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Effects of dynamic neuromuscular stabilization training on the core muscle contractility and standing postural control in patients with chronic low back pain: a randomized controlled trial

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Abstract

Background Patients with chronic low back pain (CLBP) usually demonstrate poor postural control due to impaired core muscle function. Dynamic neuromuscular stabilization (DNS) is based on developmental kinesiology principles, utilizing infant motor patterns to treat motor disorders. DNS has been shown to improve postural control in cerebral palsy patients by activating core muscle. However, whether the DNS approach is superior for enhancing core muscle contractility and postural control in CLBP patients still remains unclear.

Objectives This study aimed to compare the effects of DNS training and conventional core exercises on core muscle contractility and standing postural control in CLBP patients.

Methods Sixty CLBP patients were randomly assigned to a DNS group or a control group. Participants in the DNS group received DNS training, while those in the control group completed conventional core exercises. Both groups completed 12 sessions over 4 weeks (3 sessions/week, 50 min/session). Pre- and post-intervention evaluations included diagnostic musculoskeletal ultrasound to assess the change rate of core muscles (transversus abdominis (TrA), lumbar multifidus, and diaphragm), a balance assessment system to evaluate postural control performance (center of pressure displacement (COP)), and clinical questionnaires (Visual Analog Scale (VAS), Oswestry Disability Index (ODI), and Roland-Morris Disability Questionnaire (RDQ)) for pain intensity and disability.

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Results After 4 weeks, comparisons between both groups revealed significant statistical differences in the interaction effects of time*group. These differences were observed in the change rates of the left and right TrA ($F_{1,58}$=4.820 and 3.964, p=0.032 and 0.041), diaphragm change rate ($F_{1,58}$=11.945, p=0.001), as well as COP velocity ($F_{1,58}$=5.283, p=0.025), variability ($F_{1,58}$=13.189, p=0.001) in the anterior-posterior (AP) direction, COP path length ($F_{1,58}$=6.395, p=0.014), and COP area ($F_{1,58}$=5.038, p=0.029) in the eye-closed condition. DNS participants showed significantly greater muscle change rates and reduced COP ($p < 0.05$). The scores of VAS ($F_{1,58}$=173.929, p=0.001), ODI ($F_{1,58}$=60.871, p=0.001), and RDQ ($F_{1,58}$=60.015, p=0.001) decreased significantly over time, although no group differences were found between both groups ($p > 0.05$).

Conclusions DNS is superior to conventional core exercises in enhancing core muscle contractility and standing postural control in CLBP patients, showing potential to reduce pain and improve disability. Its mechanism may involve the enhancement of proprioceptive feedback, particularly when visual feedback is blocked.

Trial registration This study was registered in the Chinese Clinical Trial Registry (ChiCTR) with the registration number ChiCTR2300074595 on 10 August 2023.

Keywords Chronic low back pain, Dynamic neuromuscular stabilization, Core muscle, Postural control, Pain intensity, Disability

Background

Chronic low back pain (CLBP) is one of the most common musculoskeletal disorders with a lifetime prevalence of 13.1–20.3%, according to the latest epidemiological survey [1]. Since 1990, the worldwide number of patients with CLBP has dramatically increased from 0.37 billion to 0.57 billion, leading to an increase in years lived with disability (YLDs) for people [2]. CLBP has a profound impact on patients' lives, families, and work [3]. Moderate medical evidence suggests that core stability exercises may be an effective treatment for CLBP compared to no treatment, usual care, or placebo for pain [4, 5]. Although there have been some advances in the assessment and treatment of CLBP in recent years, the clinical efficacy is still unsatisfactory [6, 7]. Traditional treatments often yield suboptimal outcomes, highlighting the need for innovative and targeted approaches. Moreover, limited attention has been paid to the diaphragm's crucial role in core stability, further underscoring the need for novel intervention strategies. These research gaps highlight the necessity of more comprehensive and integrated treatment approaches that target both respiratory and postural components. CLBP is characterized by persistent pain and impaired postural control, often linked to core muscle atrophy, impaired postural control and dysfunctional motor control [8–12]. Emerging evidence suggests that improving core stability and postural control could be a key focus for intervention.

Posturography is a recognized method for objectively assessing postural control in CLBP patients, using metrics such as center of pressure (COP) trajectory and displacement to identify balance impairments [13, 14]. CLBP patients typically exhibit increased COP sway and larger displacement, especially in the anterior-posterior (AP) direction, indicating poor postural control [15]. These impairments are closely linked to core muscle dysfunction, as shown by reduced transversus abdominis (TrA) and lumbar multifidus (MF) thickness and increased COP path length in CLBP patients compared to healthy controls [16]. Panjabi attributes postural control deficits to a lack of core stability, maintained by co-contraction of core muscles [17].While core exercises can improve muscle contractility and postural control [18, 19], many studies neglect the diaphragm's role in core stability and respiration. CLBP patients show reduced diaphragm excursion during postural tasks, reflecting impaired coordination [20, 21]. Conventional core exercises often fail to integrate breathing patterns, limiting diaphragm activation and its contribution to core stability [20]. This lack of focus on integrated breathing and postural control highlights a critical gap in current rehabilitation protocols, which this study aims to address. In contrast, Dynamic neuromuscular stabilization (DNS) training is specifically designed to integrate postural control with a precise breathing pattern, which improves both the function of core muscles and the coordination of respiratory muscles.

DNS is a novel functional approach based on developmental kinesiological models, which utilizes the infant motor development process to address motor-related disorders [22]. DNS aims to achieve optimal body function by aligning the head and spine, integrating postural awareness, breathing patterns, and motor control [23]. It emphasizes the coordination of body segments to maintain a neutral, functional position and facilitate precise muscle contractions for both breathing and postural control. The goal of DNS training is to activate the appropriate respiratory and core muscles to maintain core stability in any position or during locomotor tasks [22]. Conventional core exercises focus on strengthening deep abdominal and spinal muscles to improve postural control and protect the spine. These exercises, such as planks and bridging, aim to enhance muscular endurance and coordination. In comparison to conventional core exercises, the DNS training has been proven to be effective in improving the breathing pattern, increasing lumbar stability and intra-abdominal pressure [24]. Despite its potential, DNS application in CLBP patients remains limited. Existing studies suggest its effectiveness in improving pain and disability but lack quantitative assessment of its impact on muscle contractility and postural control [25]. Furthermore, the comparative effectiveness of DNS versus conventional core exercises remains unclear, emphasizing the need for further research. Therefore, the present study aimed to investigate the effects of the DNS training on the core muscle thickness change, the postural control performance, pain intensity, and the LBP-related disability in CLBP patients. Unlike conventional core exercises, DNS training focuses on optimizing the coordination of respiratory and postural muscles, which may offer superior benefits for improving these outcomes. By addressing the gap in current rehabilitation protocols, this study could provide new insights into the clinical application of DNS for CLBP treatment.

Methods

Study design

The study adhered to CONSORT guidelines for randomized controlled trials. This was a single-blinded, randomized controlled trial with parallel groups of CLBP patients. The details of the recruiting process are illustrated in Fig. 1.

Randomization

Participants were randomly assigned to either the DNS group or the control group using block randomization with a block size of [insert block size, e.g., 4 or 6]. The randomization sequence was generated by statistical software (IBM SPSS 25.0).

Allocation concealment

To ensure allocation concealment and reduce selection bias, we utilized sealed, opaque, and sequentially numbered envelopes. The envelopes were prepared by an independent researcher not involved in participant recruitment or intervention delivery. These envelopes

