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Specifications of an electromyogram-driven neuromuscular stimulator for upper limb functional recovery*

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***Abstract* — An electromyogram (EMG)-driven neuromuscular stimulator for upper limb functional recovery (Muraoka et al., 1998) can stimulate target muscles in proportion to the amount of voluntary EMG of the identical target muscles. Furthermore, it can facilitate the contraction of paralyzed muscles by electrical stimulation at subthreshold intensity level.**

Although it has been suggested that to use the stimulator for as long a time as possible might be needed for more effective treatment, the utilization time was limited by the size of the stimulator, which involved a laptop personal computer. To use in daily life, the device was improved to be a smaller size of 95×65×40 mm (including batteries) which was equivalent to a mobile phone (in 2002). The stimulator was called the Integrated Volitional-control Electrical Stimulator (IVES). IVES has already been manufactured and its use has spread in Japan since 2008. Nowadays, therapy using IVES is an effective therapy to improve the motor function of the upper limb in post-stroke patients with hemiparesis. However, the signal processing and internal structure of IVES has not yet been reported.

In this study the device specification of IVES is described, especially its electrical circuits and signal processing that detect voluntary EMG and stimulate from the same electrodes. IVES uses two DIACs for detecting voluntary EMG from stimulating electrodes. The DIACs switch passively between the stimulation circuit and the EMG amplifier circuit. Furthermore, the signal processing of the time-shifted difference of the 2-cycle EMG signal following identical stimulation pulses eliminates stimulation artifacts and evoked potentials, and extracts voluntary EMG.

I. Introduction

Many stroke patients suffer from a paralyzed upper extremity, including functional limitation of the affected arm and limitations in their activities of daily living (ADL) [1]. Recovery of function in the paretic upper limb is noted in fewer than 15% of patients after stroke [2]. Patients often compensate for their paretic upper limb by using their intact limb in the performance of everyday tasks [3].

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Paretic muscles due to central nervous system impairment such as spinal cord injury or stroke can be externally contracted by electrical stimulation (FES: Functional Electrical Stimulation) and functions of the paretic limb can be restored. One of the FES techniques employed to facilitate motor restoration in chronic stroke patients is electromyogram (EMG)-triggered electrical stimulation [4], [5], [6], [7]. This method requires the patient's voluntary muscle contractions to exceed a target threshold for the onset of electrical stimulation. If the EMG activity exceeds the threshold, the muscle contractions are augmented by electrical stimulation that assists the patients to achieve joint movements through the full range of motion (ROM). However, there is a problem associated with this method: it cannot modify the intensity of electrical stimulation according to voluntary EMG signals because EMG activity is not monitored while the preprogrammed electrical stimulation is being delivered. Thus, the programmed electrical stimulation can disturb intended voluntary movements during ADL.

Another method uses an EMG-controlled electrical stimulator that applies electrical pulses to the muscle depending on the amount of voluntary EMG. This method reinforces the voluntary muscle contraction. Several kinds of EMG-controlled electrical stimulator [8], [9], [10] have been reported. Sennels et al. [9], and Thorsen et al. [10] proposed this type of functional electrical stimulator, for C5/C6-lesion tetraplegic patients. Their approach was to record voluntary EMG signals from a paralyzed muscle by surface electrodes, and to modify the amplitude of electrical stimulation to the same muscle, thereby resulting in an amplification of muscle contraction. Their method was applied to the paretic wrist extensor muscle to obtain a feasible grasp. This system needs five surface electrodes placed on the skin over a target muscle: two for stimulation, two for recording, and one for reference.

Muraoka et al. [11], [12], [13] developed a novel type of EMG-controlled electrical stimulator. This system could apply electrical pulses via EMG recording electrodes with Photo-MOS Relays. Only three electrodes were required per muscle: two for recording/stimulation and one for reference. The device size was 150×170×85 mm and used for EMG biofeedback and therapeutic electrical stimulation (TES) in therapy sessions [12], [14]. However, the device was too large for the patients to wear on the body and to carry around. With this type of stimulator, it is difficult to lessen chronic hemiparetic upper extremity impairment because of its limited therapeutic time.

