Human-FES cooperative control for wrist movement: a preliminary study

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Abstract

Functional electrical stimulation (FES) sometimes applies to patients with partial paralysis, so human voluntary control and FES control both exist. Our study aims to build a cooperative controller to achieve human-FES cooperation. This cooperative controller is formed by a classical FES controller and an impedance controller. The FES controller consists of a back propagation (BP) neural network-based feedforward controller and a PID-based feedback controller. The function of impedance controller is to convert volitional force/torque, which is estimated from a three-stage filter based on EMG, into additional angle. The additional angle can reduce the FES intensity in our cooperative controller, comparing to that in classical FES controller. Some assessment experiments are designed to test the performance of the cooperative controller.
Key Words: functional electrical stimulation, artifacts removal, impedance control, cooperative control.

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Functional electrical stimulation (FES) is a promising and effective method to restore motor functions for paralyzed patients. It generates electrical stimulus for the muscle to produce a desired movement. Sometimes, FES applies to subjects with partial muscle deficiency, like incomplete spinal cord injury (SCI), aging and muscle atrophy.[1,2] In this case, both FES-induced and voluntary muscle contraction exist. Recently, some literature has indicated the interplay of FES-induced force and volitional force in isometric muscular contraction.[3,4] It was proved that the resultant force was the nonlinear combination of the FES-induced and the volitional force. But the controller to realize certain motions was not provided in the case of volitional force. The involvement of volitional force/torque during FES rehabilitation training may improve rehabilitation efficacy, lower FES intensity, and alleviate muscle fatigue.[5] Our study designed a cooperative strategy for FES-induced and volitional force/torque to achieve the predefined wrist movements. Generally, the volitional force/torque is estimated from voluntary electromyography (EMG),[6,7] while the EMG is contaminated with simulation artifacts and M-wave caused by FES.[8] A three-stage filter was designed to extract the voluntary EMG from the overall EMG.[8] The main aim of this paper is to introduce impedance control strategy into the FES controller, which is widely used in robotic control to achieve hybrid position-force control.[9]

Materials and Methods

A. Experimental Setup

The experimental setup of our controller is shown in Fig.1. Subjects sat on a chair with their forearm fixed on the chair. The wrist was in free state. A commercial FES device (MotionStim 8, Germany) was employed as the stimulator. The stimulator generated electrical pulse on the targeted electrodes based upon the commands from the controller. A pair of FES electrodes was put on flexor carpi ulnaris, which caused flexion of wrist. To extract the volitional force, a physiological signal, electromyography (EMG), was selected as indicator. EMG signals of flexor carpi ulnaris were collected by a commercial device (f-s=1000Hz, Biometrics Ltd, UK). Targeted positions for EMG electrodes were cleaned with alcohol to reduce the impedance. Movement of wrist was acquired by a goniometer (fs=20Hz, Biometrics Ltd, UK).

Three-Stage Filter

To estimate the volitional force/torque from the overall EMG, a three-stage filter based on software was designed.

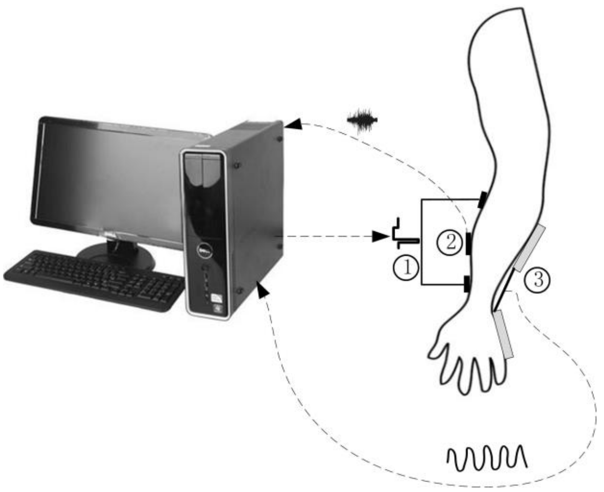

***Fig 1**. The experimental setup of our study. The EMG and angle of wrist was fed into computer. The controller in computer would then send commands to a FES device. The FES device exerted electrical stimulation on the targeted muscle. 1: FES electrodes, 2: EMG electrode, 3: goniometer.*

1. Blanking Window: The first stage was a blanking window, which aimed to shield the stimulation artefacts. Normally, the simulation of artefacts was much higher than the voluntary EMG. It even led the amplifier in EMG sensor into saturation.

