LETTER

A Feasibility Study of Fuzzy FES Controller Based on Cycle-to-Cycle Control: An Experimental Test of Knee Extension Control

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SUMMARY Functional Electrical Stimulation (FES) can be effective in assisting or restoring paralyzed motor functions. The purpose of this study is to examine experimentally the fuzzy controller based on cycle-to-cycle control for FES-induced gait. A basic experimental test was performed on controlling maximum knee extension angle with normal subjects. In most of control trials, the joint angle was controlled well compensating changes in muscle responses to electrical stimulation. The results show that the fuzzy controller would be practical in clinical applications of gait control by FES. An automatic parameter tuning would be required practically for quick responses in reaching the target and in compensating the change in muscle responses without causing oscillating responses.
key words: *functional electrical stimulation, FES, fuzzy control, cycle-to-cycle control, knee joint*

1. Introduction

Functional Electrical Stimulation (FES) can be an effective method of assisting or restoring paralyzed motor functions caused by spinal cord injury or celebrovascular disease. However, controlling paralysed limbs using FES is a difficult problem because of nonlinearity, time varying properties, significant time delay and so on in the responses of the musculoskeletal system to electrical stimulation.

The cycle-to-cycle control is a control method for restoring cyclic movement such as gait by using FES. In the early stage of studies on the cycle-to-cycle control, the control method was implemented in a proportional-integral-derivative (PID) controller for experimental tests of controlling knee extension angle [1] or hip flexion angle range [2]. Although these previous works showed usefulness and effectiveness of the cycle-to-cycle control, their controllers were only for restoring single joint movements. Therefore, we proposed fuzzy controller based on the cycle-to-cycle control for controlling complicated multi-joint (the hip, the knee and the ankle) movements in the swing phase of FES-induced gait [3]. In computer simulation study using a musculoskeletal model, the fuzzy control system showed better performance than PID controllers [3], [4].

In this paper, an experimental test of the fuzzy controller was performed in a simple control objective in order to show clinical applicability of the fuzzy controller. Maximum knee extension angle was controlled by stimulating the vastus muscles with neurologically intact subjects.

2. Method

2.1 Fuzzy Controller Based on Cycle-to-Cycle Control

The cycle-to-cycle control is not the tracking control, but several target angles such as the maximum knee extension angle is set in a cycle of gait [3]. Outline of the cycle-to-cycle control is shown in Fig. 1. Each muscle is stimulated by single burst duration of stimulation pulses with constant pulse amplitude, pulse width and frequency to induce joint movement reaching the target joint angle. The burst duration of stimulation pulses of a current cycle $TB[n]$ is regulated based on the error in the previous cycle as shown by

$$TB[n] = TB[n-1] + \Delta TB[n] \tag{1}$$

where $TB[n-1]$ is the stimulation burst duration for the cycle just before the current one and $\Delta TB[n]$ is the output of the fuzzy controller.

Structure, membership function and rule sets of the fuzzy controller were based on our previous work [3], [5]. Input variables were error and desired range of joint angle of the previous cycle. The desired range was joint angle

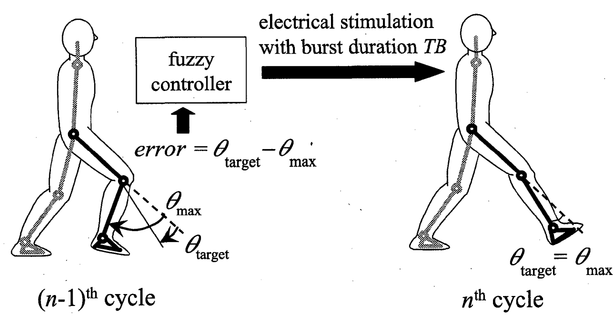

Fig. 1 Conceptual diagram of cycle-to-cycle control as an example of controlling maximum knee extension angle of swing leg.

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range between the angle at the stimulation onset and the target angle.

Input membership functions were expressed by triangular and trapezoidal fuzzy sets. The membership functions of the 'error' and 'desired range' comprised 7 and 3 linguistic terms, respectively, and that of the output variable was expressed as 11 fuzzy singletons [3]. The fuzzy inference was accomplished by using the Mamdani method. Center of gravity (COG) was used in the defuzzification process.

