Original Article

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Effects of a Pilates-Based Exercise Program versus transcranial direct current stimulation on Gait, Balance, and Quality of Life in stroke patients: A Randomized Controlled Trial

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Abstract: Emerging evidence highlights the role of targeted neuromodulation and structured exercise interventions in enhancing functional recovery following stroke. This study compared the effects of transcranial direct current stimulation (tDCS) targeting the supplementary motor area and Pilates-based core stability training, within a physical activity–based rehabilitation framework, on balance and gait performance in individuals with subacute stroke. Sixty-six patients were randomly assigned to three groups: group (A) received anodal tDCS over the supplementary motor area combined with conventional physiotherapy; group (B) received Pilates-based core stability training with conventional physiotherapy; and control group (C) received conventional physiotherapy with sham tDCS. Assessments were conducted pre- and post-treatment and included spatiotemporal gait parameters (step length, stance time, swing time, double support time, and velocity), balance indices (Overall Stability Index and Limit of Stability), and stroke-specific quality of life. All groups showed significant post-treatment improvements in gait, balance, and quality of life ($p < 0.05$). No significant differences were found between groups (A) and (B) across outcomes ($p > 0.05$). However, both groups demonstrated significantly greater improvements than the control group in key gait parameters, balance measures, and quality of life ($p \leq 0.02$). Although both interventions were associated with improvements in functional outcomes, the present study did not detect statistically significant differences between groups.

Keywords: Stroke, Transcranial direct current stimulation, Pilates-based core training, Gait, Balance, stroke-specific quality of life.

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INTRODUCTION

Globally, stroke is the predominant cause of long-term impairment in adults, particularly regarding the motor system, limiting physical activity and mobility in daily life [1]. With a high mean prevalence rate of 721.6/100,000 people, it is the second primary cause of mortality in Egypt, after ischemic heart disease [2]. Post-stroke patients commonly experience balance impairments, which significantly increase their risk of falls, fear of falling, and fall-related injuries that can raise mortality rates [3]. Although many regain independent walking, gait often remains unstable and asymmetrical [4]. These deficits are largely attributed to impaired motor control and reduced trunk stability integration following stroke. Therefore, improved gait safety, speed, and efficiency are critical goals in post-stroke rehabilitation. [5].

Conventional stroke rehabilitation focuses on restoring walking ability through physical therapy interventions that improve balance, strength, and coordination. However, functional recovery often becomes limited with conventional rehabilitation alone, highlighting the need for adjunct interventions that enhance recovery and movement quality. Therefore, newer approaches emphasize motor learning and neuroplasticity through methods such as robotic-assisted gait therapy, non-invasive brain stimulation and task specific practice [6].

Postural control is the ability to maintain stability and orientation of the body in space. It is a complex sensorimotor skill that depends on the integration of sensory inputs with central nervous system processing to plan and execute coordinated motor output [7]. Following neurological injury, disruption of these processes may impair trunk control and contribute to deficits in balance and gait [8]. Given the importance of trunk control for independence in daily living [9], interventions that target core stability and postural control, such as Pilates-based exercise or neuromodulation techniques like tDCS, are particularly relevant in post-stroke rehabilitation.

Pilates, a structured core stabilization method, emphasizes trunk strength, controlled breathing, and postural alignment, and has demonstrated benefits in balance, gait and endurance [10,11]. In addition, trunk control is a strong predictor of independence in daily living activities post-stroke, making core stability a critical rehabilitation target [12]. The development of movement control and stability follows a core-to-extremity sequence. In this context, the core musculature provides dynamic stability by stabilizing the spine, pelvis, and shoulder girdle, thereby establishing a stable foundation for efficient and coordinated limb motion. This may facilitate improved gait and balance control in individuals post-stroke [13]. Although Pilates has been investigated in conditions such as multiple sclerosis and Parkinson's disease, research on its effects in stroke patients is still limited [14].