However, Muraoka then proposed to miniaturize the stimulator for use in daily life [12]. The mobile-sized EMG-controlled electrical stimulator will enhance patients' ADL by enabling them to use it for an extended time in daily

life. Thus, extended intensive therapy sessions can be avoided. Muraoka [15] developed the mobile EMG-controlled electrical stimulator, called the Integrated Volitional Control Electrical Stimulator (IVES), in 2002. The size of the device is 95×65×40 mm including four AAA dry batteries. IVES works as follows. During periods of no muscle contraction, IVES facilitates the target muscles by submotor-threshold level stimulation. When muscle contraction is detected, IVES stimulates the muscles at an intensity proportional to the detected volitional EMG signals.

IVES has already been used for the treatment of chronic stroke patients. Hara et al. [16] found that daily IVES therapy at home resulted in enhanced motor recovery in patients with partial hand or shoulder motion. In addition, they reported the efficacy of combined treatment with IVES and motor point blocks for antagonist muscles in patients with chronic stroke [17]. Fujiwara et al. [18] showed that facilitated use of the paretic upper extremity by combining IVES with a wrist-hand splint could improve both the function of the paretic upper extremity and corticospinal modulation in chronic stroke. Yamaguchi et al. [19] demonstrated the efficacy of IVES treatment alone in patients with hemiparetic stroke. Their study suggested that 6 h/ day for 5 days of IVES treatment including during daily activities yielded a noticeable improvement in upper extremity motor functions in patients with chronic hemiparetic stroke.

Nowadays IVES has become one of the most effective therapies to improve motor function of the upper limb in post-stroke patients with hemiparesis. However, the internal structure and signal processing of IVES has not been reported. In this study the device specification of IVES is described, especially its electrical circuits and signal processing, to detect voluntary EMG that can be corrupted by electrical stimulation artifacts.

II. Methods

A. *Electrical circuit of the device* [15]

The device had dimensions of 95×65×40 mm, including four AAA dry batteries (6 V) as shown in Fig. 1. The reference electrode was placed at the posterior area of the forearm (on the extensor digitorum communis; EDC), and a pair of electrodes were placed on the posterior region of the forearm (on the extensor carpi radialis; ECR). These positions were approximately 3–4 cm proximal to the ulnar styloid, radial to the ulnar shaft and 2 cm above the elbow crease, respectively.

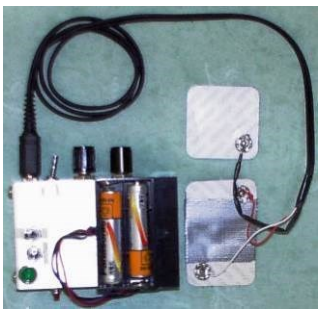

Fig. 1 Appearance of the device, which measured 95×65×40 mm (including protuberances)

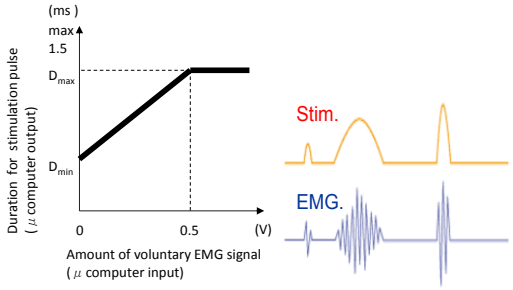

Fig. 2 Relationship between amount of voluntary EMG (contraction) and duration of stimulation pulse (intensity).

The stimulation pulse duration that corresponded to the stimulation intensities was modulated in proportion to the maximum amplitude of voluntary EMG of the ECR that was detected in the period of 49–59 ms after stimulation pulses were applied. The stimulation intensities of the reference electrode and the pair of EMG recording electrodes were controlled independently by a microcomputer. The relationship between the amount of voluntary EMG and the stimulation intensity (pulse duration) is shown in Fig. 2. During the detection of voluntary EMG, the signal was amplified so that the maximum amplitude of the voluntary EMG was equal to 0.5 volts. During periods of no voluntary contraction, the duration of stimulation pulses (D_{min}) were adjusted to the threshold intensity of contraction to facilitate voluntary contraction. During maximum voluntary contraction, the durations of the stimulation pulses (D_{max}) were equivalent to the maximum endurable intensity.

