

# Passive Biaxial Ankle Movement Training with Electrical Stimulation for Ankle Sensorimotor Function in Chronic Stroke

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## Research

**Keywords:** sensorimotor function, stroke, electrical stimulation, ankle

**Posted Date:** November 19th, 2020

**DOI:** <https://doi.org/10.21203/rs.3.rs-108748/v1>

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# Abstract

## Background

Post stroke had both ankle sensory and motor impairments that affect ankle motor control. The purpose of this study was to investigate the effect of passive biaxial ankle movement training coupled with electrical stimulation (AMT-EST) on ankle proprioception, ankle strength, balance, and gait in chronic stroke.

## Methods

Thirty-five stroke subjects were randomized to an experimental or control group, and 30 subjects completed the trials. The experimental group received AMT-EST on the affected ankle for 30 minutes a day, 5 times a week for 4 weeks, for a total of 20 sessions. The control group received electrical stimulation therapy on the affected ankle. The primary outcome measures were ankle proprioception, passive range of motion, and strength. The secondary outcome measures were balance and gait-related functional abilities.

## Results

The experimental group showed significant post-training improvement in ankle proprioception of eversion, the ankle passive range of motion (inversion and eversion), ankle strength (dorsiflexion, plantarflexion, inversion, and eversion) Fugl–Meyer Assessment (FM-A), Berg Balance Scale (BBS), Timed Up and Go test, Fall Efficacy Scale, and walking speed ( $p < 0.05$ ). Significant group×time interactions were observed in ankle passive range of motion (inversion and eversion), ankle strength (dorsiflexion), and FM-A ( $p < 0.05$ ). All ankle proprioception moderately correlated with ankle passive range of motion (eversion), ankle strength (dorsiflexion and eversion), the BBS, and FM-A ( $p < 0.05$ ).

## Conclusions

The findings suggest that AMT-EST can be proposed as an ankle rehabilitation program for people with chronic stroke with ankle sensorimotor impairment.

## Trial Registration

KCT0004688. Registered 01 Jan 2020

# Background

Somatosensory impairment in stroke patients is common and appears in approximately 89% of stroke survivors [1], and the damage to proprioception and tactile sensation is more pronounced in the lower extremities than in the upper extremities [2]. Proprioception provides self-information regarding position, movement, or force necessary for the body to make motor adjustments [3]. In the lower extremity, ankle

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proprioception provides essential information to enable the adjustment of ankle position and plays a key role in maintaining balance [4]. Furthermore, the sensory system, including ankle proprioception, plays an important role in both feedforward and feedback operations to achieve novel ankle motor tasks and motor learning [5]. Therefore, interventions to improve ankle proprioception potentially affect ankle motor control, balance, and daily functioning [6].

Considering the importance of the sensory system, studies have investigated interventions for sensory function and functional activity in stroke patients. Electrical stimulation (ES) aims to achieve sensorimotor integration, thereby ensuring better function and pain control in paraplegic individuals [7, 8]. Furthermore, ES induces a sensory cue to activate motor neurons or reflex pathways via stimulation of sensory nerve fibers [9]. These effects are related to sensory facilitation of neural plasticity by increasing the strength of afferent inputs to promote motor learning [10]. Therefore, ES is used frequently to improve performance in hemiparetic stroke patients who have difficulty controlling ankle movements due to muscle weakness. Combination therapy with ES and other modalities (e.g., gait trainer, treadmill, rocker board, and cycling) has been found to modulate ankle spasticity [11], functional ability [11, 12], gait characteristics [11–13], and recovery of physical condition [14]. However, as these modalities focused on the physical performance of the lower extremities, persistent ankle impairment was unresolved. Therefore, the application of ES and functional movement training focused on the ankle is helpful to improve the ankle sensory function in stroke patients.

Understanding the ankle joint structure and movement is useful for re-education and effective training of functional ankle movement. The ankle is a biaxial structure with an obliquely aligned subtalar joint axis. As the movement of the subtalar joint significantly contributes to foot position, ankle inversion (INV) and eversion (EV) are important ankle functional movements. The effects of a passive biaxial ankle training, including ankle INV and EV movement, on ankle functional ability and functional performance related to balance and gait in chronic stroke patients were reported previously [15]. Passive range of motion (PROM) exercise aims to maintain or increase joint mobility by influencing the extensibility of the lower motor neurons as well as soft tissues, thereby reducing spasticity and directly or indirectly increasing muscle extensibility [16]. Moreover, PROM provides sensory information derived from muscle spindles, Golgi tendon organs, and joint and cutaneous receptors [17, 18]. Thus, ES as an adjunct to ankle biaxial PROM exercise can effectively provide sensory information to stroke hemiparetic patients who have difficulty with active ankle movements. A recent meta-analysis showed that a combination of PROM and ES was more effective for improving sensory impairment [19], and further research on the ankle is needed.

