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Article

Dynamic Neuromuscular Stabilization for Middle-Aged Women With Frozen Shoulder: Clinical Effects on Pain and COP

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Abstract

Background: Frozen shoulder (FS) leads to pain, reduced shoulder function, and deficits in postural stability and sensorimotor control during upper-limb weight-bearing tasks. This study investigated how an eight-week Dynamic Neuromuscular Stabilization (DNS) program affected Center of Pressure (COP) control and pain in middle-aged women with FS. **Methods:** Twenty-two middle-aged women with FS were randomly assigned to a DNS group (DNSG, $n = 11$) or a control group (CG, $n = 11$). The DNSG performed DNS exercises twice weekly for eight weeks, while the CG performed dynamic stretching. COP variables (distance, velocity, and root mean square (RMS) in the anterior–posterior (AP) and medial–lateral (ML) directions) were measured using a force platform under affected-side single-hand support with visual input and bilateral hand support with and without visual input. Pain was assessed using the Visual Analog Scale (VAS). All variables were analyzed using a two-way mixed ANOVA. **Results:** Under the affected-side single-hand support condition, significant group-by-time interaction effects were found in AP distance, AP velocity, ML velocity, and ML RMS ($p < 0.05$). In the bilateral hand-support conditions with and without visual input, additional COP variables also showed significant interactions ($p < 0.05$), and VAS-measured pain decreased over time in both groups. **Conclusions:** The DNS intervention demonstrated positive changes in postural stability and pain during upper-limb weight-bearing tasks in middle-aged women with FS. These findings suggest that DNS has potential as an intervention strategy to support functional recovery and enhance sensorimotor control in individuals with FS.

Keywords: dynamic neuromuscular stabilization; frozen shoulder; shoulder rehabilitation; center of pressure; postural stability; middle-age

1. Introduction

FS is a disorder characterized by shoulder joint pain and limitation of range of motion [1], in which progressive restriction of movement occurs due to inflammation and fibrosis of the joint capsule [2,3]. This condition most commonly occurs after the age of 40, particularly between the ages of 50 and 60, and has been reported to show a higher prevalence in women [4]. As fibrosis and contracture of the shoulder capsule progress, pain is accompanied by limited active and passive movement of the shoulder, leading to increased stiffness [3,5]. Such painful stiffness of the shoulder causes discomfort in daily life and decreases quality of life [3,6], continuously emphasizing the need for evidence-based exercise interventions aimed at pain reduction and restoration of shoulder function and stability [7].

Particularly in middle-aged women, it is known that a decrease in estrogen after menopause leads to a reduction in muscle mass and deterioration in muscle fiber quality [8]. When lifestyle factors such as housework or repetitive use of the upper limbs are added, continuous mechanical loading is applied to the shoulder, exacerbating pain [9–11]. These mechanical factors reduce joint position sense, causing an imbalance in the normal muscle coordination that maintains joint stability

[12], consequently leading to decreased postural stability of the shoulder and increased pain [13]. Therefore, middle-aged women can be considered a vulnerable group in which physiological and environmental factors act in combination in the development of frozen shoulder.

In general, exercise interventions such as stretching are utilized in the treatment of FS [6]. These treatments are effective for pain reduction and temporary improvement of range of motion; however, reports related to the recovery of proximal–distal coordination and enhancement of neuromuscular control ability remain limited [14]. That is, a purely passive approach alone is insufficient to fully restore the intermuscular coordination and postural control functions required to maintain shoulder stability. Therefore, to fundamentally improve shoulder stability and postural control ability, an active rehabilitation approach that strengthens neuromuscular control is necessary.

Pain is an unpleasant sensory and emotional experience associated with actual or potential tissue damage, and it acts as a major cause of musculoskeletal dysfunction [15,16]. Shoulder pain is known to increase during joint movement and tends to show heightened pain sensitivity at night [17,18]. Such pain is not merely a sensory stimulus but directly affects neuromuscular control [19]. The pain in FS occurs due to inflammation and fibrosis of the joint capsule [20], and when it becomes chronic, it has been reported to cause tension in the surrounding muscles and avoidance of movement [21,22]. As a result, joint stiffness develops, and imbalances in muscle activation and abnormal movement patterns are gradually reinforced [23]. Prolonged exposure to pain decreases the accuracy of shoulder proprioception, destabilizing intermuscular coordination and postural control, which in turn may lead to weakened dynamic stability and increased postural sway, ultimately reducing the efficiency of shoulder function [13,24]. Recently, DNS training has gained attention as an exercise method to restore impaired neuromuscular control [25,26].

DNS is an active rehabilitation approach that reorganizes intermuscular coordination and reactivates the movement control ability of the central nervous system through the integrated regulation of breathing, posture, and movement [27–29]. This neurological mechanism enhances the coordination of muscle activation between the deep stabilizing muscles and the upper-limb muscles, helping to maintain dynamic stability of the shoulder joint during upper-limb movements [28,30]. Furthermore, DNS training has been reported to be effective in improving mobility, reducing pain, and re-educating functional movement patterns in patients with joint pain [26,29]. Ultimately, by strengthening the central nervous system–based motor control ability, DNS can restore proximal–distal coordination and enable stable postural control during movement [31,32]. These characteristics complement the limitations of conventional passive therapeutic approaches and provide evidence-based intervention benefits for active neuromuscular recovery and improvement of shoulder stability.

