

A test of multichannel closed-loop FES control on the wrist joint of a hemiplegic patient

Watanabe T¹, **Matsudaira T**², **Hoshimiya N**³, **Handa Y**⁴

¹ Information Synergy Center, Tohoku University, Sendai, Japan

² Graduate School of Engineering, Tohoku University, Sendai, Japan

³ Tohoku Gakuin University, Sendai, Japan

⁴ Tohoku University Graduate School of Medicine, Sendai, Japan

nabe@isc.tohoku.ac.jp

Abstract

The multichannel closed-loop FES control method using PID controllers developed in our research group was found to perform well with neurologically intact subjects in our previous studies. The PID controller could solve the ill-posed problem in the stimulation intensity determination for multichannel control of multi-degrees of freedom of movement. In this paper, the PID control method was examined with a hemiplegic patient. The dorsi/palmar and the radial/ulnar flexions were controlled by stimulating the ECR, the ECU, the FCR and the FCU using surface electrode stimulation. The tracking control of the wrist joints were achieved reasonably at vertical and horizontal positions of the upper limb. The multichannel PID control method would provide a basic technique for multichannel closed-loop FES control.

1. INTRODUCTION

A closed-loop control of paralyzed limbs using FES has been desired for clinical application. However, there are problems on a sensor to measure a feedback signal and a multichannel control algorithm to determine stimulation parameters to muscles. We focused on the algorithm for multichannel closed-loop FES control and have developed a method using the PID controller for the redundant musculoskeletal system that involved an ill-posed problem in stimulus intensity determination [1, 2].

The method was found to be effective on the tracking control of two degrees of freedom of movement of the wrist joint stimulating four muscles through experiments with neurologically intact subjects. The method could solve the ill-posed problem in calculation of stimulus intensities. However, good tracking

control was not achieved with a hemiplegic patient at the first clinical test because of the small range of motion of the wrist radial flexion and increased reflex function [3].

In this paper, a clinical test of the closed-loop FES control was performed again with another hemiplegic patient who had experiences in FES and TES.

2. METHODS

2.1. Control Algorithm

The PID control algorithm was described by the following equation:

$$S_n = S_{th} + K_P e_n + K_I \sum_{t=0}^n e_t + K_D (e_n - e_{n-1})$$

where S_n , S_{th} and e_n are stimulation intensity vector at present time n , the minimum stimulation intensity vector for FES control, and error vector at present time n that is the difference between targets and measured joint angles, respectively. The elements of PID parameter matrices K_P , K_I , K_D were calculated by the followings [1]:

$$K_{Pij} = \frac{0.6T_i}{L_i} m_{ij}^-, \quad K_{Iij} = \frac{0.6\Delta t}{L_i} m_{ij}^-, \quad K_{Dij} = \frac{0.3T_i}{\Delta t} m_{ij}^-$$

L_i and T_i are delay time and time constant of step response, respectively, when the muscle i is stimulated separately. In case of a muscle has two or more degrees of freedom of movement, the delay time and the time constant obtained from every movement are averaged respectively. Δt is the sampling interval. m_{ij}^- is the element of the generalized inverse matrix M^- of the matrix M . Elements of matrix M are slopes of approximated linear lines of the input-output (stimulus intensity-joint angle) characteristics calculated by the least squares method between the minimum and the maximum stimulation intensities. The inverse matrix of M does not exist in general because M is not the square matrix (i.e. usually, the number of muscle

stimulated is larger than that of degree-of-freedom of movement controlled). Therefore, we introduced the generalized inverse matrix of M that was calculated uniquely under the limitation of the sign of the elements and the least square condition [4].

2.2. Experimental Method

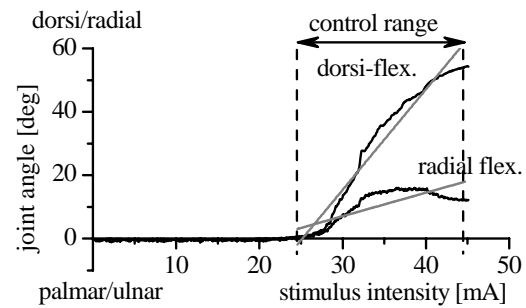
Wrist joint angles of the dorsi/palmar- and the radial/ulnar-flexions of the paretic side of a right hemiplegia (63 years old, male) were controlled by stimulating the flexor carpi radialis (FCR), the flexor carpi ulnaris (FCU), the extensor carpi radialis longus/brevis (ECR) and the extensor carpi ulnaris (ECU). Stimulus current pulse amplitudes (pulse frequency: 20Hz, pulse width: 0.2ms) were regulated by the controller and applied to the muscles through isolator (5384, NEC Medical Systems) and surface electrodes (F-150M, Nihon Koden). Maximum pulse amplitude was determined in order to get enough control range without pain. The wrist joint angles were measured with the magnetic 3-D position and orientation sensor (FASTRAK, Polhemus) with 20Hz of sampling frequency [2].

The subject sat on a chair and relaxed his right upper extremity during experiments. The closed-loop control was performed under two different upper limb positions: in the direction of the gravity with the neutral position of the forearm in the pronation/supination angle (vertical position) and in the horizontal plane with almost full extended elbow joint and 90deg pronation of the forearm (horizontal position). The horizontal position was maintained by supporting the forearm and the upper arm with wooden pedestal. Parameter values of the PID controller were determined at the vertical position, which were fixed for all control experiments. Target joint trajectory was circle on the joint angle plane with 10s or 5s of cycle period.

