Başar and Alp
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RESEARCH

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The effects of concomitant application of TENS and NMES on chronic stroke patients: a prospective randomized controlled study

Betül Başar[1*] and Ömer Faruk Alp[1]

Abstract

Background The aim of our study was to compare the effects of TENS, NMES, and their combined application on posture, functional independence, and spasticity in patients with post-stroke hemiparesis.

Methods Sixty patients (twenty-six female and thirty-four male), with a mean age of 61.1 years (range, 27 – 81 years) were included in our study. Patients were randomly assigned to one of four treatment groups: TENS, NMES, TENS + NMES, and isolated exercise program. The patients' posture, functional independence, and ankle plantar flexor spasticity were evaluated after 1 month of treatment and at the 4-month follow-up.

Results Concomitant application of TENS and NMES was more successful in improving posture, functional independence and reducing spasticity at 1 and 4 months follow-up than either application alone. The application of TENS or NMES together with the exercise program provided better results in terms of posture and functional independence at the 1st month. However, it did not achieve a significant difference compared to the exercise program at the 4th month. An exercise program alone was insufficient for reducing spasticity of the ankle plantar flexors. While an additional physical therapy modality (TENS or NMES) was effective in reducing spasticity in the early period, this effect disappeared at the 4th month follow-up and similar results were achieved with an isolated exercise program.

Conclusion Although TENS or NMES combined with exercise programs achieves successful results immediately after the treatment, it is insufficient after a few months in chronic stroke patients. In concomitant application of TENS and NMES, better results are achieved both after treatment and in a few months of follow-up. Therefore, TENS and NMES should be applied concomitantly.

Trial registration ClinicalTrial.gov, ID NCT06619262, 21/09/2024, retrospectively registered 2024–09-21.

Keywords TENS, NMES, Stroke, Hemiparesis, Exercise program

Introduction

Stroke is a cerebrovascular disorder that can lead to permanent disability and a decline in quality of life [1]. Chronic stroke patients often experience decreased balance control, which negatively affects activities of daily living and their ability to walk independently [2, 3]. The most recognized impairments are deficits in motor control and limited mobility. Chronic stroke patients may develop spasticity, which is the main cause of decreased balance and gait. The rate of post-stroke spasticity is 4—27% in the 6th week, increasing to 42.6% by the 6th month. Electrical stimulation has been used in numerous studies to decrease spasticity [4].

*Correspondence:
Betül Başar
betulakarvardar@hotmail.com
[1] Department of Physical Medicine and Rehabilitation, Gaziosmanpaşa Training and Research Hospital, University of Health Sciences, Karayolları Mah. TEM Avrupa Konutları 32/52 Gaziosmanpaşa, İstanbul, Turkey

Electrical stimulation has been widely used in stroke rehabilitation, including transcutaneous nerve stimulation (TENS) and neuromuscular electrical stimulation (NMES). NMES is an effective and conventional therapeutic method for improving motor function in patients with lower extremity paralysis after stroke [5]. During NMES, current pulses are applied to the muscles or motor nerves through surface electrodes to induce muscle contractions to mimic exercise therapy [6]. NMES can help improve muscle strength, joint range of motion, and promote motor relearning. TENS, another electrical stimulation, is used to relieve pain, improve muscle strength and motor function, and reduce spasticity through transdermal output pulses [7]. The motor recovery mechanism of TENS involves the presynaptic inhibition of the hyperactive stretch reflexes in spastic muscles and decreased co-contraction of the spastic antagonist muscles [8].

Numerous studies have investigated the benefits of TENS or NMES applied to the lower extremities. These studies have revealed that both forms of electric stimulation are effective in the recovery of chronic stroke patients [7, 9–11]. On the other hand, studies are being conducted on new treatment protocols to enhance the success of treatment.

However, there is no comparative study on the effect of TENS and NMES applied individually versus their concomitant application. The combined application of TENS and NMES may yield better results. The aim of our study is to compare the effects of TENS and NMES, applied both individually and concomitantly, on posture, functional independence, and spasticity. Our hypothesis is that the concomitant application of TENS and NMES will achieve better results than individual application, which is partially successful in treatment. Perhaps it will provide the targeted success in chronic stroke patients.

Materials & methods

Research design

This was a prospective randomized assessor-blind comparison study designed to compare the effects of individually and concomitant TENS and NMES on posture, functional independence, and spasticity in chronic stroke patients.

Ethical considerations

This study was conducted in accordance with the principles of good clinical and ethical practice and was approved by the Ethics Committee of Gaziosmanpaşa Training and Research Hospital, University of Health Sciences (2022–154). Along with the Declaration of Helsinki, all participants gave written informed consent after being informed about the study´s protocol. [12]. All methods were performed according to relevant guidelines and regulations. The contents of this study adhere to the CONSORT reporting guidelines [13].

