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Original Article

Contralaterally controlled functional electrical stimulation immediately improves hand function

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ABSTRACT
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Objective: The purpose of this study was to investigate the immediate effects of contralaterally controlled functional electrical stimulation (CCFES) on upper limb function in stroke patients.
Methods: CCFES and mirror therapy (MT) exercises were conducted for 13 stroke patients at least 4 weeks post-onset. A sufficient interval of at least 24 hours was left between the two types of rehabilitation exercises. Before treatment and immediately after each training session, grip strength, Fugl-Meyer Assessment for Upper Extremity (FMA-UE) score and FMA-UE subscores for the shoulder/elbow/forearm, wrist, hand, and coordination were evaluated.
Results: Grip strength, FMA-UE and FMA-UE shoulder/elbow/forearm, wrist, and coordination did not differ significantly after CCFES and MT compared to before therapy. FMA-UE hand did not change significantly after MT compared to before therapy, but it improved significantly after CCFES ($p = 0.013$).
Conclusion: CCFES for the upper extremities immediately improves hand function and may be effective in maintaining and improving patients' motivation for rehabilitation treatment.
Key words: stroke, functional electrical stimulation, contralateral control, immediate effect, hand function

Introduction

It is estimated that around 75% of stroke patients have upper extremity disabilities [1], and motor dysfunction of the upper limbs is a major factor that impairs activities of daily living (ADL). Therefore, recovery of upper limb function is essential to improve ADL in stroke patients [2]. Zheng et al. [3] reported that early recovery of wrist dorsiflexion function contributes not only to the improvement of upper limb function, but also to the improvement of ADL.

Therapeutic electrical stimulation (TES) and functional electrical stimulation (FES) are rehabilitation therapies to restore the function of fingers and joints. In many cases of paralysis caused by upper motor neuron failure such as stroke, normal electrical excitability remains in the lower motor neurons and the muscles innervated by them. Therefore, TES is expected to provide therapeutic effects such as muscle recovery, voluntary stimulation, inhibition and improvement of muscle atrophy progression, relief of spasticity, and improvement of joint range of motion. FES can reconstruct the motor function of the paralyzed limb and improve functional impairment and disability [4−6]. FES/TES systems can be divided into three types according to the electrodes used: surface electrodes, percutaneously implanted electrodes, and fully implanted electrodes [5]. In recent years, FES systems using surface electrodes that do not require electrode implantation surgery have become available, and the surface electrode FES NESS H200 hand rehabilitation system (NESS H200®, Bioventus LLC, Durham, NC, USA) has been reported to improve

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upper limb function after stroke [7].

On the other hand, in addition to the conventional FES treatment, contralaterally controlled functional electrical stimulation (CCFES) has been proposed as a method to improve the function of paralyzed upper limbs after stroke [8]. CCFES uses a control signal from the non-paralyzed side of the extremity to adjust the strength of the electrical stimulation administered to the paralyzed muscles, and its characteristic feature is that it requires active participation by the patient rather than simply giving electrical stimulation to a paralyzed muscle or extremity. Shen et al. [9] compared the effectiveness of CCFES and conventional FES in a study of subacute stroke patients and found that more effective improvement was achieved with CCFES over the long term.

CCFES is thought to be useful for improving the upper limb function of stroke patients [10], but it takes time to prepare with the conventional device because the position of the surface electrode needs to be set each time. Therefore, we developed a new CCFES device using wireless electromyography (EMG). In addition, CCFES for upper limb dysfunction in stroke patients has been reported to improve upper limb function in the long term [9], but its immediate effects remain unknown.

The purpose of this study was to investigate the immediate effect of CCFES using a new device on the upper extremity function of stroke patients.

Methods

1. Patients

The study subjects were 13 patients (6 males and 7 females, median age 71 years) who had been hospitalized for stroke for 4 weeks after onset between April 2020 and March 2021.