2. Comb Filter: After the first-stage processing, the filtered EMG was fed into the second-stage filter: comb filter. This filter was to eliminate the M-wave from the overall EMG, which arose from the muscle contraction caused by FES. The formulation of comb filter is illustrated in Eq. 1.

$$y(t_i) = \frac{x(t_i) - x(t_i - T)}{\sqrt{2}} \qquad (1)$$

where $x(t_i)$ is the raw EMG signal at t_i, $y(t_i)$ is the filtered EMG signal at t_i; T denotes the duration of FES; $\sqrt{2}$ is a scale coefficient to sustain the same power for EMG signal before and after filtering.

3. Low-pass Filter: Now the volitional EMG was obtained.The volitional EMG was rectified, low-pass filtered to obtain the relative smooth volitional force/torque. The cut-off frequency of the low-pass filter was 20Hz. Because of the linear relation between the joint force/torque and volitional EMG, the output of three-stage filter was regarded as the volitional force/torque.

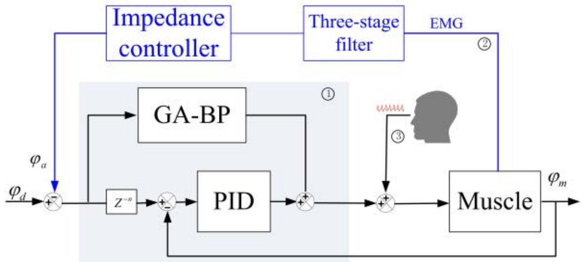

***Fig 2.** The whole framework of our cooperative controller. It consisted of a FES controller and an impedance controller. The FES controller was composed of a GA-BP networkbased feedforward controller and a PID-based feedback controller. A three-stage filter was designed to extract volitional force/torque from raw EMG. 1: FES controller, 2: impedance controller, 3: voluntary contribution.*

B. Controller Design

The whole control framework of our cooperative controller is depicted in Fig. 2. It consisted of a two-layer controller. The inner loop was a pulse width-modulated FES controller. In our experiment, the frequency and amplitude of FES was fixed at 25 Hz and 12 mA, respectively. The pulse width of FES was modulated by the FES controller. The outer loop contained a three-stage filter and an impedance controller. The impedance controller would generate an additional angle (φ_a) based on the volitional force/torque. This additional angle adjusted the desired angle (φ_d) to achieve human-FES cooperation. For example, when the volitional force/torque contributed to the wrist movement ($\varphi_a > 0$), then the actual angle input to FES controller got less than φ_d. Finally, the pulse width of FES decreased, in comparison to the pulse width without the volitional force/torque.The sampling frequency of the whole controller was 50Hz.

FES controller

For the single DOF movement controlled by FES, there are already many controllers. Here, a neuro-PID controller was adopted, consisting of a back

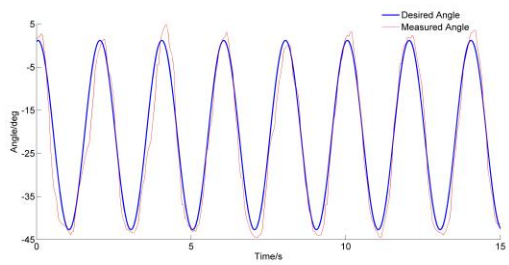

***Fig 3**. The tracking performance for FES controller alone.*

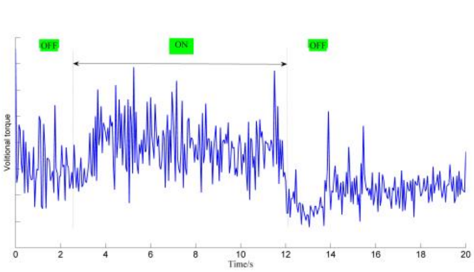

Fig 4. *The volitional torque extract from raw EMG by the three-stage filter. 'On' meant volitional torque was generated by subject. 'OFF' meant no volitional torque.*

