J. Phys. Ther. Sci. 34: 473–477, 2022

The Journal of Physical Therapy Science

Case Study

Improvement in lower extremity hemiplegia in a post-operative brain tumor patient by applying an integrated volitional control electrical stimulator

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Abstract. [Purpose] This study aimed to evaluate the improvement in lower extremity hemiplegia following brain tumor operation with an integrated volitional control electrical stimulator (IVES). [Participant and Methods] A 40 year-old male with anaplasic oligodendroglioma in the right frontal lobe underwent IVES in the rectus femoris and tibialis anterior muscles using the power-assist and sensor-trigger modes. Lower extremity motor function was assessed before and after the therapy sessions. An assessment was conducted using various techniques, including static posturography and surface electromyography. [Results] Static posturography showed an improvement in the center of pressure and sway area after IVES gait training. Based on a time-series statistical parametric mapping analysis, the activation pattern of each muscle after the treatment was different. Muscle synergy analysis revealed decreased total variance accounted for by a single synergy in the affected and normal sides after the treatment. [Conclusion] Patients with chronic hemiplegic lower extremity impairment responded well to IVES gait training. Electromyography-triggered functional electrical stimulation may enhance sensory-motor integration. Proprioceptive feedback plays a crucial role in improving motor control.
Key words: Functional electrical stimulation, Integrated volitional control electrical stimulator, Muscle synergy

(This article was submitted Jan. 31, 2022, and was accepted Mar. 6, 2022)

INTRODUCTION

In middle-aged patients, lower extremity hemiplegia is caused by secondary neurological deficits related to the central nervous system, such as stroke, brain injury, and brain tumor[1)]. Impairments in lower extremity motor functions severely impact patients' quality of life. Various treatments, including functional electrical stimulation (FES) therapy, have been suggested to be effective in patients with lower extremity hemiplegia[1)]. FES is a conventional stimulation therapy, and electromyography (EMG) activities are uncontrolled in its system once preprogrammed electrical stimulation is performed[2)].

An integrated volitional control electrical stimulator (IVES) was developed as an EMG-triggered FES[3)]. An IVES can automatically change its stimulation intensity in direct proportion to changes in the voluntarily generated EMG amplitudes[3)]. Electrical stimulation of target muscles during voluntary movements can therefore promote appropriate contraction of these muscles. IVES may improve the motor performance of the affected limb in patients with central neurological complications such as stroke, even in chronic stages[4, 5)]. In the present study, we report the effects of IVES on a patient with a brain tumor and lower extremity hemiplegia, which caused postoperative hemiplegia.

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PARTICIPANT AND METHODS

The patient was a male in his 40s who was diagnosed with anaplasia oligodendrocytes in the frontal lobe. He noticed that he was urgently transported with stiffness of his left hand and loss of consciousness in X-7 years. After that, the patient convulsed several more times, and the tumor increased in size. Therefore, the first craniotomy to remove the tumor was performed every X-2 year, and a definitive diagnosis of IDH-mutant and 1p/19q-codeletion, WHO grade II in the oligodendrocytes was made. In year X, a neurological symptom appeared that hindered daily activities and driving; thus, a second craniotomy was performed. During the preoperative evaluation, the Fugl-Meyer Assessment (FMA): Lower score was found to be 10 points, and physical and occupational rehabilitation therapy was started on the second postoperative day. Both physical and occupational therapy, such as neuromuscular re-education, strength training, and ADL, were performed. The patient began walking independently with a cane, but his automatic movement of the left ankle joint remained at 0°. The FMA lower limb item was 12 points, and the muscle strength measurement using a hand-held dynamometer (HDD) examination revealed that it was impossible that the voluntary movement of the ankle dorsiflexion was difficult. The Brunnstrom recovery stage (BRS) in the upper limbs was III, BRS in the finger was II, and BRS in the lower was I, and severe sensory impairment was observed in the lower limb. The patient exhibited marked swirling and foot drop when walking. No improvement in gait was observed postoperatively, and postoperative physiotherapy was aimed at around the trunk and hip joint and improving walking. We practiced muscle function, walking on the paralyzed side during the swing and stance phases, and reduction in toe clearance during the swing phase and pelvic compensation with the patient. The back knee was clearly observed during the walking and stance phases, the stability and walking speed were reduced, and the patient had poor functional control of the ankle joint until 40 days after the operation. To improve lower extremity motor function, the gait training was initiated using IVES.

