On the Development of a Practical Functional Electrical Stimulation (FES) Cycling System Using EMG Investigation Technique

J. Arnin*, T. Yamsa-ard, P. Triponyuwasin, P. Wechakarn, and Y. Wongsawat**

***Abstract*— The purpose of this study was to contribute the functional electrical stimulation (FES) system with practical use for spinal cord injury patient based on motor driving concept. The proposed system consists of three modules i.e. low-power control system, precise processor unit, and 4-channel stimulating unit. A self-adhesive electrode with carbon conductive was employed for stimulation. Three able-bodied participants were selected to perform the experiment; to observe a pattern of muscle contraction by recording Electromyogram (EMG) signal while cycling, to apply their own individual EMG cycling patterns to the stimulation system. One spinal cord injury patient was asked to test the device performance by implementing the prior collected cycling pattern from able-bodied subjects. As a result of the experiment, it appears that the proposed system accomplishes well and practically with highly precise stimulating pattern. Nevertheless, the muscle fatigue can be occurred if the stimulating time is too long. This condition is not obviously related to stimulating pattern that still need to be further investigated.**

I. Introduction

Nowadays, a great number of spinal cord injury patients are highly increasing every year. Vehicle crashes, followed by falls, and acts of violence are main causes of the injury [1]. As a stroke, another related disease that is a major cause of disability worldwide, has various effects, including loss of walking ability, postural control, and muscle strength, all of which lead to disability and additional secondary health impairments [2-4]. Besides, the most widespread basis of neurologic disability in young adults emanates from Multiple sclerosis [5, 6]. This inflammatory demyelinating disease of the central nervous system induces impairments that can harshly block a person's activity, participation in daily activities, and quality of life. Unfortunately, there is no way to recover these losses to the spinal cord. Nonetheless, many groups of researcher are constantly working on new treatments, including prostheses and medications that may support nerve cell rejuvenation or recover the function of the nerves that persist after a spinal cord injury. Meanwhile, spinal cord injury treatment focuses on avoiding additional injury and empowering people with a spinal cord injury to return to better life.

Designing assistive technologies that are suitably sufficient and cosmetically pleasing, environmentally pleasant, and cost effective is a challenge thing that most rehabilitation engineers are overlooking at present. More research and development in this field is necessary to expand the life quality of these persons [7]. A wheelchair, one technology that mostly serves the spinal cord patients for their mobility. Therefore, the engagement in all activities of the patients depends on matching and fitting of the wheelchair design. Furthermore, current ambulation technologies let the person with spinal cord injury in attaining upright vertically loaded carriages when their weakness conquers, and the devices can be easily adjusted, either mechanically or electronically, to proceed the level of struggle, thus augmenting the rehabilitation objectives. According to the assistive technologies, the functional electrical stimulation (FES) has been powerful in enhancing the rehabilitation consequences of those patients [8]. Regarding the development in computer technologies and present understanding of the muscle nerve relations, the FES technology has advanced meaningfully so far. However, the application of implementing the FES devices for individual rehabilitation in those patients still has limitation.

In accordance with FES technologies, there are a great deal of its application including drop foot stimulation, gait training combined with the FES, even upper-limb or lower-limb rehabilitation [9-13]. In some paraplegic patients, FES devices are extensively considered as a tool to restore walking function but this was shown that it is practically tough because there are numerous degrees of freedom concerning walking phrase [14]. FES cycling is contributed for those patients and has the benefits that cycling can be preserved for sensibly extended period of time in trained muscles. Thus the risk of falls is quite low although the cost of this technology may be high-priced. In addition, the previous study shows significant relationship between Electromyogram (EMG) signal and FES during cycling [15-21]. Those study revealed the contribution of stimulating voltage and pattern that can be supplementary applied for practical use while the fatigue condition is still to be investigated more. As the FES cycling [22-24], many studies show the relevance of the effective application of FES cycling containing the effects on muscle size, strength and function, and the cardiovascular and bone changes. Practically, the FES cycling has to be concerned with the application of surface electrodes, intensive training and setting up the stimulator limitations, implanted stimulators and FES cycling along with FES cycling in groups and other FES exercises such as FES rowing.

In this paper, the FES cycling stimulator and stimulation technique are proposed for a practical use with a patient. An analysis of EMG was implemented to generate an individual stimulation pattern. As an inexpensive designed system, the device can be easily rearranged for massive production.

