statistically significant (MD = 1.500, $p = 0.066$). In the DNS group, LMC improved significantly from pre-test to post-test (MD = 1.056, $p =$

0.006), but the pre-test-to-follow-up difference was no longer statistically significant (MD = 0.500, $p = 0.297$); moreover, LMC deteriorated significantly from post-test to follow-up (MD = -0.556, $p = 0.019$). Pain decreased significantly from pre-test to post-test (MD = 13.094, $p < 0.001$) and from pre-test to follow-up (MD = 6.378, $p < 0.001$), although a significant rebound occurred between post-test and follow-up (MD = -6.717, $p < 0.001$). Disability followed a similar pattern, with significant improvements from pre-test to post-test (MD = 7.167, $p < 0.001$) and follow-up (MD = 3.944, $p < 0.001$), accompanied by significant deterioration from post-test to follow-up (MD = -3.222, $p < 0.001$). QoL increased significantly from pre-test to post-test (MD = -6.756, $p < 0.001$) and from pre-test to follow-up (MD = -2.756, $p < 0.001$), but declined significantly between post-test and follow-up (MD = 4.000, $p < 0.001$). In the CONT group, no significant pre-test-to-post-test or pre-test-to-follow-up changes were observed in LMC or pain (all $p > 0.05$). Disability also showed no significant change from pre-test to either post-test or follow-up, although a significant reduction in the disability score occurred from post-test to follow-up (MD = 2.056, $p = 0.033$). QoL did not differ significantly between pre-test and post-test ($p = 0.060$) or between pre-test and follow-up ($p = 0.255$), but increased significantly from post-test to follow-

up ($MD = -2.167$, $p = 0.004$). Taken together, these findings indicate that both active DNS-based interventions produced improvements in clinical and movement-control outcomes, while the PNE + DNS condition showed the most pronounced descriptive changes and greater maintenance of improvements in pain and quality of life across the follow-up period.

4. Discussion and Conclusion

The present three-arm randomized controlled trial examined the effects of pain neuroscience education combined with dynamic neuromuscular stabilization, DNS alone, and conventional core exercise on lumbar motor control, pain intensity, functional disability, and quality of life in individuals with chronic non-specific low back pain. The findings demonstrated significant Time, Group, and Time $\times$ Group effects for all four outcomes, indicating that changes over the intervention and follow-up periods differed according to treatment condition. The PNE + DNS group showed the most pronounced overall improvements, particularly for pain intensity, functional disability, quality of life, and lumbar motor control. DNS alone also produced meaningful improvements in most outcomes, but these changes were generally smaller and showed greater attenuation at follow-up. In contrast, the conventional core exercise group exhibited comparatively limited changes. The interaction effect was largest for quality of life, followed by pain and disability, whereas the interaction effect for lumbar motor control was smaller but remained statistically significant. Collectively, these findings suggest that combining PNE with DNS may enhance both clinical and movement-related outcomes beyond those achieved through DNS or conventional core exercise alone.

The improvement in lumbar motor control observed in the PNE + DNS group is consistent with the theoretical framework of DNS, which emphasizes restoration of coordinated postural stabilization through developmental movement patterns, diaphragmatic function, intra-abdominal pressure regulation, and integrated trunk control. DNS is designed to optimize stabilization strategies rather than merely strengthen isolated trunk muscles, and this feature may explain the substantial reduction in movement-control deficits observed after treatment (Frank et al., 2013). The postural role of the diaphragm also provides a plausible physiological basis for these findings, as altered diaphragmatic contribution to postural stabilization has been demonstrated in individuals with chronic low back pain

(Kolar et al., 2012). Improvement in the ability to control lumbar and pelvic movement may therefore reflect better coordination among respiratory, trunk, and proximal stabilizing systems.

The present findings also align with evidence showing that individuals with low back pain frequently demonstrate impaired performance on standardized lumbar movement-control tests compared with healthy individuals (Luomajoki et al., 2008). These impairments may reflect deficient neuromuscular coordination, altered proprioceptive control, protective motor strategies, or pain-related movement avoidance. DNS may help address these deficits through repeated exposure to controlled developmental positions and transitional movements that require maintenance of trunk alignment under gradually increasing task demands. Recent evidence further supports this interpretation, as DNS training has been shown to improve core muscle contractility and standing postural control in individuals with chronic low back pain (Huang et al., 2025). The reduction in LMC scores in the present study therefore appears consistent with both the movement-control rationale of DNS and the emerging evidence that DNS can modify neuromuscular and postural mechanisms rather than functioning solely as a pain-relieving exercise approach.