Postural stability is considered to result from neuromuscular control and sensory integration [33,34]. COP analysis serves as an indicator that quantitatively evaluates this postural control ability [35]. Variables such as COP velocity, distance, and RMS are known to reflect subtle body sway and stabilization ability [35,36]. Edouard et al. (2012) proposed a procedure for measuring COP in an upper-limb support position as a method to assess shoulder postural control and sensorimotor control, and verified its reliability in healthy adults [37]. In particular, they reported high reproducibility of COP distance and velocity variables when the lower limbs were supported up to the anterior superior iliac spine (ASIS). This suggests that these parameters can reflect changes in shoulder stability and neuromuscular control ability. Although that study demonstrated the validity and reliability of the measurement method, it has not been applied in pathological shoulder conditions or clinical contexts such as rehabilitation interventions. The present study aimed to address these limitations by applying the measurement procedure proposed by Edouard et al. to patients with frozen shoulder and analyzing COP changes before and after DNS intervention, thereby expanding the clinical applicability of upper-limb support–based COP assessment. This approach holds academic significance in that it deepens the clinical application scope of COP as an objective indicator for quantitatively evaluating sensorimotor control of the shoulder.

In addition, previous studies have reported substantial evidence that DNS is effective in improving trunk stability [27,29]. However, no study has quantitatively verified the effects of DNS intervention on neuromuscular control and postural stability in middle-aged women with FS through COP analysis in a shoulder-supported posture. Therefore, the purpose of this study was to investigate the effects of an 8-week DNS training program on postural stability (COP) and pain (VAS) in middle-aged women with FS, and to provide clinical evidence for shoulder function recovery in this population.

2. Materials and Methods

2.1. Participants

Participants were recruited from a community welfare center and Busan University of Foreign Studies located in B metropolitan city. Before enrollment, all individuals were provided with a detailed explanation of the study objectives and procedures, and written informed consent was obtained from those who agreed to participate voluntarily. The study protocol was reviewed and approved by the Institutional Review Board (IRB approval number: P01-202509-01-052), and the trial was registered in the Clinical Research Information Service (CRIS) on November 20, 2025 (registration number: KCT0011186).

The target sample size was determined using the G*Power 3.1 program (Kiel University, Germany), referencing prior research with a comparable design. Parameters were set at an effect size of $f = 0.25$, an alpha level of 0.05, and a statistical power of 0.60 [38]. The calculation indicated that at least 20 participants were required, and to account for an anticipated dropout rate of approximately 20%, 24 participants were recruited.

Group allocation was performed using a random draw method, in which participants selected numbered balls from sealed containers. According to the assigned numbers, participants were placed into either the DNS group or the dynamic stretching group. During the intervention period, two participants discontinued participation due to health-related reasons, resulting in a final sample of 22 participants (11 per group) included in the analysis. All assessments were carried out by the same trained investigator following standardized measurement protocols, and all testing conditions were maintained consistently throughout the study to minimize procedural bias. Data analysis was conducted only after the intervention and post-assessments had been completed. To reduce the risk of bias, participants were blinded to their group allocation and were not informed about the detailed study hypotheses.

Inclusion Criteria

Participants were included in the study if they met all of the following criteria:

- (1) Women aged between 40 and 64 years.
- (2) Diagnosed with FS by an orthopedic or rehabilitation medicine specialist.
- (3) In the chronic phase, with symptoms persisting for more than three months.
- (4) Able to understand the study procedures and provided written informed consent.
- (5) Able to participate in the entire intervention program consisting of two sessions per week for eight weeks (a total of 16 sessions), as well as all pre-, mid-, and post- intervention assessments.

Exclusion Criteria

Participants were excluded from the study if any of the following conditions applied:

- (1) History of surgery involving the upper extremity or trunk within the past year.
- (2) Presence of acute trauma, inflammation, or other medical conditions affecting the shoulder or upper limb.
- (3) Inability to perform exercise due to severe pain or acute inflammatory symptoms.

In addition, to verify the baseline homogeneity between the experimental and control groups, independent t-tests were conducted for age, height, weight and Body Mass Index (BMI). The results showed no statistically significant differences between the groups in age ($t = -3.712$), height ($t = 2.523$), weight ($t = 0.325$), BMI ($t = -1.141$). The general characteristics of the participants are summarized in

Table 1, and the recruitment and group allocation procedures are illustrated in Figure 1 as a flowchart.

Table 1. Participant characteristics summary (n=22).

	DNSG (n = 11)	CG (n = 11)
Age (years)	54.63 ± 4.27	60.09 ± 2.34
Height (cm)	161.42 ± 6.08	156.20 ± 3.19
Weight (kg)	56.66 ± 3.87	57.99 ± 12.97
BMI (kg/m²)	21.82 ± 2.28	23.73 ± 5.03

Note. Values are presented as mean ± standard deviation. DNSG, DNS group; CG: Control group.

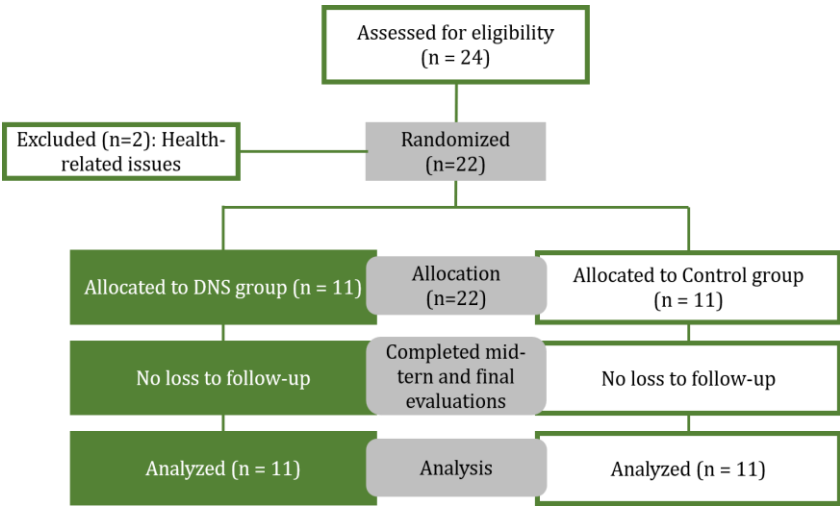


Figure 1. Flow diagram of participant recruitment and allocation.