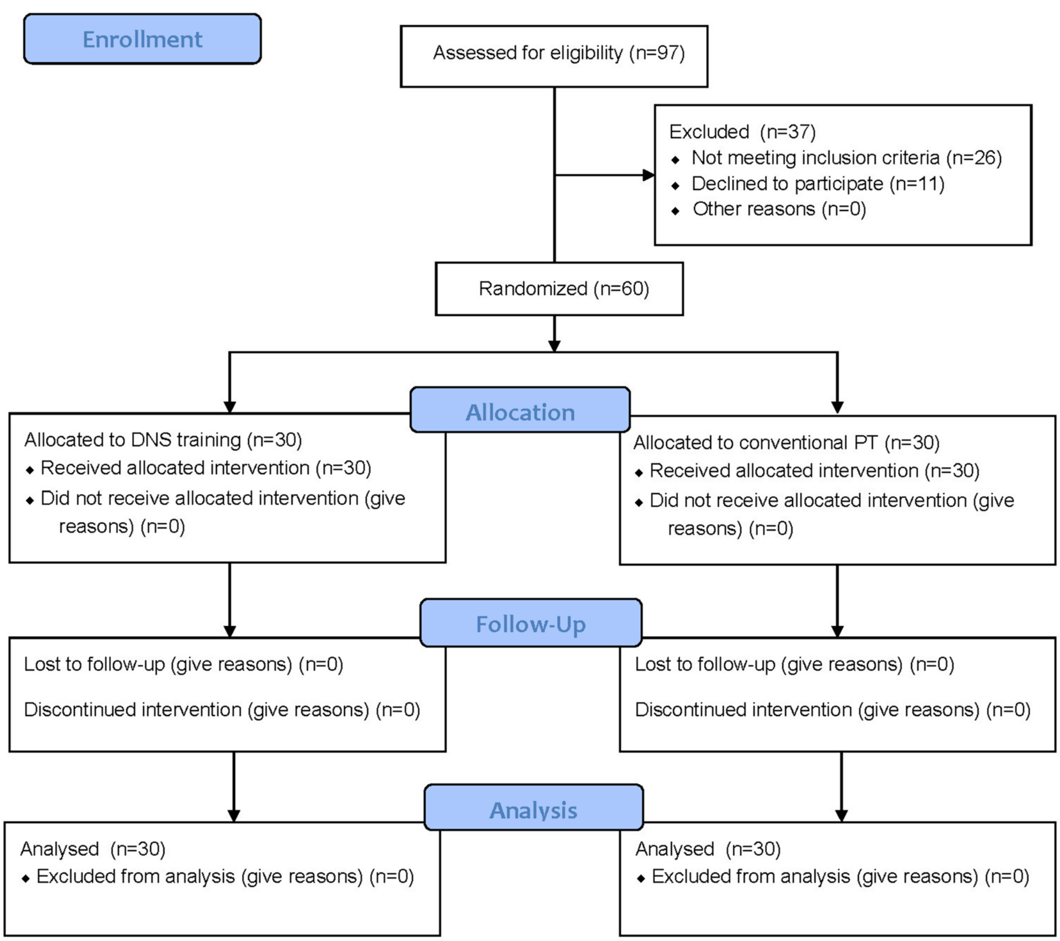

Fig. 1 CONSORT flow diagram for this study

were opened only after participants completed their baseline assessment.

Blinding

A designated researcher responsible for the clinical assessment of participants and experienced physical therapists who assisted participants during the intervention were blinded to group allocation. This single-blind design ensured objectivity during assessments and interventions.

This study was carried out in accordance with the Declaration of Helsinki (https://www.wma.net/policies-post/wma-declaration-of-helsinki/) with the approval of the Independent Ethics Committee for Clinical Research and Animal Trials of the First Affiliated Hospital of Sun Yat-sen University (IRB# [2023] 324), and had also been enrolled in the Chinese Clinical Trial Registry (ChiCTR# 2300074595). Written informed consent was obtained from each participant at the day of inclusion, and detailed information about this study was also provided. Participants were free to withdraw from the study at any time without providing a reason.

Participants and sample size calculation

Patients with CLBP were recruited between May 2023 and February 2024 from the Department of Rehabilitation Medicine, the First Affiliated Hospital of Sun Yat-sen University, Guangzhou, China. On the day of recruitment, each participant was subjected to a clinical evaluation by an experienced physician, and their medical history was reviewed in detail.

The inclusion criteria were as follows: (1) diagnosed with non-specific LBP with pain persisting for more than 3 months according to the diagnostic guidelines from the American College of Physicians and the American Pain Society [26]; (2) aged between 18 and 60 years; (3) visual analog scale (VAS) ≥ 3 cm; (4) body mass index ≤ 28 kg/m^2; (5) Intact psychological and cognitive functions, which were assessed based on the following criteria: (a) no reported history of psychological or cognitive disorders; (b) participants' ability to understand and complete study instructions during an initial clinical interview; (c) confirmation through clinical judgment by an experienced clinician. Additionally, baseline physical activity levels were assessed using prior training experience, which was self-reported by participants. Participants were excluded if they had any of the following: (1) previous back surgery, spinal tumors, deformities or infections; (2) LBP of traumatic or structural origins or LBP with neurological symptoms. Neurological symptoms were defined as the presence of radiating pain, muscle weakness, sensory deficits, or abnormal reflexes in the lower extremities, based on the clinical diagnostic criteria outlined in the guidelines of the American College of Physicians and the American Pain Society [26]; (3) previous neurological and/or cardiopulmonary diseases, including chronic obstructive pulmonary disease (COPD), that severely affected locomotor performance. COPD was identified through a review of participants' medical histories, supplemented by self-reported diagnoses provided during the initial screening interview; (4) pregnancy. Furthermore, potential confounding health conditions were identified through the review of participants' medical histories.

The determination of sample size was based on a previous publication [18] via the computation of power analysis through G*power (http://www.gpower.hhu.de/). Based on their study, recruitment of 34 participants would generate a power of 80% and a level of significance of 5% (two-sided) for detecting a true difference. According to the Partial Eta Squared method, the $\eta^2 = 0.138$ as the large effect size was used to calculate the effect size *f* [27]. Therefore, with the calculated effect size *f* as 0.4 and the potential drop-out rate of 15%, recruiting 57 patients with CLBP should be statistically sufficient for identifying the true difference in outcomes of interest.

Interventions

In this study, prior to the intervention period, participants received health education about CLBP to ensure understanding of the training process and goals. Participants in the DNS and control groups were treated with a 4-week intervention. Each participant completed a total of 12 training sessions (3 sessions per week), with each session lasting 50 min. Each training session followed a structured format consisting of three main components: a 5-minute warm-up, 40 min of main exercises, and a 5-minute cool-down. Two experienced physical therapists assisted participants in completing the intervention. The study personnel were trained to implement study protocols in an effort to ensure standardization within and cross sites. Adherence to the intervention was monitored using attendance logs and exercise diaries, where participants recorded their exercise sessions and any difficulties they encountered. Participants were contacted regularly by the research team through phone calls or emails to encourage adherence, remind them of upcoming sessions, and address any concerns or challenges they faced with the exercises. Additionally, the research team provided guidance on how to modify exercises if participants experienced discomfort or difficulty, ensuring they felt supported throughout the intervention period. If any intolerable pain or symptoms occurred, the intervention would be terminated immediately, and participants would be provided with sufficient rest or medical care as necessary. During the intervention, appropriate breaks were provided for participants to avoid excessive muscle fatigue. Participants were also allowed to request more rest according to their individual status and needs. If any participants did not accomplish the intervention, they were treated as dropouts and excluded from data analysis. To ensure the proper execution of exercises, the physical therapists provided continuous supervision and feedback throughout each session. Participants were also re-evaluated periodically to ensure they were performing the exercises correctly and safely.

Intervention protocols for participants in DNS and control groups were shown as follows.

(1) **Warm-Up**: Each session began with a 5-minute warm-up, which included light stretching and dynamic movements aimed at preparing the lower back and core muscles for the main exercises.
(2) **Main Exercises**:

① **DNS group** Participants in the DNS group performed six exercises, including supine diaphragmatic breathing, dead-bug exercise, side-lying rolling, bear-crawl exercise, high side plank and kneeling-sitting transfer (Fig. 2) [25]. According to the DNS approach, participants in the DNS groups were guided by oral feedback from an experienced physical therapist to follow three basic DNS principles, to ensure a high quality of training [22]. Firstly, learning abdominal respiration skills to maintain an appropriate intra-abdominal pressure during the DNS training. Secondly, maintaining spinal stability in the sagittal plane to achieve good spinal alignment and curvature. Thirdly, inducing the co-contraction of agonists and antagonists by specific positioning of joints. Each exercise was designed as 2 sets with 10 repetitions per set. A mandatory 2-minute break was assigned to every participant between each exercise.

② **Control Group** Participants in the control group received conventional core exercises for CLBP, consisting of single/double leg-bridge, side bridge, crunch, prone plank and the bird-dog exercises (Fig. 3) [28]. Participants were required to control their movements slowly and steadily, as well as maintaining a natural, rhythmic breathing pattern to avoid the Valsalva maneuver. Each exercise was designed as 2 sets with 10 repetitions per set. A mandatory 2-minute break was assigned to every participant between each exercise.