The IVES system (OG GIKEN, Okayama, Japan) is a portable electrical stimulator that performs various stimulus treatment methods[3)] and continually changes its stimulation intensity in proportion to the amplitude of volitional EMG signals and performs electrical stimulation at the submotor and suprathreshold intensities (e.g., no visible muscle contraction, but a tingling sensation is felt) electrically. Stimulation was applied at a frequency of 20 Hz at intervals of 50 μs. The electrodes were manually placed on target muscles[3)]. We applied the IVES power-assist mode to the rectus femoris (REF), and sensor trigger mode to the tibialis anterior (TA)[6)].

From day 40 after the operation, we attempted to train with the IVES external assist mode to improve foot drop[6)]. A pressure sensor was installed on the foot to improve gait, and the electrical stimulation by the pressure sensor was turned on. We used the IVES heel sensor, which is a sensor-trigger mode in which the “off” is controlled. In addition, since there is a risk of knee breakage when using IVES with only the anterior tibial muscle, the IVES heel sensor is also used for the straight thigh muscles when walking. The patient was stimulated while walking for 5 minutes. The IVES gait training was applied regularly during the scheduled physical therapy. The patient was also asked to voluntarily flex his hip and dorsiflex his ankle outside therapy sessions and encouraged to use the affected leg during daily activities.

To assess lower extremity motor function, static posturography and surface EMG (sEMG) were performed before and after IVES. Static posturography was conducted using a computer-driven coordination and balance analysis device (Twin Gravicorder GP-6000, ANIMA, Tokyo, Japan). The patient was asked to remain to stand upright and barefoot on a platform with his eyes open and closed. The measurement time was 30 s in each phase. The center of pressure (CoP) data was used to calculate CoP path length (cm) and Sway area (cm^2)[7)].

Muscle activity data were collected bilaterally with sEMG from the REF, biceps femoris, gastrocnemius, and TA. The activity patterns of these muscles were measured using an instrumented treadmill system (FDM–THM–S, Zebris Medical GmbH, Weitnau, Germany) with a sampling rate of 1,000 Hz. Surface Ag/AgCl electrodes were placed on the skin in accordance with the SENIAM (surface EMG for non-invasive assessment of muscles) guidelines[8)]. The patient was asked to walk on the treadmill for 30 s at 1.0 km/h.

A total of 15 consecutive gait cycles before and after treatment are selected for the sEMG analysis. The sEMG signals were sampled at 1,000 Hz and filtered with a 4th Butterworth bandpass filter cut-off frequency of 20 and 400 Hz. Subsequently, the sEMG signals were rectified, smoothed with a 4th Butterworth lowpass filter with a frequency of 6 Hz, and normalized to the maximum value of each muscle and gait cycle. Then, the sEMG signals were time normalized to 200 time points. The processed sEMG data were used to further analysis. Non-negative matrix factorization (NNMF) was applied to calculate muscle synergies and the total variance accounted for by one synergy from the sEMG data as previously reported[9, 10)].

MATLAB (version R2020a; MathWorks, Inc., Natick, MA, USA) was used for the sEMG signal processing and statistical analysis. The Shapiro–Wilk test was used for to assess data distribution. The paired two-tailed t-test were used to compare the differences between before and after treatment. P-values of <0.05 were considered statistically significant. MATLAB-based spm1d-package was used to assess the differences in sEMG time-series, and to generate the two-tailed t-values maps (https://www.spm1d.org/index.html). The sEMG time-series were significantly different if any values of statistical parametric mapping (SPM) over the entire gait cycle exceeded the critical threshold (alpha=0.05)[11)].

This study was approved by the Ethics Committee of Nara Medical University. The procedures of study were performed in accordance with the ethical standards of the ethics committee, Declaration of Helsinki. The participant provided verbal informed consent after receiving information about this study.

RESULTS

The 10 m walking speed before and after IVES gait training improved from 10.9 to 9.34 s, and the patient's gait also exhibited a reduction in strolling at pelvic compensation during the swing phase, along with reduced toe clearance (Table 1).

To assess the changes in the functional ability to maintain balance before and after IVES, we performed static posturography on the patient with his eyes open and closed. The results of static posturography are shown in Table 1. In the first session, the patient demonstrated a shorter Cop path length and smaller sway area after the treatment than those observed previously with his eyes open. In the second session, the patient had an even longer Cop path length and larger sway area after the treatment than those seen before with his eyes open. These results indicate that IVES gait training improved the patient's functional ability to maintain balance.

To compare muscle activity patterns before and after IVES gait training, a time-series statistical parametric mapping analysis was performed. Comparing the activation pattern of each muscle before and after treatment revealed different timing and duration of sEMG activity in various muscles (Fig. 1). The activity patterns differed significantly before and after treatment, especially in the REF and TA muscles of the affected side. The REF and TA muscles were the target muscles for the treatment. These results indicate that IVES gait training changes the muscle activity time series.