2.2. Assessment of COP and Data Acquisition

In this study, the primary and secondary outcomes were evaluated separately. The primary outcome was the COP variable measured during eyes-open affected-side single-hand support. The secondary outcomes included COP variables measured under eyes-open bilateral support and eyes-closed double-hand support conditions, as well as the VAS score for pain intensity.

In this study, the COP was analyzed to quantitatively evaluate changes in postural stability following the DNS intervention. COP measurements were obtained using a force plate (AMTI OR6, Watertown, MA, USA) with a sampling frequency of 100 Hz. The assessment was conducted in the prone position, and to ensure consistent trunk alignment, both ASIS were positioned at the anterior edge of the treatment table. The upper limbs were extended forward to support body weight, and both palms were placed securely on the force plate.

The measurement procedure was adapted from the protocol of Edouard et al. [37], which evaluated COP changes during upper-limb weight-bearing tasks. The postural setup followed the criteria below: (1) the alignment from the shoulder joint to the wrist was adjusted to approximately 90°, (2) the wrists were maintained at approximately 15° of flexion, (3) the distance between both wrists was standardized to 4 cm, and (4) the examiner continuously monitored the participant’s posture throughout each trial to prevent compensatory trunk or scapular movements Figure 2.

The assessment was performed under three conditions: (1) eyes open with unilateral (affected-side) hand support. (2) eyes open with bilateral hand support and (3) eyes closed with bilateral hand support. Each condition was maintained for 30 seconds, with 30 seconds of rest between conditions and a 1-minute rest between sets.

The raw COP signals were extracted using AMTI NetForce software and smoothed using a fourth-order Butterworth low-pass filter with a cutoff frequency of 6 Hz. The displacement, velocity

and RMS values were calculated for both the AP and ML directions. Each condition was measured five times, and the mean value of the middle three trials was used for analysis. All evaluations and data processing were performed by the same investigator to ensure measurement reliability.

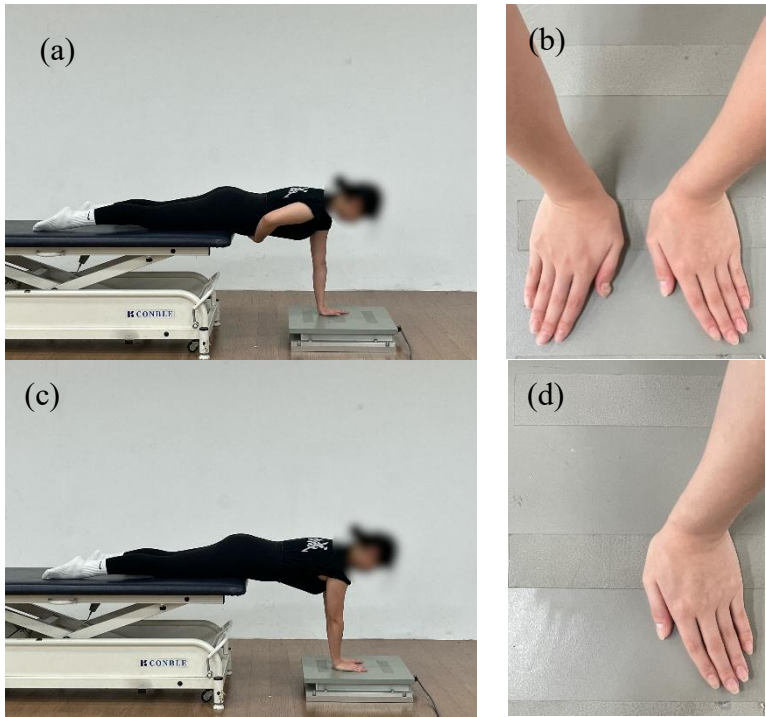


Figure 2. (a) Affected-side single-hand support position; (b) Hand placement on the force plate during single-hand support; (c) Bilateral support position; (d) Hand placement on the force plate during bilateral support.

2.3. Evaluation of Pain Intensity (VAS)

The VAS consisted of a 10-cm horizontal line, with the left end (0 point) indicating “no pain” and the right end (10 point) indicating “extreme pain.” The assessment was conducted immediately before the COP measurement at each time point (0, 4, and 8 weeks). Participants were instructed to mark the point on the line that best represented the intensity of pain they were experiencing at that moment. All evaluations were performed by the same examiner under identical environmental conditions and consistent procedures to minimize external factors and ensure the reliability and objectivity of the measurements.

2.4. Exercise Intervention

The experimental group participated in an exercise program based on the developmental kinesiological principles of DNS. The participants performed the program twice per week for eight weeks, completing a total of 16 sessions. Each session lasted approximately 50 minutes and consisted of a 10-minute warm-up, a 35-minute main exercise phase, and a 5-minute cool-down. Exercise intensity was progressively adjusted based on the number of repetitions, with each movement performed for 6 repetitions during Weeks 0–4 and 8 repetitions during Weeks 5–8. The mean adherence rate was 96%, corresponding to an average attendance of 15.5 out of 16 sessions.

Each session consisted of three phases: warm-up, main exercise, and cool-down. In the warm-up phase, participants were re-educated to form intra-abdominal pressure (IAP) and to reestablish basic trunk stabilization strategies based on the breathing – posture synergy. In the main exercise phase, closed-chain neuromuscular control training was performed using developmental positions such as supine, side-lying, quadruped, and modified prone. These exercises were designed to promote posterior – inferior stabilization of the scapula, regulate trunk stiffness, and enhance integrated strength and coordination during upper-limb support tasks [39]. The cool-down phase

involved low-intensity postural readjustment and breathing recovery exercises aimed at stabilizing overall body tension.

The control group performed a dynamic stretching program with the same duration and frequency as the experimental group. Dynamic stretching is an active stretching technique that elongates the target muscle by voluntarily contracting its antagonist and repeatedly moving the associated joints [40]. This program focused on improving the mobility of the soft tissues surrounding the shoulder joint and restoring functional range of motion. Sequential stretching patterns incorporating active movements were applied to provide a control condition that ensured general joint mobility without specific neuromuscular stabilization training. The structure and detailed components of the training program are presented in Table 2 and Figure 3.