Researchers have been exploring novel options like non-invasive brain stimulation (NIBS), particularly transcranial direct current stimulation (tDCS), which alters cortical excitability in a polarity-dependent way, thereby facilitating motor recovery through neuroplasticity [15]. Clinical studies suggest tDCS can enhance motor recovery, postural stability, and balance in post-stroke patients [16], with the primary motor cortex (M1) and supplementary motor area (SMA) being important targets for gait and balance control [17-19]. Non-invasive brain stimulation (NIBS), such as tDCS, represents a promising approach to enhance neuroplasticity and motor recovery after stroke.

Exercise-based rehabilitation and neuromodulation approaches represent different therapeutic strategies that may support post-stroke recovery through distinct mechanisms. Exercise interventions are widely accessible, relatively low cost, and feasible in clinical and community settings, whereas neuromodulation techniques aim to facilitate cortical reorganization and motor recovery through direct modulation of neural excitability.

Despite encouraging findings for both interventions individually, no study has directly compared Pilates-based exercise training and tDCS in stroke rehabilitation and specifically assessed multidimensional outcomes of gait, balance and quality of life. Further investigations are needed for better understanding the effects of these distinct approaches on rehabilitation outcomes compared to conventional physiotherapy. Therefore, and guided by theories of motor learning and neuroplasticity, this study aimed to examine the effects of Pilates-based exercise and tDCS on gait performance, balance, and stroke-specific quality of life. We hypothesized that both interventions would improve physical activity outcomes compared with conventional physiotherapy alone.

MATERIAL AND METHODS

Participants

Seventy-two patients with clinically and radiologically verified subcortical stroke were enrolled from the outpatient clinics of Cairo University Hospitals between June 2024 and July 2025. Each participant completed a written consent after being informed of the study's objectives and methodologies.

Participants were adults aged 50–60 years with a first-ever ischemic or hemorrhagic stroke occurring more than eight weeks prior, presenting with mild to moderate spasticity (Modified Ashworth Scale < 3) and adequate cognitive function (Mini-Mental state examination ≥ 24). They were required to have been ambulatory before the stroke and able to stand or walk with or without walking aids. Participants were excluded if they had a history of seizures, bilateral or multifocal stroke, other pre-existing neurological or musculoskeletal disorders that could affect balance or motor function or unstable medical conditions.

Study design

The research was conducted as a randomized controlled trial with pre- and post-intervention evaluations. Sample size calculation was performed using G*POWER statistical software (version 3.1.9.2; Franz Faul, Universität Kiel, Germany), utilizing step length data from pilot research including 5 patients per group, which indicated that the necessary sample size for this investigation was n=66. The calculation was conducted with α=0.05, power of 80%, and an effect size of 0.40. The anticipated dropout rate was projected at 10%, leading to a determination of 72 participants.

Randomization

Participants were randomly allocated into three groups using a computer-based random generator with permuted blocks. Allocation was done using sealed opaque envelopes and the process was performed by an independent member of staff, not involved in the study. There were no dropouts following randomization. Outcome assessment was conducted by an independent assessor blinded to group allocation, in order to minimize detection bias. Participants were blinded to whether they received active or sham tDCS; however, blinding was not possible for the Pilates intervention due to its nature. Group (A) received anodal tDCS over the SMA plus conventional physiotherapy; group (B) received Pilates-based core training plus conventional physiotherapy; and group (C), receiving conventional physiotherapy plus sham tDCS. Each session lasted 60 minutes, three times per week for six weeks. Attendance and adherence were monitored throughout the intervention period, and participants completed the sessions according to the study protocol. No adverse events were reported during the study period.

Assessment

The study assessed the primary outcomes as gait and balance performance variables. The secondary outcome was health-related quality of life, assessed using the Stroke-Specific Quality of Life scale (SS-QOL).

Gait parameters were analyzed using a motion capture system comprising a high-definition camera and Kinovea® 2D motion analysis software. Kinovea is a validated tool for kinematic and spatiotemporal analysis, demonstrating excellent test–retest reliability for step length, stance time, and swing time (ICC > 0.90), good reliability for gait speed (ICC = 0.76–0.90), strong inter-rater agreement (ICC > 0.90), and excellent criterion validity (r > 0.80) [20]. The following variables were assessed pre- and post-intervention: step length, stance time, and swing time of the affected side, double support time, and gait speed.