II. Materials

A. Design of the Proposed FES Device

In this work, we design the functional electrical stimulation device that can be efficiently used for controlling the recumbent bike. The idea is that the designed FES device will make the stimulation non-uniformly according to the

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amount of muscle contraction. The amount of muscle contraction during each phase of cycling will be pre-acquired via the EMG signals. This will be explained in Session III. Overview of the device is shown in Figure 1. The proposed FES device consists of three parts, i.e.

1. The voltage generator: the device can generate the voltage from 5 to 45 Volts according to the EMG amplitudes. For the cycling phases which require high EMG amplitude, we will assign high volt. Meanwhile, the low volt will be assigned to the cycling phases which require low EMG amplitude.

2. The processor unit: This unit will generate the pulse sequences used for the stimulation.

3. The stimulation module: This module has 4 stimulating channel which frequency, duty cycle, and voltage are adjustable. Each channel will have a maximum current limit of 100 mA. The stimulation pattern is shown in Figure 2.

The self-adhesive with carbon conductive pad is employed as the stimulating electrode. Due to large muscle size, electrodes of size 2x4 inch are selected.

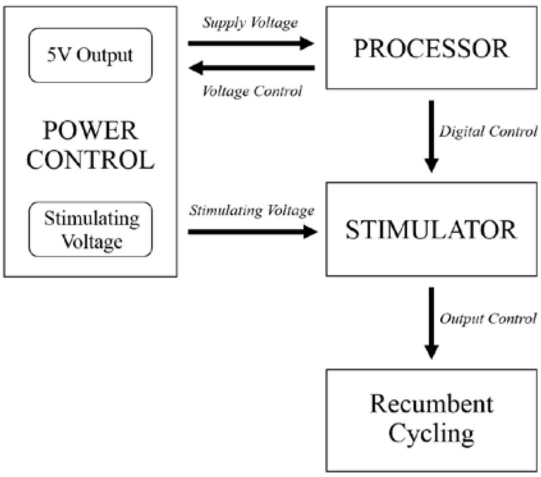

Figure 1. System diagram of proposed FES device

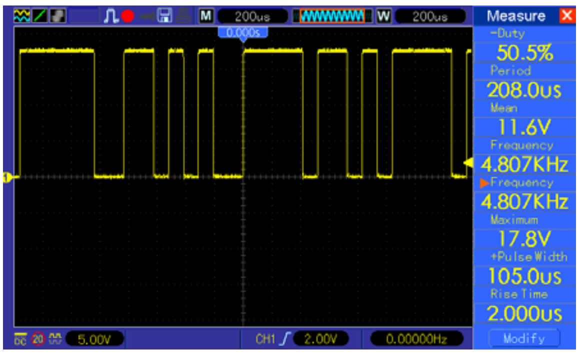

Figure 2. Stimulation pattern applied to the FES system

B. *Selected Recumbent Bike*

The selected recumbent frame is made by aluminum alloys which has the average weight equals to 18.4 Kg and 120 kg for rider weight limit. There are 27 adjustable speeds (The recumbent bike consists of 9 back cogs and 3 front chain ring). The wheel size is equal to 20"/700c. Figure 3 illustrates the recumbent with cycling training equipment.

III. EXPERIMENTS

A. *Subject Selection*

In this work, three able-bodied subjects and one spinal cord injury patient are recruited. Able-bodied subjects cannot be under abnormal conditions in walking and cycling. Steroid or stimulate substrate do not permitted during the experiments.

B. *EMG Acquisition*

Four channels EMG signals were measured with the EMG recording system in which the CMRR is higher than 85 dB. The sampling rate of acquisition is 1000 samples per second with 24 bit ADC resolution. Signal is filtered by 5 Hz high-pass filter. The bandwidths of acquisition are 30-500 Hz with signal gain of 2,000 times.

C. *Experiment Setup*

There are two processes of experimenting in normal participants. The first stage is to observe muscle contraction while cycling using by 1000 samples per second of EMG signal equipment. Participants were assigned to be cycling for 8 minutes and maintain their speed of cycling by 60 rpm. However, EMG measurement started after participant reach 60 rpm of cycling rate and maintain it. Electrodes were placed at quadriceps and hamstring muscles. The second stage is a FES for cycling. Participants were placed a stimulate electrode at hamstrings and quadriceps muscles. Then they were stimulated by FES device from 10V until their muscles responded the stimulation. The stimulating voltage is individual so that we have to record participant's stimulating voltage. After that, participants were stimulated 60 times with their own stimulating voltage. The other characteristic of stimulation was referred from prior behavior of cycling which is observed by EMG pattern.