2.2 Experimental Method

Maximum knee extension angle was controlled by stimulating the vastus muscles (the vastus medialis and lateralis) using surface electrodes (F-150M, Nihon Koden) with 3 neurologically intact subjects (male, 23-27 y.o.). Subject's consent to participate in the experiment was obtained. The subject sat on the stage that he could move his knee joint freely in extension and flexion, and relaxed his legs during experiments.

The knee joint is extended from the resting position by electrical stimulation, and then, the knee joint is flexed by the gravity when electrical stimulation is stopped. Control of the next cycle was started at the stimulation onset time that was detected as the time when changes of knee joint angle in most recently sampled consecutive 10 data (sampling interval was about 50 ms) were less than or equal to 0.3 deg. In order to determine the burst duration *TB* for the next cycle, the maximum extension angle was detected by comparing consecutive 3 sampled values of the joint angle.

The target value of the maximum knee joint angle was set at 30 deg (0 deg means full knee extension). The knee joint angle was measured with an electric goniometer (M180, Penny & Giles). Pulse width and pulse frequency was fixed at 200 μs and 20 Hz, respectively. Stimulus pulse amplitude was determined in order to get enough control range without pain before the experiment. Values of fuzzy membership functions were determined in previous experiments with other subjects and fixed for this experiment. That is, those values were not adjusted or optimized for each subject before control. Each control trial was started with the initial burst duration time of 0 s. Three control trials (about 35 cycles in one trial) were performed with the time interval between 15 min and 20 min.

3. Results

The maximum extension angle was controlled appropriately by regulating stimulation burst duration *TB* by the fuzzy controller as seen in Figs. 2 and 3. In Fig. 2, the joint angle was controlled well until the 28th cycle, in which muscle fatigue was considered to be compensated by increasing burst duration *TB*. However, the muscle produced larger force in the cycles after electrical stimulation with large *TB* was applied (about 1.9 s at the 29th cycle). The increased force production was not compensated before the end of control trial, although the fuzzy controller decreased *TB*. The force

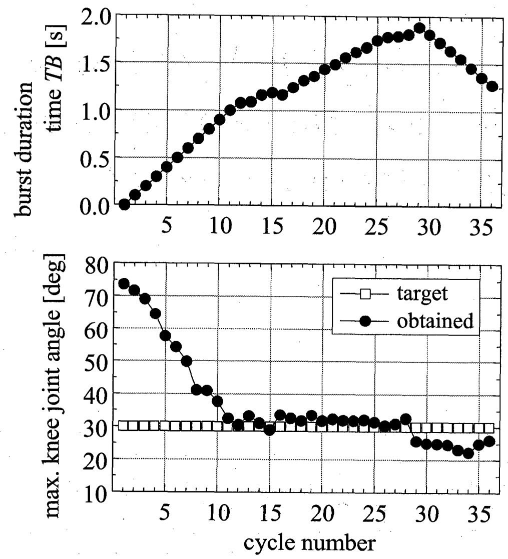


Fig. 2 A result of the cycle-to-cycle control of maximum knee extension angle by fuzzy controller (subject A, 1st trial).

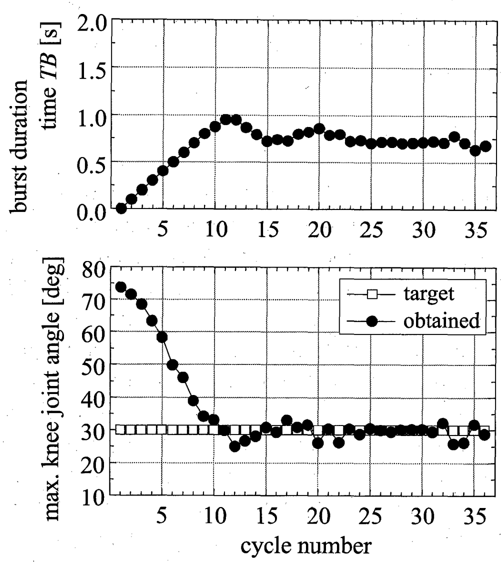
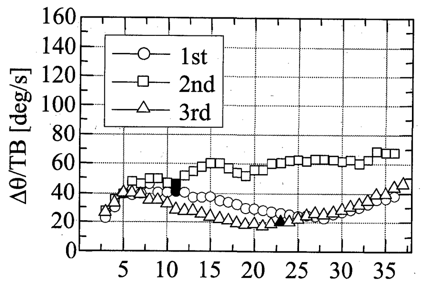