The inclusion criteria were: (i) stroke diagnosed by computed tomography (CT) or magnetic resonance imaging (MRI); (ii) at least 1 month elapsed since stroke diagnosis; (iii) age 20−80 years; and (iv) upper extremity Brunnstrom stage III or less.

The exclusion criteria were: (i) unstable condition due to progressive stroke; (ii) unable to follow treatment instructions due to severe cognitive impairment or communication difficulties; (iii) implanted pacemaker; and (iv) absence of informed consent.

All subjects provided written, informed consent before the start of the study.

2. CCFES system

We have developed a new CCFES device that uses wireless EMG. In the present study, EMG signals in the frequency band range of 4.8 Hz−452 Hz, recorded while the patient voluntarily extended the non-paretic hand wearing the glove-type recording electrodes and held the extended position, were full-wave rectified. The integrated value per unit time (iEMG) was subsequently calculated and the recording was wirelessly transmitted to a computer (dynabook B65/J, Dynabook Inc., Tokyo, Japan). The NESS was wired to an electrical stimulator (SEN-8203, Nihon Kohden Co., Tokyo, Japan), and stimulation electrodes were attached to the extensor pollicis brevis and extensor digitorum communis muscles. The stimulation intensity (stimulation frequency: 40 Hz, pulse width: 0.2 ms) for each patient was the minimum value at which the paralyzed finger began to extend and the maximum value at which the finger fully extended.

The NESS used only the orthosis and stimulation electrodes, excluding the control unit. When the finger on the non-paralyzed side was extended and the myoelectric activity reached the set threshold, the electrical stimulation was output to the paralyzed side, and the finger on the paralyzed side was programmed to extend (Figure 1).

Our newly developed CCFES device allows the wearer to control the paralyzed upper limb voluntarily by measuring the muscle activity of the non-paralyzed side and feeding it back to the paralyzed side. It can also provide stimulation to the paralyzed upper limb at times freely selected by the patient instead of at predetermined routine training intervals. In addition, unlike existing reports on CCFES systems [10], the myoelectric measurements of our system are conducted wirelessly, which permits a greater amount of freedom when undergoing rehabilitation.

3. Methods

The patients were evaluated before the start of the treatment (before therapy), underwent rehabilitation treatment with regular occupational therapy (20 min per session), and then underwent training with CCFES for 20 min and were evaluated after completion (after CCFES). More than 24 h later, the patients underwent the usual rehabilitation treatment by occupational therapy (20 min per session), followed by 20 min of mirror therapy (MT) [11], and they were evaluated again after completion (after MT). In the CCFES training, the patients were instructed to dorsiflex the wrists and extend the fingers of both hands at their own pace. While the paralyzed side was stimulated with the electrical signal generated by the movement of the non-paralyzed side, they were instructed to dorsiflex and extend the wrist and fingers on the paralyzed side, and then to rest for 3 s after this wrist dorsiflexion and finger extension were complete before repeating the movements. The therapist guided the patients to look at the hand on the paralyzed side during these exercises.

MT (20 min per session) was conducted by an occupational therapist after regular rehabilitation therapy. For 20 min, the patients watched their non-paralyzed hand in a mirror positioned so that it appeared to be their paralyzed hand, and they were instructed to carry out wrist dorsiflexion and finger extension while making their movements as bilaterally