Table 2. Dynamic neuromuscular stabilization training program.

Training	DNSG	CG	Time/Reps
Warm-up	1. Supine breathing 2. Supine cross-pattern activation	1. Standing shoulder circles 2. Arm swing (forward/backward & lateral)	10min /8reps
		3. Upper thoracic extension stretch (wall-supported) 4. Shoulder internal rotation stretch 5. Cross-body posterior capsule stretch	
Exercise	1. Side-lying rolling 2. Prone & quadruped rocking 3. Prone position with head and chest elevation 4. Contralateral hip extension in quadruped 5. Transition from quadruped to oblique sitting via lower extremity loading 6. 3-Point transition to tall kneeling with contralateral reach 7. Quadruped Locomotion Pattern 8. Transition from Quadruped to High Side Support 9. Bear 10. Bear with alternating upper limb unloading	1. Shoulder external & internal rotation (standing / supine) 2. Scapular retraction exercise 3. Scapular protraction/elevation control ("Y" & "T") 4. Quadruped push-up plus ("Camel") 5. Lawn mower pull (bodyweight version) 6. Doorway pectoral stretch 7. Supine cane flexion (without equipment) 8. Cross-body shoulder stretch	35min /6reps -8 reps
Cool-down	1. Resting position for deep stabilization 2. Prone resting with diaphragmatic control	1. Repeat upper thoracic stretch 2. Arm and shoulder swing	5min /8reps

Note. DNSG, DNS group; CG: Control group.

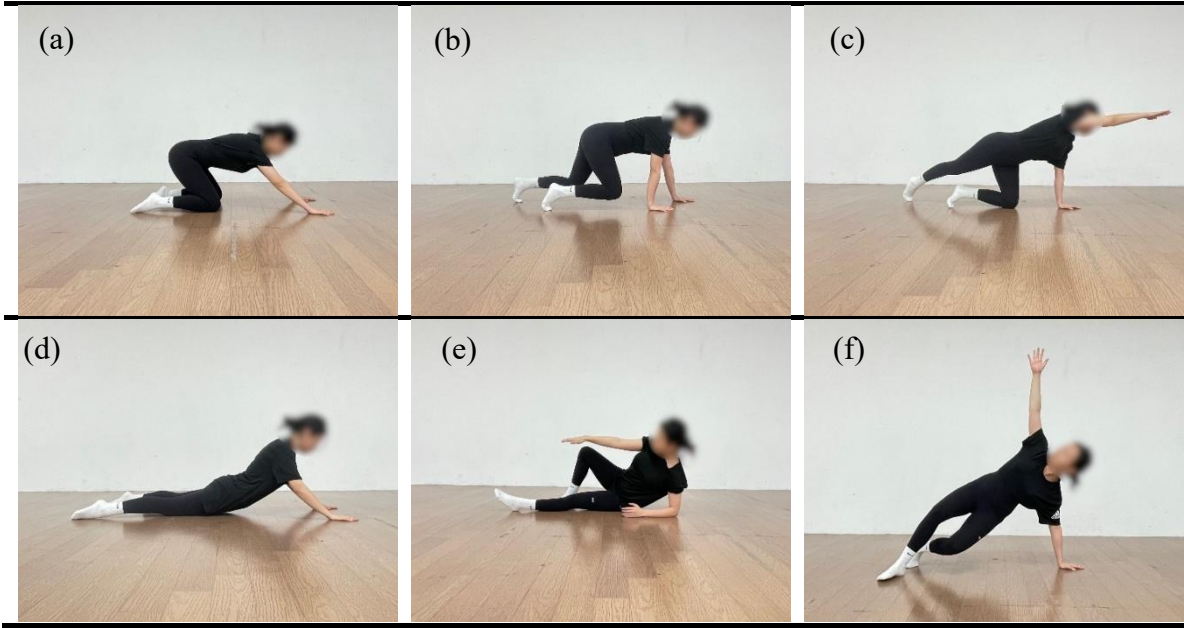


Figure 3. DNS exercise : (a) Prone and quadruped rocking; (b) Bear position; (c) Contralateral hip extension in quadruped; (d) Prone position with head and chest elevation; (e) Oblique sitting with trunk rotation; (f) Three-point transition to tall kneeling with contralateral reach.

2.5. Statistical Analysis

All data collected in this study were analyzed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). Each variable was presented as mean ± standard deviation (SD). To examine baseline demographic characteristics between the two groups before the intervention, an independent t-test was conducted, and data normality was verified using the Shapiro – Wilk test.

A mixed-design two-way repeated-measures analysis of variance (ANOVA) was performed to evaluate the effects of the intervention. The group (experimental, control) was set as the between-subject factor, and time (pre-, mid-, and post-intervention) was set as the within-subject factor. When significant group × time interactions or main effects were observed, post-hoc analyses with Bonferroni correction were applied to identify differences between time points.

The effect size was calculated using partial eta squared (ηp^2), interpreted according to Cohen’ s criteria: $\eta p^2 = 0.01$ (small), 0.06 (medium), and 0.14 (large). The level of statistical significance was set at $p < 0.05$ for all analyses.

3. Results

The analysis results of the COP variables and pain scores measured under each condition are presented in Tables 3 – 6.

Table 3. Changes in COP parameters under eyes-open affected-side single-hand support condition.