Randomization and blinding

Patients were randomly assigned to one of four groups:

> TENS Group: This program included TENS and an exercise program.
> NMES Group: This program included NMES and an exercise program.
> TENS + NMES Group: This program included both TENS and NMES, along with an exercise program.
> Control (Exercise Program) Group: This program included only an exercise program.

Patients were randomly assigned to the four groups using a closed envelope randomization procedure. The physiotherapist opened the envelope 6 h before the patient began treatment. The same physiotherapist, who was blinded to the group assignments, performed initial evaluation, post-treatment (at 1 month), and 4-month follow-up evaluation.

Sample size calculation

Gpower 3.1.9.2 software was used to calculate the sample size. In the present study, the mean power was at 0.8, and the alpha error at 0.05. The sample size was calculated based on the Posture Assessment Scale for Stroke Patients from a pilot study [14]. The analysis of Gpower software indicated that at least 14 participants per group would constitute an acceptable sample size; therefore, 68 participants were recruited, accounting for a potential drop-out rate of 20% [14].

Participants

Participants with lower-extremity hemiparesis were recruited from Gaziosmanpaşa Training and Research Hospital, University of Health Sciences from November 2022 to December 2023. Sequence data supporting the findings of this study have been deposited in the Gaziosmanpaşa Education and Research Hospital Physical Therapy and Rehabilitation Archive. Data and additional files can be obtained from gopeah.info@saglik.gov.tr with the approval of the authors.

Inclusion criteria

The criteria of inclusion were (1) first episode of unilateral stroke with hemiparesis caused by hemicerebrum damage; (2) stroke confirmed by CT and/or MRI (3) ability to understand and follow verbal commands; (4) Mini-Mental Scale (MMS) score of 24–30; (5) ablity to independently stand up from a chair, (6) age between

35 to 85 years; (7) no peripheral or central nervous system dysfunction; (8) ankle dorsiflexion strength of $\leq 3/5$ (Lovett scale); (9) stroke duration > 6 months; and (10) the Modified Ashworth Scale (MAS) ≥ 1,

Exclusion criteria

The criteria for exclusion were (1) cerebellar or brainstem stroke; (2) inability to cooperate with assessment and treatment due to severe cognitive and communication impairment; (3) previous surgical treatment history on the affected extremity; (4) complication with severe heart, lung, liver, kidney, or infectious disease; (5) presence of a cardiac pacemaker; (6) orthopedic disease affecting sit-to-stand movement; (7) contraindications of TENS or NMES: and (8) non-compliance with treatment recommendations or inadequately application.

Rehabilitation protocols

TENS

Each patient in the TENS group received transcutaneous electrical nerve stimulation (Chattanooga Intellect®, frequency = 100 Hz) for 30 min. TENS electrodes were attached over muscle belly of the tibialis anterior, and quadriceps on the stroke-affected lower extremity. Stimulation was delivered in 200 µs pulses at 100 Hz in the constant mode at the participant's sensory level, without causing muscle contraction [15]. The tibialis anterior, and quadriceps muscles were chosen because they are associated with walking and daily living activities, and because they are superficially located and easily identified. The minimal tingling sensation felt by the patients was defined as the sensory threshold. The patients were asked to inform the physiotherapist if they felt any discomfort or involuntary muscle contraction during TENS. The physiotherapist also observed whether the movement caused by muscle contraction. Stimulation intensity was gradually increased until the patients reported a tingling or buzzing sensation in the tibialis anterior, and quadriceps regions, without pain and visible movement [14].

NMES

Two dual-channel biofeedback electrical stimulators (Chattanooga Intellect®) were connected to a schedule timer to create a stimulation unit for neuromuscular electrical stimulation in the NMES group. Stimulation was applied via electrodes (5 × 3.5 cm). One electrode on the motor point of the rectus femoris (mid-thigh), the other electrode over the vastus medialis or lateralis for quadriceps femoris muscle. For the tibialis anterior muscle, one electrode was placed on the motor point just below the knee on the lateral side, and the other electrode was positioned along the shin, near the distal end of the muscle. The patients were instructed to relax their paretic extremities during NMES. The waveform of stimulation was a biphasic rectangular wave with a frequency of 30 Hz and a pulse width of 200 µs. The duty cycle was programmed as five seconds on and five seconds off, with a ramp-up and descent time of one second each. This duty cycle was chosen because it could be easily implemented in rehabilitation [14]. Contractions with short pulse durations were preferred in order to prevent central force development during stimulated contractions and limit premature fatigue of the assigned motor units [16]. Stimulation intensity was adjusted to the movement threshold to trigger visible muscle contractions, resulting in partial joint movement. Muscle contractions were achieved in Brunnstrom stages 2, 3, 4, and 5.

