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Gait-Phase-Based Transcutaneous Electrical Nerve Stimulation During Gait Training in Chronic Stroke

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INTRODUCTION

Transcutaneous electrical nerve stimulation (TENS) has been investigated as an adjunct to gait training after stroke. However, most studies have delivered TENS without consideration of the gait cycle, and no previous study has evaluated the effects of gait-phase-based TENS during gait training. This study aimed to investigate the effects of **gait-phase-based TENS during gait training** and to compare functional outcomes according to stimulation method.

METHODS

■ Study design

- Randomized, single-center, single-blinded pilot clinical trial

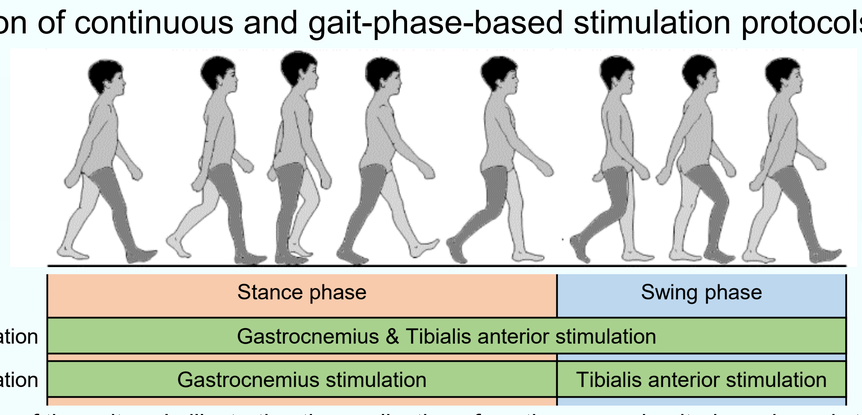
■ Participants

- Age 20–90 years
- Stroke (ischemic or hemorrhagic), ≥6 months post-onset
- Unilateral hemiplegia
- Functional ambulatory category 2–4

■ TENS protocol (Fig. 1)

- Device: A wearable TENS system (FIT 3.0, Compex, UK; myRIO, National Instruments, USA) (Fig. 2)
- Site: tibialis anterior and gastrocnemius muscles of the hemiplegic side
- Stimulation: intensity, 1.5–2 x the individual sensory threshold; frequency, 100 Hz; pulse width, 0.2 ms

Fig. 1. Comparison of continuous and gait-phase-based stimulation protocols

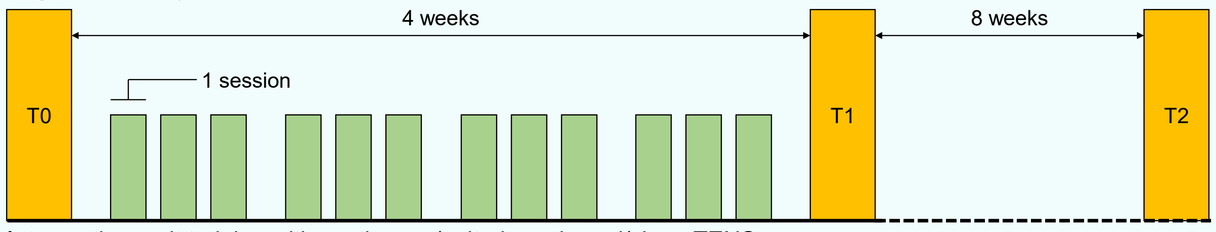


Schematic representation of the gait cycle illustrating the application of continuous and gait-phase-based stimulation. In the continuous protocol, both the gastrocnemius and tibialis anterior muscles are stimulated throughout the gait cycle. In the gait-phase-based protocol, gastrocnemius stimulation is applied during the stance phase, while tibialis anterior stimulation is applied during the swing phase. The gait cycle illustration is adapted from “Phases of gait cycle” (Physio-pedia), licensed under CC BY-SA 4.0. Modifications were made for layout and clarity.

■ Gait training program

- 10 minutes of simple gait training on flat ground
- 10 minutes of complex gait training such as stair climbing, sideway walking, backway walking
- 3 times a week for 4 weeks, total 12 sessions (Fig. 3)

Fig. 3. Study timeline and intervention schedule



Intervention: gait training with continuous/gait-phase-based/sham TENS
20 minutes per 1 session, 12 sessions for 4 weeks
All participants received 12 sessions of continuous, gait-phase-based, or sham TENS during gait training (3 sessions per week for 4 weeks). Outcome measures are assessed at baseline (T0), immediately after the intervention (T1), and 8 weeks post-intervention (T2).

■ Group classification

- All participants were randomly assigned to three groups
- **Continuous stimulation (CS) group**
  : gait training with continuous dual-channel stimulation
- **Gait-phase-based stimulation (GS) group**
  : gait training with gait-phase-based dual-channel stimulation
  : stimulation to the anterior lower leg during swing phase
  : stimulation to the posterior lower leg during stance phase
- **Sham group**
  : gait training with sham stimulation
  : dual-channel stimulation for the initial 15 seconds only

■ Outcome assessment

- Before intervention (T0), after intervention (T1), after 8 weeks (T2)
- Primary outcome: 10MWT (comfortable & maximal speed)
- Secondary outcome: TUG, K-BBS, FAC, K-MBI, EQ-5D-3L

Fig. 2. Experimental setup for TENS-assisted gait training

(A) A participant performing gait training while wearing a TENS system around the waist, with electrodes placed on the tibialis anterior and gastrocnemius muscles of the affected leg. (B) Force-sensing resistor (FSR) insole sensors used to detect gait phases (stance and swing) in real time, enabling gait-phase-based stimulation.