Balance was assessed using the Biodex Balance System (BBS; Biodex Inc.), a multiaxial platform capable of tilting up to 20° in anterior–posterior and medial–lateral directions [21]. Platform stability ranged across eight levels, with lower levels indicating greater instability. Two tests were conducted: Overall Stability Index (OSI), measuring postural sway during 20-second trials (higher scores indicate poorer balance), and Limit of Stability (LOS), assessing voluntary center-of-gravity shifts (higher scores indicate better balance). Both measures demonstrate strong reliability and good construct validity [22]. Testing was performed with eyes open and free arm movement. Three trials (20 seconds each) with 10-second rest intervals were conducted, and mean scores were analyzed. Participants were evaluated pre- and post-rehabilitation [23].

Quality of life was assessed using the Stroke-Specific Quality of Life (SS-QOL) questionnaire, a validated disease-specific tool [24]. It includes 49 items across 12 domains, scored on a five-point Likert scale, with higher scores indicating better quality of life. Total scores range from 49 to 245.

Treatment

Group A had Transcranial Direct Current Stimulation (tDCS) with conventional physical therapy. Anodal tDCS was delivered via a direct current stimulator with two saline-saturated sponge electrodes (5 x 5 cm). The anode electrode was placed around 1.8 cm anterior to Cz, following the International 10/20 EEG System, as established by mapping the centroid of the SMA onto standardized head coordinates in Talairach space [25,26]. This location has previously been utilized for transcranial direct current stimulation (tDCS) of the SMA [27,28]. The stimulation was administered at an intensity of 2.0 mA, consistent with procedures shown to augment motor cortex excitability [29]. The reference electrode was positioned at the forehead [28].

Group (B) received Pilates-Based Core Training in conjunction with conventional physical therapy exercises. Each exercise was performed eight repetitions per exercise at a beginner level, tailored to the functional capacity of stroke patients. The program was structured progressively: weeks 1–2: core activation, hundreds, basic shoulder bridge, modified single leg stretch, weeks 3–4: supine spine twist, spine twist, half roll back, knee opening to side and weeks 5–6: one leg kick, one leg circle, side leg lift series, squats. This progression emphasized trunk stability, controlled breathing, and functional strengthening to improve balance and gait.

Group (C) underwent sham tDCS, in addition to conventional physiotherapy, with an identical setup to the actual tDCS, but the intensity was deactivated 30 seconds post ramp-up.

Conventional physiotherapy exercises were standardized across all groups and included:

- slow, sustained stretching of spastic muscle groups (hip flexors, hip adductors, knee flexors/extensors, and ankle plantar flexors)

- progressive strengthening exercises targeting the major lower limb muscle groups (hip flexors, extensors, abductors; knee flexors/extensors; and ankle dorsiflexors)
- balance exercises (static and dynamic balance training with open and closed eyes, sit to stand, reaching and perturbation training)
- functional gait training (level surfaces, over obstacles, heel-toe walking, side walking and stair climbing).

Each group participated in 60-minute sessions three times per week for six weeks delivered by the same trained and licensed physiotherapist. To ensure consistency of protocol implementation across groups, all interventions were administered according to standardized written treatment protocols developed prior to study initiation. The therapist received training regarding all intervention procedures before participant enrollment, and treatment implementation was supervised periodically by the principal investigator to ensure adherence to the study protocol. Although formal fidelity scoring was not performed, session attendance and protocol adherence were monitored throughout the intervention period.

Statistical Analysis

An ANOVA test was conducted to evaluate subject characteristics among groups. A chi-squared test was employed to analyze the sex distribution between groups. The Shapiro-Wilk test was employed to assess the normal distribution of the data. Levene's test for homogeneity of variances was conducted to evaluate the consistency among groups. A mixed MANOVA was performed to assess the effects both within- and between-group on step length, stance time, swing time, speed, double support time, OSI, LOS, and SS-QOL. Subsequent multiple comparisons were performed using post-hoc analyses with the Bonferroni correction. Multivariate assumptions were evaluated prior to conducting the main analysis. Multivariate outliers were screened using Mahalanobis distance, and the assumption of homogeneity of covariance matrices was assessed using Box's M test. Intercorrelations among the eight dependent variables were inspected to ensure absence of multicollinearity ($r < 0.90$). Sphericity for the repeated-measures factor was examined using Mauchly's test; when violated, Greenhouse–Geisser corrections were applied. The significance threshold for all statistical tests was set at $p < 0.05$. All statistical analyses were conducted utilizing the Statistical Package for Social Sciences (SPSS) version 25 for Windows (IBM SPSS, Chicago, IL, USA).

