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Feasibility and Biomechanical Effects of Dynamic Neuromuscular Stabilization Training During Stair Negotiation in Middle-Aged Women with Knee Osteoarthritis: A Randomized Controlled Pilot Study

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Abstract

Background: Knee osteoarthritis (KOA) alters the performance of daily activities, such as stair negotiation, by compromising lateral stability and neuromuscular control. This pilot study evaluated the feasibility of a 10-week Dynamic Neuromuscular Stabilization (DNS) program and explored preliminary biomechanical changes during stair ascent and descent in middle-aged women with KOA. **Methods**: Twenty-six participants were randomly assigned to a DNS group ($n = 13$) or a control group ($n = 13$). The DNS group completed a 10-week intervention (twice weekly). Feasibility was assessed via recruitment, retention, and adherence. Primary outcomes were mediolateral (ML) center of pressure (COP) parameters, while secondary outcomes included anteroposterior (AP) COP parameters and lower limb range of motion (ROM). Effect sizes (η^2_P) were estimated using 3D motion analysis and force plates. **Results:** The intervention showed high potential feasibility, with 100% recruitment and retention rates and 98.5% compliance. No adverse events occurred. Large effect sizes were observed for reduced ML COP velocity (ascent: $\eta^2_P = 0.79$; descent: $\eta^2_P = 0.62$) and RMS (descent: $\eta^2_P = 0.16$). Secondary outcomes, including AP COP parameters and joint ROM (increased sagittal flexion and decreased coronal instability), also demonstrated large effect sizes. **Conclusions**: This pilot study suggests that progressive DNS training is a safe and potentially feasible intervention for patients with KOA. The preliminary effect sizes observed in COP control and lower kinetic chain mechanics provide promising evidence that may serve as foundational data for designing future large-scale clinical trials to definitively verify efficacy.

Keywords: knee osteoarthritis; dynamic neuromuscular stabilization; stair negotiation; center of pressure; biomechanics

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1. Introduction

Knee osteoarthritis (KOA) is a prevalent musculoskeletal disorder affecting approximately 23% of the global population aged 40 and older. It significantly threatens the independence of daily living, particularly in middle-aged women, who exhibit an overwhelmingly higher prevalence than men [1–3]. Consequently, these female patients experience significant declines in gait performance and elevated biomechanical burden not only during level walking but also during stair negotiation, an essential activity of daily living [4].

Stair ascent and descent generate joint loads reaching 3–4 times body weight [5] and have been reported to require a wider lower limb range of motion (ROM) and a high degree of dynamic postural control [6]. Specifically, because stair descent necessitates eccentric contraction to control weight bearing, patients with KOA adopt altered gait strategies due to pain and muscle weakness, which ultimately leads to a substantial decrease in dynamic stability [7,8].

In evaluating the dynamic stability of stair negotiation, the mediolateral (ML) velocity of the center of pressure (COP) is considered a primary indicator that sensitively reflects functional deficits in patients with KOA. While anteroposterior (AP) movement during stair walking is significantly constrained by the physical structure of the step tread [9], ML stability depends largely on the individual's neuromuscular control [10].

Furthermore, because KOA patients experience biomechanical structural deformation (varus thrust) due to cartilage damage in the medial compartment of the knee , they tend to exhibit reduced lateral control against outward pushing forces during weight-bearing [11,12]. Additionally, as a compensatory mechanism to avoid pain, they exhibit a pattern of using their lower extremities stiffly, which induces an abnormal decrease in the lower limb joint ROM essential for shock absorption and propulsion [13,14]. Therefore, to improve the stair negotiation ability of KOA patients, an intervention that restores deep muscle recruitment and neuromuscular control, rather than mere muscle strengthening, is critically required.

DNS training is an exercise technique based on developmental kinesiology that reactivates the motor control programs of the central nervous system and strengthens the deep stabilizing system [15,16]. Recent studies have reported that DNS training can enhance core stability and improve lower extremity alignment, thereby enhancing both static and dynamic balance in patients with knee pain [17,18]. This improvement in core-based anticipatory postural control ultimately provides a solid base of support for active limb movements, which is expected to have a positive impact even when performing more complex dynamic tasks.

However, despite these positive findings from previous studies, research analyzing the effects of DNS training on the dynamic biomechanical changes during 'stair negotiation', a task with high functional demands for KOA patients, is still lacking. In particular, studies quantitatively evaluating the ML COP velocity control ability during stair walking—which is closely related to lateral stability—and the changes in lower limb joint ROM required for task execution have rarely been conducted.

Therefore, the purpose of this pilot study is to evaluate the feasibility of a 10-week DNS training program in middle-aged women with knee osteoarthritis, and to explore the biomechanical changes during both stair ascent and descent. To this end, the ML velocity and RMS of the COP, which represent lateral dynamic stability, were established as the primary outcomes. Additionally, the AP COP parameters and the sagittal and coronal ROM of the lower limb joints were analyzed as secondary outcomes.