The aim of this study was to investigate the effects of passive biaxial ankle movement training synchronized with electrical stimulation therapy (AMT-EST) on the enhancement of ankle proprioception, PROM, strength, and other functional abilities. We hypothesized that AMT-EST would more significantly improve ankle sensorimotor function in chronic stroke patients than in the control group. The second hypothesis was that this ankle training would improve the ankle-joint-associated functional abilities,

## Methods

### Participants and Design

Participants were recruited from among inpatients at the hospital of National Rehabilitation Center. The eligibility criteria were as follows: (1) chronic post-stroke hemiparesis; (2) weakness of ankle muscles on the affected side (Medical Research Council Scale, ankle dorsiflexion (DF) strength range, grades 1–4); (3) Modified Ashworth Scale score < 3 for spasticity in the affected ankle; (4) impaired light touch sensation on the plantar aspect of the head of the first metatarsal of the affected foot; and (5) Functional Ambulatory Category Score  $\geq$  3. Potential participants were excluded if they had complications of orthopedic disorders and cognitive impairment (Mini-Mental State Examination Score  $\leq$  24). This study was approved by the Institutional Review Board at the National Rehabilitation Center, and participants provided written informed consent before study enrollment.

A double-blind, parallel-group, randomized controlled trial with blinding of assessors and concealed allocation was conducted. A person uninvolved in the trial created a blocked random allocation schedule for 35 participants using Microsoft Excel®, and participants were divided accordingly into the experimental or control groups after the baseline assessment to receive AMT-EST or only ES, respectively, on the affected ankle for 4 weeks. Two evaluators who were not related to the study performed pre- and post- test without knowing the randomization of subjects. All participants were reassessed at the end of the 4-week intervention period.

### Ankle Movement Training System

The ankle-training device used in this study was developed for intensive and selective training on the paretic ankle in stroke patients. The main feature of the ankle training device was to reproduce the actual biaxial ankle movement that was applied by a seesaw-type foot cradle that pivoted along the transverse ankle axis, and the foot force plate was rotated along a 42°-tilted subtalar axis relative to the foot cradle. The improvement in ankle PROM, stiffness, and walking performance on uneven surface as a result of passive biaxial ankle training using this ankle device in chronic stroke patients has been reported previously [15]. In this study, an ankle function enhancement training protocol that applied ES in accordance with passive biaxial ankle movement was constructed and applied (Online Supplement I).

### Intervention

#### Experimental group

Before the training session, the participants were asked to comfortably sit on a height-adjustable chair with his/her knees flexed at 90°, to place his/her paretic foot on the footplate of the ankle-training device, and to place his/her non-paretic foot on the height-matched footrest. The paretic foot was fastened to the force plate in the foot cradle using three length-adjustable straps (Fig. 1). The two electrode pairs (5 × 9 cm; RehaTrode, Hasomed, Germany) were placed over the common peroneal nerve as it passed over the tibia anterior. Other electrode pairs were placed slightly lateral

to this and targeted toward the peroneus longus (Fig. 1). ES was applied to confirm that the location of the attached electrodes caused proper ankle DF (tibialis anterior) and EV (peroneus longus).

AMT-EST was performed for 4 weeks, with 5 sessions per week. All participants completed more than 90% of the training sessions. The duration of one training session was 40 minutes, which comprised a 5-minute warm-up, 30 minutes of ankle training, and a 5-minute cool-down. In the warm-up session, the PROM of ankle DF, plantarflexion (PF), INV, and EV were measured, and all ankle training was performed within 80% of the full ankle range of motion. Subsequently, the participants performed a PROM exercise for ankle DF, PF, INV, and EV. In the ankle-training session, the simple and combined ankle PROM exercise with ES was performed along the ankle (talocrural) and subtalar (talocalcaneal) axes. The simple movements consisted of 20 repetitions of DF-PF and INV-EV, and the combined movements consisted of 40 repetitions of inverted PF and everted DF (diagonal movements), which are more commonly used in actual movement. All ankle movement speed was slow, at  $2.14^\circ/\text{s}$ , to avoid ankle spasticity [15]. The timing of the starting and ending of the paretic ankle DF and EV movements was directly observed by the therapist who then applied ES (Microstim2, Medel GmbH, Germany) current with 0.28-ms pulses, at 35 Hz with pulse durations from 300 to 450  $\mu\text{s}$  in alternating mode within the participants' tolerance level, via surface electrodes (Online Supplementary Video). The amplitude was adjusted to produce muscle contractions without causing patient discomfort [20]. In the last cool-down, 10 simple PROM exercises were performed for ankle DF, PF, INV, and EV (Fig. 2).