(3) **Cool-Down**: Each session concluded with a 5-minute cool-down, which consisted of static stretching and relaxation exercises focusing on the lower back and core muscles to promote recovery and reduce tension.
(4) **Progressive Overload**: Both DNS training and conventional core exercise programs followed the principle of progressive overload, with the intensity, volume, and complexity of exercises gradually increased over the 4-week intervention. Specifically:

① Intensity: Participants started with lower-intensity exercises and progressed to higher intensity by the third or fourth week, with more challenging sets and longer

Fig. 2 Diagram of the dynamic neuromuscular stabilization (DNS) training. (**A**): supine diaphragmatic breathing; (**B**): the dead-bug exercise; (**C**): side-lying rolling; (**D**): the bear-crawl exercise; (**E**): high side plank; (**F**): the kneeling-sitting transfer

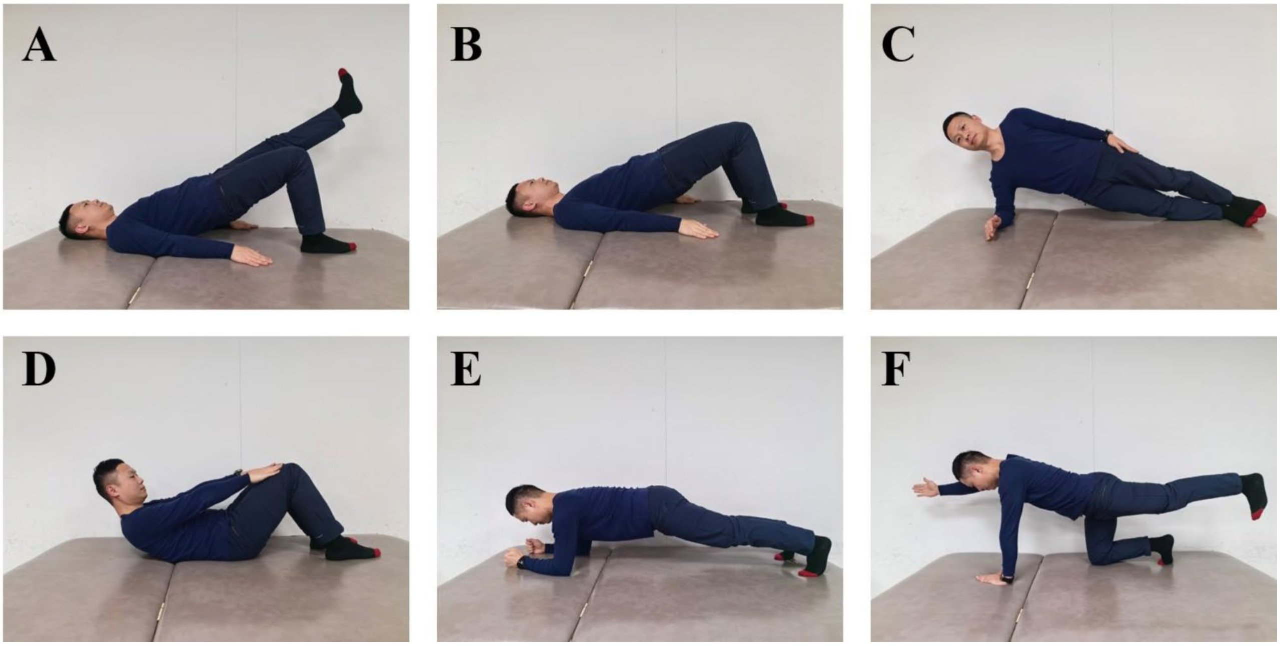

Fig. 3 Diagram of the general exercise training for chronic low back pain (CLBP). (**A**): single leg-bridge; (**B**): double leg-bridge; (**C**): side bridge; (**D**): crunch; (**E**): prone plank; (**F**): the bird-dog exercise

durations to stimulate muscle adaptation. For participants who had difficulty performing certain exercises, modifications were made by adjusting the task demands to ensure they could participate safely and effectively. These adjustments included reducing the range of motion or providing external support. As participants' abilities improved, they were gradually able to progress back to the original exercise form.

② Volume: The total number of sets and repetitions was progressively increased over the course of the intervention. In week 1, participants performed 2 sets of 10 repetitions per exercise, which increased to 2 sets of 16 repetitions by week 4.

③ Complexity: The exercises progressed in complexity, starting with basic exercises focused on isolated muscle activation and gradually moving to more complex movements that required greater coordination, balance, and stability. From weeks 3 to 4, resistance bands were added to exercises to increase difficulty without changing the core movements. For example, resistance bands were incorporated into the dead-bug exercise, side-lying rolling, bear-crawl exercise, side bridge, and the bird-dog exercise to provide added resistance and challenge core stability.

This progression was designed to ensure that participants continually challenged their muscles and progressively adapted to the exercises, aligning with the principle of progressive overload.

Outcome measures

In the present study, each participant was evaluated by a specific researcher who was a professionally-trained physician blinded to the allocation of each participant before and after the 4-week intervention. This researcher underwent standardized training in the assessment protocols, including musculoskeletal ultrasound evaluation, balance assessment using a dedicated system, and the administration of LBP-related questionnaires. The training ensured that the rater was familiar with the specific procedures for these outcome measures and minimized potential biases. The training also included regular calibration sessions with senior researchers to ensure consistency and accuracy. No participant required permanent discontinuation of the intervention due to adverse effects. Outcomes of interest included following three components.

The percent change of core muscles thickness

In this study, a diagnostic musculoskeletal ultrasound (SONIMAGE HS1, Konica Minolta Inc., Japan) with a linear transducer at 18.0 MHz and a curvilinear transducer at 4.0 MHz was used to measure the morphologic changes of core muscles (bilateral TrA and lumbar MF, and diaphragm) for each participant before and after the intervention. The ultrasound system used in this study had been calibrated to ensure high accuracy, with a minimal coefficient of variation (CV) of less than 5% for muscle thickness measurements, as confirmed by previous studies. For each core muscle, thickness was measured at rest and during maximum voluntary isometric contraction (MVIC), with each measurement repeated three times. A 1-minute break was provided for participants among measurements of muscle thickness at MVIC state to avoid muscle fatigue. Considering the impact of different demographic characteristics (sex, age, weight, and height), the percent change of muscle thickness was used to measure the contractility of core muscles and ensure the comparability among different participants. The calculation of percent change of muscle thickness was based on the following formula [29],

$$Percent\ change = \frac{Thickness\ (MVIC) - Thickness\ (Rest)}{Thickness\ (Rest)} \times 100\%$$

Then, the average values of percent change of muscle thickness at different states for a participant were regarded as the final outcome to be used in data analysis. Figure 4 demonstrated an example of core muscle ultrasound image from a participant.

To measure unilateral TrA, participants were instructed to hold a supine hook-lying position with both arms crossing over their chest and knee flexing to 90 degrees. The linear transducer with B-mode was placed on the ipsilateral mid-axillary line at the level of umbilicus (just above the iliac crest). Following a deep inspiration and then a forced expiration, participants were required to keep breathing out and voluntarily relax their abdomen to record the thickness of TrA at the rest state, he image of TrA was taken at the end of exhalation. Then, they were guided to perform the abdominal draw-in maneuver to measure the thickness of TrA at MVIC state [9]. To more accurately measure it, participants were allowed to practice this maneuver before the data collection to correctly contract the TrA.

To measure the diaphragm, participants were required to keep the above-mentioned supine hook-lying position. The linear transducer with B-mode was placed on the intersection between the right anterior axillary line and the 7th or 8th intercostal space (depending on participants' body size) to record the longitudinal image of diaphragm [30, 31]. Assessor adjusted the angle of transducer until obtaining the clear image of diaphragm and held this angle during the measurement. Participants were required to exhale as far as possible to reach maximum exhalation and record the thickness of diaphragm at the rest state. Then, they were instructed to inhale to reach total lung capacity and hold their breath to measure the thickness of diaphragm at MVIC state.

The measurement of unilateral MF followed the procedure as follow. Firstly, participants kept a prone position on a therapy table with a pillow placed under their abdomen to flatten the lumbosacral curve. To measure lumbar MF at the L5/S1 level, the curvilinear transducer with B-mode was longitudinally positioned about 2 cm lateral to the midline of the L5 spinal process, and medially angled to obtain the image of the ipsilateral L5/S1 zygapophyseal joint and MF at the rest state. Then, the thickness of MF at MVIC state was measured by participants lifting their contralateral arms 5 cm off the table and holding at shoulder abduction of 120 degrees and elbow flexion of 90 degrees [18]. Assessor would also apply a downward force to the lifted elbow to better contract the target MF.

Postural control performance

A balance evaluation system (PRO-KIN Version, PK252P, TecnoBody, Italy) was used in this study to assess the postural control performance of participants with CLBP in an upright standing position. The sample frequency was set at 50 Hz. Prior to the data collection, the detailed information about the evaluation of balance was provided for participants and any questions were answered. An individual account was established for each participant to enter the information about age, height, and weight, so as to calibrate the system for standardization. Participants were instructed to stand barefoot on the firm, stable surface of the balance system, with their arms naturally placed at either sides of the body. There were several orientation lines to guide each participant to place their feet at an angle of approximately 30 degrees to the sagittal plane, and their heels were kept apart with shoulder width. Then, participants were required to stand within the system for 1 min for familiarization. After the familiarization, a 1-minute mandatory rest was provided for each participant. There were two different standing tasks (double-leg stance with eye-open (EO) and eye-close (EC)), and each task was repeated for three times to decrease measuring error. Hence, a total of six standing trials were randomly assigned to each participants. Each standing trial lasted 30 s. During an EO trial, participants were instructed to maintain standing balance with their eyes looking forward horizontally after receiving a signal from the examiner. For the EC trial, participants were required to maintain an upright standing posture but keeping their eyes closed during the data collection. A 1-minute mandatory rest was provided between two trials to wash out the learning effect [32]. The details of the evaluation process are described in to our previous publication [16]. A safety lanyard connected with the balance system was used for participants' safety. Participants were allowed to open their eyes or hold the handrail if they felt unstable during a trial.