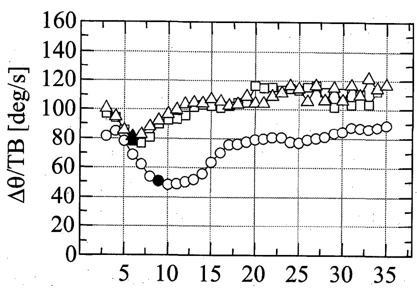
Fig. 3 A result of the cycle-to-cycle control of maximum knee extension angle by fuzzy controller (subject A, 2nd trial).

increase after stimulating with about 2.2 s of *TB* at the 24th cycle in the 3rd trial of subject A was also not compensated before the end of trial.

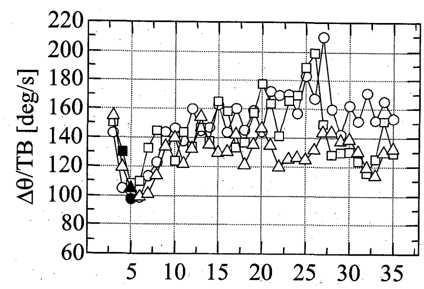
In the 2nd trial of subject B and the 2nd and the 3rd trails of subject C, maximum joint angle at the 1st and/or 2nd cycles were not detected correctly because of disturbances, although the detection and control was appropriate after those cycles. Removing these 3 trials, the maximum knee extension angle reached the target angle with the error less than 3.0 deg [3] at the 11th cycle in two trials and the 23rd cycle with subject A, at the 9th and the 6th cycle with subject B, and at the 5th cycle with subject C. In the 3rd trial of subject A, 23 cycles were needed to reach the target angle because of muscle fatigue.



(a) Subject A



(b) Subject B



(c) Subject C

Fig. 4 Joint angle production ratio to stimulation burst duration *TB*. Closed symbols show the first cycle that reached the target. The first 2 cycles were removed because inappropriate values (see text) were included in some trials.

Table 1 Evaluation results after reaching the target.

	error (mean±SD) [deg]			large error rate [%]		
	1st	2nd	3rd	1st	2nd	3rd
subj.A	3.0±2.0	1.6±1.5	5.9±2.8	19.2	3.8	66.7
subj.B	1.0±0.9	1.1±0.9	1.2±0.8	0.0	0.0	0.0
subj.C	3.3±2.0	2.1±2.0	1.3±1.1	16.1	9.4	0.0

Table 2 Average value of the joint angle production ratio to stimulation burst duration TB after reaching the target.

	$\Delta\theta/TB$ [deg/s]		
	1st	2nd	3rd
subj.A	30.9	59.5	30.6
subj.B	73.3	103.2	105.3
subj.C	151.7	143.1	128.5

After reaching the target, the maximum extension angle and the stimulation onset time were detected correctly in all trials. Mean errors in the control after reaching the target are shown in Table 1. The fuzzy controller realized good control with the mean error less than about 2 deg in 6 trials. Large error rate that was defined by the number of cycles with error larger than 5 deg after reaching the target are also shown in Table 1. The large errors of subject A (1st and 3rd trials) were caused in successive cycles because of the force increase as shown in Fig. 2. In the 1st and the 2nd trials of the subject C, small oscillations in the response increased the errors.