Exercise protocol

The patients in all four groups received exercise for 30 min once a day, five days a week, during the 4-week treatment period. The patients in the control group did not receive any passive modalities (e.g. electrical stimulation, vibration, ultrasound, heat, or ice) in addition to exercise program. The exercise program session consists of four exercises lasting 30 min in total, each completed in 5–10 min. These exercises are (1) functional training activities, (2) techniques to facilitate neurodevelopment, (3) active range of motion exercises, and (4) pelvic bridging exercises. Bed mobility, sitting balance training, standing and transfers, gait training, activities of daily living, balance and postural control exercises, stair climbing, community mobility, functional strengthening and cognitive-motor integration tasks are functional training activities [17]. Functional training activities based on motor relearning principles were also adjusted and progressed according to the patient's ability. The Bobath concept was preferred to facilitate neurodevelopment. It targets neuromuscular control, balance, and coordination, encouraging normal movement patterns while inhibiting spasticity. The Bobath approach uses hands-on guidance and tactile stimulation to activate proper muscle groups, helping to retrain the brain's motor pathways [18]. Active Range of Motion exercises are frequently utilized to improve muscle strength, flexibility, and overall motor function. These exercises involve moving the joints through their full range of motion and can help to maintain or increase muscle strength while preventing joint stiffness and deformities [19]. Pelvic bridging exercises help to restore trunk stability, strengthen the lower extremities, and improve overall motor function. These exercises target key muscle groups, including the gluteus maximus, hamstrings, and abdominal muscles, which are often weakened following a stroke. Pelvic bridging helps to improve posture, balance, and coordination, which are critical for functional independence [20]. The physical therapist monitored the progression of exercises, including increasing the number of repetitions, expanding the range of motion, adjusting the speed of motion, and decreasing the rest time between exercises as the patients' muscle strength improved.

Electrical stimulation treatment was applied for 30 min per session, once a day, five days a week for four weeks in TENS group and NMES group. In the TENS + NMES group, TENS was applied for 30 min first, followed by 30 min of NMES with a 30-min interval in between. All patients received exercise program immediately after electrical stimulation session. They were able to comply with the exercise programs. Log forms were completed for each patient for every exercise session, and all records were properly maintained.

The patients' treatments were administered by physiotherapists who had completed training in Bobath/neurodevelopmental treatment, proprioceptive neuromuscular facilitation, the motor relearning program, electrotherapy, and robotic rehabilitation.

A home-based exercise program was prescribed for all groups after one-month treatment period. The content of home exercise program was based on the recommendations from the National Stroke Foundation Clinical Guidelines and included six leg control exercises, six truck control exercises, and four mobility exercises [21]. Home-based exercise programs have been shown to improve lower limb motor functions in patients who have sustained strokes more than one year previously. Combining TENS with home-based exercise programs has been found to decrease plantar flexor spasticity, improve ankle dorsi flexor and plantar flexor strength, and significantly increase gait velocity more than TENS alone [22].

Evaluation

The same physiotherapist who performed the functional evaluations was blinded to group allocation at baseline, post-treatment, and 4th month follow-up.

Disability caused by stroke was evaluated using the National Institutes of Health Stroke Scale (NIHSS). The following domains were assessed with the NIHSS: level of consciousness, eye movements, integrity of visual fields, facial movements, arm and leg muscle strength, sensation, coordination, language, speech and neglect. Evaluation was based on a total score ranging from 0 to 42, with higher the scores indicating more severe stroke [23].

The lower extremity motor recovery was assessed using Brunnstrom's Hemiplegia Recovery Staging. There are six grades in Brunnstrom's Hemiplegia Recovery Staging for the lower extremity. A higher stage indicates better motor function. The Brunnstrom stages were preferred because they reflect the underlying motor control based on clinical assessment of movement quality [24].

Postural Assessment Scale for Stroke Patients (PASS) was developed specifically for evaluating balance in stroke patients [25]. PASS contains two subheadings for evaluating balance: maintaining posture (static PASS) and changing posture (dynamic PASS). It consists of 12 items to evaluate balance: 5 items (sitting without support; standing with support; standing without support; standing on the non-paretic leg; standing on the paretic leg) for static PASS, and 7 items (supine to affected side lateral; supine to non-affected side lateral; supine to sitting up on the edge of the mat; sitting on the edge of the mat to supine; sitting to standing; standing to sitting down; standing, picking up a pencil from the floor) for dynamic PASS. Evaluation was based on a total score ranging from 0 to 36, with higher the scores indicating more favorable balance in stroke patients [26].

Functional Independence Measures (FIM) is widely used to assess the independence of stroke patients. It contains 18 items under the following categories: self-care, sphincter control, transfers, locomotion, communication and social cognition. Each item was scored from 1 to 7, with 7 indicating complete independence and 1 indicating complete dependence. Scores below 6 indicate that the patient requires assistance or supervision from another person [24].