In the present study, outcomes of interest for postural control performance included the average displacement velocity of COP in the anterior-posterior (AP) and medial-lateral (ML) directions, the variability (standard deviation) of COP displacement in the AP and ML

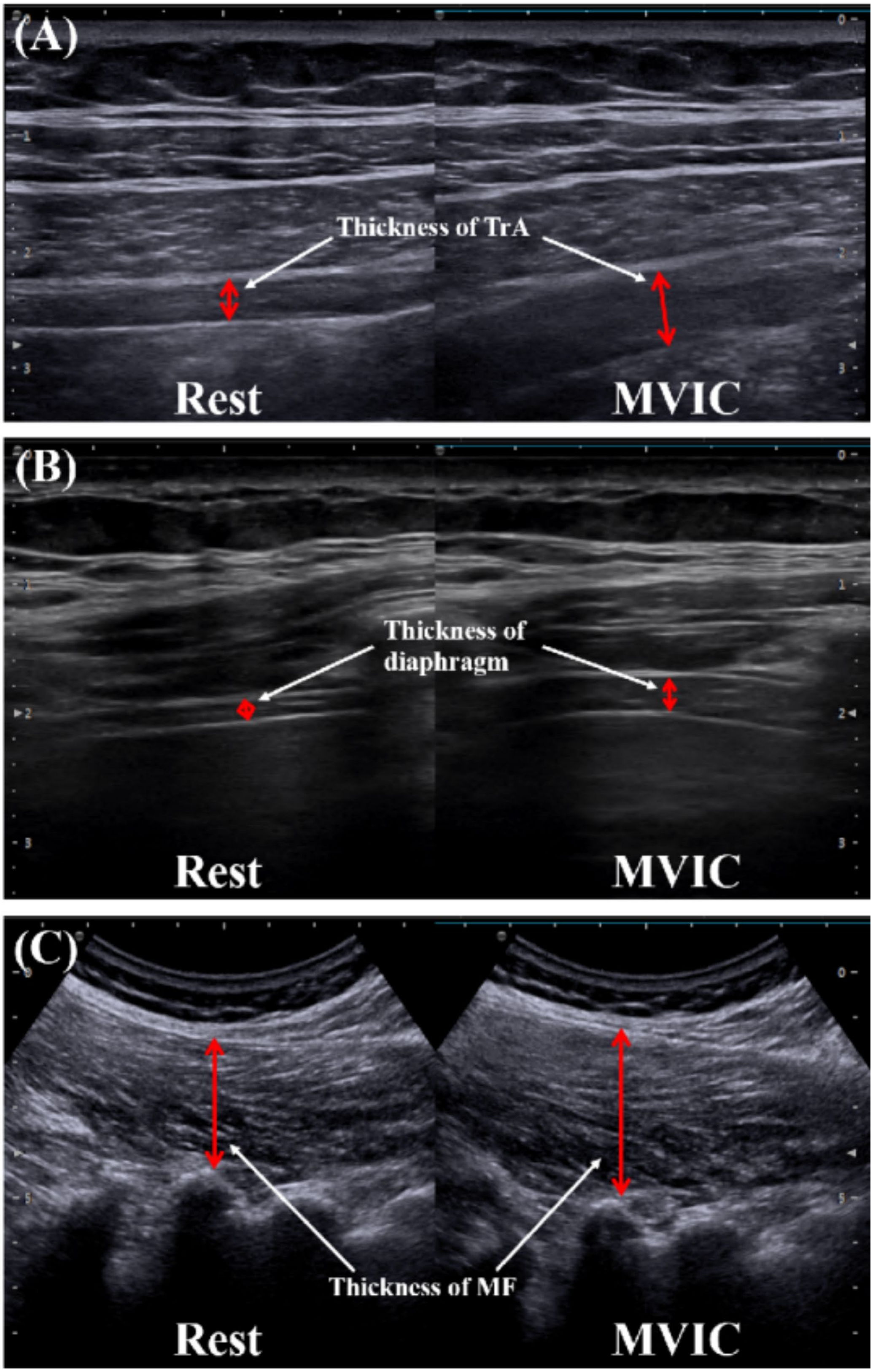

Fig. 4 An example of ultrasound images of core muscles at the rest and the maximum voluntary isometric contraction (MVIC) states. (**A**): transversus abdominis (TrA); (**B**): diaphragm; (**C**): lumbar multifidus (MF)

directions, the displacement area of COP, and the path length of COP (the total length of COP trajectory during the 30-second trial) [14]. The mean values of repeated measurements were used for data analysis. The system's reliability has been validated in previous studies, and the displacement velocity of the center of pressure (COP) is highly accurate, with a precision of 0.1 mm.

Questionnaire assessment

In this study, to understand alterations in the pain intensity and LBP-related disability, participants in two groups were assisted in completing the Visual Analog Scale (VAS), Oswestry Disability Index (ODI), and Roland-Morris Disability Questionnaire (RDQ) before and after the 4-week intervention. VAS was a commonly used clinical tool to measure the self-reported pain intensity, which required participants to place a marker on a 10-cm-long straight line to represent the intensity of pain they felt [33]. VAS has been shown to have high reliability, with a Cronbach's alpha coefficient of 0.90. In this straight line, the left endpoint (0 cm) indicated no pain and the right endpoint (10 cm) indicated the worst pain. In this study, the LBP-related disability was evaluated by ODI and RDQ. ODI included 10 items in total, and each item was measured by a 6-level ordinal scale ranging from the best (scored as 0) to worst scenario (scored as 5) [34, 35]. ODI covered activities of daily living (ADL) that may be disrupted by LBP and had been proven as an appropriate instrument with good reliability and validity for the assessment of functional status of CLBP patients [34, 35]. Additionally, RDQ was a self-rated assessment of ADL function for patients with LBP. There were 24 Yes/No questions to evaluate the ADL-related disability due to LBP [36, 37]. This self-reported questionnaire was designed to assess disability related to ADLs, with 24 Yes/No questions. RDQ is known for its ease of use and has shown strong test-retest reliability. In comparison to ODI, RDQ had the advantages of ease of use and follow-up [36]. For all three questionnaires, a higher score indicated a greater level of pain intensity and LBP-related disability due to LBP.

Table 1 Demographic information for participants with chronic low back pain (mean ± standard deviation)

	DNS group (n = 30)	Control group (n = 30)	t / χ^2	p-value
Gender (male/female)	8/22	7/23	0.089	0.766
Age (years)	39.23 ± 8.44	37.43 ± 7.38	0.880	0.383
Height (cm)	165.25 ± 9.02	162.43 ± 6.50	1.338	0.170
Weight (kg)	60.45 ± 10.47	61.30 ± 9.97	-0.322	0.749
Body mass index (kg/m^2)	22.19 ± 2.59	23.13 ± 2.59	-1.406	0.165

DNS: Dynamic neuromuscular stabilization

Statistical analysis

Data were primarily analyzed using the per-protocol (PP) approach, which included only participants who completed the intervention and follow-up as per the study protocol. Statistical analysis was performed using SPSS 25.0 (IBM Corporation, Armond, NY, USA). Continuous data were presented as the mean ± standard deviation according to normal distribution. The Shapiro-Wilk normality test and Levene test were used to measure the normality and homogeneity of variance for each dependent variable respectively. If the data was normally distributed ($p > 0.05$), an independent t-test was applied to identify any significant difference between two groups before the intervention to ensure the comparability. A two-way mixed repeated measures ANOVA was applied to investigate the interaction between the effect of DNS training and the time effect. When there was a significant interaction, *Post-hoc* comparisons were performed using the Bonferroni correction according to the guidelines from IBM SPSS Statistics (https://www.ibm.com/support/pages/calculation-bonferroni-adjusted-p-values). It should be noted that there were 4 pairwise comparisons (2 times (Pre/Post) * 2 groups) in this study; therefore, the original (unadjusted) p-values were multiplied by 4 to calculate the adjusted p-values for *Post-hoc* comparisons. Only when the adjusted p-values were less than 0.05, the difference would be considered as significant. In the event of the non-normally distributed data ($p < 0.05$), the Mann-Whitney U-test and the Friedmann's test were performed. Additionally, the Chi-square test was used to compare the sex distribution of two groups. The significance level was set at 0.05.