2. Materials and Methods

2.1. Participants

This pilot study targeted middle-aged women aged 50 to 64 years who were diagnosed with KOA. Following the sample size recommendations for pilot studies [19,20], and accommodating a potential dropout rate of 10–15%, a total of 26 participants (n = 13 per group) were recruited. This ensures sufficient data to estimate effect sizes and conduct exploratory analyses for future definitive trials. Participants were recruited through announcements posted on bulletin boards at the Lifelong Education Center and the Sports Rehabilitation Laboratory of Busan University of Foreign Studies

The inclusion criteria were: (1) individuals diagnosed with KOA (Kellgren–Lawrence grade II–III) by an orthopedic surgeon and recommended for exercise therapy (verified through medical documentation for participant safety); (2) no clinical history of musculoskeletal disorders other than KOA; (3) capable of independent stair negotiation without gait aids; and (4) those who voluntarily provided written informed consent after a full explanation of the study procedures. The exclusion criteria included: (1) intra-articular knee injections within the previous 3 months; (2) a history of knee joint surgery; (3) severe cardiovascular, neurological, or psychiatric disorders; (4) acute inflammation or intractable pain preventing exercise performance; and (5) other significant medical conditions (e.g., chronic respiratory disease or major surgery within the last 6 months).

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The 26 eligible participants were randomly allocated in a 1:1 ratio to either the experimental group (DNS training, n = 13) or the control group (activities of daily living, n = 13) using simple randomization. To minimize selection bias, an independent researcher not involved in the intervention performed the allocation using opaque, sealed envelopes. A single-blind protocol was implemented, ensuring that the evaluators remained unaware of the group assignments during all measurements. Following ethical guidelines, a wait-list control design was used; the control group was offered an 8-week DNS exercise program (twice weekly) immediately after the 10-week study period. This study was approved by the Public Institutional Review Board designated by the Ministry of Health and Welfare (Approval No.: P01-202511-01-012, approved on November 10, 2025) and was registered with the Clinical Research Information Service (CRIS) (Registration date: November 13, 2025; Registration No.: KCT0011158). All participants received a thorough explanation of the purpose and procedures of the study and voluntarily provided written informed consent prior to participation.

Baseline demographic characteristics and the CONSORT flow diagram are presented in Table 1 and Figure 1, respectively.

Table 1. Characteristics of study participants (*n*=26).

	DNSG (*n*=13)	CG (*n*=13)
Age (years)	56.77±3.03	56.46±3.64
Weight (kg)	60.18±3.33	62.18±6.32
Height (cm)	158.38±4.91	158.25±5.86
BMI (kg/m²)	24.01±1.22	24.83±0.61

Values are presented as means±standard deviations. DNSG, dynamic neuromuscular stabilization group; CG, control group.

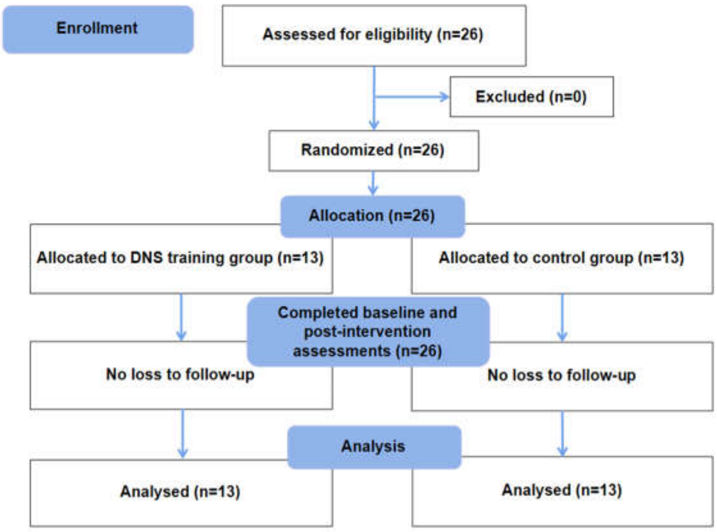

Figure 1. Flow diagram of the study participants.

2.2. Stair Ambulation Analysis

In this study, the ML velocity and RMS of the COP, representing lateral dynamic stability, were established as the primary outcomes. Additionally, the sagittal and coronal ROM of the lower limb joints and AP COP parameters were analyzed as secondary outcomes, while joint moments were evaluated as supplementary kinetic outcomes.

To evaluate these variables, a custom-built three-step staircase, constructed in accordance with Korean standard building codes (riser height: 17 cm), was utilized. To capture kinetic data, two force plates (AMTI OR6, Watertown, MA, USA) were directly embedded into the first and second steps (Figure 2).

(a) Marker placement and the transition movement of the participant

(b) Three-step staircase structure integrated with the motion analysis system and force plates.

Figure 2. Biomechanical measurement environment and experimental equipment.