The Modified Ashworth Scale (MAS) was used to assess the spasticity of the ankle plantar flexors. The physiotherapist passively moved the ankle from maximal plantarflexion to maximal dorsiflexion. The MAS assigns a grade of spasticity on a scale of 0–4 based on the level of resistance in response to passive movement. A score of 0 represents no increase in muscle tone, while a score of 4 represents rigidity of the affected part in flexion or extension [27].

Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences for Windows (Version 22.0; SPSS Inc., Chicago, IL). The conformity of the parameters to a normal distribution was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests. In addition to descriptive statistical methods, a one-way ANOVA test was used to compare quantitative data and parameters with normal distribution between groups. The Kruskal–Wallis test was used for comparing parameters that did not follow a normal distribution between groups, and Dunn's test was applied to determine the group responsible for the difference. The Wilcoxon signed-rank test was used to compare parameters that did not show a normal distribution within groups. The Chi-square test and Fisher Freeman Halton Exact Chi-square test were used for comparing qualitative data.

Differences were considered statistically significant at P-values < 0.05.

Results

Sixty-eight patients with post-stroke hemiparesis were included in our study. Eight patients were excluded during the follow-up period: four patients did not attend the follow-up, one patient experienced a myocardial infarction, one patient suffered a proximal femur fracture, one patient underwent knee joint surgery, and one patient discontinued the rehabilitation in the 3rd week. Sixty patients were evaluated after treatment and at the 4th month follow-up (Fig. 1). No side effects were observed in any of the patients after rehabilitation.

A total of 60 patients, 26 females (43.3%) and 34 males (56.7%), aged between 27 and 81 years, were included in our study. The mean age was 61.16 years (range, 27 – 81 years). There were no significant differences in age, sex, body mass index, type of stroke, location of stroke, affected side, and time to initial intervention between the groups ($P > 0.05$), (Table 1).

Pre-treatment evaluation

There were no statistically significant differences between the groups in terms of National Institutes of Health Stroke Scale, the lower extremity motor recovery of Brunnstrom's Hemiplegia Recovery Staging, Postural Assessment Scale for Stroke Patients, Functional Independence Measures and the Modified Ashworth Scale of the ankle plantar flexors before treatment ($p > 0.05$),(Table 2).

Post-treatment evaluation

Postural assessment scale for stroke at 1st month follow-up

In control group, there were no statistically significant differences in PASS scores at 1st month follow-up compared to pre-treatment ($p > 0.05$). However, in TENS, NMES and TENS + NMES groups, a statistically significant improvement was observed ($p < 0.05$). A statistically significant difference was found between the groups in terms of PASS score ($p < 0.001$) at 1st month follow-up (Table 3). Post hoc tests showed that the 1st month PASS score in control group was significantly lower compared