The last experiment is performing field test with the patient who has quadriplegia condition. The patient was assigned to be cycling the recumbent for 1 kilometer using 4-channel household FES device with the lowest force at the chain ring and crank arm condition.

Figure 3. The recumbent and its cycling training equipment

IV. RESULTS AND DISCUSSION

Table I displays the results of the first experiment which show the period of muscle contract each subject. Figure 4 demonstrates the EMG signal recording from subject 1. Regarding the experiment, we observe that there are differences in muscle contraction and pushing force represented by the frequency and amplitude of each position.

It should be noted that selected able-bodied subjects have not experienced with the recumbent bike before.

TABLE I. PERIOD OF MUSCLE CONTRACTION

Participant	*Cycle Period (ms)*
1	375
2	400
3	360

from an Able-bodied Subject

According to the second experiment, the stimulating voltage was recorded from 3 participants and stimulated 60 times from their stimulating voltage. Table II shows the voltages and number of muscle contract from stimulation. Figure 4 illustrates a practical use of the proposed FES system that the patient can be cycling approximately a kilometer in 8 minutes. It should be noted that stimulating voltages each participant obtained by calibration prior to perform the experiment. Besides, the stimulating pattern was matched with the individual EMG recorded.

TABLE II. STIMULATING VOLTAGE AND NUMBER OF CONTRACTION

Participant	*Stimulating Voltage*	*Number of Contraction*
1	17.8	60
2	20	60
3	19.4	60

The result demonstrates the behavior of stimulation. If the voltage reaches the muscle threshold with appropriate frequency and amplitude, it would make the muscle contraction occurred which is depended on a duty cycle of stimulation. It would always happen until the muscle get fatigue then the force from muscle contraction will decrease. With this reason, the accuracy of stimulation of proposed FES device is completely 100 percentage before muscle get fatigue. The result of the second experiment reveals that our FES device can be implemented in cycling application for patients who suffer from controlling their lower limb. However, there are several factors related to muscle fatigue such as muscle mass. Therefore whenever muscle getting fatigue, there are no effect from stimulation that no matter what voltage or frequency we use and patients would get fatigue easier than normal circumstance.

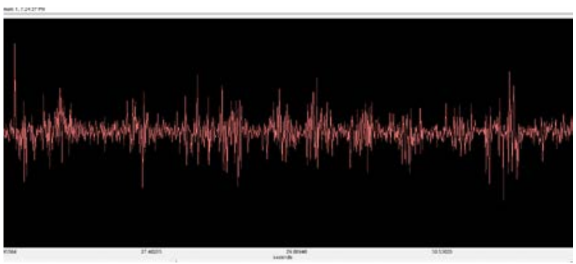

Figure 4. EMG signal from participant 1 (X-axis represented recording time and Y-axis represented the related EMG amplitude)

V. CONCLUSION

The usable technique of FES stimulating pattern for cycling was proposed by employing individual EMG pattern of muscle contraction during cycling. This approach can be used in actual patients with a high percentage of success in stimulation that might prolong a condition of muscle fatigue. It should be noted that the fatigue condition need to be further investigated to obtain the appropriate stimulating voltage and pattern. Likewise, 4-channel household FES device was contributed that is highly efficient and completely stable. In the future, we plan to implement more channels that would be more flexible and better performance for usage as well as user friendly, pleasing aesthetic, and easy to set up.

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Figure 5. An implementation of proposed FES system with a patient