Muscle synergy analysis was conducted to explore the complexity of motor control before and after IVES in the normal (right) and affected (left) sides. We evaluated the changes in the VAF_1 values before and after treatment. On the normal side, the VAF_1 values after treatment were significantly lower than those before treatment (Table 1). The VAF_1 after treatment was considerably lower than that before treatment on the affected side (Table 1). Muscle synergy analysis revealed decreased $tVAF_1$ values in the affected and normal sides after IVES. These results suggest that IVES gait training improves the complexity of motor control during gait.

DISCUSSION

In this study, we assessed the effects of IVES gait trainig on lower extremity hemiplegia patients. IVES improved balance ability and neuromuscular control in patients with chronic lower extremity hemiplegia. Compared to conventional electrical stimulation therapies, IVES is able to both provide an electrical stimulation from electrodes as well as provide various controlled stimuli by simultaneously detecting myoelectric activity from the same electrodes[2, 3)]. Recent studies have shown that IVES promotes agonist muscle contractions and inhibits antagonist muscle activity[4, 6)]. The patient showed improvement in the 10 m walking speed and balance ability after IVES gait training. The improvement observed with IVES could be explained by various mechanisms. Alternative motor pathways were recruited and activated to assist impaired efferent pathways. Based on the sensory-motor integration theory, sensor input from EMG-triggered affected limb movement directly influences subsequent motor output[2, 4)]. Proprioceptive sensory feedback may therefore play an important role in the recovery of lower extremity motor functions[2, 4)]. Furthermore, activated motor and sensory nerve fibers promoted cortical reorganization and had positive effects on postural control through sensory stimulation of the paralyzed limb muscles[2, 4)]. These findings are consistent with previous studies.

Table 1. 10-meter walk test, static posturography and surface electromyography examination before and after integrated volitional control electrical stimulator (IVES) gait training

		Before IVES	After IVES
10-meter walk test (sec)		10.9	9.43
Static posturography			
Eye-open	Path length (cm)	50.13	50.39
	Sway area (cm^2)	2.87	2.07
Eye-close	Path length (cm)	108.64	98.47
	Sway area (cm^2)	9.65	7.53
Surface electromyography			
$tVAF_1$ (%)	Right	76.88 ± 2.20	69.11 ± 3.89*
	Left	87.93 ± 1.64	86.31 ± 1.66*

In 10-meter walk test and Static posturography examination, the value is the mean value of two evaluations. CoP path length and sway area were compared between before and after IVES with eyes open and closed. In surface electromyography analysis, the total variance accounted for by one synergy ($tVAF_1$) was compared between before and after IVES conditions of $tVAF_1$ in normal (right) and affected (left) sides. *$p<0.05$. Data are presented as mean ± SD (n=15 cycles for both conditions). Cop: center of pressure; IVES: integrated volitional control electrical stimulator.; $tVAF_1$: total variance accounted for by one synergy; SD: standard deviation.

We performed muscle synergy analysis on sEMG data before and after IVES. A muscle synergy is the coordinated recruitment of a group of muscles to perform purposeful movements[12, 13]. In accordance with the modular organization of motor control, muscle synergy has been proposed as a physiological model for flexible movement with minimal neural processing of motor output[12, 13]. Recent neurophysiological studies have recommended the analysis of muscle synergies to assess the individual impairment of the patient, to design personalized rehabilitation, and to evaluate the efficacy[14–16]. A multi-channel