## Control group

Participants in the control group received ES on paretic ankle muscles for 4 weeks, with 5 sessions per week. The participants received PROM exercises by the ankle training device for the first 5 minutes (warm-up), ES on the paretic ankle for 30 minutes (training session), and then PROM exercise for the last 5 minutes (cool-down; Fig. 2). The ES (Microstim2, Medel GmbH, Germany), with a pulse frequency of 35 Hz in alternating mode and pulse duration of 300 – 450  $\mu\text{s}$ , was applied at the same position as the electrodes were applied in the experimental group in the sitting position.

## Outcome Measures

The primary outcome was ankle function, including ankle proprioception, PROM, and strength. Proprioception was assessed by evaluating the joint position sense of the ankle DF, PF, INV, and EV using an ankle-training device with constant velocities ( $2.14^\circ/\text{s}$ ). Participants wore eye masks and earplugs in a sitting position with the other lower limbs fixed to allow only ankle movement. The assessment comprised two steps. In the first step, the ankle was moved passively from the initial angle ( $0^\circ$ ) to the randomly assigned 10 target angles ( $10^\circ$ ,  $20^\circ$ , and  $30^\circ$  of ankle PF and INV;  $10^\circ$  and  $20^\circ$  of ankle DF and EV; according to normal range of motion of the ankle), while asking the participant whether the ankle movement and the direction of movement were perceivable. After staying at the target position for 5 seconds, the ankle was returned to the initial angle. In the second step, the paretic ankle was moved toward the target angle again and the participant was asked to say “stop” when they felt that they had

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eedback about results was provided to the participant during

the task. The assessment began with a period of familiarization. Three ankle movements were evaluated per direction, and a total of 38 measurements including dummy trials (no movement) were performed. For statistical analyses, the proprioception ratio were calculated in relation to angular differences, which means that the difference between the target angle and actual angle [21] was ascertained using the following equations:

$$\text{Proprioceptionratio} = \left| \frac{\text{Targetangle} - \text{Actualangle}}{\text{Targetangle}} \right|$$

Finally, the proprioception ratio for all four directions (DF, PF, INV, and EV) was calculated as the average value of the proprioception ratio that was measured three times for each angle. The larger the proprioception ratio value, the greater is the deficit.

$$\text{Ankleproprioception} = \frac{10\text{degreeratio} + 20\text{degreeratio} + 30\text{degreeratio}}{3}$$

The PROM of the paretic ankle was measured using a portable goniometer by a skilled physiotherapist. The average values of three measurements of maximum PROM of DF, PF, EV, and INV were recorded. To measure ankle strength, the isometric contraction force of the paretic ankle muscle was measured using a portable manual muscle strength tester (Lafayette, USA, 2018). The isometric strength of the ankle dorsiflexor, plantar flexor, invertor, and evertor was measured for 5 seconds, and the maximum value was recorded.

The secondary outcomes included motor, balance, and gait function, evaluated by the Fugl–Meyer Assessment for the lower extremity (FM-L), Berg Balance Scale (BBS), the Timed Up and Go test (TUG), the Korean version of the Fall Efficacy Scale, and walking speed (Online Supplement V).

## Statistical Analyses

The sample size was calculated according to the study sample of a study that reported the effect of repeated passive exercises on the knee's proprioception in patients with hemiplegia [22]. Calculations were performed with a paired *t*-test value of the knee position sense for a comparison of the before and after intervention values, using an alpha of 0.05 at 95% power. The total sample size was determined to be 6 for each group (effect size: 1.744, actual power: 0.975). The G \* Power 3.1.9.2 program was used.

The normative distribution of baseline data was assessed using the Shapiro–Wilk test. Some sample characterization data did not show normative distribution, and the Mann–Whitney *U* test or chi-square test was conducted for comparing the groups at baseline. Within each group, the Wilcoxon signed rank test was used to compare data from the pre- and post-intervention tests. To examine the main effects of the interventions, a 2 (group) × 2 (time) ANOVA with repeated measures was performed. The relationships between ankle proprioception and clinical outcome measures were examined using the Spearman's correlation coefficient (*r*). All statistical analyses were performed using SPSS ver. 22.0 (IBM, Armonk, NY,

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# Results

## Participants

The participant's baseline characteristics are presented in Table 1. At the baseline, no significant between-group differences were found for demographics or measurements. Five individuals in the control group dropped out due to discharge from the hospital during the training. Therefore, the post-intervention testing and analysis were completed for 18 individuals in the experimental group and 12 in the control group (CONSORT flow chart, Online Supplement II).