REFERENCES

[1] "Spinal Cord Injury Facts and Figures at a Glance," The Journal of Spinal Cord Medicine, vol. 35, pp. 197-198, 2012.
[2] O. A. Howlett, "Functional electrical stimulation improves activity after stroke: a systematic review with meta-analysis," Arch Phys Med Rehabil, vol. 96, pp. 934-43, May 2015.
[3] N. Takeuchi and S. Izumi, "Rehabilitation with poststroke motor recovery: a review with a focus on neural plasticity," Stroke Res Treat, vol. 2013, p. 128641, 2013.
[4] J. McCabe, "Comparison of robotics, functional electrical stimulation, and motor learning methods for treatment of persistent upper extremity dysfunction after stroke: a randomized controlled trial," Arch Phys Med Rehabil, vol. 96, pp. 981-90, Jun 2015.
[5] M. A. Reynolds, "Pilot study: evaluation of the effect of functional electrical stimulation cycling on muscle metabolism in nonambulatory people with multiple sclerosis," Arch Phys Med Rehabil, vol. 96, pp. 627-32, Apr 2015.
[6] T. Street, "Effectiveness of functional electrical stimulation on walking speed, functional walking category, and clinically meaningful changes for people with multiple sclerosis," Arch Phys Med Rehabil, vol. 96, pp. 667-72, Apr 2015.
[7] S. A. Sisto, "Technology for mobility and quality of life in spinal cord injury," IEEE Eng Med Biol Mag, vol. 27, pp. 56-68, Mar-Apr 2008.
[8] D. B. Popovic, "Advances in functional electrical stimulation (FES)," J Electromyogr Kinesiol, vol. 24, pp. 795-802, Dec 2014.
[9] G. M. Lyons, "A review of portable FES-based neural orthoses for the correction of drop foot," IEEE Trans Neural Syst Rehabil Eng, vol. 10, pp. 260-79, Dec 2002.
[10] M. K. Cho, "Treadmill gait training combined with functional electrical stimulation on hip abductor and ankle dorsiflexor muscles for chronic hemiparesis," Gait Posture, vol. 42, pp. 73-8, Jun 2015.

[11] H. Kim, "Effect of functional electrical stimulation with mirror therapy on upper extremity motor function in poststroke patients," J Stroke Cerebrovasc Dis, vol. 23, pp. 655-61, Apr 2014.

[12] M. Kutlu, "Upper-limb stroke rehabilitation using electrode-array based functional electrical stimulation with sensing and control innovations," Medical Engineering & Physics, vol. 38, pp. 366-379, 4// 2016.

[13] P. Sampson, "Using Functional Electrical Stimulation Mediated by Iterative Learning Control and Robotics to Improve Arm Movement for People With Multiple Sclerosis," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 24, pp. 235-248, 2016.

[14] S. C. Abdulla, "Functional electrical stimulation-based cycling assisted by flywheel and electrical clutch mechanism: A feasibility simulation study," Robotics and Autonomous Systems, vol. 62, pp. 188-199, 2014.

[15] J. A. Norton, "Simple EMG control for FES-cycling," in 9th Annual Conference of the International Functional Electrical Stimulation Society, ed. Bournemouth, United Kingdom: IFESS_2004, 2004.

[16] C.-C. Chen, "An EMG Feedback Control Functional Electrical Stimulation Cycling System," Journal of Signal Processing Systems, vol. 64, pp. 195-203, 2011.

[17] J. Szecsi, "Functional electrical stimulation assisted cycling of patients with subacute stroke: kinetic and kinematic analysis," Clin Biomech (Bristol, Avon), vol. 23, pp. 1086-94, Oct 2008.

[18] N. C. Chesler and W. K. Durfee, "Surface EMG as a fatigue indicator during FES-induced isometric muscle contractions," Journal of Electromyography and Kinesiology, vol. 7, pp. 27-37, 1997.

[19] T. E. Johnston, "Differences in pedal forces during recumbent cycling in adolescents with and without cerebral palsy," Clinical biomechanics (Bristol, Avon), vol. 23, pp. 248-251, 2008.

[20] R. T. Lauer, T. E. Johnston, B. T. Smith, and S. C. K. Lee, "Lower Extremity Muscle Activity during Cycling in Adolescents with and without Cerebral Palsy," Clinical biomechanics (Bristol, Avon), vol. 23, pp. 442-449, 2008.

[21] M. O. Ibitoye, "The effectiveness of FES-evoked EMG potentials to assess muscle force and fatigue in individuals with spinal cord injury," Sensors (Basel), vol. 14, pp. 12598-622, 2014.

[22] D. J. Newham and N. Donaldson Nde, "FES cycling," Acta Neurochir Suppl, vol. 97, pp. 395-402, 2007.

[23] T. E. Johnston, "Biomechanics of recumbent cycling in adolescents with cerebral palsy with and without the use of a fixed shank guide," Gait & posture, vol. 27, pp. 539-546, 2008.

[24] K. Chen, "An improved design of home cycling system via functional electrical stimulation for paraplegics," International Journal of Industrial Ergonomics, vol. 34, pp. 223-235, 2004.