Results

Demographic characteristics of participants

A total of 60 patients with CLBP were recruited in this study and randomly allocated to DNS group (n = 30) and control group (n = 30). Participants in each group accomplished the DNS training or conventional core exercises for 4 weeks. Both DNS training and conventional core exercises were implemented with close monitoring of participants' response to the interventions. No serious adverse effects were reported during the course of the study. However, some participants in both groups experienced mild discomfort such as muscle soreness and fatigue, particularly during the early weeks of the intervention. These effects were transient and resolved within a few hours after each session. If any participant reported intolerable pain or discomfort, the intervention was adjusted or temporarily halted, and they were provided with rest or medical care as necessary. No participant dropped out from either group during the entire intervention period. Demographic characteristics of all participants were illustrated in Table 1. There was no statistical difference between participants in two groups regarding sex ($p = 0.766$), age ($p = 0.383$), height ($p = 0.170$), weight ($p = 0.749$), and body mass index ($p = 0.165$). At baseline, the outcomes of interest from participants in both groups showed no significant difference ($p > 0.05$). Table 2 presents the changes in primary outcome measures, including percent change of core muscles, postural control performance, and questionnaire evaluation for both DNS and control groups, before and after the 4-week intervention period.

Differences in the percent change of core muscles of participants in DNS and control groups

As shown in Fig. 5, significant interactions between the effect of DNS training and the time effect were observed in left TrA ($F_{1,58}$=4.820, $p = 0.032$), right TrA ($F_{1,58}$=3.964, $p = 0.041$), and diaphragm ($F_{1,58}$=11.945, $p = 0.001$). *Post hoc* comparisons indicated that after the intervention period, patients with CLBP in the DNS group demonstrated significantly higher percent change of left TrA ($p = 0.001$), right TrA ($p = 0.031$), and diaphragm ($p = 0.002$) than those who received 4-week conventional core exercises. No significant difference appeared on the percent change of left and right MF ($p > 0.05$).

Differences in the postural control performance of participants in DNS and control groups

In the eye-open condition, there was no significant interaction between the effect of DNS training and the time effect observed in all COP variables ($p > 0.05$) (Fig. 6). Patients with CLBP in two groups demonstrated no significant difference on all COP variables before and after the intervention ($p > 0.05$). However, significant time effects were observed in COP velocity in the AP direction ($p = 0.038$ for DNS group; $p = 0.042$ for control group), COP variability in the AP direction ($p = 0.033$ for DNS group), and COP path length ($p = 0.040$ for DNS group; $p = 0.045$ for control group).

As shown in Fig. 7, in the eye-close condition, significant interaction between the effect of DNS training and the time effect was observed in COP velocity ($F_{1,58}$=5.283, $p = 0.025$) and variability ($F_{1,58}$=13.189, $p = 0.001$) in the AP direction, COP path length ($F_{1,58}$=6.395, $p = 0.014$), and COP area ($F_{1,58}$=5.038, $p = 0.029$). After the 4-week intervention, patients with CLBP in the DNS group showed significantly lower COP velocity in the AP direction ($p = 0.025$), COP variability in the AP direction ($p = 0.004$), COP path length ($p = 0.005$), and COP area ($p = 0.001$) than those in the control group. However,

Table 2 Summary of data for dependent variables pre- and post-intervention for participants in the dynamic neuromuscular stabilization (DNS) and control groups (mean ± standard deviation)

	DNS group ($n = 30$)		**Control group ($n = 30$)**	
	Pre	**Post**	**Pre**	**Post**
Percentage changes of core muscle thickness				
Left TrA (%)	74.03 ± 35.62	142.14 ± 55.51	63.64 ± 27.69	100.24 ± 40.44
Right TrA (%)	66.73 ± 24.98	114.91 ± 37.07	69.16 ± 23.68	97.61 ± 35.95
Diaphragm (%)	92.35 ± 30.21	155.61 ± 43.60	108.26 ± 45.30	122.55 ± 45.56
Left MF (%)	12.72 ± 9.71	19.37 ± 11.43	15.28 ± 13.04	15.79 ± 8.77
Right MF (%)	13.73 ± 11.20	20.37 ± 13.45	14.75 ± 10.60	18.26 ± 11.97
Postural control performance with eye-open				
COP velocity_AP (mm/s)	6.27 ± 2.51	5.52 ± 1.59	6.08 ± 1.54	5.38 ± 1.68
COP velocity_ML (mm/s)	4.13 ± 2.37	4.01 ± 1.45	4.60 ± 2.16	4.39 ± 1.11
COP variability_AP (mm)	4.27 ± 1.70	3.71 ± 1.38	4.64 ± 2.17	4.63 ± 1.79
COP variability_ML (mm)	2.80 ± 1.01	2.48 ± 1.06	2.58 ± 1.03	2.53 ± 0.69
COP path length (mm)	272.52 ± 103.72	249.23 ± 75.77	264.77 ± 53.99	248.26 ± 86.72
COP area (mm^2)	233.42 ± 166.22	190.20 ± 103.03	234.78 ± 217.03	218.39 ± 132.07
Postural control performance with eye-close				
COP velocity_AP (mm/s)	14.36 ± 3.09	9.47 ± 6.57	14.73 ± 2.83	11.62 ± 4.82
COP velocity_ML (mm/s)	13.54 ± 5.15	9.23 ± 3.79	14.77 ± 1.91	11.05 ± 2.33
COP variability_AP (mm)	6.60 ± 2.15	4.86 ± 1.78	6.35 ± 2.00	5.71 ± 1.88
COP variability_ML (mm)	4.08 ± 1.23	3.32 ± 1.37	3.70 ± 1.43	3.51 ± 1.21
COP path length (mm)	489.99 ± 172.54	399.07 ± 151.47	476.27 ± 115.99	439.25 ± 112.29
COP area (mm^2)	526.77 ± 295.76	348.89 ± 236.27	511.72 ± 358.57	412.24 ± 237.71
Clinical questionnaires				
Visual Analogue Scale (mm)	4.20 ± 1.21	1.67 ± 1.71	3.60 ± 1.16	1.47 ± 1.28
Roland Morris Disability Questionnaire	8.08 ± 5.01	2.23 ± 3.03	10.23 ± 5.42	5.47 ± 5.37
Oswestry Disability Index	13.37 ± 4.78	6.43 ± 4.38	11.40 ± 5.50	6.17 ± 5.55

DNS: Dynamic neuromuscular stabilization; AP: Anterior-posterior; COP: Center of pressure; MF: Lumbar multifidus; ML: Medial-lateral; TrA: Transversus abdominis