Table 1  
Baseline characteristics of the experimental and control groups (N = 30)

	Experimental group (n = 18)	Control group (n = 12)	P-value
Age (years)	51.8 ± 12.0	55.0 ± 10.9	0.589 <sup>†</sup>
Sex (M/F)	14/4	9/3	0.798*
Weight (kg)	69.6 ± 9.4	70.6 ± 12.2	0.982 <sup>†</sup>
Height (m)	169.8 ± 7.7	169.6 ± 8.9	0.893 <sup>†</sup>
Time post stroke (months)	11.6 ± 4.1	8.6 ± 3.9	0.065 <sup>†</sup>
Stroke side (R/L)	9/9	5/7	0.815*
Modified Ashworth Scale (0/1/1+/2)	0/5/12/1	1/4/7/0	0.436*
Functional Ambulation Category (0–5)	4.4 ± 1.0	4.3 ± 0.6	1.000 <sup>†</sup>
K-MMES score	26.8 ± 2.5	28.4 ± 1.1	0.114 <sup>†</sup>
K-MMES, Korean Version of the Mini-Mental State Examination.			
<sup>a</sup> Values are expressed as mean (SD) unless otherwise stated.			
*Chi-square test			
<sup>†</sup> Mann–Whitney <i>U</i> test			

## Primary Outcomes: Ankle Proprioception, Passive Range of Motion, and Strength

The specific values for ankle functional improvements before and after the training are presented in Table 2 (Online Supplement III and IV). After completing the 20 sessions of ankle training, proprioception of ankle EV showed a significant group effect ( $F = 4.742$ ,  $p = 0.038$ , Table 2), whereas the ankle PROM of Loading [MathJax]/jax/output/CommonHTML/jax.js

INV and EV showed significant improvements only in the experimental group ( $p < 0.05$ ). Moreover, significant group  $\times$  time interactions were found in the ankle PROM of INV ( $F = 5.311$ ,  $p = 0.029$ ) and EV ( $F = 10.842$ ,  $p = 0.003$ ). Furthermore, the ankle strength of all directions (DF, PF, INV, and EV) showed significant improvement in the experimental group ( $p < 0.05$ ). Particularly, significant time effects on ankle DF ( $F = 6.611$ ,  $p = 0.016$ ), INV ( $F = 8.882$ ,  $p = 0.006$ ), and EV ( $F = 7.296$ ,  $p = 0.012$ ) and significant group  $\times$  time interactions in ankle DF ( $F = 6.199$ ,  $p = 0.020$ , Table 2) were found.

Table 2  
Outcome values before (pre) and after (post) the 4-week treatment (N = 30)

Measures (unit)		Experimental group (n = 18)		Control group (n = 12)		P-value		
		Pre	Post	Pre	Post	Time	Group	Group × Time
Ankle proprioception (%)	Dorsiflexion	61.1 ± 37.0	60.3 ± 34.6	40.4 ± 30.3	40.0 ± 32.5	0.896	0.106	0.967
	Plantarflexion	60.6 ± 36.0	52.1 ± 34.2	35.0 ± 27.0	33.6 ± 29.0	0.240	0.073	0.403
	Inversion	57.2 ± 35.8	48.4 ± 29.3	38.1 ± 32.0	31.9 ± 23.3	0.071	0.123	0.753
	Eversion	65.8 ± 35.3	58.4 ± 36.8	37.5 ± 29.3	33.6 ± 26.6	0.143	0.038	0.651
Ankle PROM (°)	Dorsiflexion	12.2 ± 6.2	14.7 ± 7.5	15.7 ± 6.3	11.6 ± 7.1	0.676	0.924	0.079
	Plantarflexion	44.7 ± 10.1	45.2 ± 8.9	41.3 ± 8.8	40.9 ± 9.7	0.991	0.211	0.809
	Inversion	21.1 ± 4.5	<b>24.3 ± 4.7*</b>	24.5 ± 2.9	23.0 ± 2.5	0.401	0.369	<b>0.029</b>
	Eversion	19.2 ± 4.3	<b>23.0 ± 3.8†</b>	21.0 ± 3.9	19.3 ± 4.7	0.231	0.488	<b>0.003</b>
Ankle strength (N)	Dorsiflexion	10.8 ± 3.7	<b>16.4 ± 4.6†</b>	13.6 ± 3.9	13.7 ± 6.4	<b>0.016</b>	0.981	<b>0.020</b>
	Plantarflexion	14.9 ± 6.5	<b>18.2 ± 5.7*</b>	14.3 ± 3.3	15.0 ± 5.7	0.090	0.311	0.241
	Inversion	7.7 ± 3.2	<b>10.7 ± 2.1†</b>	9.1 ± 2.1	9.7 ± 2.6	<b>0.006</b>	0.796	0.051
	Eversion	7.2 ± 3.2	<b>9.8 ± 2.2†</b>	7.8 ± 1.2	8.5 ± 2.1	<b>0.012</b>	0.609	0.147