The dimensions of all steps were identical across the staircase, ensuring standardized measurement conditions for all participants. Three-dimensional kinematic data were recorded at 100 Hz using the Vicon Plug-in Gait system (Vicon Motion Systems Ltd., Oxford, UK), with 16 retroreflective markers attached to specific anatomical landmarks of the lower extremities, synchronously with ground reaction force data sampled at 1000 Hz. To calculate the kinetic variables, data from the force plate that the participants first contacted during both stair ascent and descent were used for analysis. Prior to calculating the biomechanical variables, the raw data were processed using a zero-lag, fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz [21,22].

Prior to data collection, participants were allowed sufficient practice trials to familiarize themselves with the experimental setup. Participants performed both stair ascent and stair descent tasks barefoot at a self-selected, comfortable pace. For each task, five trials were initially recorded. Subsequently, three successful trials that met the predetermined criteria for consistent and artifact-free execution were selected, and their average was used for the final analysis. Based on these filtered trajectory and force data, the COP was extracted. To account for individual variations, COP velocity was normalized by dividing it by each participant’s gait speed, resulting in a dimensionless ratio. Furthermore, lower extremity joint kinematics and internal joint moments were analyzed using the Plug-in Gait model. Specifically, the ROM was calculated as the difference between the maximum and minimum joint angles in the sagittal and frontal planes. Internal joint moments were also analyzed using their maximum peak values in the same planes; detailed data for joint moments are provided as supplementary material. The stance phase was defined as the continuous period from initial foot strike to foot-off on the embedded force plates.

Due to the bilateral nature of the symptoms, the more symptomatic leg, determined by a higher Visual Analog Scale (VAS) pain score, was designated as the index limb for the stair ambulation analysis. As a safety precaution, bilateral handrails were installed on the customized staircase, and an evaluator closely monitored all trials. To prevent any confounding effects on the biomechanical data, participants were instructed to perform the tasks without utilizing the handrails. Ultimately, all participants successfully completed the tasks independently without any safety incidents.

2.3. Intervention and Control Conditions

The intervention group completed a 10-week, bi-weekly DNS exercise program (50 min/session). Based on developmental kinesiology, the protocol focused on postural alignment and intra-abdominal pressure (IAP) regulation. Exercises were modified to ensure optimal neuromuscular activation and minimal joint stress for female patients with knee osteoarthritis [17,23]. Training occurred in small groups (n=6-7) under the direct supervision of an experienced certified trainer, ensuring high exercise fidelity through continuous feedback. Intensity was systematically progressed by advancing to more complex kinematic positions (e.g., from lateral recumbent to weight-bearing upright postures), permitted only when participants maintained proper IAP control and joint centration without pain or compensation.

Conversely, participants assigned to the control group did not receive the DNS intervention and were instructed to maintain their habitual lifestyle and daily activities throughout the 10-week study period. To isolate the effects of the intervention, all participants were prohibited from initiating any new structured exercise programs. To ensure safety and ethical compliance, researchers continually monitored for medical consultations, medication use, or significant lifestyle changes. While incidental physical therapy was permitted if prescribed for medical necessity, no participants in either group reported seeking additional therapeutic interventions or experiencing exacerbation of knee pain during the study. Consequently, no confounding variables related to external treatments were introduced into the analysis.

The exercise components are illustrated in Figure 3, and the specific set configurations are summarized in Table 2.

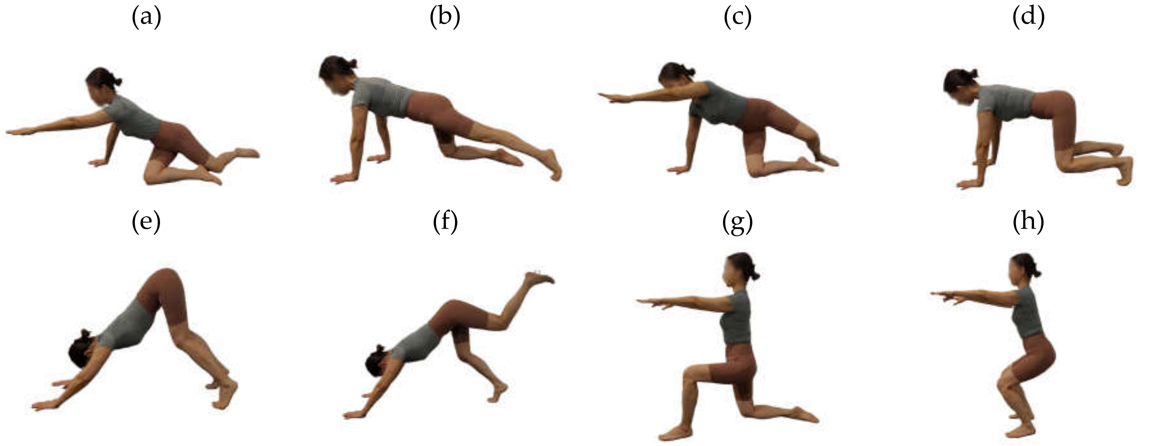

Figure 3. Representative exercises of the 10-week Dynamic DNS program. (a) Asymmetrical kneeling transition with contralateral reach; (b) Unilateral hip extension with core stabilization in four-point kneeling; (c) Contralateral reciprocal crawling pattern; (d) Closed-kinetic chain stabilization in levitated four-point kneeling; (e) Transition to high plantigrade quadruped position for posterior chain elongation; (f) Unilateral lower extremity lift in plantigrade quadruped position; (g) Transition from asymmetrical sitting to unilateral weight-bearing lunge; (h) Closed-kinetic chain squatting from plantigrade quadruped posture.