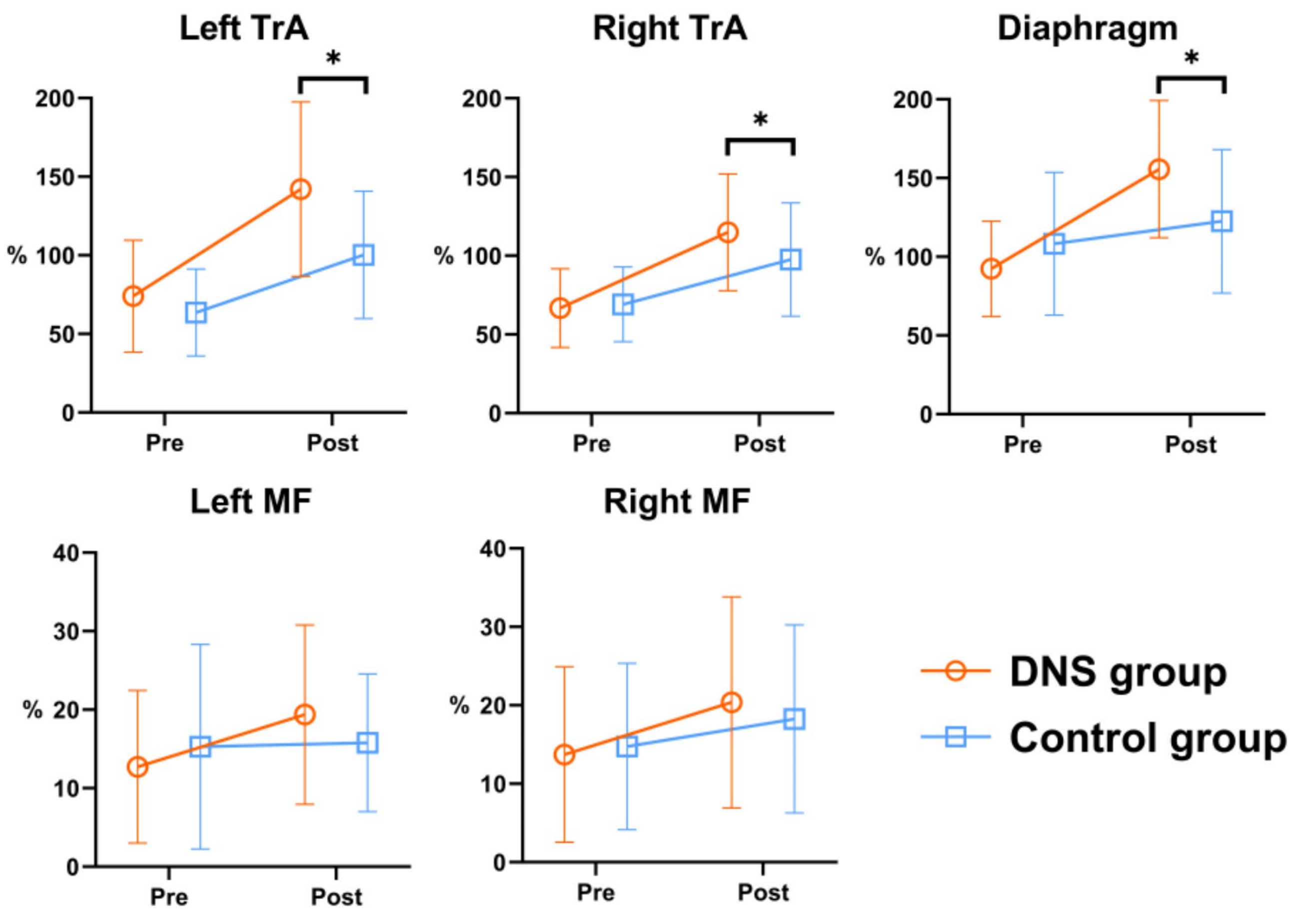

Fig. 5 The percentage change of core muscles before and after interventions for patients with chronic low back pain in dynamic neuromuscular stabilization (DNS) and control groups. * indicates the significant difference between DNS and control groups after the intervention ($p<0.05$). TrA, transversus abdominis; MF, multifidus

there was no significant interaction observed in COP velocity and variability in the ML direction ($p>0.05$).

Differences in the questionnaire evaluation of participants in DNS and control groups

As shown in Fig. 8, no significant interaction between the effect of DNS training and the time effect was observed in scores of VAS, RDQ, and ODI ($p>0.05$). Patients with CLBP in two groups demonstrated no significant difference on scores of all three questionnaires before and after the intervention ($p>0.05$). However, significant time effect was observed that the scores of VAS, RDQ, and ODI significantly decreased after 4-week intervention in both DNS and control groups ($p<0.05$).

Discussion

The present study investigated the effectiveness of the DNS training on the contractility of core muscles, postural control performance, pain intensity and the LBP-related disability in CLBP patients after the 4-week intervention. The results partially supported our hypotheses, as DNS training significantly increased the percent change of TrA and diaphragm thickness, and decreased the COP displacement in the eye-close condition compared to conventional core exercises. However, the DNS training demonstrated the similar effects on decreasing pain intensity and the LBP-related disability as conventional core exercises.

The DNS training further enhanced the contractility of TrA and diaphragm than conventional core exercises

In the present study, participants with CLBP in both DNS and control groups demonstrated significantly increased percent change of TrA after 4-week intervention, with significant differences observed between groups post-intervention. Our results indicated that in comparison to conventional core exercises, DNS training demonstrated a better effect on increasing the contractility of TrA in CLBP patients, which was consistent with previous studies [12, 18]. According to previously published studies, TrA was crucial for maintaining core stability and providing proprioceptive feedback to the lumbar spine [12]. Proprioception, the ability to sense joint position and movement, plays a critical role in spinal stability

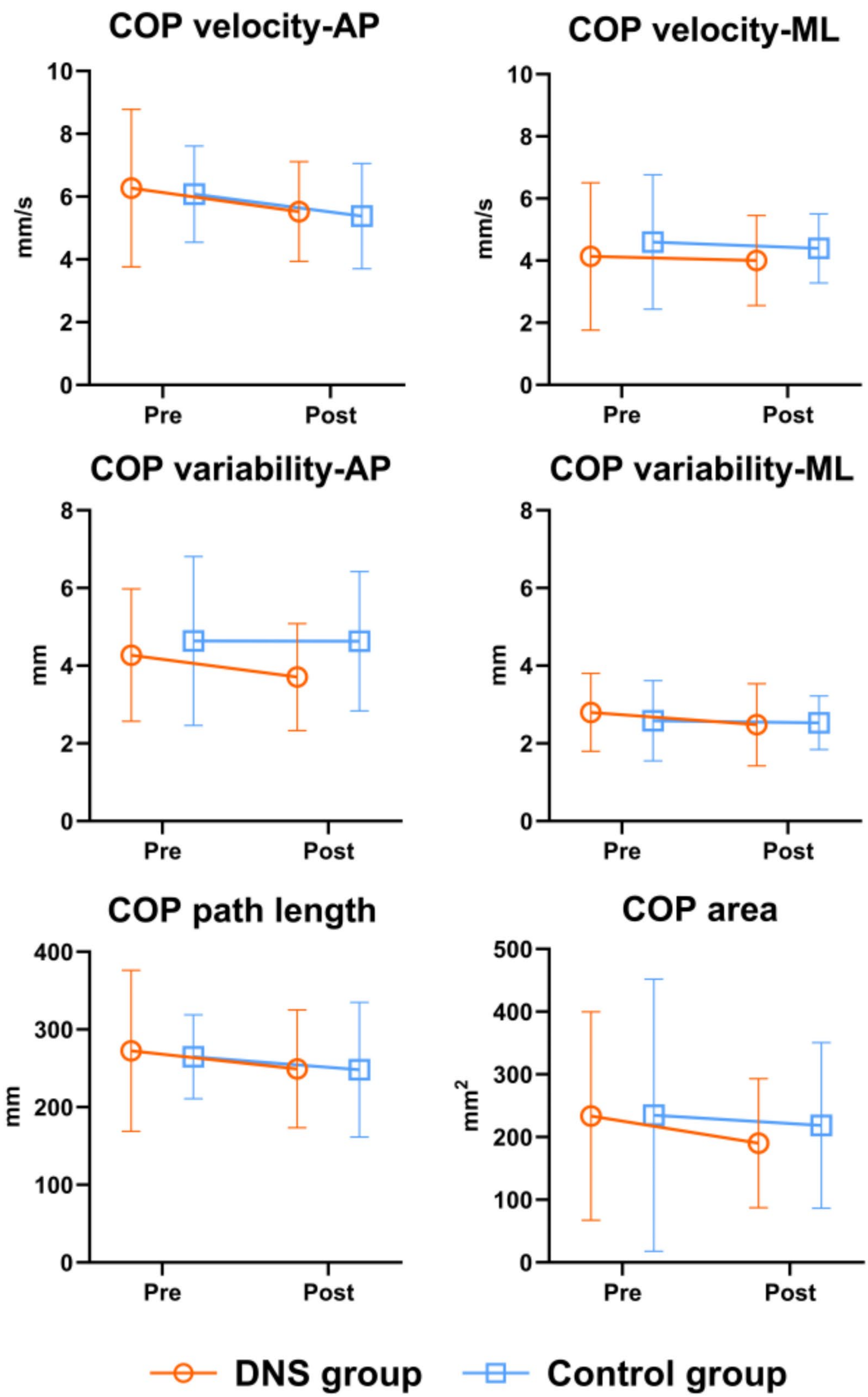

Fig. 6 Postural control performance in the eye-open condition before and after interventions for patients with chronic low back pain in dynamic neuromuscular stabilization (DNS) and control groups. No significant difference was observed between DNS and control groups before and after the intervention ($p < 0.05$). AP, anterior-posterior direction; COP, center of pressure; ML, medial-lateral direction

