Proceedings of the 26th Annual International Conference of the IEEE EMBS
San Francisco, CA, USA • September 1-5, 2004

A Noninvasive Functional Electrical Stimulation System with Patient-Driven Loop for Hand Function Restoration

Ying-Han Chiou[1], Shih-Ching Chen[2], Jin-Shin Lai[3], Te-Son Kuo[1, 4]

[1]Department of Electrical Engineering, National Taiwan University, Taiwan, R.O.C.
[2]Department of Physical Medicine and Rehabilitation, Taipei Medical University and Hospital, Taiwan, R.O.C.
[3]Department of Physical Medicine and Rehabilitation, National Taiwan University Hospital, Taiwan, R.O.C.
[4]Graduate Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

Abstract—**In this study, a noninvasive functional electrical stimulation (FES) system is proposed to restore hand functions. The control strategy of this system is based on the patient-driven control loop. The patient can use his sound extremity to control FES system to generate the electrical stimulation so that the paralyzed muscles will be excited. In addition, electromyographic (EMG) signals, which are recorded by the sensors in the electrical stimulator, can serve as the trigger for the initialization of the system and the adjustment of the electrical stimulation parameters. From the preliminary results, they show that the subjects can successfully control the proposed system. We hope that patients will benefit a lot from this kind of FES system with patient-driven control loop.**

Keywords—**Noninvasive Functional Electrical Stimulation, FES, Patient-Driven Control, Hand Function Restoration, EMG Control**

I. Introduction

Due to the advances in computer technology, many electrical stimulation systems have been developed in the different kinds of applications, and they have been shown the feasibility and versatility of themselves [1-5]. Electrical stimulation, which can excite muscle fibers or nerve cells, has been used for many decades as a modality to maintain or restore the muscle activity of paralyzed patients, who suffer from neuromuscular disease, spinal cord injuries (SCIs), or related neural impairments.

Many researchers have dedicated their efforts to the control methods of functional electrical stimulation (FES) for the restoration of hand movements, and many clinic trials or case reports have been published in these groups [6-10]. However, owing to the complicated control strategies or the unfamiliar ways for patients to operate the system, it surely needs an acceptable or effective control method for patients to restore their lost functions. In addition, after the long-term electrical stimulation on the paralyzed extremities, muscle fatigue or force decreases will occur. If we can optimize or finely tune the parameters of the electrical stimulation, it will help both the patients and FES system to have better performance during the long-term electrical stimulation.

Because of the problems described above, in this paper, we propose a noninvasive FES system with patient-driven control to restore hand functions of the patients. And, this system will detect the electromyographic (EMG) signals from the subjects and adjust the stimulation parameters to improve system performance. We hope that it can help patients to control FES system and to maintain the muscle force during stimulating the paralyzed muscles.

II. Methodology

In the study, a noninvasive FES system is proposed for hand function restoration. The electrical stimulator used here was designed by our research group [5]. In addition, a digital signal processor with its high computing capability as the system kernel showed the versatility of itself. It could provide four-channel stimulation with arbitrary waveforms. The control strategy of this system is patient-driven loop, as depicted in Fig. 1. Patients can drive a command controller to have good posture control of the hand. If the user likes to grasp an object, for instance, he can change the control variables so that the hand is closing to contact the object and further increasing the force to secure the object further. During the grasping practice, he can vary the control back and forth to finely tune the hand posture until a good grasping is achieved.

On the other hand, there are the analog-to-digital converters (ADCs) (AD7862, Analog Device) mounted in the electrical stimulator for recording the bio-signals from the subjects. The block diagram of FES system is illustrated in Fig. 2. Here the bio-signals used in this experiment are the myoelectric signals, or EMG signals. We have made a four-channel EMG recording device with the surface active electrodes. Connecting this instrument with the ADCs in the electrical stimulator, EMG signals will be easily recorded as the feedback signals. In our previous study, we had designed the stimulation sequences for different kinds of hand movements, or the so-called motion-oriented module [11]. The same method is also applied here, and EMG signals are used as the triggers for the stimulation sequences as mentioned above. In addition, EMG signals will serve to adjust the command controller of FES system so that the system can get suitable electrical stimulation parameters to excite the paralyzed muscles and have better performance. Then the electrical stimulation parameters will be changed and finely tuned for avoiding the occurrence of the muscle fatigue or force decreases.

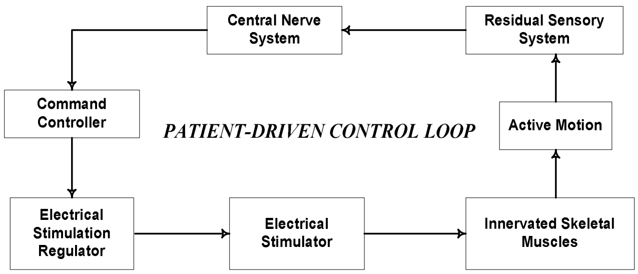

Fig. 1. Patient-driven control loop of FES system.