Task	Variables	Group	0 Weeks	4 Weeks	8 Weeks	Source	<i>p</i>	ηp^2	Post Hoc
EO-AH	AP-Distance (mm)	DNSG	86.62±14.08	66.59±11.36	49.44±8.96	Group × Time	0.048	0.160	0–4weeks: 0.013
									4–8weeks: 0.000
		CG	86.84±10.16	61.39±5.45	58.75±7.79	Time	0.000	0.799	0–8weeks: 0.000
									0–4weeks: 0.000
									4–8weeks: 0.555
									0–8weeks: 0.000

AP-velocity (mm/s)	DNSG	2.88±0.46	2.21±0.37	1.71±0.28	Group × Time	0.041	0.168	0–4weeks: 0.013
								4–8weeks: 0.001
	CG	2.83±0.39	1.96±0.37	1.97±0.32	Time	0.000	0.770	0–8weeks: 0.000
								0–4weeks: 0.001
AP-RMS (mm)	DNSG	0.21±0.02	0.15±0.01	0.12±0.01	Group × Time	0.233	0.071	4–8weeks: 0.001
								0–8weeks: 0.005
	CG	0.21±0.05	0.14±0.02	0.14±0.04	Time	0.000	0.742	0–8weeks: 0.000
								0–4weeks: 0.001
ML- Distance (mm)	DNSG	87.24±13.57	69.55±10.65	57.81±13.82	Group × Time	0.238	0.069	4–8weeks: 0.002
								0–8weeks: 0.002
	CG	84.75±20.41	58.96±11.58	57.59±12.38	Time	0.000	0.688	0–4weeks: 0.001
								4–8weeks: 1.000
ML- velocity (mm/s)	DNSG	2.90±0.45	2.31±0.35	1.91±0.30	Group × Time	0.030	0.161	0–8weeks: 0.000
								0–4weeks: 0.016
	CG	2.82±0.31	2.02±0.33	2.12±0.15	Time	0.000	0.706	4–8weeks: 0.020
								0–8weeks: 0.000
ML-RMS (mm)	DNSG	0.20±0.03	0.17±0.03	0.13±0.02	Group × Time	0.009	0.208	0–4weeks: 0.000
								4–8weeks: 0.002
	CG	0.20±0.02	0.16±0.01	0.15±0.02	Time	0.000	0.840	0–8weeks: 0.000
								0–4weeks: 0.000

Note: Data are presented as mean ± standard deviation.DNSG, DNS group; CG: Control group.*p*-values are based on mixed-design two-way ANOVA.Post hoc comparisons were adjusted using the Bonferroni correction. ηp^2 = Partial eta squared (effect size): small = 0.01, medium = 0.06, large = 0.14.AP = anterior–posterior; ML = medial–lateral.EO: eyes open; AH: affected hand.

Table 4. Changes in COP parameters under eyes-open bilateral support condition.

Task	Variables	Group	0 Weeks	4 Weeks	8 Weeks	Source	<i>p</i>	ηp^2	Post Hoc
		DNSG	58.32±9.14	49.65±8.24	40.35±7.04	Group × Time	0.730	0.016	0–4weeks: 0.103
									4–8weeks:

EO-BH	AP-Distance (mm)								0.000	
									0–8weeks: 0.001	
									0–4weeks: 0.001	
	CG	57.87±13.51	46.13±11.86	38.95±5.88	Time	0.000	0.688	4–8weeks: 0.116		
									0–8weeks: 0.000	
	AP-velocity (mm/s)	DNSG	1.94±0.30	1.58±0.21	1.23±0.18	Group × Time	0.029	0.189	0–4weeks: 0.010	
									4–8weeks: 0.000	
									0–8weeks: 0.000	
									0–4weeks: 0.001	
		CG	1.89±0.52	1.55±0.36	1.56±0.26	Time	0.000	0.601	4–8weeks: 0.942	
								0–8weeks: 0.001		
	AP-RMS (mm)	DNSG	0.17±0.03	0.12±0.02	0.09±0.01	Group × Time	0.590	0.026	0–4weeks: 0.009	
									4–8weeks: 0.000	
									0–8weeks: 0.000	
									0–4weeks: 0.001	
		CG	0.20±0.04	0.14±0.04	0.13±0.02	Time	0.000	0.697	4–8weeks: 0.936	
									0–8weeks: 0.001	
		ML-Distance (mm)	DNSG	65.19±13.62	45.25±6.79	37.86±4.30	Group × Time	0.754	0.010	0–4weeks: 0.003
										4–8weeks: 0.001
										0–8weeks: 0.000
										0–4weeks: 0.000
		CG	67.20±11.37	45.31±8.75	40.83±3.60	Time	0.000	0.782	4–8weeks: 0.371	
									0–8weeks: 0.000	
		ML-velocity (mm/s)	DNSG	2.17±0.45	1.50±0.22	1.33±0.22	Group × Time	0.557	0.029	0–4weeks: 0.003
										4–8weeks: 0.189
										0–8weeks: 0.000
										0–4weeks: 0.001
		CG	2.22±0.74	1.35±0.34	1.23±0.24	Time	0.000	0.719	4–8weeks: 0.889	
									0–8weeks: 0.001	
		ML-RMS (mm)	DNSG	0.18±0.03	0.15±0.04	0.09±0.00	Group × Time	0.000	0.326	0–4weeks: 0.127
										4–8weeks: 0.001
										0–8weeks: 0.000
										0–4weeks: 0.000
		CG	0.17±0.03	0.12±0.02	0.12±0.02	Time	0.000	0.737	4–8weeks: 1.000	
									0–8weeks: 0.000	

Note: Data are presented as mean ± standard deviation.DNSG, DNS group; CG: Control group.*p*-values are based on mixed-design two-way ANOVA.Post hoc comparisons were adjusted using the Bonferroni correction.

ηp^2 = Partial eta squared (effect size): small = 0.01, medium = 0.06, large = 0.14. AP = anterior–posterior; ML = medial–lateral. EO: eyes open; BH: bilateral hand support.

Table 5. Changes in COP parameters under eyes-closed bilateral support condition.