propagation (BP) neural network-based feedforward controller and a PID-based feedback controller.[10,11]
The function of feedforward controller was to learn the inverse FES-muscle model. The input to neural network was the angle and angular velocity of wrist, the output was the pulse width of FES. Conjugate gradient descent algorithm was utilized as the training algorithm for the neural network. Genetical algorithm (GA) was employed to give a set of better initial values for the network. The training dataset included 30 seconds experiment data. More details about the feed forward controller could be found in Chang G-C, et al. 1997.[10] PID, a classical and simple feedback control technique, was used for the feedback purposes. The parameters of the PID controller were tuned by Ziegler-Nichols method.
The muscle contraction caused by FES always exhibited time delay. Thus, a delay operator (Z^{-n}) was embedded between the feedforward controller and feedback controller. The coefficient n was set at 4 in our experiments.

Impedance controller: Typically, the mathematical description for one-DOF impedance controller is shown in Eq.2.

$$\tau_{vol} = M_d(\varphi - \varphi_d) + B_d(\varphi - \varphi_d) + K_d(\varphi - \varphi_d) \quad (2)$$

where φ_d and φ are the desired and actual angle for wrist, respectively. T_{vol} represents the volitional torque, which is the final output of three-stage filter. K_d, B_d, and M_d are the desired stiffness, damping, and inertial coefficient, respectively, which are equal or greater than zero. These coefficients were adjusted in experiments, so that it gave comfortable experience for subjects.
Let $\varphi_a = \varphi - \varphi_d$. The relationship of φ_a and τ_{vol} could be written as Eq.3. When there existed a volitional torque to help the wrist move, the additional angle (φ_a)derived from Eq.3 was positive. The angle fed into FES controller was less than the predefined desired angle. Therefore, smaller pulse width of FES was needed in this case. By impedance controller, FES controller intelligently adjusted the stimulation intensity to cooperate with human, according to the volitional torque.

$$\frac{\varphi_a}{\tau_{vol}} = \frac{1}{M_d s^2 + B_d s + K_d} \quad (3)$$

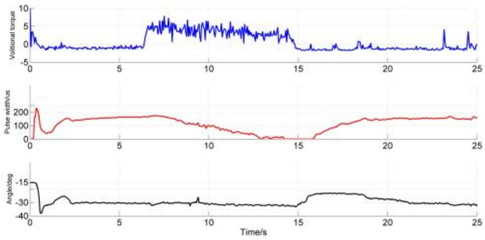

Fig 5. *The performance of cooperative controller. These subplots show the waveforms of volitional torque, pulse width of FES, and angle of wrist, respectively.*

C. Controller Assessment

Assessment for the controllers included two sessions. The first session was to demonstrate the tracking performance of FES controller alone. A sinusoid trajectory with 0.5Hz was considered as the desired movement for the wrist. The second session aimed to show the property of cooperative controller (FES controller + impedance controller). A step task was designated. One healthy subject attended the whole experiments (male, 25 yrs, 62 kg).

Results and Discussion

Performance of FES Controller

Firstly, we tested the performance of FES controller alone. In this situation, the purpose of FES controller was to track a predefined sinusoid trajectory without impedance controller. The result is illustrated in Fig.3. We observed that our FES controller was qualified to perform the tracking task.