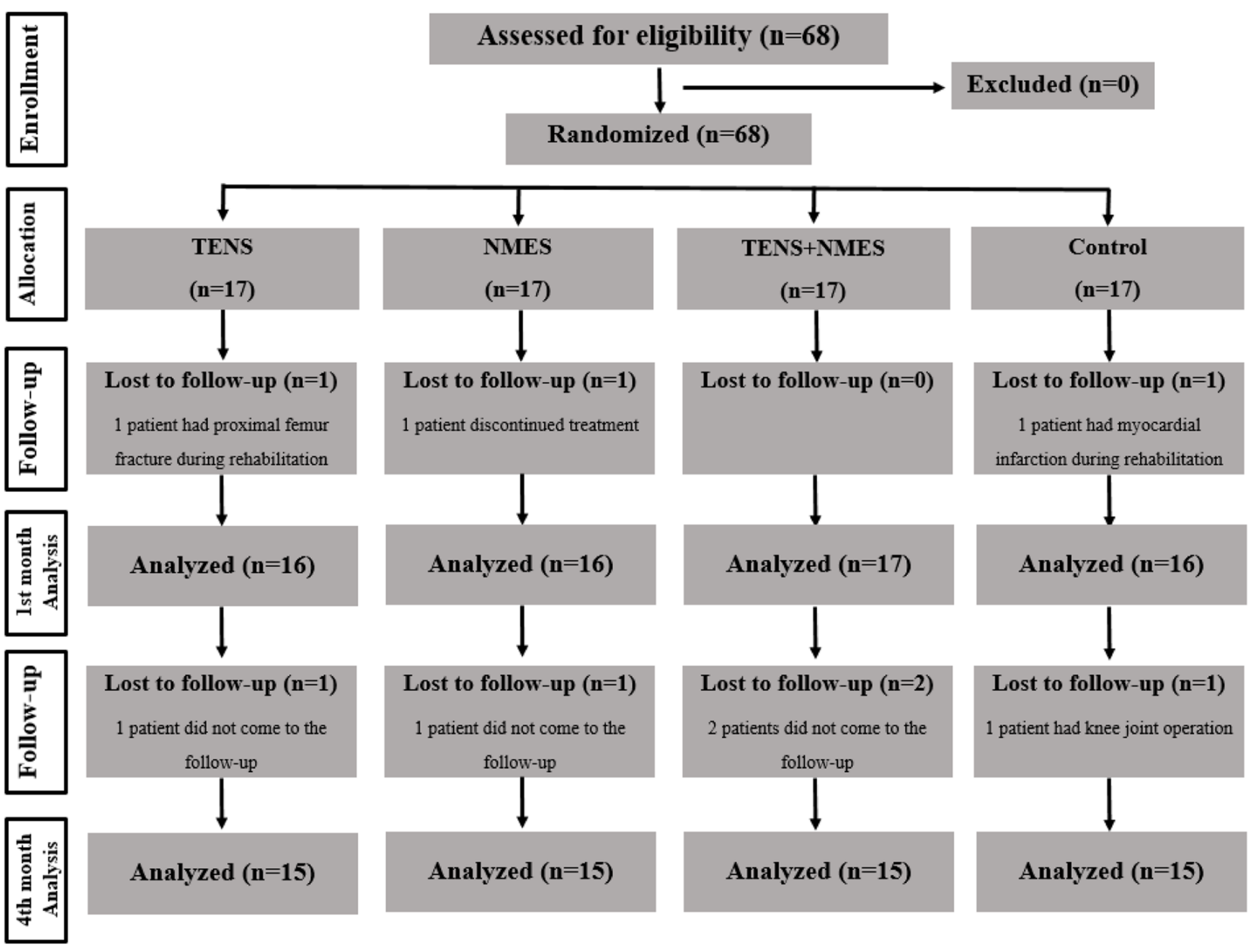

Fig. 1 The flow chart for patient recruitment and follow-up

Table 1 Demographic characteristics of the groups

Group	TENS	NMES	TENS + NMES	Control	P
Age	66.0 ± 10.1	60.8 ± 13.1	56.6 ± 17.3	61.0 ± 8.9	0.267[a]
Gender n%					
Male	11 (73.3%)	10 (66.7%)	7 (46.7%)	6 (40%)	0.247[b]
Female	4 (26.7%)	5 (33.3%)	8 (53.3%)	9 (60%)	
BMI	26.3 ± 3.7	25.8 ± 2.7	27.7 ± 4.8	28.2 ± 4.6	0.333[a]
Stroke Type					
İschemic n%	9 (60%)	10 (66.7%)	10 (66.7%)	12 (80%)	0.706[c]
Hemoragic	6 (40%)	5 (33.3%)	5 (33.3%)	3 (20%)	
Stroke Location					
Cortical n%	12 (80%)	10 (66.7%)	12 (80%)	11 (73.3%)	0.806[b]
Subcortical	3 (20%)	5 (33.3%)	3 (20%)	4 (26.7%)	
Affected Side					
Right n%	6 (40%)	9 (60%)	9 (60%)	8 (53.3%)	0.657[b]
Left	9 (60%)	6 (40%)	6 (40%)	7 (46.7%)	
The period between stroke and treatment (month) mean ± SD	12.4 ± 6.8	15.7 ± 8.8	13.8 ± 5.4	16.8 ± 7.6	0.367[d]

BMI Body Mass Index, *TENS* Transcutaneous nerve stimulation, *NMES* Neuromuscular electrical stimulation, *ANOVA* Analysis of variance

[a] One way ANOVA test

[b] Chi-square test

[c] Fisher Freeman Halton Exact test [d] Kruskal Wallis Test

Table 2 Initial values of the groups

Group	TENS	NMES	TENS + NMES	Control	P
Initial NIHSS scores	7.2 ± 2.9	7.8 ± 3.4	6.0 ± 3.2	5.6 ± 2.7	0.205[d]
Initial Brunnstrom stage-affected lower limb (II/III/ IV/V) *	4/5/4/2	4/3/7/1	3/6/5/1	3/4/6/2	0.965[b]
Initial PASS scores	13.9 ± 5.7	15.3 ± 6.6	15.4 ± 4.9	12.0 ± 5.5	0.262[d]
Initial FIM scores	62.1 ± 20.1	65.7 ± 16.2	67.1 ± 23.3	57.4 ± 15.2	0.786[d]
Initial MAS scores	2.7 ± 0.7	2.6 ± 0.8	2.8 ± 0.6	2.7 ± 0.6	0.942[d]

NIHSS National Institutes of Health Stroke Scale, *PASS* Postural Assessment Scale for Stroke, *FIM* Functional Independence Measure, *MAS* Modified Ashworth Scale

* The Brunnstrom lower extremity motor staging consists of six stages. There were no patients in stage 1 or stage 6 included in this study

[b] Using Chi-square test

[d] Kruskal Wallis Test

to TENS group ($p = 0.005$), NMES group ($p = 0.005$) and TENS + NMES group ($p < 0.001$). On the contrary, PASS score were significantly higher in TENS + NMES group than in TENS group ($p = 0.004$) and NMES group ($p = 0.017$). There were no statistically significant differences between TENS and NMES groups ($p > 0.05$).