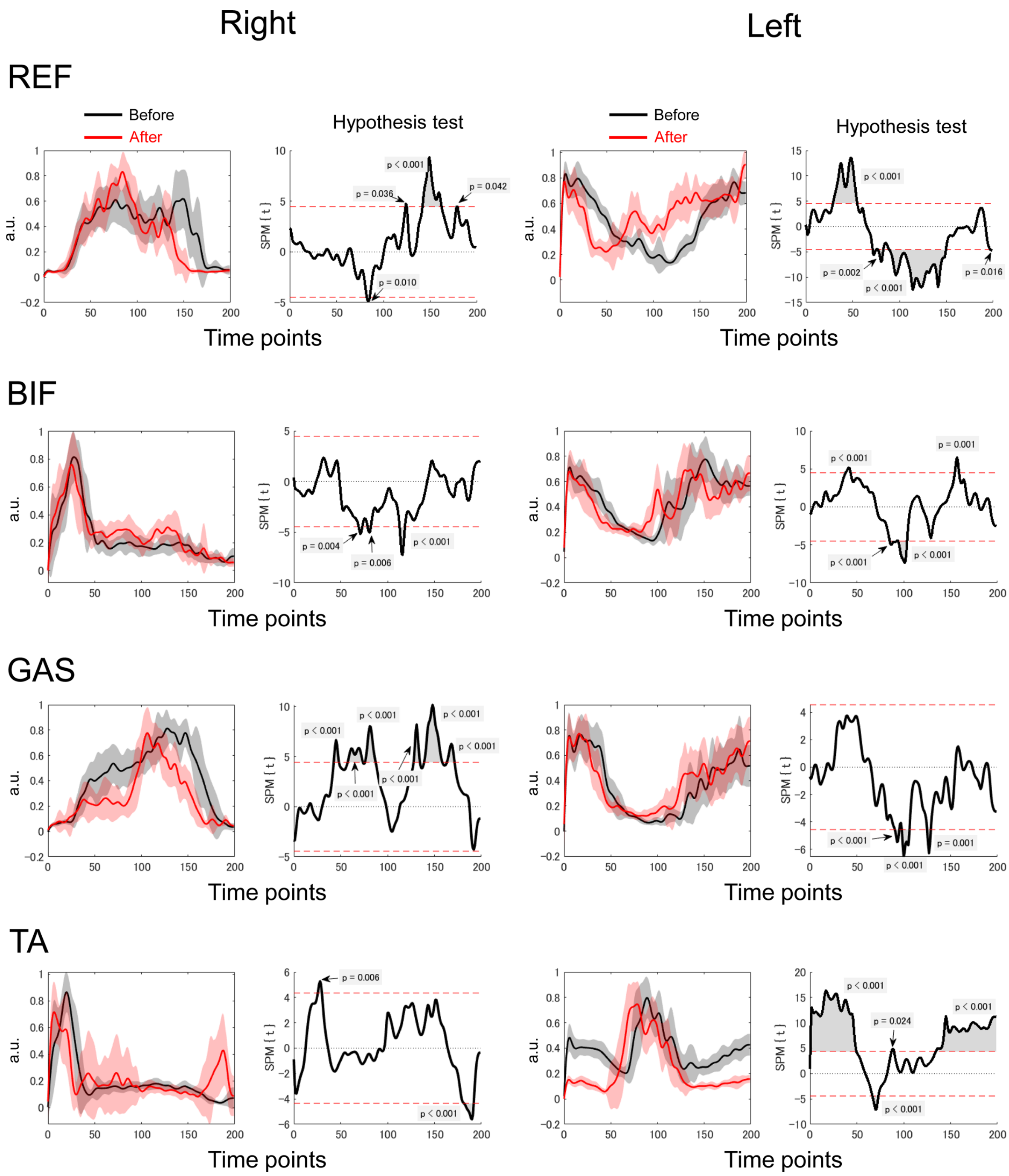

Fig. 1. Statistical parametric mapping analysis. The conditions of sEMG time-series in normal (right) and affected (left) sides compared between before and after IVES gait training. Data are expressed as mean ± SD (n=15 cycles for both conditions). Black lines indicate before treatment condition, and red lines indicate after treatment condition. Hypothesis test results show time-dependent t-values of the statistical parametric mapping. Horizontal red dashed line indicates p=0.05 level. Gray zones indicate regions with statistically significant differences. IVES: Integrated volitional control electrical stimulator; sEMG: surface electromyography; SD: standard deviation; REF: rectus femoris; BIF: biceps femoris; GAS: gastrocnemius; TA: tibialis anterior; a.u.: Arbitrary unit.

FES-based personalized treatment for post-stroke patients increased the number of muscle synergies and improved muscle coordination in gait[15]. The FES-based walking rehabilitation alleviated the problems of muscle coordination and the weakness of specific muscles in stroke patients[16]. We calculated and evaluated $tVAF_1$ values, and these values showed lower after treatment in normal and affected sides. In muscle synergy analysis, $tVAF_1$ can quantify the complexity of muscle activation patterns, and lower $tVAF_1$ values represent increased complexity of motor control[10]. In this study, the patient showed left extremity hemiplegia caused by brain tumor in the right frontal lobe. High level motor structures, such as the primary motor cortex, may contribute to coordinating and activating limb muscles for complex motor tasks by incorporating a subset of muscle synergies[17]. A previous study reported that IVES facilitate the perfusion of the sensory-motor cortex and result in functional improvement of the hemiparetic upper extremity[18]. In our case, it is suggested that IVES changed sensory-motor cortical activation, and as a result, increased motor control complexity assessed by muscle synergy analysis.

The present study is a case study, therefore, a large-scale study with appropriate sample size is required to validate our results. In conclusion, the IVES gait training was effective for a patient with chronic hemiparetic lower extremity impairment. An EMG-triggered FES may facilitate sensory-motor integration. Proprioceptive sensory feedback plays a vital role in improving motor control.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

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