Table 2. The 10-week DNS-based exercise program.

DNS Training	Program	Time/Reps
Warm-up	1. Diaphragmatic breathing with functional IAP regulation 2. Reciprocal cross-pattern activation in the 3-month supine position	10/6
Main phase 1 (1-3week)	1. Trunk rotation with core stabilization in lateral recumbent 2. Anterior-posterior weight shifting in four-point kneeling 3. Unilateral hip extension with core stabilization in four-point kneeling	35 / 8-10
Main phase 2 (4-7week)	4. Asymmetrical kneeling transition with contralateral reach 5. Contralateral reciprocal crawling pattern 6. Closed-kinetic chain stabilization in levitated four-point kneeling 7. Transition from four-point kneeling to unilateral lateral support	35/8-10
Main phase 3 (8-10week)	8. Transition to high plantigrade quadruped position for posterior chain elongation	35/8-10

	9. Unilateral lower extremity lift in plantigrade quadruped position 10. Transition from asymmetrical sitting to unilateral weight-bearing lunge 11. Closed-kinetic chain squatting from plantigrade quadruped posture	
Cool-down	1. Deep spinal flexion in quadruped resting position 2. Prone resting with integrated respiratory-postural stabilization	5/6

2.4. Statistical Analysis

All statistical analyses were performed based on the intention-to-treat (ITT) principle. Given the 100% retention rate and the absence of protocol violations, the ITT population was identical to the per-protocol (PP) population.

All data collected in this study were analyzed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as means and standard deviations for all variables. To verify the homogeneity of demographic characteristics and baseline variables between the groups, an independent t-test was performed. Prior to the main analyses, the Shapiro–Wilk test was utilized to assess the normality of the data distribution.

To evaluate the intervention effects, an Analysis of Covariance (ANCOVA) was initially conducted, with baseline values entered as covariates. Prior to conducting the ANCOVA, the assumption of homogeneity of regression slopes was tested. For variables that satisfied this assumption, a standard ANCOVA was applied to determine the differences between the groups. Conversely, for a subset of joint moment variables in the supplementary material that violated this assumption, the intervention effect was analyzed using change scores (post-intervention minus baseline values) via independent t-tests. Effect sizes were reported as partial eta squared (η^2_p) for ANCOVA and Cohen's *d* for t-tests (small: η^2_p = 0.01, *d*=0.20; medium: η^2_p=0.06, *d*=0.50; large: η^2_p=0.14, *d*=0.80).

The Benjamini-Hochberg False Discovery Rate (FDR) procedure was used to correct for multiple comparisons among the secondary outcomes, and the level of statistical significance was set at $p < 0.05$ for all analyses.

4. Results

The results of the ANCOVA comparing between-group differences in primary and secondary outcomes, with baseline values as covariates, are presented in Tables 3–5, while additional data regarding joint moments are provided in the Supplementary Material (Tables S1 and S2).

Table 3. ANCOVA-adjusted group differences in post-intervention center of pressure.

Variable	Group	Baseline (M±SD)	Post (M±SD)	LSM (95% CI)	MD (95% CI)	*F*	*P*	η^2_p
ASC ML-velocity	DNSG	0.18±0.04	0.15±0.03	0.14 (0.14-0.15)	-0.05 (-0.06, -0.04)	84.34	0.000	0.79
(normalized)	CG	0.18±0.04	0.19±0.03	0.19 (0.19-0.20)				
ASC ML-RMS	DNSG	1.01±0.54	0.91±0.49	0.94 (0.77-1.12)	-0.24 (-0.49, 0.01)	3.91	0.060	0.15
(cm)	CG	1.09±0.67	1.21±0.63	1.18 (1.00-1.35)				
ASC AP-velocity	DNSG	0.44±0.08	0.45±0.04	0.45 (0.43-0.46)	0.01	1.39	0.250	0.06

					(-0.01, 0.03)			
(normalized)	CG	0.45±0.09	0.44±0.06	0.44 (0.42-0.45)				
ASC AP-RMS	DNSG	3.63±0.76	3.23±0.84	3.26 (2.91-3.62)	-0.58 (-1.08, -0.07)	5.60	0.027	0.20
(cm)	CG	3.73±0.68	3.88±0.72	3.84 (3.49-4.20)				
DSC ML-velocity	DNSG	0.20±0.05	0.16±0.04	0.16 (0.14-0.17)	-0.05 (-0.07, -0.04)	37.37	0.000	0.62
(normalized)	CG	0.19±0.05	0.21±0.04	0.21 (0.20-0.22)				
DSC ML-RMS	DNSG	0.76±0.27	0.68±0.20	0.69 (0.55-0.82)	-0.20 (-0.39, -0.00)	4.46	0.046	0.16
(cm)	CG	0.81±0.34	0.89±0.28	0.88 (0.75-1.02)				
DSC AP-velocity	DNSG	0.51±0.08	0.49±0.07	0.49 (0.45-0.53)	-0.04 (-0.09, 0.01)	2.30	0.143	0.09
(normalized)	CG	0.49±0.08	0.52±0.07	0.53 (0.49-0.56)				
DSC AP-RMS	DNSG	2.61±0.87	2.47±0.98	2.37 (1.96-2.78)	-0.59 (-1.18, -0.01)	4.43	0.047	0.16
(cm)	CG	2.24±1.00	2.86±0.72	2.96 (2.55-3.37)				