Postural assessment scale for stroke at 4th month follow-up

In all groups, the increase in the 4th month score compared to the pre-treatment PASS score is statistically significant ($p < 0.05$). A statistically significant difference was found between the groups regarding the 4th month PASS scores after treatment ($p < 0.001$) (Table 3). Post hoc tests revealed that the 4th month PASS scores in the TENS + NMES group were significantly higher than those in the TENS group ($p = 0.005$), the NMES group ($p = 0.012$), and the control group ($p < 0.001$). No statistically significant differences were observed between the other groups ($p > 0.05$).

Functional independence measure at 1st month follow-up

In control group, there were no statistically significant differences in FIM scores at 1st month follow-up compared to pre-treatment ($p > 0.05$). However, in TENS, NMES and TENS + NMES groups, a statistically significant improvement was observed ($p < 0.05$). A statistically

Table 3 Initial, 1st and 4th month values of the groups

Group	TENS	NMES	TENS + NMES	Control	P
① PASS scores	13.9 ± 5.7	15.3 ± 6.6	15.4 ± 4.9	12.0 ± 5.5	0.262[d]
② PASS scores	19.5 ± 5.0	20.1 ± 5.6	25.3 ± 4.4	14.3 ± 4.9	< 0.001[d]
③ PASS scores	20.6 ± 4.6	21.0 ± 5.4	26.4 ± 4.6	19.1 ± 4.1	0.002[d]
P	0.003[d]	0.032[d]	< 0.001[d]	0.001[d]	
① FIM scores	62.1 ± 20.1	65.7 ± 16.2	67.1 ± 23.3	57.4 ± 15.2	0.786[d]
② FIM scores	78.0 ± 14.4	79.3 ± 12.1	92.4 ± 12.8	64.4 ± 14.1	0.001[d]
③ FIM scores	84.0 ± 16.7	86.6 ± 11.6	99.7 ± 12.1	75.0 ± 12.5	0.001[d]
P	0.016[d]	0.002[d]	< 0.001[d]	0.004[d]	
① MAS scores	2.7 ± 0.7	2.6 ± 0.8	2.8 ± 0.6	2.7 ± 0.6	0.942[d]
② MAS scores	1.8 ± 0.6	1.7 ± 0.4	1.0 ± 0.6	2.4 ± 0.6	0.008[d]
③ MAS scores	2.0 ± 0.5	2.0 ± 0.7	1.1 ± 0.4	2.2 ± 0.6	0.005[d]
P	0.032[d]	0.037[d]	< 0.001[d]	0.296[d]	

①**:** Initial scores ②**:** 1st month scores ③**:** 4th month follow-up scores. [d] Kruskal Wallis Test

significant difference was found between the groups in terms of FIM score ($p < 0.001$) at 1st month follow-up (Table 3).

Post hoc tests showed that the 1st month FIM score in control group was significantly lower compared to TENS group ($p = 0.016$), NMES group ($p = 0.005$) and TENS + NMES group ($p < 0.001$). On the contrary, FIM score were significantly higher in TENS + NMES group than in TENS group ($p = 0.016$) and NMES group ($p = 0.013$). There were no statistically significant differences between TENS and NMES groups ($p > 0.05$).

Functional independence measure at 4th month follow-up

In all groups, the increase in the 4^{tht} month score compared to the pre-treatment FIM score is statistically significant ($p < 0.05$). A statistically significant difference was found between the groups regarding the 4th month FIM scores after treatment ($p < 0.001$) (Table 3). Post hoc tests revealed that the 4th month FIM scores in the TENS + NMES group were significantly higher than in the TENS group ($p = 0.016$), the NMES group ($p = 0.014$), and the control group ($p < 0.001$). No statistically significant differences were observed between the other groups ($p > 0.05$).

Modified ashworth scale at 1st month follow-up

Nine patients with ankle plantar flexor spasticity were evaluated in the TENS group, 10 patients in the NMES group, 11 patients in the TENS + NMES group and 10 patients in the control group. In all groups except the control group, there was a statistically significant improvement at the 1st month follow-up compared to pre-treatment ($p < 0.05$). There was a statistically significant difference between the groups in terms of the Modified Ashworth Scale scores for ankle plantar flexor at the 1st month follow-up ($p < 0.001$) (Table 3). Post hoc tests showed that, for the Modified Ashworth Scale score of ankle plantar flexor, the 1st month follow-up scores of TENS + NMES group were significantly better than those of TENS group ($p = 0.022$) and NMES group ($p = 0.017$). No statistically significant difference was found between TENS and NMES groups in terms of the Modified Ashworth Scale scores for ankle plantar flexor at the 1st month follow-up ($p > 0.05$).

