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Volitional EMG Controlled Wearable FES System for Lower Limb Rehabilitation

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Abstract— **Muscle rehabilitation by functional electrical stimulation (FES) is one of the effective treatments for the patients with neuromuscular diseases. The conventional FES applications, however, have limitations that utilize predetermined or repetitive stimulation patterns with the help of experts such as physical therapists. Therefore, we propose a wearable FES system in which the stimulus intensity is dynamically controlled by the motion intention of user in this paper. The proposed FES system utilizes electromyography (EMG) and inertial measurement unit (IMU) sensors for estimating the motion intention regardless of electrical stimulation, and is designed for the lower limb rehabilitation. The overall system configurations including hardware and software are presented in this paper, and the system performance was tested by lower limb exercises, e.g., squat, heel lift, and gait.**

I. INTRODUCTION

Functional electrical stimulation (FES) utilizes electrically induced muscle contractions to generate functional movements of human joints and has been researched for decades to restore the function of wounded or aged muscles. FES has been actively applied to patients with muscle motor disorders due to various diseases in the field of rehabilitation [1]–[4]. In addition, electrical muscle stimulation (EMS) training has recently been studied to exploit the FES technology for muscle strength training of athletes and healthy subjects [5]–[7].

The studies cited above have shown positive effects on rehabilitation and strengthening of muscle function. In particular, a common suggestion is that the continuous and steady long-term FES rehabilitation can increase the effectiveness of muscle restoration or muscle fiber adaptation. However, conventional FES rehabilitation systems have been limited to hospital treatment requiring expert physical therapists. Few FES systems can be used by patients themselves, and these are limited to specific applications. Moreover, these systems cannot sufficiently reflect the various motion intentions of patients because they are operated by certain predetermined stimulation patterns generated as a result of cyclic gait patterns or simple on/off buttons. This limitation makes it difficult for FES to be applied to a variety of behaviors that are not repetitive or cyclic. Consequently, these restrictions not only make it difficult for the FES system to be applied to activities of daily living (ADL) but can also lead to serious accidents such as falls because the FES system cannot respond to rapid changes in behavior patterns.

However, if the FES system can be operated for various behaviors depending on the motion intention of patients, the effect of FES rehabilitation can be increased [8]. For this purpose, the following should be improved: First, electrical stimulation patterns should be modulated in real time according to the motion intention of the patient, rather than using predetermined or cyclic stimulation patterns. This is because the better the motion intentions of the patient are reflected, the more naturally and safely the FES system is synchronized with the various behaviors of patients [9]. Although a small number of FES system modulates the stimulation intensity and period through closed-loop control [10], [11], the researches for the FES system which is fully synchronized with motion intentions should be developed. Moreover, FES rehabilitation can be extended from limited conventional patterns to various ADL behaviors. Second, the wearability of the FES system should be improved, and a wearable system must be developed. This is because patients should be able to use it comfortably in their ADLs, not only in the hospital.

As an effective solution to these problems, we propose a wearable FES system controlled by motion intention that allows patients to use intentionally and comfortably in this study. The electromyography (EMG) sensor was utilized to identify the motion intention, and a volitional EMG (vEMG) signal estimation method from our previous research [12] was applied to estimate the motion intention via the EMG sensor regardless of electrical stimulation. In addition, the proposed FES system was applied to lower extremity muscles to develop a prototype for relatively large muscles such as the extensor and flexor of the thigh and calf. Notably, the proposed FES system is controlled by the intention of voluntarily contracting their own muscle; thus, it was developed for the elderly or normal people without impairment of muscle motor functionalities who can intentionally contract and relax their own muscles. In following sections, we introduce the hardware and software configuration of the proposed FES system and provide experimental test results of motion-intention-based rehabilitation exercises.

II. SYSTEM CONFIGURATION

Figure 1 represents the proposed vEMG controlled wearable FES system. The proposed FES system includes one main controller and four modules, and each component are designed to be fastened by wearable straps. To optimize the positions between modules without disturbing movement of

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Fig. 1: vEMG controlled wearable FES system

the lower limb joint, the main controller is designed to be fixed to the waist and the modules to the thighs and calves. Note that the weight of the entire system is $1.5\,\mathrm{kg}$, including the battery; the battery used for the proposed FES system had $12\,\mathrm{W}$ $(12\,\mathrm{V},\ 1\,\mathrm{A})$ with a capacity of $5000\,\mathrm{mA\,h}$.