Although both DNS groups improved lumbar motor control, the PNE + DNS group demonstrated the greater descriptive improvement, and the gain remained significant at follow-up. One explanation is that pain neuroscience education may have reduced the perceived threat associated with movement, allowing participants to perform stabilization exercises with less guarding and more confidence. PNE aims to reconceptualize pain by distinguishing nociception from the conscious pain experience and by explaining the contribution of sensitization, nervous-system plasticity, contextual influences, and protective responses (Louw et al., 2016). Chronic pain may involve imprecise protective responses in which movements or contexts associated with pain become generalized as threatening even when they are not harmful (Moseley & Vlaeyen, 2015). Reducing this perceived threat may facilitate more normal movement exploration during DNS and improve the acquisition of motor-control strategies.

The findings for pain intensity were particularly notable. The PNE + DNS group experienced a substantial reduction from baseline to post-test, and this improvement was largely maintained at the 2-month follow-up, whereas the DNS group showed significant improvement followed by a

greater rebound during follow-up. These findings are consistent with previous research demonstrating favorable effects of PNE when combined with exercise. Kim et al. reported that PNE combined with lumbar stabilization exercise reduced pain and improved physical outcomes in patients with chronic low back pain (Kim et al., 2022). Similarly, combining PNE with physiotherapy has been associated with improvements in pain and functional status in individuals with chronic low back pain (Lendraitienė et al., 2024). Systematic evidence also indicates that PNE can reduce pain in the short term, particularly when integrated with active treatment rather than delivered as an isolated educational intervention (Ma et al., 2024). More recent syntheses further support beneficial effects of PNE in chronic non-specific low back pain (García Cancela et al., 2025; Medina-Viedma et al., 2025).

The sustained reduction in pain in the combined group may reflect an interaction between altered pain interpretation and improved physical control. PNE may reduce catastrophizing, fear, and threat-related interpretation of symptoms, while DNS provides repeated behavioral confirmation that movement can be performed safely and effectively. This combination may be more powerful than education or exercise acting independently because it integrates cognitive reconceptualization with direct movement experience. The educational component may help participants reinterpret transient discomfort during exercise as less threatening, thereby decreasing protective muscle guarding and promoting greater engagement. This interpretation is compatible with the broader rationale for combining PNE with neuromuscular exercise in chronic low back pain (Alvani et al., 2024). It is also supported by evidence that PNE can reduce kinesiophobia and catastrophizing in addition to pain and disability (Medina-Viedma et al., 2025).

The reduction in pain observed in the DNS-only group is also consistent with previous evidence. DNS has been shown to reduce pain and improve function in different populations with low back pain, including postpartum women (Ghavipanjan et al., 2022). In individuals with non-specific chronic low back pain, an 8-week DNS program has also been associated with improvements in pain, functional disability, and quality of life that persisted to follow-up (Rabieezadeh et al., 2024). Systematic review and meta-analytic evidence indicates that DNS and related developmental stabilization approaches can produce favorable effects on pain intensity and physical function (Kong et al., 2024). More recent randomized evidence has

additionally shown reductions in pain and disability alongside changes in muscle activity following DNS training (Rezazadeh et al., 2025). The present findings therefore reinforce the clinical value of DNS while suggesting that the addition of PNE may improve the magnitude or durability of treatment response.

Functional disability followed a similar pattern. Both active DNS-based interventions significantly reduced disability from baseline to post-test and follow-up, whereas the magnitude of improvement was greatest in the combined PNE + DNS group. Disability in chronic low back pain reflects more than pain severity alone and is influenced by movement confidence, physical capacity, fear, beliefs, and behavioral adaptation. The substantial reduction observed in the combined group may therefore be explained by simultaneous improvement in physical movement strategies and pain-related cognition. Previous investigations have shown that combining exercise with additional therapeutic components can produce clinically meaningful improvements in patients with chronic low back pain (Blanco-Giménez et al., 2024). PNE may enhance the effects of exercise by helping patients reinterpret pain during daily activity and reduce unnecessary avoidance, while DNS improves the physical ability to perform such activities with more efficient stabilization.