Note. Baseline and post-intervention values are presented as mean ± standard deviation (SD). Adjusted means (least squares means, LSM) and 95% confidence intervals (CI) were calculated after controlling for baseline values as a covariate. MD = mean difference between groups (DNSG – CG). *F* and *p*-values were derived from analysis of covariance (ANCOVA). Partial eta squared (η^2_p) represents the effect size (0.01 = small, 0.06 = medium, 0.14 = large). DNSG = dynamic neuromuscular stabilization group; CG = control group; ASC = ascent; DSC = descent.

Table 4. ANCOVA-adjusted group differences in post-intervention range of motion during stair ascent.

Variable	Group	Baseline (M±SD)	Post (M±SD)	LSM (95% CI)	MD (95% CI)	*F*	*P*	η^2_p
Hip ROM (deg)	DNSG	61.59±4.80	64.85±5.66	65.32 (63.01-67.64)	4.01 (0.71, 7.30)	6.33	0.019	0.23
Saggital plane	CG	62.88±4.13	61.80±4.53	61.32 (59.00-63.64)				
Hip ROM (deg)	DNSG	18.58±4.55	17.85±3.95	17.25 (16.32-18.17)	-1.27 (-2.59, 0.05)	3.96	0.059	0.15
Coronal plane	CG	17.11±5.56	17.91±4.92	18.51 (17.59-19.44)				

Knee ROM (deg)	DNSG	52.45±6.73	60.43±9.55	60.86 (58.00-63.71)	9.70 (5.65, 13.74)	24.60	0.000	0.52
Saggital plane	CG	53.30±8.81	51.59±9.01	51.16 (48.30-54.02)				
Knee ROM (deg)	DNSG	31.83±5.24	29.41±4.07	29.93 (28.45-31.40)	-3.85 (-5.94, -1.75)	14.47	0.001	0.39
Coronal plane	CG	33.07±5.87	34.28±6.14	33.77 (32.30-35.24)				
Ankle ROM (deg)	DNSG	15.81±4.79	18.14±5.68	18.96 (17.71-22.22)	2.92 (1.12, 4.72)	11.26	0.003	0.33
Saggital plane	CG	17.52±4.08	16.87±3.68	16.05 (14.79-17.31)				
Ankle ROM (deg)	DNSG	8.75±2.12	7.50±2.21	7.34 (6.35-8.33)	-0.37 (-1.76, 1.04)	0.29	0.595	0.01
Coronal plane	CG	8.25±2.95	7.54±2.51	7.71 (6.72-8.69)				

Note. Baseline and post-intervention values are presented as mean ± standard deviation (SD). Adjusted means (least squares means, LSM) and 95% confidence intervals (CI) were calculated after controlling for baseline values as a covariate. MD = mean difference between groups (DNSG – CG). F and p-values were derived from analysis of covariance (ANCOVA). Partial eta squared (η^2_P) represents the effect size (0.01 = small, 0.06 = medium, 0.14 = large). DNSG = dynamic neuromuscular stabilization group; CG = control group; deg = degrees.

Table 5. ANCOVA-adjusted group differences in post-intervention range of motion during stair descent.

Variable	Group	Baseline (M±SD)	Post (M±SD)	LSM (95% CI)	MD (95% CI)	*F*	*P*	η^2_P
Hip ROM (deg)	DNSG	15.40±2.73	17.82±3.64	18.48 (17.04-19.92)	2.81 (0.74, 4.89)	7.84	0.010	0.25
Saggital plane	CG	17.12±3.57	16.32±3.21	15.67 (14.22-17.11)				
Hip ROM (deg)	DNSG	18.91±6.33	17.28±5.31	16.42 (15.04-17.79)	-2.31 (-4.28, -0.35)	5.91	0.023	0.21
Coronal plane	CG	16.78±3.83	17.87±4.31	18.73 (17.35-20.10)				
Knee ROM (deg)	DNSG	47.95±9.31	56.49±7.40	57.74 (55.26-60.22)	9.87 (6.32, 13.41)	33.12	0.000	0.59
Saggital plane	CG	51.41±8.68	49.13±8.07	47.87 (45.39-50.36)				