A. *Hardware Configuration*

Figure 2 shows the components of the system module including EMG, FES, and inertial measurement unit (IMU). The thigh and calf modules were designed to rehabilitate the muscles used for flexion and extension of the knee and ankle joints, i.e., biceps femoris (BF), rectus femoris (RF), gastrocnemius (GCM), and tibialis anterior (TA). In addition, the modules are located on the side of thigh and calf and consist of EMG, FES, and IMU, as shown in Fig. 2(a). It should be noticed that one module was designed to rehabilitate two muscles. The two channels of EMG and one FES channel were designed for one muscle to estimate the vEMG of the stimulated muscle, and one IMU was designed to estimate the joint angle. Consequently, four channels of EMG, two channels of FES, and one IMU sensor were stacked on a base board, as shown in Fig. 2(b). The modules of this system can be connected to each other via USB c-type cables and were connected to the main controller through a daisy-chain structure.

Figure 2(c) represents the electrode configuration and data flow diagram of the proposed vEMG controlled FES system. The array electrodes were attached to the skin surface to form the EMG and FES electrodes. Note that because the proposed system utilizes EMG and FES simultaneously, the vEMG must be estimated by removing unnecessary EMG signals induced by electrical stimulation such as stimulus artifact and M-wave. For this purpose, the vEMG estimation method during FES by dual-channel EMGs was exploited, as proposed in our previous study [12]. Moreover, we used the set of EMG and FES electrodes to minimize and optimize the number and position of electrodes. Note that the conventional EMG electrode configuration of one channel requires three electrodes: two measuring electrodes and one reference electrode. In order to minimize the number of electrodes, the two channels of the EMG electrodes were designed with four electrodes by sharing the reference electrode and one measuring electrodes among two channels. In addition, the position of the electrodes was optimized through experiments, and suggested electrode composition is shown in Fig. 2(c).

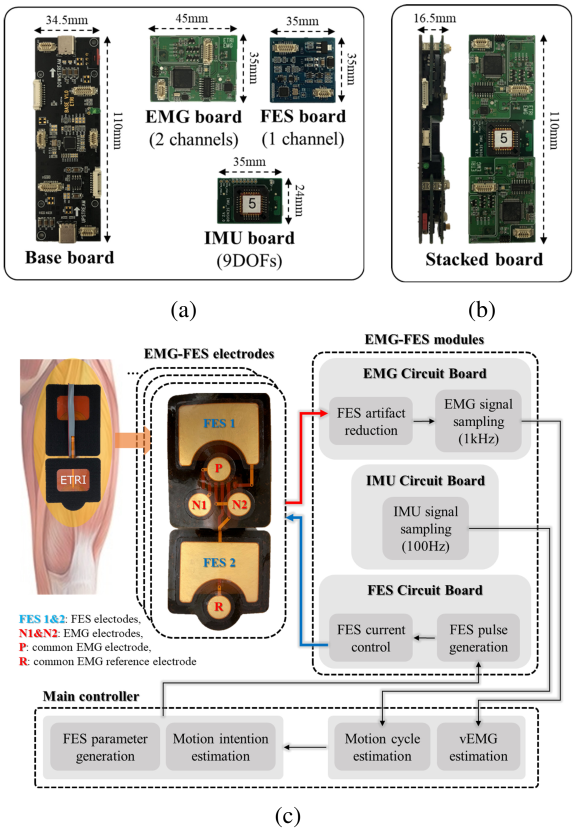


Fig. 2: vEMG controlled FES system hardware configuration; (a) components of the system module including EMG, FES, IMU, and base boards, (b) the board with stacked components, and (c) electrode configuration and data flow diagram

The FES circuit board configuration is as follows: MCU, step-up booster circuit for adjusting output voltage to control the stimulation current, H-bridge circuit for PWM signal control, and sample-hold circuit for measuring skin contact resistance. Consequently, the FES circuit can generate mono- or bi-phasic pulses with a maximum stimulation intensity of $120\,\mathrm{V}$ and $35\,\mathrm{mA}$ and a stimulation frequency of $100\,\mathrm{Hz}$. In addition, the EMG circuit board configuration was as follows: MCU, TI ADS1292 AFE, which can measure the EMG signal at $1\,\mathrm{kHz}$, power isolation circuit to reduce the interference with the FES circuit, analog LPF, and switching circuit for removing the spike noise induced by the stimulation current. Lastly, the Xsens MTi-3 was utilized for the IMU circuit board, and Raspberry Pi 3B+ was employed to measure the signals and operate as a main controller over serial communications.

