Human-FES Cooperative Control for Wrist Movement: A Preliminary Study

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Abstract— Functional electrical stimulation (FES) sometimes applies to patients with incomplete 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.

I. INTRODUCTION

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. However, the controller to realise 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 concentration 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].

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II. METHODOLOGY

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 the flexion of wrist. To extract the volitional force, one kind of physiological signal, electromyography (EMG), was elected as the indicator. EMG signals of flexor carpi ulnaris were collected by a commercial device (fs=1000Hz, Biometrics Ltd, UK). The targeted position for EMG electrodes was cleaned with alcohol to reduce the contact impedance. The movement of wrist was acquired by a goniometer (fs=20Hz, Biometrics Ltd, UK).
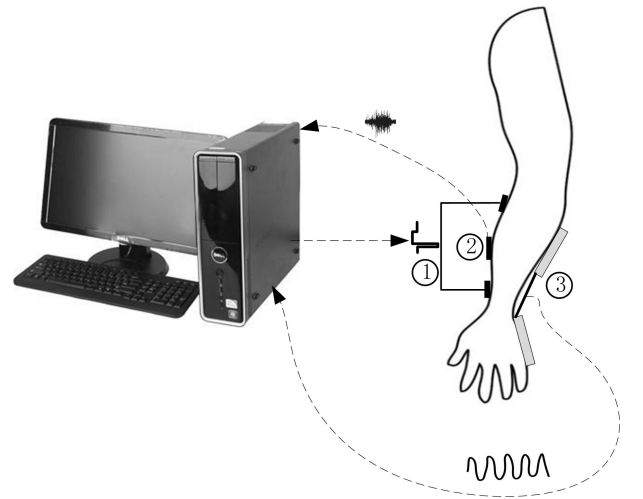

Fig. 1. The experimental setup of our study. The EMG and angle of wrist was fed into computer. The controller in computer would then send commands to a FES device. The FES device exerted electrical stimulation on the targeted muscle. ①: FES electrodes, ②: EMG electrode, ③: goniometer.

B. Three-Stage Filter

To estimate the volitional force/torque from the overall EMG, a three-stage filter based on software was designed [10].

1) Blanking Window: The first stage was a blanking window, which aimed to shield the stimulation artifacts. Normally, the simulation artifacts 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 Equation (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 cutoff 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.

C. 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 25Hz and 12mA, 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.
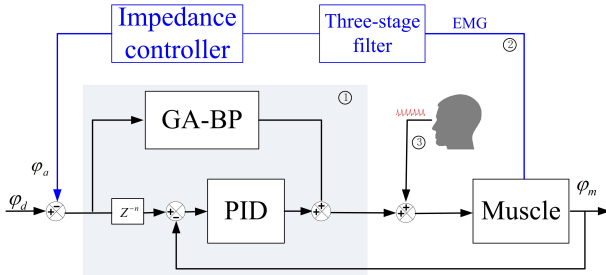

Fig. 2. The whole framework of our cooperative controller. It consisted of a FES controller and an impedance controller. The FES controller was composed of a GA-BP network-based feedforward controller and a PID-based feedback controller. A three-stage filter was designed to extract volitional force/torque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

1) 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 propagation (BP) neural network-based feedforward controller and a PID-based feedback controller [11], [12].

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 utilised 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 feedforward controller could be found in [11].

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.

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

$$\tau_{vol} = M_d(\ddot{\varphi} - \ddot{\varphi}_d) + B_d(\dot{\varphi} - \dot{\varphi}_d) + K_d(\varphi - \varphi_d) \qquad (2)$$

where φ_d and φ are the desired and actual angle for wrist, respectively. τ_{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 Equation (3). When there existed a volitional torque to help the wrist move, the additional angle (φ_a) derived from Equation (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.

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

D. Controller Assessment

The 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, 62kg).

III. RESULTS AND DISCUSSION

A. 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.
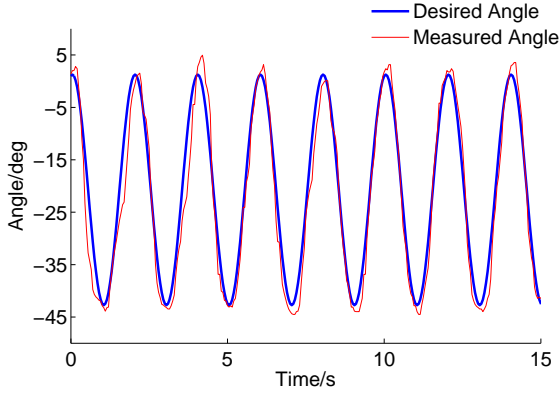

Fig. 3. The tracking performance for FES controller alone.

B. 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.
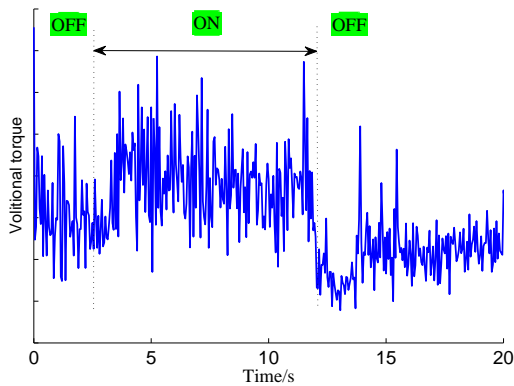

Fig. 4. The volitional torque extract from raw EMG by the three-stage filter. 'On' meant the volitional torque was generated by subject. 'OFF' meant no volitional torque.

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.
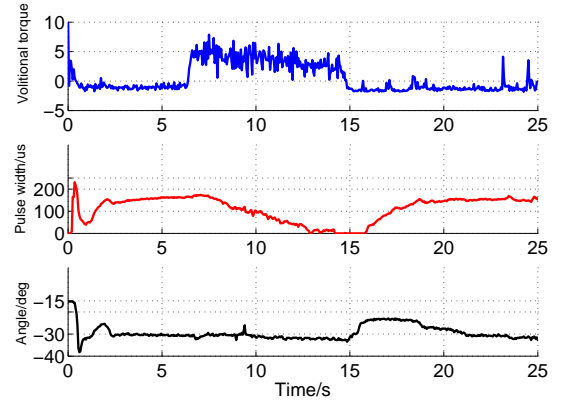

Fig. 5. The performance of cooperative controller. These subplots show the waveforms of volitional torque, pulse width of FES, and angle of wrist, respectively.

Further, the distribution of FES intensity between the PID controller and the neural network controller was explored. Table I 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, the total stimulation intensity reduced.

TABLE I
THE PULSE WIDTH OF FES IN EACH CONTROLLER

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

IV. CONCLUSION AND FUTURE WORK

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.

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