Modified ashworth scale at 4th month follow-up

There was a statistically significant improvement in MAS scores only in the TENS + NMES group at the 4th month follow-up compared to pre-treatment. There was no statistically significant difference in the other groups compared to pre-treatment. There was a statistically significant difference between the groups in terms of the Modified Ashworth Scale scores for ankle plantar flexor at the 4th month follow-up ($p = 0.001$) (Table 3). Post hoc tests showed that, for the Modified Ashworth Scale score of ankle plantar flexor, the 4th month follow-up scores of TENS + NMES group were significantly better than those of TENS group ($p = 0.010$), NMES group ($p = 0.018$) and control group ($p = 0.003$). No statistically significant difference was found between TENS, NMES and control groups in terms of the Modified Ashworth Scale scores for ankle plantar flexor at the 4th month follow-up ($p > 0.05$).

Discussion

In terms of posture and functional independence, isolated exercise application did not improve at the 1st month follow-up compared to pre-treatment, while TENS, NMES and TENS + NMES along with an exercise program showed significant improvements. Among these, the TENS + NMES combination was significantly more effective than either isolated TENS or NMES, although no significant difference was observed between isolated TENS and NMES. At the 4th-month follow-up, all groups demonstrated improvement compared to pre-treatment. However, significantly greater improvement was observed in the TENS + NMES group compared to the other groups, with no significant differences between the remaining groups. Although TENS or NMES combined with an exercise program yielded better outcomes in terms of posture and functional independence at the 1st-month follow-up, no significant difference was observed compared to isolated exercise by the 4th month. The combination of TENS + NMES with an exercise program was more effective in improving posture and functional independence than the other three treatment options at both the 1st- and 4th-month follow-ups.

In terms of plantar flexor spasticity, isolated exercise application did not improve at the 1st month follow-up compared to pre-treatment, while TENS, NMES and TENS + NMES along with an exercise program provided significant improvement. At the 4th month follow-up, significant improvement was only observed in the TENS + NMES group, with no improvement found in the other groups. An exercise program alone is insufficient for treating spasticity of the ankle plantar flexors, and additional physical therapy modalities are needed to reduce spasticity. Adding TENS or NMES to an exercise program significantly improves spasticity at the 1st-month follow-up but has no lasting effect by the 4th month. While TENS or NMES along with an exercise program reduces spasticity in the early period, this benefit disappears at the 4th month follow-up. In contrast, the TENS + NMES combination not only reduces spasticity at the 1st month but also maintains this reduction at the 4th month, making it the most effective option for long-term spasticity management.

TENS and NMES enhance motor learning and motion control by promoting the formation of new connections in the nervous system (neuroplasticity). When combined with exercise, these effects are synergistically amplified [28]. NMES directly stimulates muscles through motor neurons, targeting muscle groups that cannot be activated during passive exercise. This is particularly important for paretic (partially paralyzed) muscles and can accelerate muscle strength improvement [29]. TENS stimulates nerve endings on the skin's surface, delivering increased sensory input to the brain, which can aid in reorganizing motor control. When combined with exercise, it facilitates more effective re-coordination of sensory and motor pathways [30]. NMES can relax spastic muscles by stimulating their antagonist muscles through the reciprocal inhibition mechanism. TENS helps balance muscle tone by providing inhibition at the spinal level [3, 10]. While isolated exercise focuses solely on active movement and muscle strength, TENS and NMES simultaneously target both the motor and sensory systems, offering a more comprehensive treatment approach [31]. TENS and NMES applications make it easier and less painful for patients to perform exercises, thereby enhancing compliance with treatment. NMES helps facilitate movements that cannot be performed actively, enabling passive motion. This supports the transition to active exercise as the patient gains strength [5, 7].

TENS parameters used in studies on stroke treatments vary between 1.7–100 Hz frequency, session duration between 15 and 60 min, and number of sessions between 1 and 30 [32]. The use of different parameters is rarely justified and is often based on parameters used in previous studies. There is no consensus on standardized parameters and protocols for the use of TENS in stroke treatments. In our study, we applied TENS at a frequency of 100 Hz for 30 min per day for 4 weeks, following the approach used in most studies in the literature [7].

There are various studies on the duration and frequency of NMES application, but no consensus has been reached on the optimal duration and frequency. We preferred the 30-min period used in most studies in the literature. We preferred low frequency because high-frequency NMES application can sometimes lead to muscle fatigue and a decrease in contraction strength, which can increase the muscle tone of the affected limbs [10, 33].