Task	Variables	Group	0 Weeks	4 Weeks	8 Weeks	Source	<i>p</i>	ηp^2	Post Hoc
EC-BH	AP-Distance (mm)	DNSG	59.25±9.00	50.88±8.38	42.04±6.98	Group × Time	0.562	0.028	0–4weeks: 0.157 4–8weeks: 0.008 0–8weeks: 0.000
		CG	57.10±6.05	46.25±8.41	41.64±6.44	Time	0.000	0.636	0–4weeks: 0.002 4–8weeks: 0.453 0–8weeks: 0.000
	AP-velocity (mm/s)	DNSG	1.97±0.30	1.62±0.31	1.33±0.21	Group × Time	0.040	0.166	0–4weeks: 0.024 4–8weeks: 0.002 0–8weeks: 0.000
		CG	1.96±0.30	1.54±0.36	1.53±0.26	Time	0.000	0.736	0–4weeks: 0.001 4–8weeks: 1.000 0–8weeks: 0.000
	AP-RMS (mm)	DNSG	0.15±0.02	0.12±0.01	0.10±0.02	Group × Time	0.382	0.047	0–4weeks: 0.007 4–8weeks: 0.012 0–8weeks: 0.000
		CG	0.18±0.03	0.14±0.01	0.12±0.01	Time	0.000	0.688	0–4weeks: 0.003 4–8weeks: 0.090 0–8weeks: 0.002
	ML-Distance (mm)	DNSG	65.97±9.61	45.27±6.48	39.53±6.35	Group × Time	0.877	0.007	0–4weeks: 0.000 4–8weeks: 0.015 0–8weeks: 0.000
		CG	67.70±8.67	45.07±9.68	40.94±8.07	Time	0.000	0.832	0–4weeks: 0.000 4–8weeks: 0.588 0–8weeks: 0.000
	ML-velocity (mm/s)	DNSG	2.25±0.20	1.51±0.20	1.12±0.15	Group × Time	0.045	0.164	0–4weeks: 0.000 4–8weeks: 0.000 0–8weeks: 0.000
		CG	2.24±0.51	1.53±0.41	1.55±0.34	Time	0.000	0.829	0–4weeks: 0.001 4–8weeks: 1.000 0–8weeks: 0.001
	ML-RMS (mm)	DNSG	0.16±0.02	0.13±0.03	0.09±0.01	Group × Time	0.002	0.273	0–4weeks: 0.001 4–8weeks: 0.001 0–8weeks: 0.000

							0.000
							0-4weeks: 0.317
							4-8weeks: 1.000
							0-8weeks: 0.214
CG	0.15±0.02	0.13±0.03	0.13±0.04	Time	0.000	0.584	

Note: Data are presented as mean ± standard deviation.DNSG, DNS group; CG: Control group.*p*-values are based on mixed-design two-way ANOVA.Post hoc comparisons were adjusted using the Bonferroni correction. ηp^2 = Partial eta squared (effect size): small = 0.01, medium = 0.06, large = 0.14.AP = anterior–posterior; ML = medial–lateral.EC: eyes closed; BH: bilateral hand support.

Table 6. Changes in VAS according to time and side.

Task	Group	0 Weeks	4 Weeks	8 Weeks	Source	<i>p</i>	ηp^2
AH	DNSG	6.27±1.42	3.63±1.62	1.90±1.37	Group × Time	0.186	0.081
	CG	5.36±0.80	3.72±1.00	2.18±1.60	Time	0.000	0.756

Note: Data are presented as mean ± standard deviation.DNSG, DNS group; CG: Control group.*p*-values are based on mixed-design two-way ANOVA.Post hoc comparisons were adjusted using the Bonferroni correction. ηp^2 : Partial eta squared (small=0.01, medium=0.06, large=0.14).AP = anterior–posterior; ML = medial–lateral.AH: affected hand.

3.1. Changes in COP Under the Affected-Side Single-Hnad Support Condition

For the AP-direction COP variables, the assumption of sphericity was violated for all variables; therefore, the Greenhouse – Geisser correction was applied. The analysis revealed significant group × time interaction effects for AP-distance ($p = 0.048$, $\eta p^2 = 0.160$) and AP-velocity ($p = 0.041$, $\eta p^2 = 0.168$), whereas AP-RMS ($p = 0.233$, $\eta p^2 = 0.071$) was not significant. The main effect of time was significant for all variables [AP-distance ($p < 0.001$, $\eta p^2 = 0.799$), AP-velocity ($p < 0.001$, $\eta p^2 = 0.770$), and AP-RMS ($p < 0.001$, $\eta p^2 = 0.742$)]. For the AP-direction COP variables, both interaction effects showed large effect sizes and sufficient statistical power. AP-distance ($\eta p^2 = 0.160$, $f = 0.44$) and AP-velocity ($\eta p^2 = 0.180$, $f = 0.47$) demonstrated post hoc powers ($1 - \beta$) of 0.97 and 0.98, respectively, exceeding the predetermined power of 0.60.

For the ML-direction COP variables, the assumption of sphericity was met; thus, the original degrees of freedom were used for the analysis. Significant group × time interaction effects were observed for ML-velocity ($p = 0.030$, $\eta p^2 = 0.161$) and ML-RMS ($p = 0.009$, $\eta p^2 = 0.208$), whereas ML-distance ($p = 0.238$, $\eta p^2 = 0.069$) was not significant. The main effect of time was significant for all variables [ML-distance ($p < 0.001$, $\eta p^2 = 0.688$), ML-velocity ($p < 0.001$, $\eta p^2 = 0.706$), and ML-RMS ($p < 0.001$, $\eta p^2 = 0.840$)]. For the ML-direction COP variables, both interaction effects showed large effect sizes and sufficient statistical power. ML-velocity ($\eta p^2 = 0.161$, $f = 0.44$) and ML-RMS ($\eta p^2 = 0.208$, $f = 0.51$) demonstrated post hoc powers ($1 - \beta$) of 0.99 and 1.00, respectively, exceeding the predetermined power of 0.60.

Post-hoc analysis revealed that in the DNS group, all AP-direction COP variables (AP-distance, AP-velocity, and AP-RMS) demonstrated significant differences across time points ($p < 0.05$). Furthermore, all ML-related variables (ML-distance, ML-velocity, and ML-RMS) also showed significant time-dependent differences ($p < 0.05$).