Knee ROM (deg)	DNSG	28.47±4.91	27.42±3.63	27.86 (27.05-28.68)	-2.27 (-3.43, -1.12)	16.56	0.000	0.42
Coronal plane	CG	29.52±6.77	30.57±6.33	30.14 (29.32-30.95)				
Ankle ROM (deg)	DNSG	65.63±5.75	68.82±4.89	69.14 (66.86-71.41)	3.95 (0.73, 7.18)	6.43	0.018	0.22
Saggital plane	CG	66.63±7.41	65.51±6.46	65.19 (62.91-67.46)				
Ankle ROM (deg)	DNSG	6.55±2.09	6.17±2.02	6.22 (5.74-6.70)	-0.69 (-1.37, -0.02)	4.50	0.045	0.16
Coronal plane	CG	6.67±3.51	6.96±2.85	6.91 (6.44-7.39)				

Note. Baseline and post-intervention values are presented as mean ± standard deviation (SD). Adjusted means (least squares means, LSM) and 95% confidence intervals (CI) were calculated after controlling for baseline values as a covariate. MD = mean difference between groups (DNSG – CG). F and p-values were derived from analysis of covariance (ANCOVA). Partial eta squared (η^2_p) represents the effect size (0.01 = small, 0.06 = medium, 0.14 = large). DNSG = dynamic neuromuscular stabilization group; CG = control group; deg = degrees.

4.1. Feasibility, Retention, and Intervention Adherence

In accordance with the primary objectives of this pilot study, feasibility was evaluated through the recruitment rate, participant retention, adherence to the intervention program, the incidence of adverse events, and assessment completion. All 26 eligible individuals agreed to participate, achieving a 100% recruitment rate. Consequently, all 26 randomized participants successfully completed the 10-week study period, resulting in a 100% retention rate and a 0% dropout rate. Participants in the DNS experimental group demonstrated excellent adherence to the 20-session (twice a week) program. Specifically, 11 out of the 13 participants (84.6%) attended all sessions, with only two individuals missing two sessions each due to personal reasons. As a result, the overall compliance rate was calculated at 98.5% (256 out of 260 total expected sessions). Furthermore, no adverse events, such as exercise-related injuries or exacerbation of knee pain, occurred throughout the study period, and all participants successfully completed the biomechanical assessments without any technical missing data or dropouts. These findings confirm the safety and high tolerability of the applied DNS program.

4.2. Primary Outcomes

4.2.1. Mediolateral COP Velocity and RMS During Stair Ascent and Descent

During stair ascent, ANCOVA revealed a group effect on ML-velocity ($F = 84.34$, $p < 0.001$, $\eta^2_p = 0.79$; MD = -0.05 cm/s, 95% CI: -0.06 to -0.04). For ML-RMS, the group effect was $F = 3.91$, $p = 0.060$, $\eta^2_p = 0.15$ (MD = -0.24 cm, 95% CI: -0.49 to 0.01).

During stair descent, ANCOVA revealed a group effect on ML-velocity ($F = 37.37$, $p < 0.001$, $\eta^2_p = 0.62$; MD = -0.05 cm/s, 95% CI: -0.07 to -0.04). For ML-RMS, the group effect was $F = 4.46$, $p = 0.046$, $\eta^2_p = 0.16$ (MD = -0.20 cm, 95% CI: -0.39 to -0.00).

4.3. Secondary Outcomes

4.3.1. Anteroposterior COP Velocity and RMS During Stair Ascent and Descent

During stair ascent, ANCOVA revealed a group effect on AP-velocity ($F = 1.39$, $p = 0.250$, FDR-adjusted $p = 0.250$, $\eta^2_p = 0.06$; MD = 0.01 cm/s, 95% CI: -0.01 to 0.03). For AP-RMS, the group effect was $F = 5.60$, $p = 0.027$, FDR-adjusted $p = 0.054$, $\eta^2_p = 0.20$ (MD = -0.58 cm, 95% CI: -1.08 to -0.07).

During stair descent, the group effect on AP-velocity was $F = 2.30$, $p = 0.143$, FDR-adjusted $p = 0.143$, $\eta^2_p = 0.09$ (MD = -0.04 cm/s, 95% CI: -0.09 to 0.01). For AP-RMS, the group effect was $F = 4.43$, $p = 0.047$, FDR-adjusted $p = 0.094$, $\eta^2_p = 0.16$ (MD = -0.59 cm, 95% CI: -1.18 to -0.01).

4.3.2. Sagittal and Coronal Joint Range of Motion During Stair Ascent

For sagittal ROM, the group effects were: hip ($F = 6.33$, $p = 0.019$, FDR-adjusted $p = 0.029$, $\eta^2_p = 0.23$; MD = 4.01°, 95% CI: 0.71 to 7.30), knee ($F = 24.60$, $p < 0.001$, FDR-adjusted $p < 0.001$, $\eta^2_p = 0.52$; MD = 9.70°, 95% CI: 5.65 to 13.74), and ankle ($F = 11.26$, $p = 0.003$, FDR-adjusted $p = 0.006$, $\eta^2_p = 0.33$; MD = 2.92°, 95% CI: 1.12 to 4.72).

