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# Fuzzy FES controller using cycle-to-cycle control for repetitive movement training in motor rehabilitation. Experimental tests with wireless system

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**A prototype of wireless surface electrical stimulation system combined with the fuzzy FES controller was developed for rehabilitation training with functional electrical stimulation (FES). The developed FES system has three features for rehabilitation training: small-sized electrical stimulator for surface FES, wireless connection between controller and stimulators, and between controller and sensors, and the fuzzy FES controller based on the cycle-to-cycle control for repetitive training. The developed stimulator could generate monophasic or biphasic high voltage stimulus pulse and could output stimulation pulses continuously more than 20 hours with 4 AAA batteries. The developed system was examined with neurologically intact subjects and hemiplegic subjects in knee joint control. The maximum knee joint angle was controlled by regulating burst duration of stimulation pulses by the fuzzy controller. In the results of two experiments of knee extension angle control and knee flexion and extension angle control, the maximum angles reached their targets within small number of cycles and were controlled stably in the stimulation cycles after reaching the target. The fuzzy FES controller based on the cycle-to-cycle control worked effectively to reach the target angle and to compensate difference in muscle properties between subjects. The developed wireless surface FES system would be practical in clinical applications of repetitive execution of similar movements of the limbs for motor rehabilitation with FES.**

**Keywords:** Cycle-to-Cycle Control, Functional Electrical Stimulation, Rehabilitation, Surface Electrical Stimulation, Wireless System

## Introduction

Functional electrical stimulation (FES) can be an effective method of assisting or restoring paralyzed motor functions caused by spinal cord injury or cerebrovascular disease. FES has been utilized as an orthotic and therapeutic aid in the rehabilitation of the upper and lower limb motor functions. The therapeutic effects during rehabilitation with FES have been shown to improve muscle strength [1–3] and muscle recruitment [3–4]. The repetitive movement therapy mediated by the electrical stimulation also has the potential to facilitate motor relearning [5].

In motor rehabilitation, goal-oriented repetitive movement training of the paralyzed limbs has been applied. One of the therapeutic effects is motor relearning, which is reacquisition of previously learned motor skills after central nervous system injury. In general, assistance provided by therapists is required to perform repetitive execution of identical or similar movements of the limbs in the rehabilitation training. On the other hand, several large-scale robotic systems have been developed to reduce the workloads for the therapists and improve repeated training for patients [6]. However, these equipments are large and expensive, which are installed in hospitals or rehabilitation centers, and therefore generally unsuitable for home rehabilitation and daily exercise.

For motor rehabilitation with FES, surface electrical stimulation would be useful because of its noninvasive nature. However, the electrical stimulator for surface FES is usually required to generate high stimulation intensity pulses, which leads to an increase of size and power consumption of the stimulator. In addition, wired connection between controller and stimulators and between controller and sensors are sometimes cumbersome and can obstruct the movement of the limb. Therefore, this study focused on miniaturizing the electrical stimulator and on removing the connection code using wireless technology.

In training with FES for rehabilitation, repetitive movements of limbs have to be controlled appropriately by stimulating the relevant muscles. Closed-loop FES control is required to suppress variations of initial position and muscle response, and muscle fatigue in the exercise and to derive benefit from

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the rehabilitation. Tracking control of joint angles of the lower limb is a difficult problem because of nonlinearity and significant time delay, both affecting the responses of the musculoskeletal system to electrical stimulation. For this purpose, the fuzzy FES controller based on the cycle-to-cycle control [7–9] was modified and implemented in the wireless FES system for rehabilitation in this study. The cycle-to-cycle control is a control method for restoring cyclic movements such as gait by using FES [10–11]. Each muscle contraction is controlled by single burst of stimulation pulses with constant pulse amplitude, pulse width and frequency to induce joint movement reaching the target joint angle, in which the stimulation burst duration is regulated.

The purpose of this study is to show the effectiveness of the wireless FES system in which the fuzzy cycle-to-cycle control was implemented for repetitive movement control through control tests with neurologically intact and hemiplegic subjects. In this paper, the wireless surface electrical stimulation system combined with the fuzzy FES controller based on the cycle-to-cycle control was developed. The developed wireless feedback FES system was examined in knee joint control. First, the maximum knee extension angle control stimulating one muscle was performed to find the basic performance of the closed-loop control with the wireless system with neurologically intact subjects and hemiplegic subjects. Then, the maximum knee flexion and extension angle control was performed as a preliminary test of controlling a sequence of movements stimulating two muscles with neurologically intact subjects.