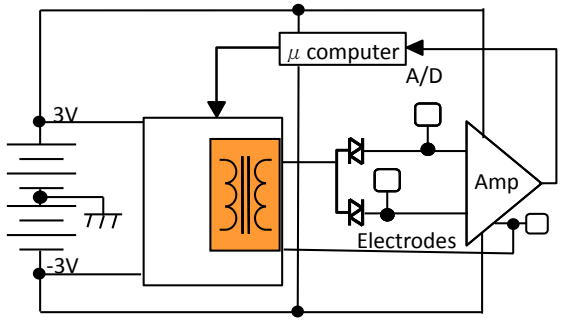

Fig. 3 Block diagram of the device

The block diagram of the device is shown in Fig. 3. The two DIACs (diode for alternating current: a diode that conducts current only after its breakover voltage, V_{BO}, has been reached momentarily) were located between one side of the stimulator output and each electrode. During the recording of voluntary EMG, these DIACs isolated the amplifiers from the stimulation circuit using an output transformer to reduce the noise of the stimulation circuit and to avoid short-circuits between each of the electrodes. The electrical charge on the electrodes due to the stimulation pulses was passively discharged via the stimulation output transformer. The pulse was applied every 60 ms and unsymmetrical biphasic rectangular waveforms with a duration of 0-1 ms were applied to the pair of electrodes. Because the muscle could be contracted by a negative polar pulse, the present device had two channel outputs i.e. from the reference electrode and the electrode pair. During the delivery of stimulation pulses, when

the voltages between the terminals of each DIAC exceeded 0.5 volts, the DIACs automatically switched on and allowed the electric pulses to reach the electrodes in the stimulation circuits. Any background noise, such as artifacts from the stimulation pulses from the stimulation output, was commonly inputted to the first stage amplifier.

B. Signal processing for voluntary EMG extraction

Fig. 4 shows a waveform diagram that explains the signal process of a controller for detecting a voluntary EMG signal while removing stimulation artifacts and evoking potential signals. The bottom line represents the stimulation pulse signal consisting of stimulation pulse waveforms expressed every 60 ms. One unit of stimulation pulse signal consists of two identical stimulation pulse waveforms. Therefore, the stimulation waveforms were renewed every 120 ms. Following input from the controller, the voluntary EMG signal was passed to the A/D conversion input PIN, sampled at a sampling cycle of 1 ms and converted to a digital signal. The waveform, as shown in the second line from the bottom, was a signal formed by convolving the EMG signal including an M-wave with the stimulation signal and the artifact. The stimulation signal was input at the beginning of the 60−ms cycle. The amplitude of the signal was extremely large comparing to the voluntary EMG signal, and the stimulation signal was not necessary for the following signal processing; therefore, the amplitude of the signal was limited not to exceed the predetermined level of the two DIACs. The two stimulation waveforms at a 60-ms cycle were the same so that the corresponding two artifacts and the M-waves were also the same. Therefore, only the voluntary EMG signal could be extracted by cancelling the artifacts and the M-waves out. The signals were not stable from the beginning of the 60-ms cycle for a while (approximately 20 ms); therefore, it became possible to extract the component of the voluntary EMG signal stably by taking the difference near the end of the cycle

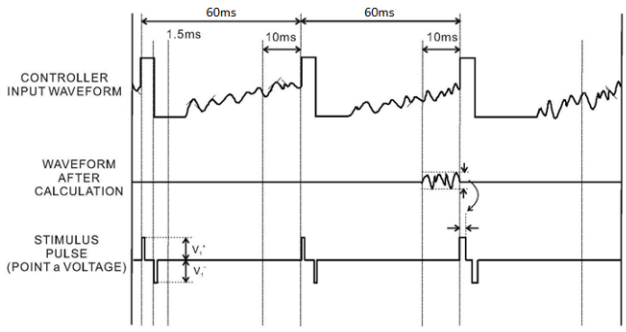

Fig. 4 Signal processing for the extraction of the amount of voluntary contraction

(the difference was taken over 10 ms before the end in the below-described example but may be taken over a longer period).

III. Performance Test

The relationship between the input (the signal with voluntary EMG) and the output (for stimulation control pulse) of the microcomputer were examined as a performance test in a healthy subject. The pair of electrodes was set on the belly of the ECR, and the reference electrode was placed at the posterior area of the forearm (on the EDC). The results are shown in Fig. 5. The upper panels of Fig. 5 represent the input signal to the microcomputer, the voluntary EMG from the ECR. Output 1 and output 2 in the lower panels of Fig. 5 are the control signals for stimulating EDC and ECR, respectively. Each output signal was controlled independently.