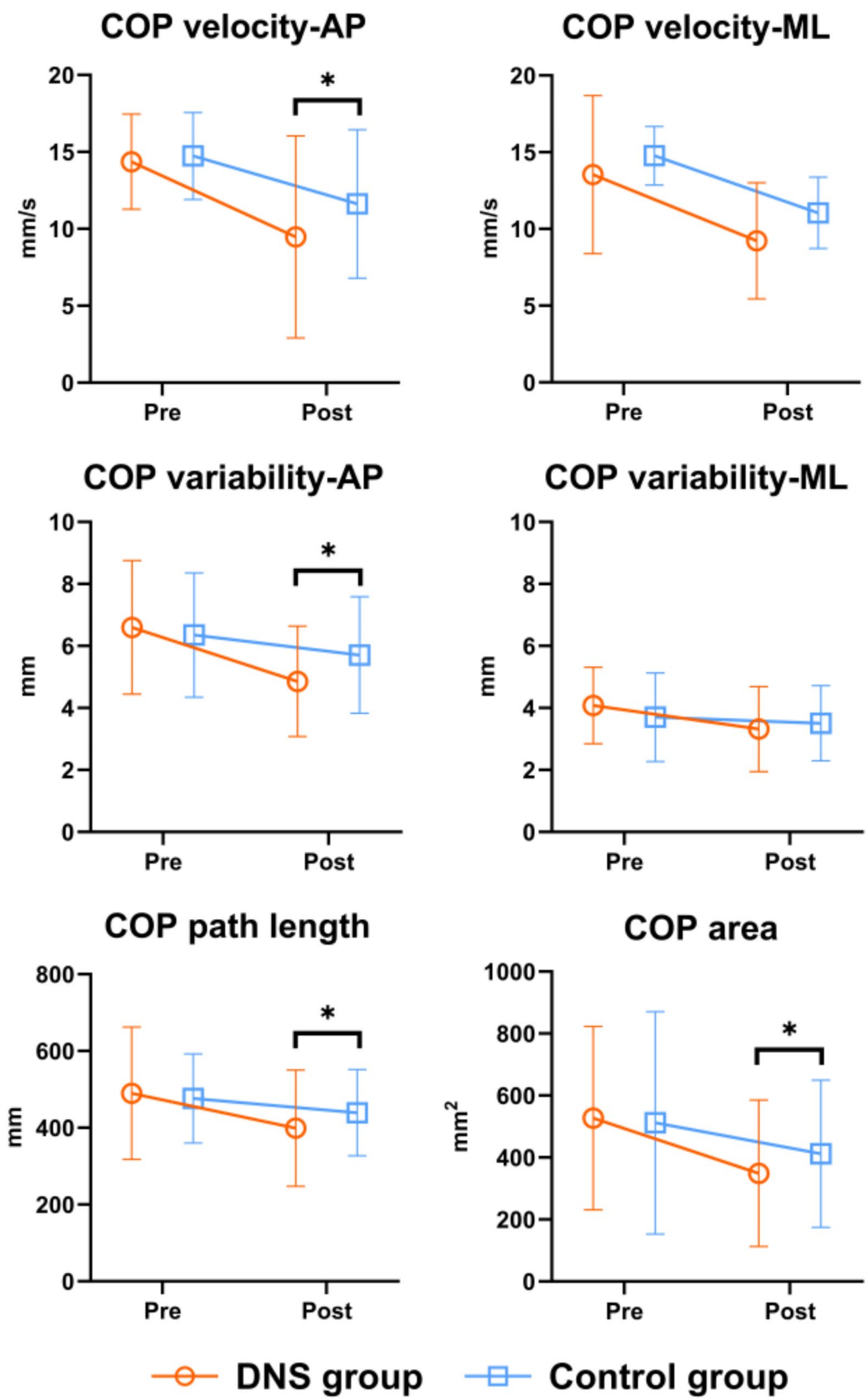

Fig. 7 Postural control performance in the eye-close condition before and after interventions for patients with chronic low back pain in dynamic neuromuscular stabilization (DNS) and control groups. * indicates the significant difference between DNS and control groups after the intervention ($p<0.05$). AP, anterior-posterior direction; COP, center of pressure; ML, medial-lateral direction

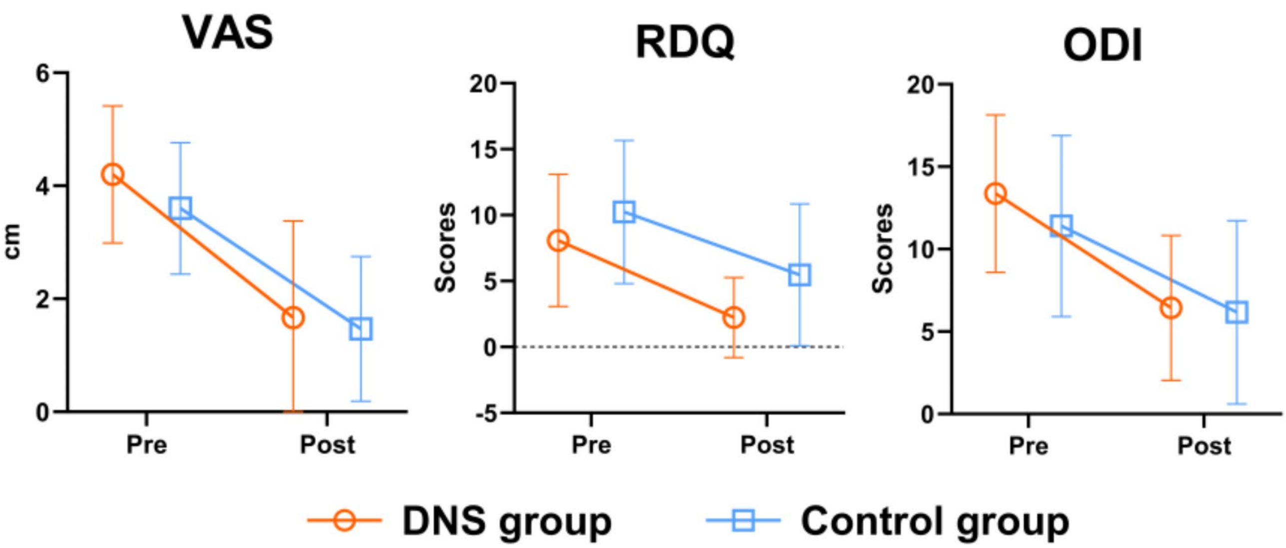

Fig. 8 Results of clinical questionnaires for patients with chronic low back pain in dynamic neuromuscular stabilization (DNS) and control groups. No significant difference was observed between DNS and control groups before and after the intervention ($p > 0.05$). VAS, Visual Analogue Scale; RDQ, Roland Morris Disability Questionnaire; ODI, Oswestry Disability Index

and postural control [12]. Impaired proprioception in CLBP patients may lead to compensatory movement patterns and increased spinal stress, perpetuating pain and dysfunction [38]. DNS training integrates specific breathing patterns with precise postural adjustments, which enhances the synchronization of TrA activation and spinal alignment. This combination likely facilitates more effective recruitment of deep stabilizing muscles, improving their response to dynamic challenges. Additionally, DNS emphasizes maintaining a neutral spinal posture and increasing intra-abdominal pressure, both of which are key factors in enhancing TrA contractility and overall lumbar stability. Therefore, based on our results, applying a 4-week DNS training program proved effective in enhancing the contractility of TrA in CLBP patients. Unlike conventional core exercises, which typically focus on static strength training, DNS training emphasizes dynamic activation, coordinated stabilization, and efficient muscle recruitment during functional movements, which likely contributed to the greater improvement in TrA activation. However, it should be mentioned that this conclusion could be controversial. Park et al. [39] found no significant difference in the thickness of TrA in young CLBP patients after the 4-week conventional core exercises. A possible explanation involved that short-term conventional core exercises might be insufficient to induce significant changes in the morphology of TrA. The ability of DNS to enhance TrA contractility may also stem from its emphasis on neuromuscular re-education. By training participants to achieve precise timing and coordination of muscle contractions, DNS might improve not only TrA strength but also its efficiency during tasks requiring postural control. This improved efficiency could lead to a more stable core when maintaining a standing posture or performing other functional tasks. Additionally, the measurement of percent change might be a better indicator than the assessment of muscle thickness to evaluate the short-term effect of the DNS training on core muscles.

Furthermore, the present study also evaluated the contractility of diaphragm of CLBP patients in two groups before and after the 4-week intervention. However, previous clinical trials involving CLBP patients did not pay much attention to the measurement of diaphragm function [12, 18, 38]. The diaphragm is one of the key core muscles responsible for maintaining stability during standing tasks. Understanding how exercise interventions influence the contractility of the diaphragm is essential. Such investigations provide valuable insights into changes in core stability and postural control in CLBP patients. Our results showed that patients in the DNS group demonstrated significantly higher percent change of diaphragm thickness than those in the control group, indicating that the DNS training could further improve the contractility of diaphragm compared to conventional core exercises. The superior effects of DNS training on diaphragm thickness can be attributed to its focus on integrating diaphragmatic breathing with spinal stabilization. By teaching participants to synchronize diaphragmatic contractions with abdominal wall activation, DNS enhances intra-abdominal pressure, a key element in postural stability. This approach likely contributes to better coordination between the diaphragm and other core muscles, such as TrA and the pelvic floor, improving their collective ability to stabilize the spine. Increased diaphragm contractility might be linked to the first DNS principle, where participants were instructed to utilize abdominal respiration to maintain appropriate intra-abdominal pressure during DNS training, further enhancing diaphragm participation compared to conventional core exercises [22]. Therefore, in comparison to conventional core exercises, DNS training could demonstrate a better effect on promoting diaphragm function [40]. This integrated approach of improving both diaphragmatic and core stability through DNS training likely explains the superior effect on diaphragm contractility observed in the current study. To our best knowledge, the present study was the first one that investigated the effectiveness of the DNS training on the diaphragmatic function in CLBP patients. Lee et al. [41] examined the real-time effects of a single DNS session on diaphragm and core muscle activation in non-symptomatic individuals with core instability. However, their study did not involve systematic interventions or CLBP patients. In contrast, We focused on the long-term effects of DNS training in CLBP patients, providing unique insights into its clinical benefits. What's more, Son et al. [42] applied the DNS training on patients with cerebral palsy and found that the 4-week DNS training significantly improved the activation of diaphragm and its movement, as well as the postural control performance in a standing position. Combined with the results of the present study, DNS training was promising, effective intervention for facilitating the contractility of core muscles, thereby enhancing the core stability in CLBP patients.