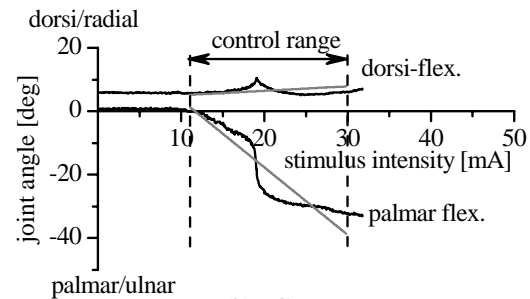
3. RESULTS

Examples of the input-output characteristics of stimulated muscles are shown in figure 1. The approximated linear lines between the minimum and maximum intensities for FES control are also shown in the figure.

Figure 2 shows examples of control results of tracking target joint angles. In the first 5s, joint positions were moved from the relaxed position to the starting position on the target trajectory. In the experiments, parameters of the PID



(a) ECR



(b) ECU

figure 1 Examples of measured input-output characteristics of stimulated muscles (black line) and approximated linear lines for PID parameter determination (gray line). The minimum and the maximum stimulation intensities for FES control are shown by the control range.

controller were not optimized after the first determination from the input-output characteristics and the responses to step-shaped stimulations. In the case of controlling at the vertical position, tracking control was almost achieved although small amplitude of oscillation of joint angles was observed. Even in the case of controlling at the horizontal position, the tracking was not so severely deteriorated. Especially, little oscillation was caused in the first half of the control. These results were similar to those of the previous experiments with neurologically intact subjects. The PID controller was considered to perform well with the hemiplegic patient.

4. DISCUSSION AND CONCLUSIONS

The PID controller could regulate stimulus currents properly after the PID parameter determination by simple measurements. In the experiment of this paper, fine tuning of the PID parameters was not performed considering clinical application since the trial and error tuning of the parameters causes burdens on patients. Simplifying parameter determination process is one of important factors for clinical

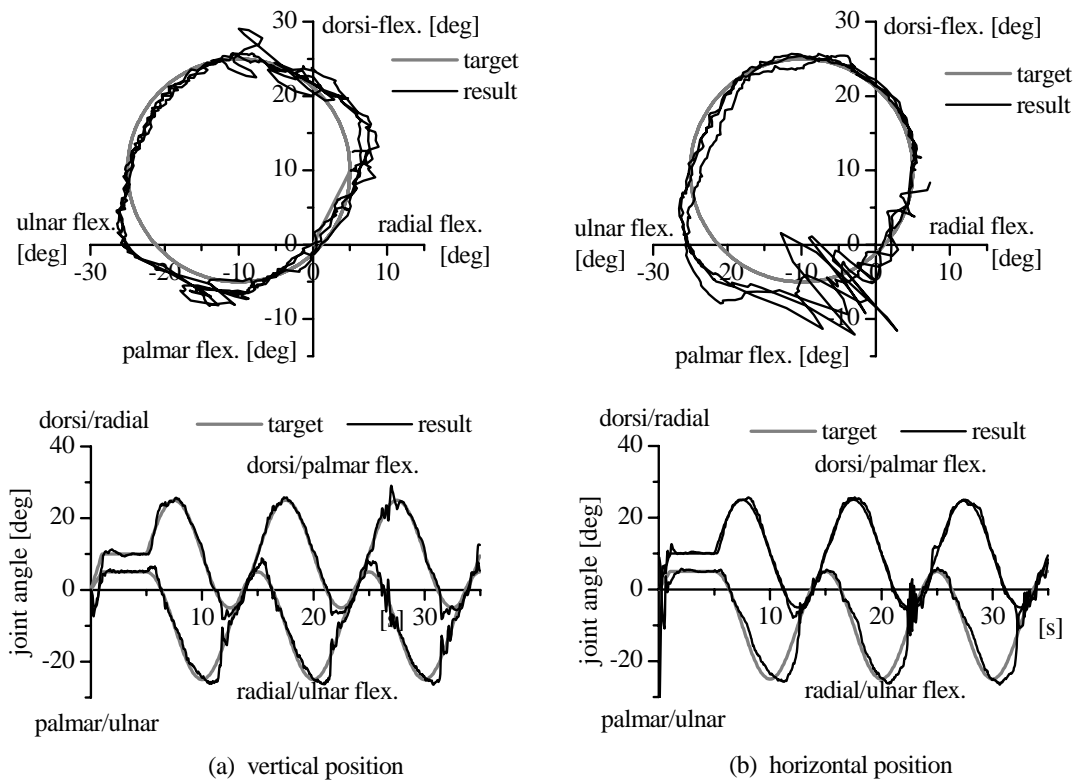


figure 2 Examples of tracking control results with a hemiplegic patient. Target and measured joint angle trajectories on the joint angle plane (upper figures) and time responses of them (bottom figures) are shown.

applications of FES controllers.

In the experimental results, the ECU had steep response in the input-output characteristic and little contribution to the dorsiflexion. These were considered to be a reason of the undesirable responses such as the oscillation of joint angles. As seen in our previous clinical test with a hemiplegic patient, the small range of motion and reflex like response caused oscillating responses [3]. It will be necessary to vary controller parameters considering stimulation intensity and/or joint angles and so on during control.

Results of this paper showed that the multichannel PID control method would be effective in FES control. Development of fine tuning method of the controller parameters and expansion of the PID controller to multijoint movement control will be necessary for practical clinical use.

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