In order to find muscle fatigue and force increase in control trials, the ratio of produced joint angle to the burst duration *TB* was calculated and shown in Fig. 4. In the first several cycles, the ratio, generally, decreases or increases because of nonlinear muscle response to increasing *TB*. In the 1st and the 3rd trials of subject A, muscle fatigue is found by decreasing of the ratio. Increasing of the ratio is also observed in these trials of subject A, which shows force increase. In other 7 trials, although the ratio increased within about 10 cycles after reaching the target, large increase in error was not caused by the increase in force or the error was compensated within a few cycles as seen in Fig. 3. Although the ratio decreased at several cycles after the 25th cycle in the 2nd and the 3rd trials of subject B and the 2nd trial of subject C, they did not cause large increase in error.

4. Discussions

The fuzzy controller realized reaching the target within about 10 cycles. In most of trials, mean error after reaching the target was less than about 2 deg. Those errors were similar to variations of movement during gait of normal subjects [3]. In those trials, the number of cycles that had larger error than 5 deg was small (Only 4 cycles for 175 cycles in 6 trials). As seen in Fig. 2 and also in our previous computer simulation study [3], gradual decrease of muscle force caused by muscle fatigue could be compensated by the fuzzy controller. The force increases as shown in Fig. 4 were also compensated in most of trials. Therefore, the fuzzy controller is expected to be practical in clinical applications.

The fuzzy controller with fixed parameter values worked well without adjusting the parameter values for each subject. However, the force enhancement caused in the control could not be compensated within about 10 cycles for subject A and small oscillations in responses increased errors in trials of subject C. Therefore, for practical clinical applications, it is better to adjust the values during control in order to reach the target and to compensate the change in muscle response quickly without causing oscillating responses. We tested an automatic parameter adjustment in our previous computer simulation study [3]. It was found that the automatic parameter adjustment would be effective in controlling various subjects.

Average values of the joint angle production ratio after reaching the target are shown in Table 2. As seen in Fig. 4 and Table 2, it is found that subject A had smaller values of the ratio than other subjects, which suggests controller gain was small for subject A. Therefore, it is considered that force increase could not be compensated quickly in the 1st and the 3rd trials and 23 cycles were required to reach the target in the 3rd trial. On the other hand, subject C had larger value of the ratio, which suggests that oscillating responses were caused by large controller gain for subject C. The controller parameters in the experiment are considered to be appropriate for the ratio between about 60 and 130 deg/s. In some trials (the 2nd trial of subject A, all trials of subject B and the 3rd trial of subject C), in which the ratio was in this range at most of cycles, the controller compensated the force increase within a few cycles and did not cause oscillating responses. For smaller ratio, controller gain should be increased for quick compensation. For larger ratio, the gain should be decreased in order not to cause oscillating responses. The ratio as shown in Table 2 and also in Fig. 4 will give us useful information to realize practical automatic parameter adjustment method.

Increased *TB* of electrical stimulation is suggested to cause change in muscle response to electrical stimulation. Muscle force potentiation [6], [7] may be a reason of this phenomenon. The potentiation is well known as increased muscle force production after applying electrical stimulation pulses with sufficient duration and enough high frequency. Myosin light chain phosphorylation has been suggested to be a possible reason of the potentiation [6], [7].

Muscle fatigue may have some problems on the cycle-to-cycle control of FES-induced gait. Since the cycle-to-cycle control compensates muscle fatigue by increasing burst duration *TB*, longer movement time may be needed after muscle fatigue. It is also considered to be difficult to compensate significantly reduced muscle force by severe muscle fatigue. However, it may be possible to improve ability of muscle fatigue compensation of this controller by using pulse amplitude or pulse width modulation for increasing the number of recruited motor units. Hybrid-FES that uses orthosis with FES can also be an option.

5. Conclusion

In this paper, the fuzzy controller based on the cycle-to-cycle control for FES gait control was tested experimentally in maximum knee extension angle control with neurologically intact subjects. In most of control trials, the joint angle was controlled well compensating changes in muscle responses to electrical stimulation (muscle fatigue and force enhancement). The experimental results show that the fuzzy controller would be practical in clinical applications. In addition, it was considered that increased *TB* of electrical stimulation pulses enhanced muscle force. For practical clinical applications, it is desirable to design an automatic parameter adjustment of the fuzzy controller for quickly reaching the target and for quick compensation of changes in muscle response without causing oscillating response.

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