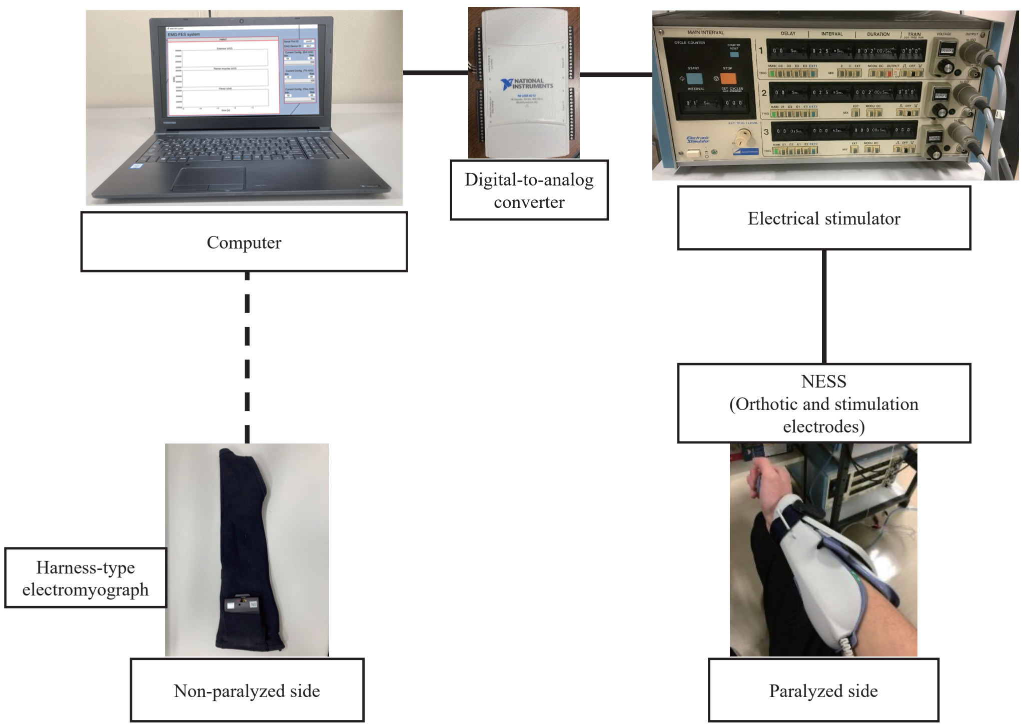

Figure 1. The new contralaterally controlled functional electrical stimulation (CCFES) device using wireless electromyography.
The voluntary EMG detected by the orthotic wireless EMG on the non-paralyzed side is analyzed by a computer, and then an electrical stimulus proportional to the EMG is given to the paralyzed side.

symmetrical as possible. During this exercise, the occupational therapist passively flexed and extended the hand on the paralyzed side so that its movements mimicked those of the non-paralyzed side. The goal of both CCFES and MT was to perform about 10 movements per min, with appropriate guidance from the occupational therapist according to the patient's concentration and degree of paralysis.

Grip strength, the Fugl-Meyer Assessment for Upper Extremity (FMA-UE) score, and the individual FMA-UE subscores for the shoulder/elbow/forearm, wrist, hand, and coordination were evaluated. These evaluations were conducted before therapy, after CCFES, and after MT. Grip strength, the FMA-UE score, and the subscores between before therapy and after CCFES, and between before therapy and after MT were tested for significant differences using the Wilcoxon test. All statistical analyses were conducted with JMP 14.2.0 (SAS, Cary, NC, USA), with $p < 0.05$ regarded as significant. This study was approved by the Ethics Committee of Akita University Hospital (approval number 1967).

Results

The median time from the onset of stroke to the start of treatment was 86 days. Eight subjects were diagnosed with cerebral infarction, five with cerebral hemorrhage, and seven with upper limb Brunnstrom stage II and six with stage III motor palsy (Table 1).

There was no significant difference in grip strength before and after each treatment (Table 2). FMA-UE, FMA-UE shoulder/elbow/forearm, wrist, and coordination did not differ significantly before and after CCFES and MT treatment. FMA-UE hand did not change significantly after MT compared to before treatment, but it improved significantly after CCFES ($p = 0.013$). No adverse events were observed.

Discussion

In this study, training using the newly developed CCFES device for hemiplegic stroke patients did not significantly improve grip strength and FMA-UE after CCFES and MT compared to before treatment. Only FMA-UE hand did not change significantly after MT compared to before treatment, but it did improve significantly after CCFES.