In contrast, in the control group, AP-distance, AP-velocity, and AP-RMS showed significant changes only between 0 and 4 weeks ($p < 0.05$), with no additional changes observed between 4 and 8 weeks. Similarly, ML-distance, ML-velocity, and ML-RMS showed significant differences between 0 and 4 weeks but no significant changes from 4 to 8 weeks.

3.2. Changes in COP Under the Eyes-Open Bilateral Hand Support Condition

For the AP-direction COP variables, the assumption of sphericity was violated for AP-distance and AP-velocity; therefore, the Greenhouse - Geisser correction was applied, whereas AP-RMS met the assumption and was analyzed using the original degrees of freedom. The Time $\times$ Group interaction effects were observed for AP-distance ($\eta p^2 = 0.016$), AP-velocity ($\eta p^2 = 0.189$), and AP-RMS ($\eta p^2 = 0.026$). The main effect of Time showed effect sizes of AP-distance ($\eta p^2 = 0.688$), AP-velocity ($\eta p^2 = 0.601$), and AP-RMS ($\eta p^2 = 0.697$).

For the ML-direction COP variables, the assumption of sphericity was violated for ML-distance; therefore, the Greenhouse-Geisser correction was applied, whereas ML-velocity and ML-RMS met the assumption and were analyzed using the original degrees of freedom. The Time $\times$ Group interaction effects were found for ML-distance ($\eta p^2 = 0.010$), ML-velocity ($\eta p^2 = 0.029$), and ML-RMS ($\eta p^2 = 0.326$). The main effect of Time showed effect sizes of ML-distance ($\eta p^2 = 0.782$), ML-velocity ($\eta p^2 = 0.719$), and ML-RMS ($\eta p^2 = 0.737$).

3.3. Changes in COP Under the Eyes-Closed Bilateral Hand Support, Condition

For the AP-direction COP variables (AP-distance, AP-velocity, AP-RMS), the assumption of sphericity was met for AP-distance and AP-RMS, whereas AP-velocity violated the assumption; thus, the Greenhouse - Geisser correction was applied. The Time $\times$ Group interaction effects were observed for AP-distance ($\eta p^2 = 0.028$), AP-velocity ($\eta p^2 = 0.166$), and AP-RMS ($\eta p^2 = 0.047$). The main effect of Time showed effect sizes of AP-distance ($\eta p^2 = 0.636$), AP-velocity ($\eta p^2 = 0.736$), and AP-RMS ($\eta p^2 = 0.688$).

For the ML-direction COP variables (ML-distance, ML-velocity, ML-RMS) the assumption of sphericity was met for ML-distance and ML-RMS, whereas ML-velocity violated the assumption; thus, the Greenhouse - Geisser correction was applied. The Time $\times$ Group interaction effects were found for ML-distance ($\eta p^2 = 0.007$), ML-velocity ($\eta p^2 = 0.164$), and ML-RMS ($\eta p^2 = 0.273$). The main effect of Time showed effect sizes of ML-distance ($\eta p^2 = 0.832$), ML-velocity ($\eta p^2 = 0.829$), and ML-RMS ($\eta p^2 = 0.584$).

3.4. Changes in Pain Indicator (VAS)

The VAS scores satisfied the assumption of sphericity and were analyzed using the original degrees of freedom.

The Time $\times$ Group interaction showed an effect size of $\eta p^2 = 0.081$, while the main effect of Time demonstrated an effect size of $\eta p^2 = 0.756$.

4. Discussion

This study aimed to analyze changes in the COP during upper-limb weight-bearing postures in middle-aged women with frozen shoulder and to determine the effects of a DNS intervention on shoulder stability and pain (VAS). The primary outcome of this study was the COP measured during the affected-side single-hand weight-bearing posture under eyes-open conditions, and the secondary outcomes were the COP measured during bilateral hand support under eyes-open and eyes-closed conditions, as well as pain (VAS).

The analysis revealed significant improvements in COP during the affected-side single-hand support posture, which was the primary outcome. These changes can be interpreted as indicating that the DNS intervention enhanced the load-control capacity and postural control efficiency of the shoulder complex, thereby enabling more stable maintenance and regulation of the body's center during weight-bearing tasks. In other words, DNS suggests a positive effect on restoring shoulder stability and improving functional supportability in middle-aged women with frozen shoulder.

The COP results during the affected-side single-hand support posture in this study showed significant differences between groups. DNS is known to optimize the alignment of the scapula-upper limb-trunk in a closed-chain environment and to enhance proximal stability, thereby reducing

unnecessary fluctuations of the body's center during load transfer. These mechanisms are reflected in the significant reductions in COP variables observed in the affected-side single-hand support posture following the DNS intervention in this study. In a closed-chain condition, where the wrist and elbow are fixed, the coordination between the glenohumeral and scapulothoracic joints plays a key role in postural control [37]. DNS is interpreted to act by reorganizing such joint coordination and increasing coactivation of the muscles surrounding the shoulder, thereby enhancing the stability of the shoulder complex during weight-bearing tasks. In addition, the weight-bearing load generated during upper-limb support is transmitted through an integrated kinetic chain that extends to the trunk and lower limbs, and DNS activates this sequential movement, allowing the load to be redistributed throughout the body rather than concentrated on specific joints [41,42]. During this process, sensory feedback generated from each segment facilitates sensory-motor integration and helps the body reposition the COP within a more stable and efficient range in response to changes in ground reaction forces (GRF) [43–45].