## Wireless surface electrical stimulation system

The wireless surface electrical stimulation system consists of three parts: the fuzzy FES controller implemented on the PC, surface electrical stimulator and sensor. For wireless communication between the controller and the stimulator and between the controller and the sensor, a 2.4 GHz wireless transceiver module (WCU-241, K2-denshi) was used. The stimulus data determined by the fuzzy FES controller is transmitted to the stimulator through the wireless transceiver modules. The stimulator generates electrical stimulation pulses immediately after receiving the stimulus data. The data was composed of stimulus voltage, stimulus pulse width and monophasic/biphasic pulse type. The current system can send the stimulus data of up to 4 channels together. The sensor data are digitized by a 10 bit A/D converter with 40 Hz of sampling frequency in the wireless transceiver module and transmitted to the fuzzy FES controller through wireless transceiver module as feedback signal. It is possible to receive the sensor data of up to 4 channels simultaneously. The topology of wireless communication is the point-to-point connection between the controller and the stimulator and between the controller and the sensor, in which the original protocol (the packet consisting of the data of Preamble, Address, Payload and Cyclic Redundancy Check) is used. The bit rate and the latency of the transceiver module are up to 250 kbit/s and about 2 ms, respectively.

Electrical stimulator consists of the wireless transceiver module, the boost converter and the stimulation pulse generator. The boost converter stores electric charges in a tank capacitor and generates high voltage pulse required for the surface electrical stimulation (maximum output voltage: 128 V). The stimulator generates monophasic or biphasic pulse. The maximum stimulation frequency was 520 Hz. In usual FES control, stimulation pulses with a constant stimulation frequency smaller than about 100 Hz are used. High frequency stimulation pulses are sometimes used in research work as a doublet or a triplet [12–13], in which stimulation frequency is about up to 300 Hz. The overall size of the produced stimulator was 70 × 55 × 30 mm. The stimulator's power is supplied by 4 AAA batteries. The electrical stimulator could output stimulation pulses continuously more than 20 hours (monophasic pulse train, frequency: 20 Hz, pulse width: 0.3 ms, pulse amplitude: 80 V).

## Outline of fuzzy FES controller based on cycle-to-cycle control

The block diagram of the fuzzy FES control for repetitive movement is shown in figure 1. Output of the fuzzy controller was automatically adjusted by two parameters: error-based output adjustment factor (E-OAF) and sensitivity-based factor (S-OAF). Therefore, the burst duration of stimulation pulses of a current cycle TB[n] is regulated by the following formula:

$$TB[n] = TB[n-1] + \Delta TB[n]$$

where TB[n-1] is the stimulation burst duration for the cycle just before the current one and ΔTB[n] is the output of the fuzzy controller adjusted by the 2 factors.

The fuzzy controller was designed as multi-input single-output (MISO) controller with two inputs of 'error' and

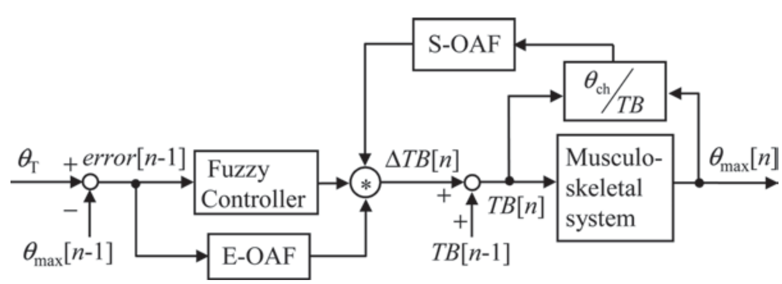


Figure 1. Block diagram of the Fuzzy FES control for repetitive movement. S-OAF, sensitivity-based output adjustment factor; E-OAF, error-based output adjustment factor; $\theta_T$, target maximum angle; $\theta_{max}$, maximum joint angle produced by TB; $\theta_{ch}$, joint angle change produced by TB.

'desired range'. The 'error' was defined as the difference between the target angle and the maximum angle elicited by the burst stimulation pulses. The 'desired range' was defined as the difference between the target angle and the angle at the stimulation onset. The E-OAF is determined by the error of the cycle just before the current cycle, which increases the output value of the controller if the error is large, and decreases if the error is small. The S-OAF is determined by joint angle production ratio that is defined as the ratio of joint angle change to stimulation burst duration, $\theta_{ch}/TB$, which means sensitivity of the muscle to electrical stimulation.

figure 2 shows an example of input and output membership functions of the fuzzy controller for knee extension angle control. 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. The membership functions of the E-OAF comprised 5 linguistic terms, and the output variable was expressed as 5 fuzzy singletons. The membership functions of the S-OAF comprised 3 linguistic terms, and the output variable was expressed as 3 fuzzy singletons.