RESULTS

Table 1. Baseline demographic and clinical characteristics

	CS group (n=8)	GS group (n=6)	Sham group (n=7)	*P*-value
Age (years)	63.12 ± 11.47	74.50 ± 3.45	62.86 ± 15.99	0.160
Height (cm)	162.62 ± 5.73	163.00 ± 6.10	166.57 ± 6.60	0.426
Body weight (kg)	64.38 ± 8.23	65.67 ± 5.68	68.90 ± 15.47	0.713
Sex, n (male/female)	4/4	4/2	4/3	0.823
Side of hemiplegia, n (right/left)	6/2	2/4	4/3	0.297
Hypertension, n	5	2	4	0.531
Diabetes mellitus, n	2	2	1	0.720
Dyslipidemia, n	1	1	3	0.344
Cardiac disease, n	2	2	0	0.269
10-meter walk test (m/s)				
Comfortable speed	0.97±0.16	0.65±0.17	0.63±0.27	**0.008* (CS>GS,sham)**
Maximal speed	1.16±0.22	0.82±0.20	0.75±0.36	0.053
Timed up and go test (s)	7.18±1.24	10.23±2.07	13.53±6.47	**0.012* (CS<GS,sham)**
Berg balance scale (points)	45.13±5.41	32.50±5.09	31.14±7.67	**0.003* (CS>GS,sham)**
Functional ambulatory category (level)	4.50±0.53	3.83±0.41	3.71±0.76	0.091
Korean version of the Modified Barthel index (points)	87.88±5.67	84.17±2.64	79.43±12.84	0.213
EQ-5D-3L (index score)	7.25±2.25	8.33±1.97	9.00±1.41	0.276

Abbreviations: CS, continuous stimulation; GS, gait-phase-based stimulation. P-values were obtained using one-way ANOVA or the Kruskal–Wallis test with Bonferroni correction for continuous variables, and the chi-square test or Fisher’s exact test for categorical variables. * indicates a statistically significant difference ($p < 0.05$).

Table 2. Primary and secondary outcome measures across time points

	Group	T0	T1	T2	Time effect*	Group×Time effect*	ηp²
Primary outcome							
10-meter walk test, (m/s)							
Comfortable speed	CS	0.97±0.16	0.96±0.15	1.04±0.14	0.239		
	GS	0.65±0.17	0.63±0.20	0.71±0.19	0.139	**0.005†**	0.228
	Sham	0.63±0.27	0.66±0.25	0.68±0.26	0.133		
Maximal speed	CS	1.16±0.22	1.16±0.20	1.26±0.19	0.067		
	GS	0.82±0.20	0.81±0.22	0.84±0.19	0.494	**0.009†**	0.261
	Sham	0.75±0.36	0.80±0.31	0.83±0.32	0.097		
Secondary outcomes							
Timed up and go test (s)	CS	7.18±1.24	7.27±1.40	6.63±1.01	**0.019†**		
	GS	10.23±2.07	10.56±3.13	10.04±3.33	0.662	**0.026†**	0.130
	Sham	13.53±6.47	11.46±4.03	11.80±5.28	0.156		
Berg balance scale (points)	CS	45.13±5.41	45.50±5.18	47.29±5.56	0.223		
	GS	32.50±5.09	33.83±4.49	37.67±3.39	**0.006†**	**0.001†**	0.421
	Sham	31.14±7.67	34.71±6.42	35.50±5.74	0.068		
Functional ambulatory category (level)	CS	4.50±0.53	4.50±0.53	4.71±0.49	0.154		
	GS	3.83±0.41	3.83±0.41	4.17±0.41	0.175	**0.038†**	0.197
	Sham	3.71±0.76	4.00±0.82	4.00±0.82	-		
Korean version of Modified Barthel index (points)	CS	87.88±5.67	87.88±5.67	87.57±6.05	-		
	GS	84.17±2.64	84.17±2.64	84.17±2.64	-	0.183	-
	Sham	79.43±12.84	79.43±12.84	82.75±13.82	-		
EQ-5D-3L (index score)	CS	7.25±2.25	6.88±1.73	6.86±1.57	0.341		
	GS	8.33±1.97	8.17±1.60	7.83±2.23	0.591	0.090	0.030
	Sham	9.00±1.41	9.00±1.63	10.00±0.00	0.194		

Abbreviations: CS, continuous stimulation; GS, gait-phase-based stimulation. *Time and group × time interaction effects are presented as P-values obtained using repeated-measures ANOVA, with Greenhouse–Geisser correction where appropriate. † indicates a statistically significant difference ($p < 0.05$). – indicates that the analysis was not estimable due to lack of variability.

CONCLUSION

TENS combined with gait training was associated with changes in gait, mobility, and balance in individuals with chronic stroke. **The pattern of functional change differed according to the timing of stimulation delivery.** This may reflect **differences in sensorimotor integration**, with gait-phase-based stimulation providing task-specific sensory input and continuous stimulation offering more generalized facilitation during movement. These findings support the potential role of timing-specific sensory stimulation in optimizing gait rehabilitation strategies.

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