The goal of this study is to restore hand functions, such as palmar grasping, lateral pinching, etc. The electrical stimulation sequences for different kinds of patterns will be initiated by the digital I/O in the electrical stimulator. The currents, which are modulated by EMG signals, will excite the paralyzed muscles. By this kind of modulation, the electrical stimulator will produce suitable stimulation parameters to excite muscles. Six people are recruited in this experiment (five able-bodied subjects and one hemiplegic patients with stable neurological status, please see Table I). The nature of experimental procedures is explained to them, and they all agree to participate in this study. In the next several parts, there will be the preliminary results and discussion of the proposed FES system.

III. Results

We want to develop a noninvasive functional electrical stimulation for hand function restoration. In addition, the control method of this system used is patient-driven control loop. We have used a four-channel electrical stimulator with biphasic waveform stimulation. EMG signals are recorded from the biceps brachii and triceps brachii of the subjects. In the preliminary results, the subjects can successfully control the system by EMG signals from the selected muscles. Fig. 3 is one of the subjects' electrical stimulation sequences by the control of EMG signals. The system has different thresholds for the surface EMG signals, and the electrical stimulation sequences will be initiated when EMG signals are above the thresholds. Because the subjects can use their residual capabilities to produce different movements, we have used these patterns as the command signals to control the system so that the hand functions will be restored by the stimulation sequences. The estimated recognition rates of EMG signals as the command signals to control FES system is depicted in Fig. 4. By this kind of the patient-driven loop, the subjects can successfully control the system to achieve the goal of this study. During different motion-oriented modules, hand functions will be produced, such as palmar grasping, lateral pinching, and precise prehension.

In addition, to avoid the force decreases or muscle fatigue during the long-term stimulation, the system will adjust the electrical stimulation parameters by the conditions of the muscles. We have implemented the control strategies in the LabVIEW-based environment combined with the user friendly man-machine interfaces, which were proposed in our previous study [12].

IV. Discussion & Conclusion

A noninvasive FES system with patient-driven control loop to restore hand functions is showed in this paper, and the same control strategies of our previous study are also used in this experiment [11]. The system can produce suitable electrical stimulation parameters to excite the paralyzed muscles. By patient-driven control loop, the subjects can use their residual capabilities to control FES system. In this experiment, we choose the most commonly and acceptable signals as the input sources, i.e., EMG signals, for FES system control. EMG signal, which is the electrical manifestation of the neuromuscular activation associated with a contracting muscle, can serve as the control signal for FES system by the residual capabilities of the subjects. The subjects can generate suitable control signals to the system, as you may see from the preliminary results. In addition, they can also modify the stimulation currents by different EMG signals they generate. However, some of the subjects think that this kind of method might be sort of time-consuming even though they have successfully achieved the goal of this study. We will choose other input sources, like the force feedback signals or the head-motion control, for further research in the future.

Although there are some drawbacks in this system, the preliminary results show that the subjects can successfully control FES system to restore hand functions by the surface electrical stimulation. To improve the system performance, we may add the forearm orthotics or position sensors in the elbow and shoulder joints for a hybrid FES system in our next step. It will increase the versatility to the system, and more subjects will be included for further study. In the future, we will have more research and work done about this study.

Acknowledgment

The authors acknowledge the financial support of the National Science Council of the Republic of China under grant NSC 91-2614-E-038-001.

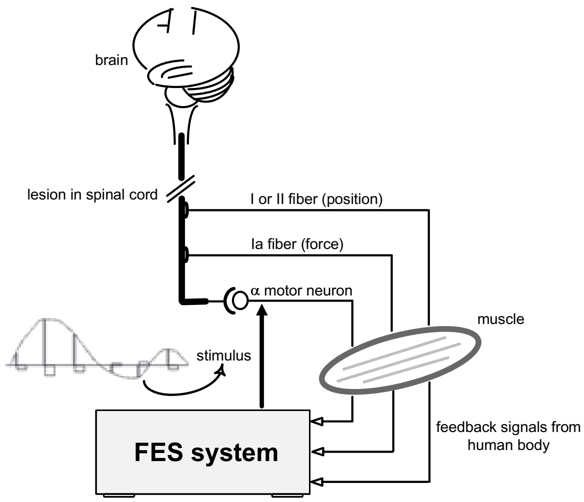

Fig. 2. Block diagram of the proposed FES system.