Performance of Cooperative Controller

To achieve a good collaboration between human and FES, it was very important to estimate the volitional force as precisely as possible. Fig.4 gives a typical example of the output of three-stage filter. The volitional torque appeared in the middle period of experiment. It was obvious that our three-stage filter predicted the volitional torque quite well. There remained burrs in the waveform because of the stimulation artifacts. Since the impedance controller was a Butterworth filter in essence, it rejected these burrs. We designed a step task to evaluate the property of cooperative controller. Initially, the wrist was driven by the FES controller alone from -15 degree to -30 degree. Then, the impedance controller was open. The subject exerted volitional torque on the wrist to help move. Finally, the impedance controller closed. The wrist was kept at -30 degree by the FES controller again. Fig. 5 demonstrates the waveforms of volitional torque, pulse width of FES, and angle of wrist during the whole experiment. It was indicated that the FES controller intelligently modulated stimulation intensity based on the volitional torque. The purpose of human-FES cooperation was completed. Further, the distribution of FES intensity between the PID controller and the neural network controller was

Table 1. *The pulse width of FES in each controller*

	PW/μs	$PW_{pid}/\mu s$	$PW_{network}/\mu s$
FES controller	225	26	198
Cooperative controller	198	-2	200

explored. Table 1 lists the FES distribution in the FES controller alone and the cooperative controller, respectively. For the same task, the FES intensity of the FES controller was higher than that of the cooperative controller. The main reason for this variation was the influence of the PID controller. In the case of cooperative controller, the angle ($\varphi_d - \varphi_a$) would less than φ_m. Because of the effect of integral ($K_i \int (\varphi_d - \varphi_a) - \varphi_m dt$), the output of PID controller would decrease. Thus, total stimulation intensity reduced. In conclusion, an impedance controller embedded in the classical FES controller was designed to achieve human-FES cooperation for wrist movement. From the assessment experiment, this novel controller could intelligently modulate FES intensity based on the volitional torque of subjects. Presently, the controller could only realise simple tasks (like step task). In future, the inverse FES-muscle model will be improved to achieve some complex tasks.

Acknowledgement

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Contributions

KG and DZ introduce impedance control to FES, to achieve human-FES cooperative control; HY: Extracting voluntary torque information from contaminated EMG.

Conflict of Interest

The author declare no potential conflict of interests.

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References

1. Gui K, Zhang D. Influence of volitional contraction on muscle response to functional electrical stimulation. 19th International Functional Electrical Stimulation Society Annual Conference (IFESS). IFESS, 2014, pp. 1–4.
2. Langzam E, Isakov E, Nemirovsky Y, Mizrahi J. Muscle force augmentation by low-intensity electrical stimulation. 27th Annual International Conference of the Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2006;5808–11.
3. Langzam E, Nemirovsky Y, Isakov E, Mizrahi J. Partition between volitional and induced forces in electrically augmented dynamic isometric muscle contractions. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2006;14:322–35.
4. Perumal R, Wexler AS, Kesar TM, Jancosko A, Laufer Y, Binder-Macleod SA. A phenomenological model that predicts forces generated when electrical stimulation is superimposed on sub-maximal volitional contractions. J Appl Phys 2010;108:1595–1604.
5. Lotze M, Braun C, Birbaumer N, Anders S,Cohen LG. Motor learning elicited by voluntary drive. Brain 2003;126:866–72.
6. Lee S, Sankai Y. Power assist control for walking aid with hal-3 based on EMG and impedance adjustment around knee joint. IEEE/RSJ International Conference on Intelligent Robots and Systems 2002;2:1499–1504.
7. Zhang Q, Hayashibe M, Azevedo-Coste C. Evoked electromyography-based closed-loop torque control in functional electrical stimulation. IEEE Transactions on Biomedical Engineering 2013;60:2299–2307.
8. O'Keeffe DT, Lyons GM, Donnelly AE, Byrne CA. Stimulus artifact removal using a software-based two-stage peak detection algorithm. Journal of neuroscience methods 2001;109:137–45.
9. Hogan N. Impedance control: An approach to manipulation: Part ii Implementation. Journal of dynamic systems, measurement, and control 1985;107:8–16.
10. Chang G-C, Lub J-J, Liao G-D, Lai J-S, Cheng C-K, Kuo B-L, Kuo T-S. A neuro-control system for the knee joint position control with quadriceps stimulation. IEEE Transactions on Rehabilitation Engineering, 1997;5:2–11.
11. Kurosawa K, Futami R, Watanabe T, Hoshimiya N. Joint angle control by fes using a feedback error learning controller. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2005;13:359–71.