CCFES has recently been developed as a more active form of training that reflects the patient's own intentions. The movement of the non-paralyzed side is measured, with the aim of creating movement on the paralyzed side that is bilaterally symmetrical and almost simultaneous. A randomized, controlled trial of the efficacy of CCFES was carried out by Knutson et al. [10] in 2016. They randomly allocated 80 stroke patients in the chronic phase at least 6 months after onset to receive either CCFES or neuromuscular

Table 1. Demographic data.

Age, y, Median (QR)	71 (64.3–74.5)
Sex, *n* (%)	*n*=13
Male	6 (46.2)
Female	7 (53.8)
Median days since onset (QR*)	86 (64–140)
Diagnosis	
Cerebral infarction	8
Cerebral hemorrhage	5
Upper extremity Brunnstrom stage	
II	7
III	6

*QR, quartile range.

Table 2. Grip strength and Fugl-Meyer Assessment.

	Before therapy	After CCFES	After MT	*p*-Value before therapy vs after CCFES	*p*-Value before therapy vs after MT
Grip strength (kgf)	2.5 (0–3.5)	3 (1–4.25)	2.5 (0–3.75)	0.174	0.354
FMA-UE	11 (5–18)	15 (7–23)	11 (5–20)	0.118	0.354
FMA-UE shoulder/elbow/forearm	5 (4–8)	5 (4–8)	5 (4–8)	1.000	1.000
FMA-UE wrist	2 (0–4)	3 (0–6)	2 (0–5)	0.246	0.364
FMA-UE hand	5 (1–6)	8 (3–9)	6 (1–7)	**0.013**	0.063
FMA-UE coordination	0 (0–0)	0 (0–0)	0 (0–0)	1.000	1.000

Median (quartile range); *p*-Value by Wilcoxon test.
FMA, Fugl-Meyer Assessment; FMA-UE, FMA of motor function of upper extremity; CCFES, contralaterally controlled functional electrical stimulation; MT, mirror therapy.

electrical stimulation (NMES), and they showed that 12-week CCFES therapy improved finger dexterity to a greater extent than did the equivalent amount of NMES. Shen et al. [9] also compared the effectiveness of CCFES and NMES in patients, and showed that CCFES was superior to NMES in terms of improved upper extremity function. To the best of our knowledge, however, no previous study has addressed the immediate effects of CCFES. In the present study, CCFES was shown to have an immediate effect of improving hand function in stroke patients.

In previous studies, Zheng et al. [3] reported that CCFES improved wrist dorsiflexion function and upper extremity function assessed by FMA in stroke patients soon after onset, and Kim et al. [12] reported that CCFES improved wrist dorsiflexion function and finger grip strength in stroke patients in the chronic phase. In the present study, although there was no immediate improvement in wrist dorsiflexion function, CCFES of the wrist dorsiflexion muscles did promote improved finger function as an immediate effect, and continuation of these exercises might lead to long-term functional improvement of the wrist and the upper extremities as a whole.

Regarding the immediate effects of rehabilitation therapy, it has been reported that the immediate improvement in gait speed after FES in the lower extremities is useful for setting goals and motivating therapists and patients for treatment [13]. Studies have demonstrated the importance of improved physical function as a result of exercises, the experience of success, and the provision of a wide variety of different exercises for increasing and maintaining motivation for rehabilitation treatment on the part of stroke patients [14]. Conducting exercises with CCFES in addition to conventional exercises may have a beneficial effect in making patients feel more positive about rehabilitation treatment by adding diversity to the types of rehabilitation therapy used and by giving patients the experience of success in the form of immediate functional improvement.

Regarding long-term effects, MT, which was compared in the present study, has been reported to be useful for the long-term improvement of motor function in stroke patients [15]. CCFES has also been shown to have a long-term effect on upper limb function in subacute stroke patients [9]. CCFES showed more immediate effects on hand function than MT in the present study, suggesting that CCFES may be more effective than MT, but further studies are needed to compare the long-term effects.