The DNS training improved the standing postural control of patients with CLBP in the eye-close condition

According to the results of this study, after the 4-week intervention, significant differences in COP-related variables between two groups were observed only in the eye-close condition. Our results indicated that DNS training significantly improved the standing postural control in CLBP patients via decreasing COP sway, especially in the AP direction, compared to conventional core exercises when visual feedback was absent. The non-significant difference in the eye-open condition could be interpreted as the compensatory effects of vision via the sensory reweighting theory [43]. The availability and accuracy of sensory inputs from proprioceptive, visual, and vestibular systems play important roles in maintaining postural control [44]. When one source of sensory inputs was impaired, other intact sensory systems would be more weighted to compensate for the reduced sensory inputs [43]. Therefore, in the eye-open condition, CLBP patients relied heavily on visual feedback to maintain postural control, which may have masked the true effect of the interventions on proprioceptive function. In this study, although the proprioceptive perception in CLBP patients was impaired, intact visual feedback could compensate for the decreased proprioceptive feedback, allowing them to maintain a good standing posture in the eye-open condition [12]. In other words, the eye-open condition might be not a good method to distinguish the effect of different interventions on the proprioceptive perception in CLBP patients because of the compensatory effect of vision. However, when visual inputs were blocked (the eye-close condition), participants with CLBP had no choice but relying on the proprioceptive feedback more to maintain postural control as their brain automatically allocated fewer sensory weights to the visual system. DNS training likely facilitated this shift by re-training the nervous system to improve coordination and synchronization of muscle activation, thus enhancing proprioceptive input from the lumbar region. The significantly smaller COP sway observed in the DNS group after the 4-week intervention indicates a better improvement in standing postural control compared to conventional core exercises. This suggests that DNS training might have had a more profound effect on the integration of sensory inputs, particularly proprioception and vestibular signals, which are essential for effective postural control when visual feedback is absent. Enhanced proprioception likely contributes to the observed improvements in balance and stability [18]. The vestibular system also plays a crucial role in maintaining postural stability, especially when visual inputs are unavailable. By emphasizing coordinated muscle activation and dynamic stability, DNS training likely enhances the brain's ability to integrate proprioceptive and vestibular signals, resulting in more effective postural control. The observed reductions in COP sway during the eye-close condition suggest that DNS training improves reliance on proprioceptive and vestibular inputs, addressing sensory deficits often seen in CLBP patients. Furthermore, a previous study showed that CLBP patients prioritized postural stability in the AP direction to maintain balance [45]. In this study, significantly decreased COP velocity and variability in the AP direction but not ML direction indicated that the DNS training improved the standing postural control of CLBP patients in the sagittal plane. This improvement aligns with the second DNS principle, which focuses on maintaining spinal stability in the sagittal plane through precise motor control [22]. By facilitating co-contraction of agonist and antagonist muscles, DNS training reinforces the stability needed for efficient postural adjustments. This motor control strategy likely enhances the dynamic stability of the trunk and pelvis, leading to more controlled and less variable postural sway in the AP direction.

In summary, the DNS training might be a better approach than conventional core exercises to facilitate the standing postural control in CLBP patients in clinical practice for musculoskeletal rehabilitation. Its ability to enhance sensory-motor integration, particularly through improved proprioception and vestibular function, highlights its potential as a comprehensive intervention for addressing postural instability and sensory deficits in CLBP patients.

The DNS training demonstrated similar effects on pain intensity and LBP-related disability compared to conventional core exercises

In the present study, although there was no significant difference in the results of clinical questionnaires between the two groups, participants in two groups demonstrated significantly decreased scores of VAS, ODI, and RDQ after the 4-week intervention. Our results align with previous research, indicating that DNS training has similar efficacy to conventional core exercises in reducing pain intensity and LBP-related disability [18, 19, 46]. This similarity could be attributed to the fact that both DNS training and conventional core exercises target the activation and strengthening of core muscles, which are critical for spinal stability and functional improvements. Additionally, both approaches likely improve neuromuscular coordination, which plays an essential role in reducing pain and disability in CLBP patients. Non-significant difference between DNS training and conventional core exercises might involve following two explanations. On one hand, the 4-week intervention may not be long enough to induce the superior effect of the DNS training on the pain intensity and LBP-related disability in CLBP patients. While DNS training may offer unique benefits through its emphasis on diaphragmatic breathing and deep stabilizing muscles, these effects may require a longer intervention period to manifest as measurable improvements in clinical outcomes. We suggest that a longer intervention period plus a follow-up period would be better to investigate the long-term effectiveness of the DNS training on CLBP patients in the future study. On the other hand, participants recruited in the present study were young and middle-aged patients with mild-to-moderate pain and LBP-related disability. Thus, there might be the ceiling effect when participants in two groups were evaluated by the above-mentioned questionnaires, which had been verified by Sandal et al. [47]. Another study from Ge et al. [12] which recruited older patients with CLBP showed a significant difference on scores of VAS and ODI between two groups after the intervention. It was worth noting that participants with CLBP demonstrated higher scores of VAS and ODI (moderate-to-severe pain and LBP-related disability) before the intervention in their study [12]. According to the results of this study, the DNS training demonstrated similar effects on pain intensity and LBP-related disability of CLBP patients compared to conventional core exercises.

Limitations

Several limitations should be taken into consideration in the present study. Firstly, although 60 patients with CLBP were enrolled in this randomized controlled trial, which was determined through power calculations to be an appropriate sample size, it is worth noting that the generalizability of the results to larger or more diverse populations may still be limited. Secondly, there was a lack of follow-up period in this study. It still remained unknown about the long-term effect of the DNS training on patients with CLBP. Thirdly, this study primarily included young and middle-aged patients with CLBP, with few older patients. Whether DNS training also demonstrated the positive effect on older patients with CLBP needed further research. Our team will attempt to investigate these important research questions in the near future.

Conclusion

The DNS training was a novel, effective treatment for patients with CLBP to enhance the percent change of TrA and diaphragm and reduce the body sway in standing. It also effectively reduces pain intensity and LBP-related disability of patients with CLBP. In comparison to conventional core exercises, DNS training may offer superior benefits, particularly in improving the contractility of core muscles and enhancing proprioceptive perception of the lumbar area in an upright standing position. The potential mechanism of DNS training might involve the activation and coordination of deep stabilizing muscles, which are crucial for postural control and balance. This makes it a promising intervention, especially for patients with balance issues or poor proprioception, as DNS training may facilitate improved balance and posture in an upright standing position. Based on these findings, DNS training could be recommended as an effective exercise intervention in clinical practice, particularly for CLBP patients with compromised postural control or proprioceptive dysfunction.

Abbreviations

CLBP	Chronic low back pain
YLDs	Years lived with disability
TrA	Transversus abdominis
MF	Multifidus
COP	Center of pressure
AP	Anterior-posterior
ML	Medial-lateral
DNS	Dynamic neuromuscular stabilization
VAS	Visual analog scale
ODI	Oswestry Disability Index
RDQ	Roland-Morris Disability Questionnaire
EO	Eye-open
EC	Eye-close
MVIC	Maximum voluntary isometric contraction
ADL	Activities of daily living

Supplementary Information

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Supplementary Material 1

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Author contributions
H.J.H., G.F.Z. and H.L. conceived this study. W.W.X. and L.G. performed data collection and statistical analysis. H.J.H. and H.Y.X.drafted the manuscript. S.B.C., Y.K.Z. and C.H.W. revised the manuscript. All authors read and reviewed the final manuscript.

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Data availability
The data used to support the findings of this study are available from the corresponding author upon reasonable request (Corresponding email; Hai Li, lihai2018 @smu. edu. cn).

Declarations

Ethical approval
The studies involving human participants were reviewed and approved by the Institutional Ethics Committee of the First Affiliated Hospital of Sun Yat-sen University (Ethical #: [2023] 324). All participants and respective guardians provided their written informed consent to participate in this study.

Consent for publication
All authors have provided their consent for publication. Additionally, all participants have given written informed consent for their personal or clinical details along with any identifying images to be published in this study.

Consort
This Randomized Controlled Trial adheres to the CONSORT guidelines.

Competing interests
The authors declare no competing interests.

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