Table I
Histories of the subjects in this experiment

	Age	Gender	Selected Muscles as the Input Sources		
Subject 1	26	male	biceps brachii & triceps brachii		
Subject 2	27	male	biceps brachii & triceps brachii		
Subject 3	32	female	biceps brachii & triceps brachii		
Subject 4	28	male	biceps brachii & triceps brachii		
Subject 5	35	male	biceps brachii & triceps brachii		
	Age	Gender	Diagnosis	Onset Time	Affected Side
Subject 6	42	female	CVA	3 years	right side

Legends: CVA: cerebral vascular accident

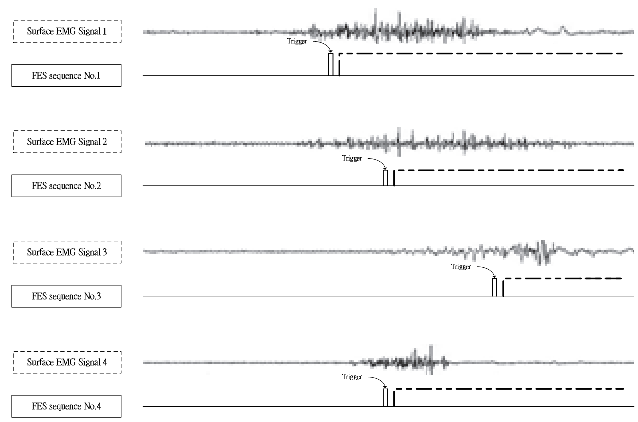

Fig. 3. Electrical stimulation sequences by the control of EMG signals.

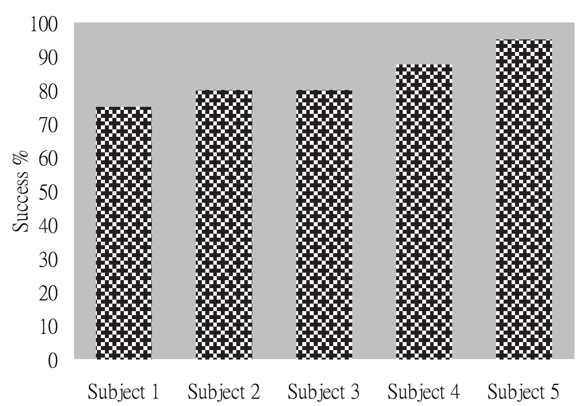

Fig. 4. Estimated recognition rates of EMG signals as the input sources to control FES system.

REFERENCES

[1] J. Chae, R.J. Triolo, K. Kilgore, and G.H. Creasey, "Functional Neuromuscular Stimulation," in *Rehabilitation Medicine: Principles and Practice*, 3rd ed., J.A. DeLisa and B.M. Gans, Eds. Philadelphia: Lippincott, 1998, pp. 611-634.

[2] J. P. Reilly, *Applied Bioelectricity: from Electrical Stimulations to Electropathology*, New York: Springer-Verlag, 1998.

[3] P. Meadows, "Portable Electrical Stimulation Systems," *IEEE AES Systems Magazine*, vol. 6, no. 10, pp. 6-10, Oct. 1991.

[4] M. Ilic, D. Vasiljevic, and D.B. Popovic, "A Programmable Electronic Stimulator for FES Systems," *IEEE Trans. Rehab. Eng.*, vol. 2, no. 4, pp. 234-238, Dec. 1994.

[5] H. C. Wu, S. T. Young, and T. S. Kuo, "A Versatile Multichannel Direct-Synthesized Electrical Stimulator for FES Applications," *IEEE Trans. Instrum. Meas.,* vo1. 51, no. 1, pp. 2-9, Feb. 2002.

[6] R. H. Nathan, "Control strategies in FNS systems for the upper extremities", *Crit. Rev. Biomed. Eng.*, pp. 485-568, 1993.

[7] P. E. Crago, N. Lan, P. H. Veltink, J. J. Abbas, and C. Kantor, "New control strategies for neuroprosthetic systems," *J. Rehab. Res. & Dev.*, 33, pp. 158-172, 1996.

[8] T. R. D. Scoot, P. H. Peckham, and K. L. Kilgore, "Tri-state myoelectric control of bilateral upper extremity neuroprostheses for tetraplegic individuals," *IEEE Trans. Rehab. Eng.*, vol.4, no. 4, pp. 251-263, Dec. 1996.

[9] J. H. Grill and P. H. Peckham, "Functional neuromuscular stimulation for combined control of elbow extension and hand grasp in C5 and C6 quadriplegics," *IEEE Trans. Rehab. Eng.*, vol. 6, no. 2, pp. 190-199, June 1998.

[10] A. Prochazka, M. Gauthier, M. Wieler, and Z. Kanwell, "The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia," *Arch. Phys. Med. Rehab.*, vol. 78, pp. 1-7, 1997.

[11] Y. H. Chiou, J. J. Luh, S. C. Chen, J. S. Lai, and T. S. Kuo, "Optimal strategy of the patient-driven command controller for restoring hand functions by functional electrical stimulation," in *25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Cancun, Mexico, pp. 1551-1553, Sept. 2003.

[12] Y. H. Chiou, R. S. Tzeng, J. S. Lai, and T. S. Kuo, "A digital signal processor based functional electrical stimulation system with its user interface design," in *Proc. 2nd Joint EMBS-BMES Conf.*, Houston, TA, U.S.A., pp. 352, Oct. 2002.