PROM, passive range of motion; FM-L, Fugl–Meyer Lower Extremity Assessment; BBS, Berg Balance Scale; TUG, Timed Up and Go test.

<sup>a</sup>Values are expressed as means (SD) unless otherwise stated.

\* $P < 0.05$  for within-group comparisons

Measures (unit)	Experimental group (n = 18)		Control group (n = 12)		P-value		
	Pre	Post	Pre	Post	Time	Group	Group × Time
FM-L (score)	17.8 ± 3.3	<b>22.4 ± 3.5†</b>	18.6 ± 2.9	20.6 ± 3.3	<b>&lt; 0.001</b>	0.642	0.041
BBS (score)	46.2 ± 6.1	<b>49.6 ± 4.7†</b>	45.0 ± 9.1	<b>47.0 ± 6.7*</b>	<b>&lt; 0.001</b>	0.440	0.238
TUG (s)	33.1 ± 16.2	<b>28.0 ± 14.9*</b>	40.1 ± 18.7	<b>34.3 ± 19.0*</b>	<b>&lt; 0.001</b>	0.306	0.788
Fall Efficacy Scale (score)	53.6 ± 30.6	<b>31.7 ± 18.2†</b>	53.8 ± 27.8	50.6 ± 33.6	<b>0.029</b>	0.297	0.098
Walking speed (cm/s)	35.8 ± 19.7	<b>41.1 ± 22.0*</b>	33.0 ± 22.1	37.0 ± 26.2	<b>0.027</b>	0.686	0.746
PROM, passive range of motion; FM-L, Fugl–Meyer Lower Extremity Assessment; BBS, Berg Balance Scale; TUG, Timed Up and Go test.							
<sup>a</sup> Values are expressed as means (SD) unless otherwise stated.							
* <i>P</i> < 0.05 for within-group comparisons							
† <i>P</i> < 0.01							

## Secondary Outcomes: Functional Abilities Related to Motor, Balance, and Gait

After the training session, the experimental group showed significant improvements in all functional ability measurements, including the FM-L, BBS, TUG, Fall Efficacy Scale, and walking speed ( $p < 0.05$ ). Similarly, the control group showed significant improvements in the BBS and TUG after the training ( $p < 0.05$ ). Particularly, the FM-L demonstrated a significant time effect ( $F = 30.186$ ,  $p < 0.001$ ) and significant group × time interactions ( $F = 4.597$ ,  $p = 0.041$ ).

## Correlation with Ankle Proprioception at the Baseline

The relationship between ankle proprioception and clinical outcome measures at the baseline is presented in Table 3. A significant correlation was found between the post-stroke duration (months) and proprioception of both ankle DF and PF ( $p < 0.05$ ). The functional ambulatory category showed moderate correlation with proprioception of ankle EV ( $p < 0.05$ ). A moderate correlation was found between all ankle proprioception (DF, PF, INV, and EV) and PROM of ankle EV ( $p < 0.05$ ), whereas no significant correlation was found between ankle proprioception and PROM of the ankle DF, PF, and INV. The strength of ankle DF Loading [MathJax]/jax/output/CommonHTML/jax.js all ankle proprioception ( $p < 0.05$ ), and the strength of ankle

PF and EV showed no significant correlation. Furthermore, all ankle proprioception showed a moderate correlation with the FM-L and the BBS ( $p < 0.05$ ).

Table 3  
Correlations between ankle proprioception and clinical outcome measures at baseline (N = 30)

Variables		Ankle proprioception			
		Dorsiflexion	Plantarflexion	Inversion	Eversion
Months post stroke		.452	.395	-	-
Functional ambulation category		-	-	-	-0.420
Ankle PROM	Dorsiflexion	-	-	-	-
	Plantarflexion	-	-	-	-
	Inversion	-	-	-	-
	Eversion	-0.557	-0.455	-0.448	-0.411
Ankle strength	Dorsiflexion	-0.577	-0.427	-0.537	-0.396
	Plantarflexion	-	-	-	-
	Inversion	-0.546	-0.501	-0.556	-0.514
	Eversion	-	-	-	-
Berg Balance Scale		-0.561	-0.498	-0.542	-0.465
Timed Up and Go test		-	-	-	-
Fugl–Meyer Lower Extremity Assessment		-0.537	-0.444	-0.449	-0.455
Walking speed		-	-	-	-
PROM, passive range of motion.					
<sup>a</sup> Only significant Spearman's correlation coefficients ( $P < 0.05$ ) are reported.					