Previous studies have reported that closed-chain exercises enhance dynamic stabilization by maintaining high joint compressive forces and joint congruency while strongly stimulating proprioceptors [46]. The upper-limb support environment provided by the DNS intervention in this study can likewise be interpreted as reinforcing such proprioceptive stimulation, thereby creating a sensory feedback-based environment in which the body must finely regulate load direction and balance. In this self-body-weight loading environment, muscles do not merely generate force but exhibit neuromuscular adaptations that actively control the direction of loading through the postural control system and demonstrate consistent regulatory patterns [47]. This process directly contributes to the reduction of small-amplitude COP fluctuations, and the decreased COP observed during affected-side support after the DNS intervention can be understood not as a simple change in local muscle strength but as the result of a more efficient reorganization of the mechanical interaction among GRF, center of mass (CoM), and COP in a self-body-weight loading environment. Therefore, the reduced variability of COP following the DNS intervention reflects the reorganization of the neuromuscular control system responsible for regulating load direction and the improvement of postural stability under weight-bearing conditions. This can be interpreted as a key mechanism by which DNS contributes to the restoration of dynamic stability of the shoulder complex in middle-aged women with frozen shoulder.

In the secondary outcome of this study, COP during eyes-open bilateral hand support showed between-group differences only in AP-velocity and ML-RMS, which demonstrates a somewhat different pattern from the changes observed under affected-side support or eyes-closed bilateral support conditions. The affected-side support or eyes-closed conditions involve either a narrower base of support or limited visual input, resulting in relatively higher postural control demands on the shoulder–scapula–trunk complex [30,48,49], and thus the effects of the DNS intervention tend to appear more clearly. In contrast, the eyes-open bilateral support task provides a wider base of support and visual feedback, making it a comparatively stable task [50], and therefore subtle neuromuscular control changes induced by DNS may be less likely to immediately manifest in COP variables. Particularly, individuals with shoulder pain tend to utilize automated compensatory strategies—such as contralateral weight shifting in stable conditions, increased visual dependence, and fixation strategies through bilateral support—which may act to reduce sway. As a result, these strategies may have limited the extent to which the effects of the DNS intervention were fully reflected in the COP outcomes.

In the secondary outcome of this study, COP during eyes-closed bilateral hand support showed changes that suggested between-group differences in AP velocity, ML velocity, and RMS. When visual cues are removed, the available information for detecting postural sway becomes limited, leading the body to naturally increase its reliance on proprioceptive input from muscles and joints to maintain balance [29]. Because DNS intervention is characterized by reorganizing coordination and synchronization of muscle activation [29], it is plausible that proprioception-based postural control strategies required for upper-limb support operated more efficiently during this sensory shift. In

upper-limb support tasks, even slight changes in the base of support can easily compromise the stability of the upper-limb joints, and it is known that proprioceptive dependence becomes further reinforced to compensate for this instability [51]. Proprioceptive input assists in detecting subtle shifts in the body's center and in modulating muscle activation accordingly [52], and this process may have contributed to regulating COP displacement within a certain range. As proprioception functions more effectively, the demand for corrective movements decreases, leading to a tendency for COP velocity to become more attenuated. Therefore, the COP changes observed in this study can be interpreted as partially reflecting the improved efficiency of sensory-based postural control following the DNS intervention.

The secondary outcome of pain (VAS) in this study did not show differences between groups, and both groups exhibited a decreasing trend. This indicates that changes in pain may have been influenced not by the specific characteristics of the intervention but by nonspecific factors such as the passage of time or increased general movement, which cannot be ruled out. Considering these pathological characteristics, it is possible that both DNS and stretching contributed to pain reduction through shared mechanisms, including the restoration of tissue flexibility, enhanced periarticular circulation, and reduced movement avoidance. DNS may help reduce unnecessary muscle tension and compressive loading during support tasks by reorganizing the coordination of breathing, posture, and muscle activation [29,32], whereas stretching has been reported to decrease pain sensitivity by increasing joint range of motion and elongating soft tissues [53,54]. Therefore, the reduction in pain observed in this study may have been influenced not by specific effects unique to each intervention method, but rather by the shared movement stimuli and mechanical or physiological changes in the tissues provided by both interventions.

The limitations of this study are as follows:

1. The intervention period was limited to eight weeks, which may not have been sufficient to evaluate the long-term neuromuscular adaptations or sustained pain-reduction effects that may result from DNS training.
2. This study was conducted with a relatively small sample size, which may have limited the statistical power for certain outcomes; therefore, caution is needed when generalizing the findings.
3. Pain assessment relied solely on the subjective VAS scale, and the evaluation of neuromuscular function was focused on COP-based analysis. The absence of objective physiological indicators such as EMG or muscle fatigue measures presents a limitation in fully elucidating the mechanisms underlying DNS.
4. The study population was restricted to middle-aged women, and given potential physiological differences by sex, the applicability of the findings to men may be limited.

The reduction in COP variability under the affected-side single-hand support condition, the primary outcome of this study, demonstrates that the DNS intervention distinctly improved neuromuscular control and dynamic stability of the shoulder complex during weight-bearing tasks. Partial changes associated with the DNS intervention were also observed in the bilateral hand support tasks included as secondary outcomes. In particular, under the eyes-closed bilateral support condition—where reliance on proprioception increases due to the absence of visual cues—it is likely that the DNS-induced changes in muscle activation coordination were partially reflected in this condition. Meanwhile, the reduction in pain may be interpreted as a general physiological and mechanical effect resulting from increased movement in both the DNS and stretching groups. Future studies should analyze EMG activity of the shoulder and trunk muscles during upper-limb support tasks in conjunction with COP variables to more clearly elucidate how the DNS intervention contributes to the regulation of dynamic stability of the shoulder complex.

5. Conclusions

This study confirmed that an eight-week DNS intervention may produce certain positive effects on postural stability and pain changes during upper-limb support postures in middle-aged women with frozen shoulder. In particular, reductions in several COP variables were observed under the

affected-side single-hand support condition, suggesting that DNS may have improved neuromuscular control among the trunk, scapula, and upper limb, thereby contributing to load transmission and postural regulation. In contrast, changes in the control group were relatively limited, indicating that the DNS intervention may have acted more effectively in specific tasks. These findings support the potential applicability of DNS as a useful intervention strategy for assisting pain management and functional recovery of the shoulder in patients with frozen shoulder.

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