Ethical approval

The ethics committee of the Faculty of Physical Therapy at Cairo University accepted the study under the reference number P.T.REC /012/004561 on 7/5/2023, in accordance with the ethical requirements for research involving human subjects as outlined in the Declaration of Helsinki. This study was prospectively registered at the Clinical Trial Registry (clinicaltrials.gov) database with the number (NCT06312306).

RESULTS

General demographic data:

Table (1) presents the characteristics of subjects in groups A, B, and C. No significant differences were observed between groups for age, weight, height, BMI, and sex distribution ($p > 0.05$).

Within group comparison:

A significant increase in step length ($p < 0.001$), stance time ($p < 0.05$), and speed ($p < 0.001$), together with a significant decrease in swing time ($p < 0.001$) and

double support time ($p < 0.01$), was seen in the three groups post-treatment compared to pretreatment (Table 2). A notable reduction in OSI ($p < 0.001$) and a substantial rise in LOS ($p < 0.001$) and SS-QOL ($p < 0.001$) were seen in the three groups post-treatment relative to pretreatment (Table 3).

Between group comparison:

Following treatment, Between-group comparisons showed no significant differences between the tDCS (Group A) and Pilates (Group B) interventions across all outcomes ($p > 0.05$). However, both groups demonstrated significantly greater improvements than the control group in step length, stance time, gait speed, double support time, limit of stability, and stroke-specific quality of life (SS-QOL) ($p \leq .02$). Effect sizes were moderate for step length, gait speed, and LOS ($\eta p^2 = 0.19–0.29$) and large for SS-QOL ($\eta p^2 = 0.66$) and double support time ($\eta p^2 = 0.46$). No significant differences were observed for swing time or OSI, with negligible to small effect sizes. (Table 4).

Table 1. General demographic data of participants (mean ± SD or n/%)

Group (n=22)	Age (y)	Wt (kg)	Ht (cm)	BMI	Onset (mo)	Sex (F/M)
A	55.55±3.78	78.27±5.39	170.05±5.46	27.05±0.97	3.69±1.16	7/15
B	55.64±2.97	78.91±6.24	170.23±6.03	27.20±0.96	3.58±1.00	9/13
C	55.23±5.35	79.18±5.12	169.64±5.47	27.51±1.00	3.99±1.11	11/11
p-value	0.94	0.86	0.94	0.28	0.44	0.47

A, Study Group A; B, Study Group B; C, Control Group C; Wt., weight; Ht., height; BMI, body mass index; y, years; mo, months; F, females; M, males, p, probability value

Table 2. Mean step length, stance time, swing time, speed and double support time pre and post treatment of groups A, B and C