The fuzzy inference was accomplished by using the Mamdani method. Center of gravity (COG) was used in the defuzzification process. Parameter values of the fuzzy controller were determined based on control results and values obtained in our previous studies [7–9], which were fixed during the experiments.

## Knee extension angle control with neurologically intact subjects and hemiplegic subjects

### Experimental methods

The vastus muscles were stimulated through surface electrodes (SRH5080, SEKISUI PLASTICS), and maximum knee extension angle was controlled by the surface electrical stimulation system (figure 3). Two neurologically intact subjects (subject A, B) and two hemiplegic subjects caused by cerebral apoplexy (subject C: 76-year-old right sided hemiplegic male patient, subject D: 38-year-old left sided hemiplegic male patient) participated in the experiments. Subjects' consent to participate in the experiment was obtained.

The subject seated in the chair (GT-30, OG Giken) and relaxed his legs during experiments. To maintain the sitting position, the trunk of hemiplegic subject was fixed to the chair with band. The sitting position of the neurologically intact subjects was determined by themselves and that of the hemiplegic subject was determined by adjusting the back of the chair in the forward and backward direction for appropriate knee joint movement. Consequently, the initial joint angle was about 65° in neurologically intact subjects and about 80° in hemiplegic subjects (0° means full knee extension). The target angle was 30° (range of knee extension angle was about 35°) for neurologically intact subjects and was 70° or 65° (range of knee extension angle was about 10° or 15°) for hemiplegic subjects. The target angle was determined based on the maximum knee extension angle developed by electrical stimulation. The