For coronal ROM, the group effects were: knee ($F = 14.47$, $p = 0.001$, FDR-adjusted $p = 0.003$, $\eta^2_p = 0.39$; MD = -3.85°, 95% CI: -5.94 to -1.75), hip ($F = 3.96$, $p = 0.059$, FDR-adjusted $p = 0.071$, $\eta^2_p = 0.15$; MD = -1.27°, 95% CI: -2.59 to 0.05), and ankle ($F = 0.29$, $p = 0.595$, FDR-adjusted $p = 0.595$, $\eta^2_p = 0.01$; MD = -0.37°, 95% CI: -1.76 to 1.04).

4.3.3. Sagittal and Coronal Joint Range of Motion During Stair Descent

For sagittal ROM, the group effects were: hip ($F = 7.84$, $p = 0.010$, FDR-adjusted $p = 0.020$, $\eta^2_p = 0.25$; MD = 2.81°, 95% CI: 0.74 to 4.89), knee ($F = 33.12$, $p < 0.001$, FDR-adjusted $p < 0.001$, $\eta^2_p = 0.59$; MD = 9.87°, 95% CI: 6.32 to 13.41), and ankle ($F = 6.43$, $p = 0.018$, FDR-adjusted $p = 0.027$, $\eta^2_p = 0.22$; MD = 3.95°, 95% CI: 0.73 to 7.18).

For coronal ROM, the group effects were: knee ($F = 16.56$, $p < 0.001$, FDR-adjusted $p < 0.001$, $\eta^2_p = 0.42$; MD = -2.27°, 95% CI: -3.43 to -1.12), hip ($F = 5.91$, $p = 0.023$, FDR-adjusted $p = 0.028$, $\eta^2_p = 0.21$; MD = -2.31°, 95% CI: -4.28 to -0.35), and ankle ($F = 4.50$, $p = 0.045$, FDR-adjusted $p = 0.045$, $\eta^2_p = 0.16$; MD = -0.69°, 95% CI: -1.37 to -0.02).

4.3.4. Supplementary Sagittal and Coronal Joint Moments

Detailed statistical data for the internal joint moments of the hip, knee, and ankle in the sagittal and coronal planes are provided in the Supplementary Material (Tables S1 and S2). Following FDR correction, no group effects were found during stair ascent. During stair descent, group effects were observed on the sagittal knee moment ($F = 7.53$, $p = 0.012$, $\eta^2_p = 0.25$) and the sagittal ankle moment ($F = 9.38$, $p = 0.006$, $\eta^2_p = 0.29$).

5. Discussion

This pilot study investigated the effects of a 10-week DNS intervention on COP characteristics and lower extremity joint mechanics during stair negotiation in women with knee osteoarthritis. ML COP parameters (velocity and RMS) were designated as primary outcomes, whereas AP COP parameters and lower extremity joint ROM were established as secondary outcomes. Given the pilot design, data analysis primarily focused on effect sizes. The findings demonstrated that the primary outcomes, ML COP velocity and RMS, decreased with large effect sizes. Furthermore, consistently large effect sizes were observed in the kinematic changes of the lower extremity joints, characterized by an increase in sagittal ROM and a decrease in coronal ROM.

The intervention in this study was conducted by systematically mimicking the stages of human motor development, from supine to standing positions, applying the principles of developmental kinesiology. This progressive approach has been reported to induce the activation of IAP through the coordination of the diaphragm and deep muscles, effectively distributing internal forces and optimizing overall motor control [24]. The improvements in COP control and the mechanical alignment of the lower limb joints observed in this study suggest that the trunk stability secured through DNS training was effectively transferred to the lower kinetic chain, thereby positively contributing to the attainment of dynamic stability during demanding weight-bearing tasks such as stair negotiation.

Stair ascent involves overcoming gravity to propel the body upward, which requires firm support during the single-leg support phase [25]. The large effect sizes for the reductions in ML COP velocity and RMS observed during the ascent task suggest that post-training, the subjects were able to more effectively control both the magnitude and speed of unnecessary lateral sway while bearing weight on a single leg. According to previous studies, DNS training establishes adequate IAP through the coordination of respiration and deep muscles, securing robust proximal stability of the trunk. This stability is known to facilitate efficient midline-directed weight shifts during dynamic postural transitions [16,18,26]. Based on these biomechanical advantages, it can be inferred that the subjects in this study also adopted an optimized movement strategy, utilizing the trunk as a solid anchor point to reduce laterally wasted forces during step-up movements.

Stair descent is a mechanically demanding task that requires controlling the downward acceleration of the body and safely accepting the load at the moment of foot contact [27,28]. During this process, patients with osteoarthritis frequently employ a compensatory strategy of excessive lateral trunk lean to avoid knee pain and instability caused by weight-bearing [29,30]. The large effect sizes for the reductions in ML COP velocity and RMS observed during the descent task in this study suggest that, rather than relying on this compensatory sway, the subjects controlled their bodies through enhanced dynamic balance during the weight acceptance phase. This finding supports the notion that the proximal stability secured through DNS training played a positive role in controlling the body's downward acceleration and effectively absorbing dynamic perturbations upon landing.