## Discussion

The findings of this study suggest that AMT-EST has several key advantages for proprioception of ankle EV, PROM of ankle INV and EV, and strength of ankle DF, INV, and EV compared with general ES ( $p < 0.05$ ). In addition, FM-L showed a significant improvement in the experimental group on between-group comparison, and the other functional abilities, including balance and gait, significantly increased in the AMT-EST group from the baseline to after the intervention.

To restore sensorimotor function and functional abilities in stroke patients, ES has been used commonly

further enhance afferent inputs to promote motor performance [23]. For example, the application of ES on ankle muscles during gait and everyday activities significantly increased ankle proprioception and ankle strength, balance, and gait speed [24]. However, such a performance includes complex movement of the entire lower extremity. Because ankle impairment is more prominent and voluntary ankle motor control is more difficult than the movement of other lower extremities in stroke patients, a focus on ankle training with ES while excluding other lower extremity movement is required. In this study, the application of ES to the ankle dorsiflexor (tibialis anterior) and evertor (peroneus longus) along with functional ankle training was associated with significant improvements in ankle PROM and strength, as well as in the ankle proprioception. When ES is applied with a focus on ankle function movement, it can enhance the generation of cortical brain perfusion to the ipsilesional sensorimotor cortex for restoring ankle sensorimotor function [25]. Furthermore, the repeated ankle movement training provides sensory input for muscle extensibility, which is responsible for the stretch receptors of the muscle spindle. Moreover, ankle movement training is effective in promoting ankle proprioception that recognizes the positional sense of joints with respect to changes in muscle length [26]. By contrast, the control group received ES without the ankle movement training to the same ankle dorsiflexor and evertor, which are generally stimulated electrically in a clinical environment. After the completion of a 20-session training, the balance ability of the control group, including BBS and TUG, was improved ( $p < 0.05$ ); however, there was no significant improvement of the ankle function. The participants of this study were all chronic stroke patients, with a post-stroke duration of 10.5 months, and general physical therapy, such as gait training, was performed equally for all participants. These results demonstrate that AMT-EST is more effective than conventional ES training for ankle function in hemiparetic stroke patients. Therefore, it can be postulated that additional concentrated ankle training, such as AMT-EST, is required to improve ankle function in chronic stroke patients.

The passive biaxial ankle movement used in this study is characterized by reproducing the ankle subtalar joint movement (INV-EV) to a single axis movement (DF-PF). After training, the results showed significant improvement in the ankle proprioception, PROM, and strength, particularly on ankle INV and EV. There was a significant improvement in balance and gait function. This implies the importance of the roles of the ankle invertors and evertors that constitute the muscles of the medial and lateral sides of the ankle. The peroneus longus and brevis muscles, which are the primary ankle evertors, pass lateral to the subtalar joint, and their primary function is foot pronation and weak PF. Similarly, the tibialis anterior and posterior muscles are the primary ankle invertors and pass medial to the subtalar axis and cause ankle DF and PF, respectively. Depending on the muscle attachment site (origin and insertion), these muscles complement each other in an INV and EV, as well as in the overall ankle movement. These results may suggest that ankle proprioception and PROM enhancement of the primary invertor and evertor would have affected the power of voluntary muscle contraction of not only the ankle invertor and evertor but also ankle dorsiflexor and functional performances.

Sensory information from the ankle has been demonstrated to be associated with the perception of verticality [27], which in turn is related to balance [28]. More importantly, because the planning and