B. *Software Configuration*

The motion intention-based FES control algorithm was designed by using EMG data. The EMG data can be employed to measure motion intention because it can measure the amount of muscle activation as the intention of motion before the intended motion is actually generated. For this purpose, the proposed FES system estimates the volitionally generated EMG regardless of electrical stimulation, i.e., the vEMG, and modulates the electrical stimulation intensity, i.e., the stimulation current, in proportion to the root mean square (RMS) value of the estimated vEMG.

Therefore, the proposed FES system determines the stimulation intensity by multiplying the RMS value of the estimated vEMG value and the maximum stimulation currents for each muscle. Note that RMS value of vEMG was normalized and coerced between 0 and 1; thus, the stimulation intensity was limited so as not to exceed the predetermined maximum current. In addition, the threshold level of the RMS value of vEMG for this study was 0.3, and the stimulation conditions regulated by the joint angles estimated by the IMU sensors were applied to avoid uncomfortable and unnecessary electrical stimulation. Consequently, the stimulation intensity of each muscle was determined as follows.

$$I_{stim} = \begin{cases} I_{max} \cdot RMS_v, & 0 \leq RMS_v < 1 \\ I_{max}, & 1 \leq RMS_v, \end{cases} \tag{1}$$

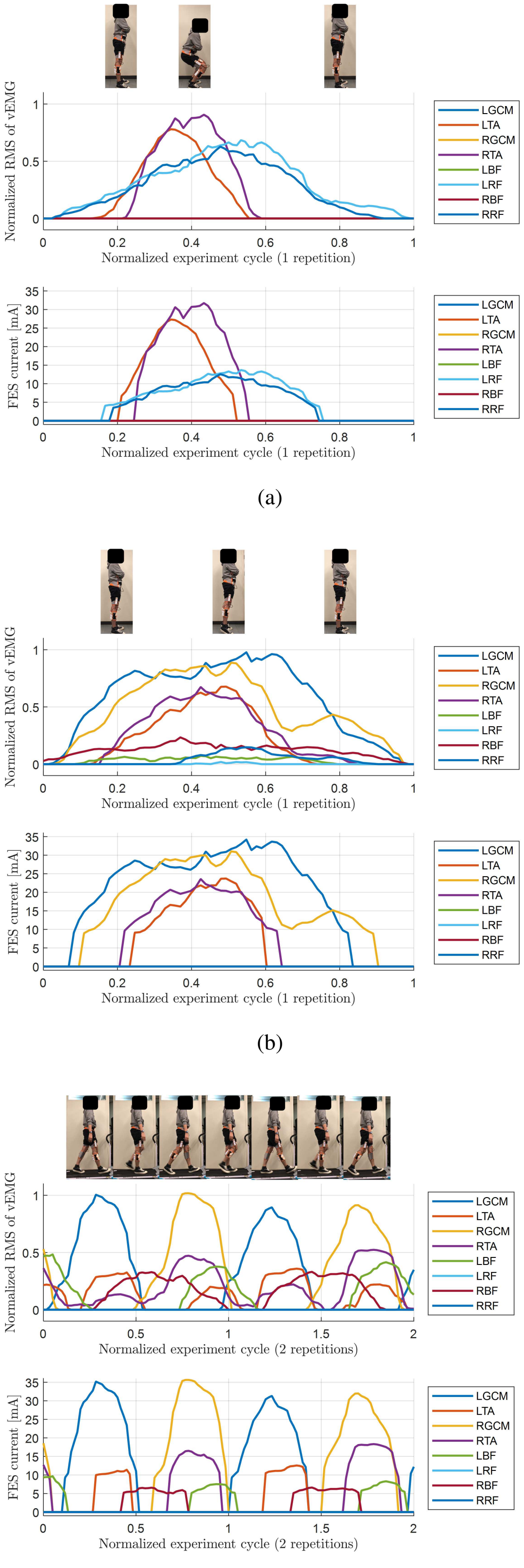
where RMS_v is the RMS value of the vEMG, and I_{stim} and I_{max} are the stimulation current and affordable maximum current of the muscle, respectively.

In order to control and monitor the proposed FES system, the software program with GUI interfaces was developed using NI LabVIEW and communicated with the main controller of the proposed FES system via the TCP/IP protocol. With this program, the system can perform processes such as adjusting the normalization scale value of RMS of vEMG and the maximum stimulation current for each muscle, monitoring the EMG and FES signals, and data logging.