The present disability findings are also consistent with systematic evidence supporting PNE. A meta-analysis demonstrated short-term reductions in disability following PNE in chronic low back pain (Ma et al., 2024), and more recent evidence suggests improvements in disability together with pain-related psychological outcomes (Medina-Viedma et al., 2025). The fact that disability increased somewhat from post-test to follow-up in both active intervention groups may indicate partial loss of supervised-treatment effects after structured sessions ended. Nevertheless, disability remained significantly improved relative to baseline in both groups, with a larger residual benefit in the PNE + DNS group. This pattern may suggest that PNE contributed to better maintenance of behavioral and functional gains by equipping participants with a more adaptive framework for interpreting symptoms after supervision ceased.

Quality of life showed the largest Time $\times$ Group interaction, with the PNE + DNS group demonstrating the greatest increase after treatment and maintaining most of this gain at follow-up. This finding is clinically important because health-related quality of life reflects broader consequences of chronic low back pain beyond symptom

intensity, including physical functioning, emotional well-being, vitality, and social participation. Chronic low back pain can substantially affect quality of life, and the relationship among pain, disability, and quality of life is influenced by multiple individual and contextual factors (Wettstein et al., 2019). Improvements in quality of life may therefore represent an integrated response to reductions in pain and disability as well as increased confidence in movement and participation.

The favorable quality-of-life response is also consistent with previous DNS research. Rabieezadeh et al. reported improvements in quality of life following an 8-week DNS intervention in individuals with non-specific chronic low back pain (Rabieezadeh et al., 2024). However, the greater improvement observed in the PNE + DNS group in the present study suggests that addressing pain-related understanding and beliefs may extend the benefits of exercise beyond physical symptoms. Participants who perceive pain as less threatening may be more willing to engage in daily, occupational, social, and recreational activities, which could contribute to improvements across multiple quality-of-life domains. Long-term work on PNE within multidisciplinary rehabilitation also suggests that educational approaches may have sustained relevance when integrated into broader rehabilitation programs (Adenis et al., 2026).

The comparative performance of the conventional core exercise group further strengthens the interpretation of the results. Conventional core exercises can improve trunk strength, endurance, and stabilization capacity, and progressive core training remains a valid component of low back pain rehabilitation (Vera-Garcia et al., 2020). Previous research has also demonstrated benefits of core stability exercise in individuals with chronic low back pain (Shamsi et al., 2015). However, in the present study, conventional core exercise produced relatively limited changes compared with DNS-based interventions. This difference may reflect the more integrated sensorimotor demands of DNS, which combines breathing, developmental positioning, joint centration, postural stabilization, and controlled transitional movement rather than emphasizing trunk strengthening alone. Accordingly, the benefit of DNS may derive from the quality and coordination of motor control rather than from strengthening in isolation.

Another clinically relevant observation was the partial attenuation of several outcomes between post-test and follow-up, particularly in the DNS-only group. Such a pattern is not unexpected after discontinuation of supervised

rehabilitation. Improvements gained during structured treatment may diminish when exercise frequency decreases or when participants no longer receive corrective feedback. The greater maintenance of pain and quality-of-life improvements in the PNE + DNS group may indicate that education contributed to longer-lasting self-management. PNE is intended to modify conceptual understanding rather than produce a transient physiological effect, and this cognitive component may persist after supervised sessions have ended. Nevertheless, the observed attenuation in some outcomes emphasizes that chronic low back pain management may require continued engagement in physical activity and reinforcement of learned movement and pain-management strategies.

Educational level was considered in the randomization process because the effectiveness of PNE may be influenced by how individuals understand and integrate pain-related information. Previous evidence has shown that educational attainment can influence response to pain neuroscience education (Bilterys et al., 2022). Stratification by educational level in the present trial may therefore have reduced an important source of imbalance between groups and strengthened interpretation of the treatment effect. More broadly, this issue highlights the importance of adapting PNE to the individual's level of health literacy and ensuring that neurophysiological concepts are presented in accessible and clinically meaningful language.