The limitations of this study are the small number of cases and the lack of a group in which the order of CCFES and MT was changed. In the future, we plan to increase the number of patients and compare the long-term effects of CCFES with those of MT.

Conclusion

CCFES for the upper limbs of stroke patients immediately improved hand function, and training with CCFES is expected to effectively maintain and improve motivation for rehabilitation treatment in stroke patients.

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References

1. Lloyd-Jones D, Adams RJ, Brown TM, Carnethon M, Dai S, De Simone G, et al. Heart disease and stroke statistics−2010 update: a report from the American Heart Association. Circulation 2010; 121: e104.
2. Wilson RD, Page SJ, Delahanty M, Knutson JS, Gunzler DD, Sheffler LR, et al. Upper-limb recovery after stroke: a randomized controlled trial comparing EMG-triggered, cyclic, and sensory electrical stimulation. Neurorehabil Neural Repair 2016; 30: 978−87.
3. Zheng Y, Mao M, Cao Y, Lu X. Contralaterally controlled functional electrical stimulation improves wrist dorsiflexion and upper limb function in patients with early-phase stroke: a randomized controlled trial. J Rehabil Med 2019; 51: 103−8.
4. Shimada Y, Sato K, Abe E, Kagaya H, Ebata K, Oba M, et al. Clinical experience of functional electrical stimulation in complete paraplegia. Spinal Cord 1996; 34: 615−9.
5. Matsunaga T. Functional electrical stimulation (1). Rinsho Nouha 2007; 49: 584−8. Japanese.
6. Handa Y, Ohkubo K, Hoshimiya N. A portable multi-channel FES system for restoration of motor function of the paralyzed extremities. Automedica 1989; 11: 221−31.
7. Alon G, Levitt AF, McCarthy PA. Functional electrical stimulation enhancement of upper extremity functional recovery during stroke rehabilitation: a pilot study. Neurorehabil Neural Repair 2007; 21: 207−15.
8. Knutson JS, Harley MY, Hisel TZ, Chae J. Improving hand function in stroke survivors: a pilot study of contralaterally controlled functional electric stimulation in chronic hemiplegia. Arch Phys Med Rehabil 2007; 88: 513−20.
9. Shen Y, Yin Z, Fan Y, Chen CF, Dai W, Yi W, et al. Comparison of the effects of contralaterally controlled functional electrical stimulation and neuromuscular electrical stimulation on upper extremity functions in patients with stroke. CNS Neurol Disord Drug Targets 2015; 14: 1260−6.
10. Knutson JS, Gunzler DD, Wilson RD, Chae J. Contralaterally controlled functional electrical stimulation improves hand dexterity in chronic hemiparesis: a randomized trial. Stroke 2016; 47: 2596−602.
11. Zeng W, Guo Y, Wu G, Liu X, Fang Q. Mirror therapy for motor function of the upper extremity in patients with stroke: a meta-analysis. J Rehabil Med 2018; 50: 8−15.
12. Kim JH, Lee BH. Mirror therapy combined with biofeedback functional electrical stimulation for motor recovery of upper extremities after stroke: a pilot randomized controlled trial. Occup Ther Int 2015; 22: 51−60.
13. Park SJ, Wang JS. The immediate effect of FES and TENS on gait parameters in patients after stroke. J Phys Ther Sci 2017; 29: 2212−4.
14. Yoshida T, Otaka Y, Osu R, Kumagai M, Kitamura S, Yaeda J. Motivation for rehabilitation in patients with subacute stroke: a qualitative study. Front Rehabil Sci 2021; 2: 664758.
15. Thieme H, Mehrholz J, Pohl M, Behrens J, Dohle C. Mirror therapy for improving motor function after stroke. Cochrane Database Syst Rev 2012; 2021 (3): CD008449.