During periods of no contraction, pulses with the duration for threshold intensity were delivered to the EDC and the ECR as shown in Fig. 5 (a). During maximum contraction, the pulses with the duration for maximum intensity were independently applied to the EDC and the ECR as shown in

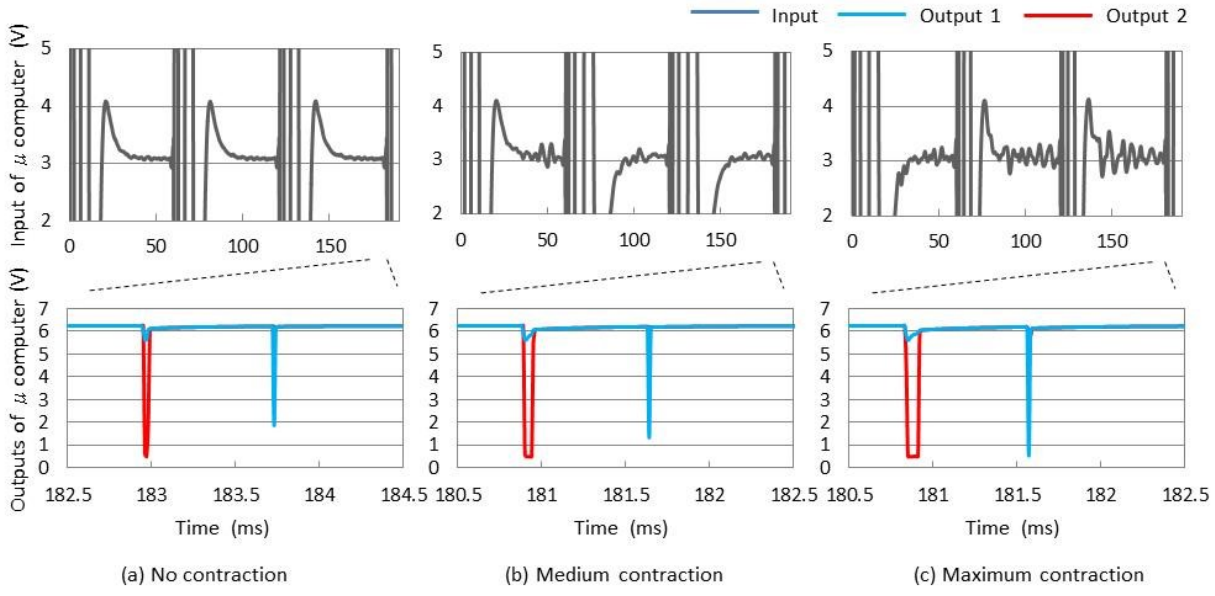

Fig. 5 The result of performance test

Fig. 5 (c). Similarly during a medium contraction, the duration of the output corresponded to a middle intensity between the maximum and the minimum as shown in Fig. 5 (b). It was confirmed that the pulse duration changed gradually between the minimum threshold value and its maximum according to the input voluntary EMG signal, and each channel output could be separately controlled.

IV. Discussion

We developed a pocket-sized device, small enough to mount on the body and carry around everywhere. The production costs are low because the DIACs are inexpensive. As the stimulation pulses automatically switch on and the pair of electrodes can be isolated from the stimulator, a microcomputer is not required to generate a control signal for switching to isolate. As a result, because the number of IO-ports are few and the amount of occupied ROM is small, a simpler and smaller microcomputer can be selected.

The signal processing of the time-shifted difference of 2-cycle EMG signals following identical stimulation pulses eliminated stimulation artifacts and evoked potentials, and extracted the correct amount of voluntary EMG. In this process, the stimulation intensity was renewed every 120 ms. It would be enough to follow the quick motion of upper extremity in stroke patients.

It is difficult for ordinary users to operate the present system because the adjustment of the gain of the EMG-amplifier and the setting of the threshold voltage of the stimulation output are complicated. For patients to use the device in activities of daily living at home, an auto-tuner should be installed [12], which will be explored in further studies.

V. Conclusion

IVES can stimulate target muscles in proportion to the level of voluntary EMG of the identical target muscles. The device has dimensions of 75×50×20 mm including four AAA dry batteries (6 V). It is small enough to mount on the body and carry around, and use during ADL. It enhances the patient's ADL by allowing them to use the system for many hours in daily life. Thus, extended intensive therapy sessions can be avoided.

The structure and mechanism of IVES was described in this study. IVES uses two DIACs for detecting voluntary EMG from stimulating electrodes, which switch to the stimulation circuit from the EMG amplifier circuit passively. Furthermore, the signal processing of the time-shifted difference of the 2-cycle EMG signal following identical stimulation pulses eliminated stimulation artifacts and evoked potential, and extracted voluntary EMG.

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