Loading [MathJax]/jax/output/CommonHTML/jax.js sensory information on body position and the prediction of

future position, activities such as balancing can be difficult with severe impairment of ankle sensation. Therefore, the impaired ankle sensory function is considered important in the recovery of physical function in stroke patients. Recent studies have found that ankle proprioceptive deficits have significant relationships with mobility, balance, balance confidence, physical functions, and activities of daily living [29, 30]. The results of this study showed that ankle proprioception had a moderate correlation with PROM, strength, BBS, and FM-L. Furthermore, the significant improvements in ankle proprioception and improved FM-L, BBS, and TUG in this study support the earlier evidence. Nonetheless, the role of sensory function in complex performance is somewhat different from that of balance. The performance of complex functions, such as walking, involves various factors including muscle strength [31–33], spasticity [32], cognition [34], motor function [33, 34], and balance [31, 33], as well as sensory information. A recent meta-analysis showed that leg somatosensory retraining after stroke significantly improved the somatosensory function and balance but not the gait [35]. However, this meta-analysis included only a few ankle proprioception-related training, and a 2-week proprioception training of the big toe and ankle was reported to be effective for improving light touch, postural control, and gait but not proprioception [36]. This study performed perception training consisting only of reposition training of the foot and ankle. Therefore, the evidence for effective proprioception training methods and their effect on functional ability is still insufficient. Nevertheless, it is clear that sensory impairments play an important role in motor recovery and physical function in stroke patients. Depending on the lesion location, strokes can damage both the motor and sensory neural systems, block the closed loop between the brain and body, and thus lead to neurological impairment that is associated with significant physical dysfunction [37, 38]. Further studies on brain plasticity for sensory function recovery in brain lesions should be considered.

Individuals with proprioception deficits experience low balance confidence as well as impaired balance and lack of independence in daily living [29]. Balance confidence, which is significantly correlated with balance (BBS,  $r = 0.44$ ) and mobility (TUG,  $r = -0.43$ ) of stroke patients [39], is closely related to fall efficacy. This study did not show a significant correlation between ankle proprioception and fall efficacy, but showed a significant improvement in fall efficacy after AMT-EST. Moreover, the participants in the experimental group reported a markedly positive improvement in confidence than those in the control group. We believe that AMT-EST of paretic ankle promotes psychological factors that are related to balance confidence as well as balance ability, and related research should be conducted.

To our knowledge, this is the first randomized controlled trial that applied intensive passive biaxial ankle movements with ES for improving ankle sensorimotor function. The novelty of this study is that the ankle training and proprioceptive measurements in this study were performed in the biaxial ankle direction and at a subdivided angle. Nonetheless, this study has several limitations. First, the small sample size, insufficient intervention intensity, and intervention period detract from the strength of the findings. Second, the long-term effects of the training could not be confirmed. Third, we could not exclude a learning effect for each evaluation system. Finally, ankle motor control and ankle muscle activity could not be directly determined. Future studies need to study the optimal intensity and duration of this ankle sensorimotor impairment. Therefore, it is difficult to generalize

the effect of ankle training to stroke patients in with the results of this study. The evidence of brain plasticity for sensory recovery should be investigated.

## Conclusions

This study provided evidence that AMT-EST significantly enhanced ankle proprioception, PROM, strength, and functional abilities related to balance and gait. These results prove that the improvement of ankle sensory function can help restore ankle motor control, and that AMT-EST is effective for stroke patients who have difficulty in active training. Thus, AMT-EST can be provided as part of an ankle rehabilitation program in hemiparetic stroke patients.

## Abbreviations

AMT-EST: ankle movement training synchronized with electrical stimulation therapy; PROM: passive range of motion; ES: electrical stimulation; K-MMES: Korean Version of the Mini-Mental State Examination; DF: dorsiflexion; EV: eversion; PF: plantarflexion; INV: inversion; FM-L: Fugl–Meyer Assessment for the lower extremity; BBS: Berg Balance Scale; TUG: Timed Up and Go test.

## Declarations

### Ethics approval and consent to participate

This study was approved by the institutional review boards of National Rehabilitation Center in South Korea (NRC-2017-04-035) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent before enrolment.

### Consent for publication

Consent for publication is acquired by all the authors.

### Availability of data and materials

The database used and analyzed during the current study is available upon reasonable request from the corresponding author.

### Conflicting Interests

The author(s) declare(s) no conflicts of interest concerning this article.

### Funding

This study was supported by the Translational Research Project for Rehabilitation Robots, Korea National Rehabilitation Center, Ministry of Health & Welfare, South Korea (grant #NRCTR-IN18003 and #NRCTR-

## Authors contributions

JE: patients recruitment, study design, analysis and interpretation of the results, writing of the manuscript; JH: patients recruitment, help in the interpretation of the results, revise the manuscript; HJ: study design, help in the interpretation of the results, revise the manuscript. All authors read and approved the final manuscript.

## Acknowledgments

We thank Dr. Dohoon Koo for assistance with 3D motion capture data acquisition and analysis.