The findings should also be interpreted in light of the distinction between statistical and clinical change. Pain, disability, motor control, and quality of life represent related but distinct dimensions, and improvement in one domain does not necessarily guarantee equivalent change in another. Measures of chronic pain should therefore be interpreted with attention to magnitude, functional relevance, and persistence over time (Ferrer-Peña et al., 2016). The significant interaction effects observed across all four outcomes suggest that the combined intervention influenced multiple dimensions of chronic low back pain rather than producing an isolated symptomatic effect. This multidimensional pattern is consistent with current recommendations that chronic primary low back pain be managed using active, non-surgical, person-centered approaches rather than relying solely on passive or symptom-focused treatment (World Health, 2023).

Overall, the present findings support the view that DNS is an effective active rehabilitation approach for chronic non-specific low back pain and that combining it with PNE may provide additional clinical benefit. The combined

intervention appears particularly advantageous because it addresses both the physical and perceptual dimensions of chronic pain. DNS targets movement coordination, breathing, stabilization, and postural control, whereas PNE targets pain-related threat, maladaptive beliefs, and fear of movement. Their combination may therefore promote a mutually reinforcing process in which patients develop more efficient motor strategies while simultaneously becoming less fearful of movement. This interpretation is consistent with the emerging literature on integrating PNE with neuromuscular and stabilization-based rehabilitation (Alvani et al., 2024; Kim et al., 2022). It also provides a plausible explanation for why the PNE + DNS group demonstrated the strongest and most persistent improvements across movement control, pain, disability, and quality of life.

Several limitations should be considered when interpreting the findings. First, the sample size was relatively modest and participants were restricted to adults aged 25–40 years, which limits generalizability to older adults, adolescents, and individuals with more complex comorbidities. Second, although the assessor was blinded, blinding of participants and the intervention provider was not feasible because of the nature of the exercise and educational interventions. Third, the follow-up period was limited to 2 months, preventing conclusions regarding longer-term maintenance of the observed improvements. Fourth, several outcomes, including pain, disability, and quality of life, relied on self-report and may have been influenced by participant expectations or reporting bias. Fifth, heterogeneity of covariance matrices and variance at some measurement occasions indicates that the assumptions of repeated-measures ANOVA were not fully satisfied, although corrected univariate procedures were used where appropriate. Finally, participants' physical activity, use of analgesic medication, and adherence to unsupervised exercise during the follow-up period were not quantified in sufficient detail and may have influenced follow-up outcomes.

Future studies should replicate these findings using larger multicenter samples with broader age ranges and greater clinical diversity. Longer follow-up periods, including 6- and 12-month assessments, would clarify whether the advantages of combining PNE with DNS persist over time. Future trials should also incorporate linear mixed-effects models or other robust longitudinal methods to better accommodate missing data and violations of covariance assumptions. Measuring psychological variables such as

pain catastrophizing, fear avoidance, kinesiophobia, pain self-efficacy, and pain-related beliefs would help identify potential mediators of the effects of PNE. Objective biomechanical and physiological measures, including trunk muscle activation, diaphragmatic function, pressure regulation, balance, and three-dimensional movement analysis, could also clarify the mechanisms underlying improvements in lumbar motor control. Further studies should examine dose-response relationships for both PNE and DNS and determine whether booster educational or exercise sessions improve maintenance of treatment effects after supervised rehabilitation ends.

In clinical practice, combining PNE with DNS may be considered when treating individuals with chronic non-specific low back pain who demonstrate both movement-control deficits and maladaptive pain-related beliefs or fear of movement. Clinicians should integrate pain education directly with active movement rather than treating education and exercise as unrelated components. PNE should be presented in accessible language, linked to the patient's own symptoms and movement experiences, and reinforced during exercise sessions. DNS progression should emphasize movement quality, diaphragmatic breathing, trunk control, and gradual exposure to increasingly functional tasks rather than rapid increases in exercise difficulty. Because some gains may diminish after supervised treatment ends, clinicians should also provide structured home programs, self-management strategies, and periodic follow-up or booster sessions to reinforce both pain-related knowledge and movement-control skills.

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 interview and participated in the research with informed consent.

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