III. SYSTEM EVALUATION

Pilot test experiments on several lower limb rehabilitation exercises were conducted to evaluate the system. The purpose of the experiments was to ensure that the vEMG was measured according to the motion intention of the user, and the corresponding FES intensity was controlled as intended. Moreover, it should be noticed that we tried to test the operational performance of the proposed FES system before applying it to the patients through these experiments. For the experiments, the following lower limb rehabilitation exercises were performed: squat, heel lift, and walking. Moreover, the maximum stimulation currents for each muscle experiencing comfortable and non-painful stimulation-induced muscle contractions were measured before the experiments, i.e., $25\,\mathrm{mA}$ for BF and RF and $35\,\mathrm{mA}$ for GCM and TA, and stimulation pulse width and frequency of biphasic waveform were equally set as $250\,\mu\mathrm{sec}$ and $50\,\mathrm{Hz}$, respectively. Lastly, note that this study was approved by the public institutional review board designated by ministry of health and welfare of Korea (P1-201 909-13-2), and the one healthy subject (age: 32, weight: $75\,\mathrm{kg}$, height: $181\,\mathrm{cm}$) participated.

The experimental results of the pilot test are shown in Fig. 3. Each graph represents the magnitude of the normalized RMS value of vEMG and the corresponding FES intensity for one repetition of squat and heel lift and for two repetitions of the walking cycle. Moreover, note that

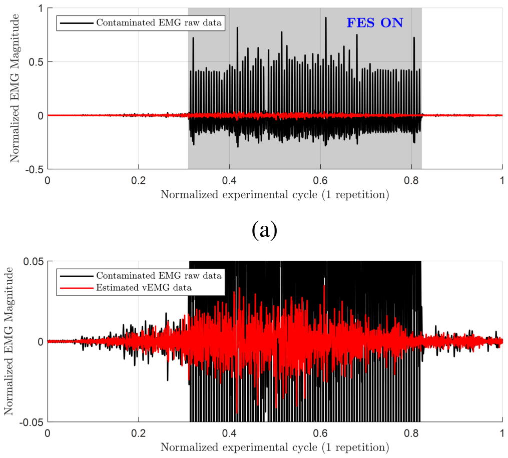


(a)

(b)

(c)

Fig. 3: Results of vEMG controlled FES experiment: (a) squat, (b) ankle, and (c) gait experiments.



(a)

(b)

Fig. 4: vEMG estimation performance of the proposed FES system during experiment: (a) full scale and (b) enlarged scale of results.

the 'L' and 'R' abbreviations separated the experimental results of muscle from each leg in Fig. 3, e.g., 'LGCM' refers to the result of GCM muscle in the left leg, 'RTA' refers to the result of TA muscle in the right leg, and so on. Figure 3(a) shows the experimental result of the squatting exercise. When a squat is performed, the center of gravity goes up and down with the help of knee and ankle joint movement, and the TA and RF muscles are mainly activated. Fig. 3(b) represents the result of the heel lift exercise. In the heel lift, the plantar and dorsiflexion of the ankle joint generate the lifting movement, and the GCM and TA muscles are mainly activated. Fig. 3(c) represents the result of the walking exercise. During walking, the whole lower limb muscles are cyclically activated in accordance with the gait cycle; especially, the GCM muscle is mainly activated when the terminal stance gait phase occurs. As shown in the figures, the vEMG signals are generated appropriately based on exercise sequences, and the stimulation currents are successfully modulated according to the RMS value of the vEMGs. Figure 4 shows the example recorded EMG data of GCM muscle during the experiments, and it is clearly shown that the vEMG was successfully estimated regardless of electrical stimulation. With this vEMG estimation capability, the stimulation intensity was appropriately and intentionally controlled in response to motion intention while the various rehabilitation exercises were performed.

IV. DISCUSSION

A wearable FES system for lower limb rehabilitation controlled by motion intention was proposed in this study. The system was designed with a strap-based wearable structure for ease of wearability and convenience; the total weight including the battery was 1.5 kg, which makes rehabilitation exercises more comfortable. In particular, the advantage of the proposed FES system over conventional FES systems is that the user can voluntarily and intentionally control the intensity of the FES in real time. However, the proposed FES system also has the following limitations. First, a clinical trial experiments should be performed in order to verify the practical rehabilitative effectiveness of vEMG controlled FES. Exploiting the convenience and functionality of the proposed FES system, it is necessary to examine a large number of patients whether the muscle function has been rehabilitated or metabolic consumption has been reduced. Moreover, a muscle fatigue caused by electrical stimulation should be considered. Therefore, in future work, a clinical trial using the proposed FES system will be performed for patients with muscle disorders, especially aging weakness such as sarcopenia. We hope that motion intention-based FES rehabilitation can provide significant clinical results that can help rehabilitate patients in their daily lives.

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