## Supplementary information

Extended Materials & Methods with six references

Online Figures  - IV

Online Video I

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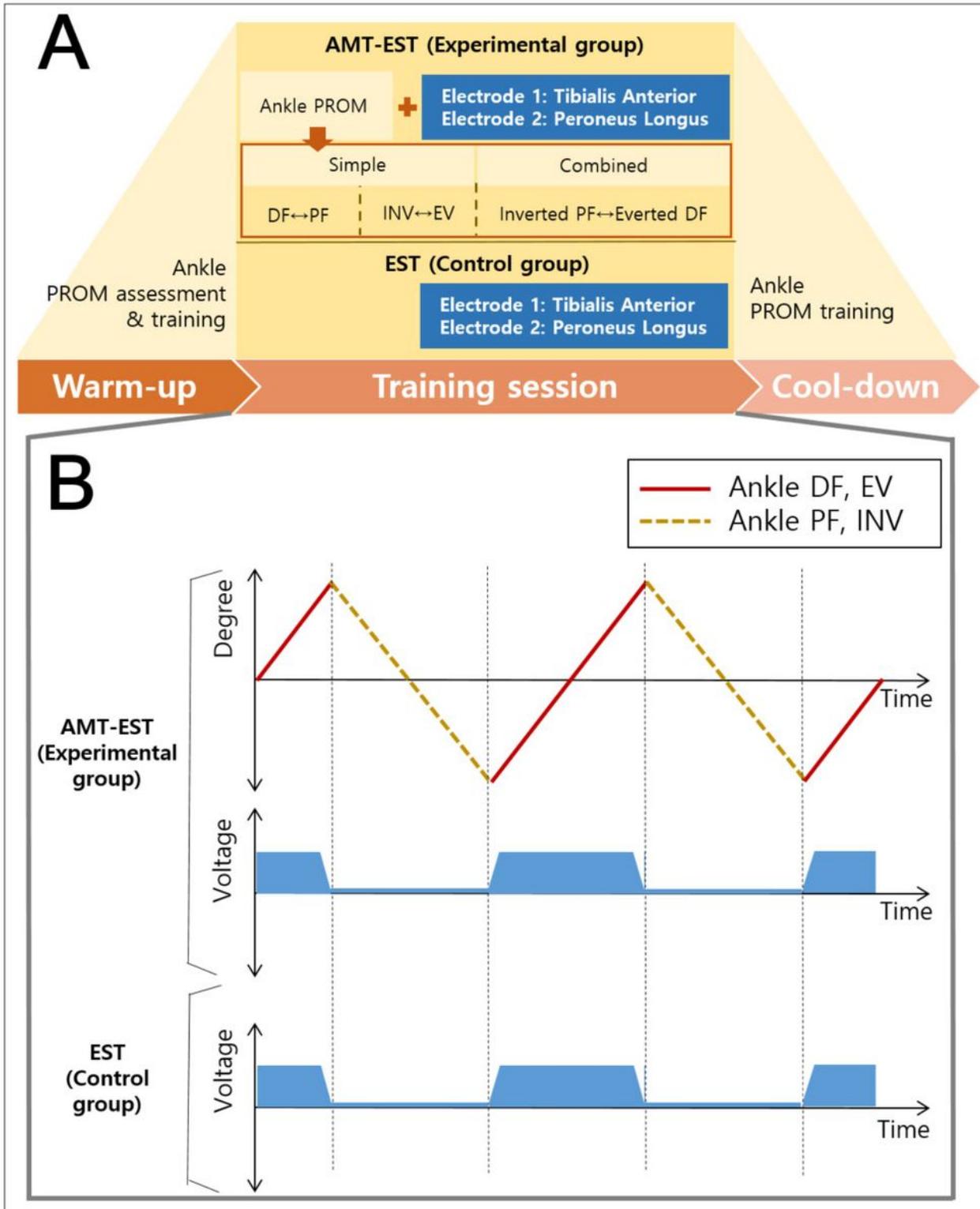
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## Figures



**Figure 1**

Before ankle movement training with electrical stimulation, the participants sat on a height-adjustable chair and their paretic foot was fastened to the force plate of the ankle-training device. The two electrode pairs were placed on the motor point of the tibialis anterior to induce ankle dorsiflexion and on the peroneus longus to induce ankle eversion.



**Figure 2**

Ankle training consisted of warm-up (5 min), training session (30 min), and cool-down (5 min). The experimental group received AMT-EST comprising single-movement and combined-movement training, and the control group received only electrical stimulation on affected ankle (A). Electrical stimulation was applied only during ankle dorsiflexion and eversion (B). Abbreviations: AMT-EST, ankle movement training

with electrical stimulation therapy; EST, electrical stimulation therapy; DF, dorsiflexion; PF, plantar flexion; INV, inversion; EV, eversion

## Supplementary Files

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