In the present study, the sagittal ROM of the joints during stair ascent increased with large effect sizes, whereas the coronal ROM of the hip and knee joints decreased. Previous studies have noted that patients with knee osteoarthritis often employ a protective stiffening strategy, restricting sagittal flexion to avoid pain during stair ascent, while compensating by excessively leaning the trunk or increasing coronal plane movements [31,32]. The increase in sagittal ROM, which is essential for generating propulsion, suggests a positive modification of this protective pattern. Specifically, it can be inferred that the subjects transitioned away from inefficient joint-locking mechanics, enabling them to more fluidly recruit the functional sagittal flexion and extension movements required to overcome gravity. Furthermore, the decrease in coronal knee ROM serves as an indicator that abnormal valgus and varus stress, which frequently occurs during the propulsion phase, was adequately controlled. This finding aligns with the 'joint centration' principle of DNS, which promotes the even distribution of mechanical loads across articular surfaces

Conversely, stair descent is a demanding eccentric control task that requires regulating downward acceleration and absorbing impact at the moment of foot contact [28]. Due to the fear associated with weight acceptance, patients with osteoarthritis tend to abnormally increase joint stiffness to counteract the impact [33,34]. The large effect sizes observed for the increase in sagittal ROM of each joint during descent can be interpreted as a gradual adaptation toward functional movements—specifically, bending the knee and ankle to dissipate impact—rather than relying on protective joint stiffness. Furthermore, the large effect sizes corresponding to the decrease in coronal ROM during descent reflect that mechanical instability exerted on the lateral aspect of the knee upon landing was adequately controlled [35]. This can be elucidated as the result of the DNS intervention suppressing upper body sway [16,24], thereby reducing the unnecessary shear forces previously imposed on the knee joint. Consequently, as presented in the supplementary data, this may have facilitated a positive kinetic shift during descent, characterized by decreased hip and knee moments alongside an increased ankle joint moment.

In summary, progressive DNS training, based on developmental kinesiology stages, systematically establishes IAP through the coordination of respiration and deep muscles. The proximal stability achieved through this process provides a biomechanical foundation that enables the lower kinetic chain to coordinate synergistically in regulating lower limb joint movements [36,37]. Consequently, this mechanical foundation is thought to have led to the positive changes observed during stair negotiation: the improvement in COP control, coupled with increased functional flexion in the sagittal plane and decreased instability in the coronal plane. These findings provide preliminary evidence that DNS interventions can improve movement strategies and mitigate mechanical vulnerabilities in patients with knee osteoarthritis.

When interpreting the results of this study, the following limitations should be considered. First, regarding the study design, this was a small-scale pilot study restricted to women with knee osteoarthritis, which limits the generalizability of the findings. Additionally, because the control group was maintained as a usual care group without intervention, differences in overall physical activity levels between the two groups may have occurred. Therefore, the possibility that the calculated effect size of the intervention was somewhat overestimated cannot be excluded.

Methodological limitations concerning the experimental setup and measurements also exist. Due to the structural constraints of the 3-step experimental staircase, it was difficult to extract data from a continuous steady-state gait phase. Consequently, the present results primarily reflect the mechanical characteristics of the transition phase from level walking to stair negotiation. Moreover, this study did not directly verify via surface electromyography (sEMG) whether the observed reduction in joint loading was attributable to a decrease in actual muscle co-contraction or alterations in neuromuscular control. Finally, to ensure the accuracy of marker tracking, the experiment was conducted under barefoot conditions. Thus, the variables associated with everyday footwear and its impact on weight acceptance and ankle joint mechanics could not be fully controlled, which remains an area to be addressed in future research.

6. Conclusions

This pilot study explored the feasibility and preliminary effects of a 10-week progressive DNS training program on the COP and mechanical characteristics of the lower limb joints during stair negotiation in patients with knee osteoarthritis. Primarily, the intervention proved to be highly feasible and safe, evidenced by a 100% retention rate, excellent adherence, and the absence of any adverse events. The results **further** demonstrated that DNS training improved mediolateral COP control during both stair ascent and descent, and induced positive mechanical adaptations, specifically an increased sagittal range of motion and decreased coronal instability in the lower limb joints. Despite the small sample size inherent in a pilot study, these findings provide preliminary evidence that the proximal stability secured through DNS can enhance the efficiency of the lower kinetic chain and alleviate joint loading. In conclusion, this study suggests that DNS training could serve as an effective intervention strategy for improving gait function in patients with knee osteoarthritis, and it holds significant value as foundational data for the design and efficacy verification of future large-scale clinical trials.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org, Table S1: Supplementary Sagittal and Coronal Joint Moments during stair ascent; Table S2: Supplementary Sagittal and Coronal Joint Moments during stair descent.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. All participants received a thorough explanation of the purpose and procedures of the study and voluntarily provided written informed consent prior to participation.:

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