Variable	Time	Group A	Group B	Group C
Step length	Pre	39.22 ± 4.61	41.52 ± 4.24	39.81 ± 5.04
	Post	47.20 ± 5.56	48.55 ± 4.04	41.48 ± 4.93
	MD (95% CI), *p*, *d*	−7.98 (−9.38 to −6.57), 0.001, 1.58	−7.03 (−8.44 to −5.62), 0.001, 1.66	−1.67 (−3.08 to −0.27), 0.001, 0.33
Stance time (s)	Pre	0.87 ± 0.08	0.89 ± 0.11	0.86 ± 0.09
	Post	0.98 ± 0.11	0.99 ± 0.13	0.89 ± 0.10
	MD (95% CI), *p*, *d*	−0.11 (−0.13 to −0.08), 0.001, 1.43	−0.10 (−0.12 to −0.08), 0.001, 1.35	−0.03 (−0.05 to 0.00), 0.02, 0.30
Swing time (s)	Pre	0.58 ± 0.07	0.61 ± 0.10	0.59 ± 0.08
	Post	0.53 ± 0.06	0.54 ± 0.09	0.55 ± 0.07
	MD (95% CI), *p*, *d*	0.05 (0.03 to 0.07), 0.001, 0.76	0.07 (0.05 to 0.09), 0.001, 0.78	0.04 (0.02 to 0.06), 0.001, 0.61
Speed (cm/s)	Pre	34.55 ± 5.56	36.68 ± 5.15	34.77 ± 4.83
	Post	40.18 ± 6.13	41.91 ± 4.69	36.00 ± 4.61
	MD (95% CI), *p*, *d*	−5.63 (−6.37 to −4.91), 0.001, 1.09	−5.23 (−5.96 to −4.50), 0.001, 1.12	−1.23 (−1.96 to −0.50), 0.001, 0.26
Double support (s)	Pre	0.36 ± 0.04	0.37 ± 0.03	0.38 ± 0.05
	Post	0.27 ± 0.05	0.29 ± 0.04	0.36 ± 0.04
	MD (95% CI), *p*, *d*	0.09 (0.08 to 0.11), 0.001, 2.00	0.08 (0.07 to 0.10), 0.001, 2.27	0.02 (0.001 to 0.03), 0.01, 0.43

Values are presented as mean ± standard deviation. Mean difference (MD) represents post − pre values. p-values indicate within-group statistical significance, d represents Cohen effect size.

Table 3. Mean OSI, LOS and SS-QOL pre and post treatment of groups A, B and C

Variable	Time	Group A	Group B	Group C
OSI	Pre	3.95 ± 0.67	4.14 ± 0.90	3.97 ± 0.91
	Post	3.24 ± 0.69	3.53 ± 0.85	3.71 ± 0.80
	MD (95% CI), *p*, *d*	0.71 (0.56 to 0.86), 0.001, 1.05	0.61 (0.46 to 0.76), 0.001, 0.70	0.26 (0.10 to 0.40), 0.001, 0.30
LOS	Pre	32.68 ± 7.34	30.27 ± 7.55	31.05 ± 6.67
	Post	42.45 ± 7.24	40.14 ± 6.65	34.68 ± 6.60
	MD (95% CI), *p*, *d*	−9.77 (−11.01 to −8.53), 0.001, 1.35	−9.87 (−11.10 to −8.62), 0.001, 1.40	−3.63 (−4.88 to −2.40), 0.001, 0.54
SS-QOL	Pre	155.09 ± 6.07	156.68 ± 6.37	157.23 ± 6.13
	Post	192.36 ± 6.64	195.68 ± 6.87	172.27 ± 9.20
	MD (95% CI), *p*, *d*	−37.27 (−38.95 to −35.60), 0.001, 5.91	−39.00 (−40.67 to −37.33), 0.001, 5.78	−15.04 (−16.72 to −13.37), 0.001, 1.96

Values are presented as mean ± standard deviation. Mean difference (MD) represents post − pre values. *p*-values indicate within-group statistical significance, *d* represents Cohen effect size.

Table 4. Comparison of step length, stance time, swing time, speed, double support time, OSI, LOS and SS-QOL between groups A, B and C post treatment

Outcome	Group A vs B		Group A vs C		Group B vs C		ηp^2
	MD (95% CI)	p value	MD (95% CI)	p value	MD (95% CI)	p value	
Step length (cm)	-1.35 (-4.89: 2.18)	0.63	5.72 (2.18: 9.25)	0.001	7.07 (3.53: 10.60)	0.001*	0.29
Stance time (sec)	-0.01 (-0.10: 0.07)	0.91	0.09 (0.01: 0.17)	0.02*	0.1 (0.02: 0.19)	0.008	0.15
Swing time (sec)	-0.01 (-0.07: 0.04)	0.79	-0.02 (-0.08: 0.04)	0.66	-0.01 (-0.06: 0.05)	0.97	0.01
Speed (cm/sec)	-1.73 (-5.48: 2.03)	0.51	4.18 (0.43: 7.94)	0.02*	5.91 (2.15: 9.67)	0.001*	0.19
Double support time (sec)	-0.02 (-0.05: 0.01)	0.24	-0.09 (-0.12: -0.06)	0.001*	-0.07 (-0.10: -0.04)	0.001*	0.46
OSI	-0.29 (-0.86: 0.27)	0.43	-0.47 (-1.04: 0.09)	0.11	-0.18 (-0.75: 0.38)	0.72	0.06
LOS	2.31 (-2.63: 7.26)	0.50	7.77 (2.83: 12.72)	0.001*	5.46 (0.51: 10.40)	0.02*	0.19
SS-QOL	-3.32 (-8.86: 2.22)	0.33	20.09 (14.55: 25.63)	0.001*	23.41 (17.87: 28.95)	0.001*	0.66