Home-based rehabilitation programs are effective lower extremity rehabilitation, increase muscle strength, and improve gait velocity in individuals with chronic stroke [22]. Hospital-based rehabilitation is superior to home-based rehabilitation in improving outcomes [34]. Therefore, we did not apply the isolated home-based rehabilitation program to patients alone. Our study revealed that home-based rehabilitation program is also effective in enhancing the success of patient treatment after discharge and in preventing the loss of improvements gained during hospital-based rehabilitation.

While studies in the literature have shown that TENS or NMES along with exercise program yields better results than an isolated exercise program, these results were typically evaluated immediately after the end of the treatment, with later outcomes not being assessed. In our study, similar to the literature, TENS or NMES combined with an exercise program yielded better results compared to an isolated exercise program. However, there was no significant difference in outcomes at the 4th month follow-up. On the other hand, TENS + NMES demonstrated better results at the 4th month than both an isolated exercise program and TENS or NMES combine with exercise [10, 32].

Postural abnormality and post-stroke spasticity contribute to disorders and disabilities that negatively affect functional recovery and lead to a decrease in quality of life [10]. TENS and NMES have been shown to be effective in improving posture, spasticity and functional independence in stroke patients [32, 35]. TENS or NMES, in addition to exercise programs, leads to greater improvements in posture, spasticity, and functional independence [35, 36].

Before reperfusion treatments for ischemic stroke became available, differences in rehabilitation outcomes were observed between ischemic and hemorrhagic strokes. Although patients with hemorrhagic stroke had worse initial rehabilitation scores compared to those with ischemic stroke, they demonstrated greater improvement during inpatient rehabilitation [37, 38]. Similarly, another study compared patients with similar initial rehabilitation scores and found that those with hemorrhagic stroke showed more significant improvement than those with ischemic stroke [39]. In recent years, the use of intravenous thrombolysis and/or endovascular thrombectomy to resolve cerebral vein occlusion has further improved rehabilitation outcomes for ischemic stroke patients [40, 41]. Recent studies have shown that there is no significant difference in functionality or recovery at discharge between patients undergoing rehabilitation after hemorrhagic or ischemic stroke [42, 43].

The mechanism of action of TENS in improving posture is rooted in its effects on sensory input, motor control, and neuromuscular function. A study conducted on healthy adults found that TENS applied to the lower extremities had an immediate effect on postural control [44]. Additionally, TENS applied to the knee in a standing position reduced postural sway [45]. The mechanism of action of NMES in improving posture is based on its ability to activate muscles, enhance neuromuscular control, and improve proprioception. Two studies have shown that NMES application to the lower extremity muscles positively affects balance. In one study, a 50% improvement in balance was observed in adult patients who received NMES on the tibialis anterior muscle for 4 weeks, while another study reported a 31.5% improvement with NMES applied to the calf muscles [46].

The mechanism of action of TENS in influencing muscle tone involves modulation of sensory and motor pathways, which can lead to a reduction in abnormal muscle tone (hypertonia or spasticity) or improvement in muscle activation in cases of hypotonia. Although studies have shown that TENS application reduces spasticity, it has been found that the improvement in spasticity is more effective when TENS is combined with exercise [3, 7]. The mechanism of action of NMES in influencing muscle tone involves the activation of motor and sensory pathways, leading to changes in muscle contraction, relaxation, and neuromuscular re-education. NMES can be used to stimulate the neuromuscular activity of the affected limbs either by directly stimulating the spastic muscles or by stimulating their antagonist muscles [10].

Conclusion

TENS or NMES combined with an isolated exercise program does not affect mid-term posture, spasticity, and functional outcomes in post-stroke hemiparesis. Although isolated TENS or NMES applications have a positive effect on early (1-month) outcomes, they do not affect mid-term (4-month) outcome. For better mid-term results in posture, spasticity, and functional outcomes, TENS + NMES should be applied combined with isolated exercise program.

Limitation of study

Since a home-based rehabilitation program was applied to all patients after discharge, the effectiveness of the program could not be compared. If a home-based rehabilitation program had not been applied to a different group after discharge, its effectiveness could have been comparable.

Although the positive effect of TENS + NMES application combined with an isolated exercise was demonstrated at the 4th month, its effect in the later period could not be demonstrated. It would be beneficial to essess whether this positive effect is permanent or a temporary with longer-term follow-up in future studies. Extending the follow-up period could help in assessing the sustainability of the treatment effects.

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Authors' contributions

BB and AÖF conceptualised the review, created aims and established inclusion and exclusion criteria. AÖF performed assessment for the risk of bias and wrote the initial draft. BB contributed to reviewing and editing. All authors were involved in interpreting the data, critically revising the manuscript, and approve the final version for publication.

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Data availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

All participants achieved written information and informed consent was obtained. The study was approved by the Ethics Committee of Gaziosmanpaşa Training and Research Hospital, University of Health Sciences (2022–154) and the investigation conforms to the principles outlined in the Declaration of Helsinki [12].

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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