Values are expressed as mean difference (MD) with 95% confidence intervals (CI). Between-group comparisons were performed using post-intervention outcomes. ηp^2 represents partial eta squared effect size. *$p < 0.05$ was considered statistically significant.

DISCUSSION

The present findings suggests the potential effectiveness of structured, exercise-based rehabilitation in improving functional outcomes following stroke. Both Pilates-based core stability training and tDCS resulted in significant improvements in gait, balance, and quality of life. No statistically significant differences were observed between Pilates and tDCS across outcomes. This indicates that improvements in functional outcomes were observed following both interventions within the context of post-stroke rehabilitation.

The large effect size observed for time ($\eta p^2 = 0.99$) highlights the substantial overall effect of rehabilitation, while the strong interaction effect ($\eta p^2 = 0.77$) suggests intervention-related effects associated with Pilates-based core training and

tDCS. Improvements in gait speed, step length, and double support time suggest enhanced functional mobility and gait stability, which are associated with independence in ambulation and fall risk reduction in post-stroke rehabilitation. The absence of between-group differences in swing time and OSI may indicate that these parameters are less responsive to short-term intervention or require longer training duration to demonstrate change.

Previous research supports the effectiveness of Pilates-based interventions in stroke rehabilitation, with reported improvements in balance, strength, gait performance, and trunk control [30–33]. These effects may be related to the combined influence of core stabilization, controlled breathing, and proprioceptive engagement. However, evidence remains limited by small sample sizes and methodological heterogeneity, and isolated core exercises appear to be less effective without Pilates principles [34], suggesting that integrated training approaches may be important.

Similarly, evidence on SMA-targeted tDCS suggests potential benefits for gait, balance, and postural control, particularly when combined with task-specific training [35–39]. tDCS may enhance cortical excitability and facilitate motor learning, thereby augmenting rehabilitation effects. However, findings are inconsistent, with some studies reporting limited or task-specific improvements [40–42]. This suggests that tDCS may be useful as an adjunct to exercise-based rehabilitation rather than a standalone intervention.

Emerging evidence supports the integration of these approaches. For example, Lee and Yim [43] demonstrated that combining SMA-targeted tDCS with Pilates significantly improved balance and reduced depression in stroke patients. This multimodal strategy highlights the potential of pairing neuromodulation with exercise-based rehabilitation to support recovery outcomes. Future research is needed to further clarify patient-specific factors that may influence responsiveness to each intervention and to determine the longer-term effects of these approaches.

This study has certain limitations that must be acknowledged when analyzing the results. Although conducted in two sites, the sample size was calculated a priori based on the primary outcome; however, effect size estimates were derived from limited prior evidence. As a result, the study may have been insufficiently powered to detect smaller or secondary effects. Future multicenter studies with larger samples and longer follow-up are needed to confirm these findings.

CONCLUSION

This study showed that both tDCS targeting the supplementary motor area (SMA) and Pilates-based core stability training produced significant improvements in gait parameters, balance control, and quality of life in stroke survivors compared with conventional physiotherapy alone. No statistically significant differences were observed between Pilates and tDCS. Improvements in gait, balance, and quality of life were observed following both interventions. Overall, these findings suggest that both exercise-based and neuromodulatory approaches may be incorporated into post-stroke rehabilitation alongside conventional physiotherapy. Further research is needed to determine long-term effects and to identify factors influencing individual response to each intervention.

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