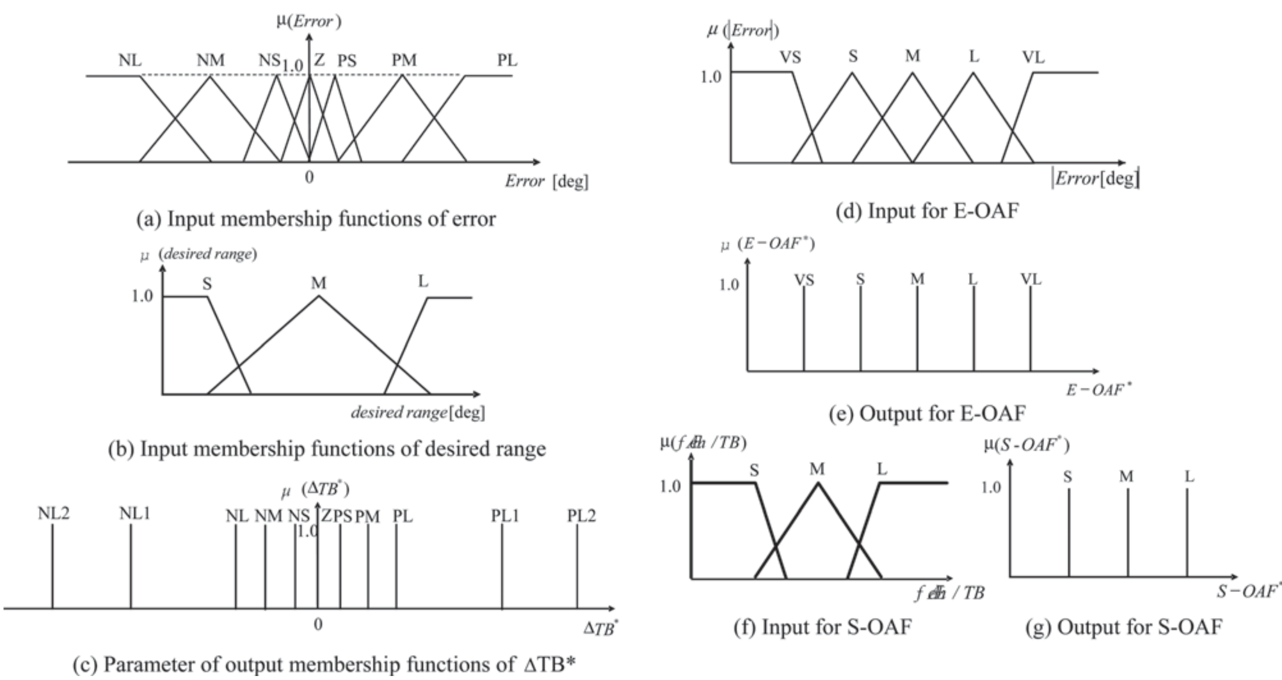


Figure 2. Input/Output membership functions of the fuzzy controller. Input membership functions were expressed by triangular and trapezoidal fuzzy sets. The membership functions of the 'error' and 'desired range' comprised 7 and 3 linguistic terms, respectively, and that of the output variable was expressed as 11 fuzzy singletons. The membership functions of the E-OAF comprised 5 linguistic terms, and the output variable was expressed as 5 fuzzy singletons. The membership functions of the S-OAF comprised 3 linguistic terms, and the output variable was expressed as 3 fuzzy singletons. S, small; M, medium; L, large; NL2, negative large 2; NL1, negative large 1;NL, negative large; NM, negative medium; NS, negative small; Z, zero; PS, positive small; PM, positive medium; PL, positive large; PL1, positive large 1; PL2, positive large 2.

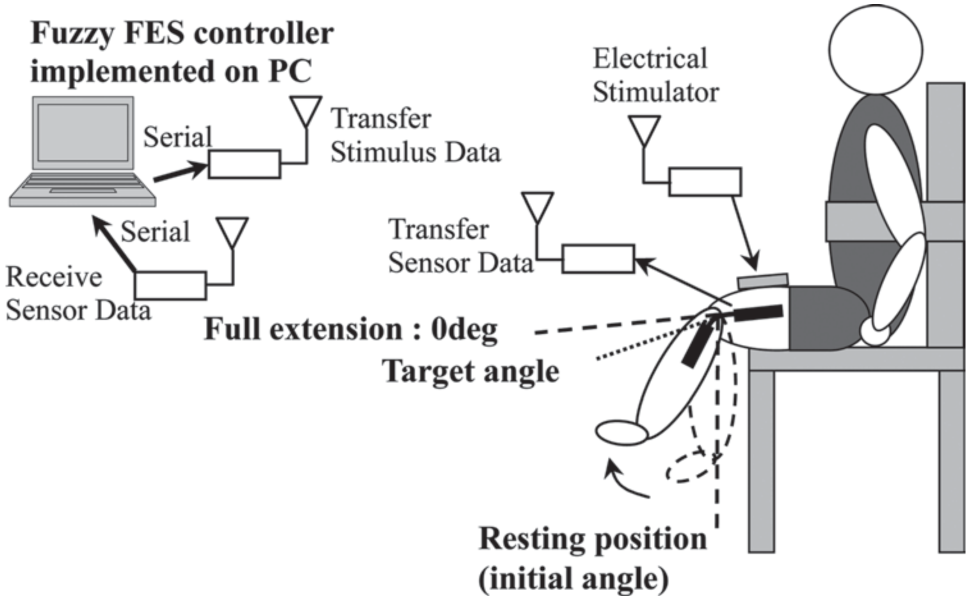


Figure 3. Experimental setup of the knee extension control.



values of fuzzy membership functions for neurologically intact subjects were determined in previous experiments with other subjects [8,9]. The values of fuzzy membership functions for hemiplegic subjects were determined after adjusting their values of neurologically intact subjects from the results of preliminary experiments.

In one experimental session, 100 cycles were performed with neurologically intact subjects, and 35 cycles were performed with hemiplegic subjects to reduce physical load. The knee joint angles were measured with an electric goniometer (M180, Penny & Giles). The output signal of the goniomenter was digitized by a 10 bit A/D converter with 40 Hz of sampling frequency. Pulse width and pulse frequency was fixed at 0.3 ms and 20 Hz, respectively. Stimulus pulse amplitude was determined so as to develop target joint angle without pain before the experiment. Initial value of TB was 0 s.

## Results

An example of control results with a hemiplegic subject (Subject C) was shown in figure 4. Stimulation burst duration TB increased as the number of cycles increased, and then the maximum extension angle was reached to the target angle at the 4th control cycle. In the first few cycles, the value of E-OAF was large, which shows the E-OAF worked effectively in early cycles in order to reach the targets with small number of cycles. The value of S-OAF was large at the most cycles, which shows the S-OAF compensated for the weak muscle response of this subject.

For evaluating control results, settling index (SI), mean error (ME) and mean variation (MV) were calculated (table 1). SI was defined as the number of cycles that were required to reach the target joint angle with absolute error that was less than or equal to 3°. ME was mean value of the absolute error between the target angle and the produced maximum extension angle in cycles after reaching the target. MV was mean of the difference in controlled joint angles between two consecutive cycles after reaching the target. The number in parentheses in table 1 shows the result for the first 35 cycles that is the same evaluation condition as the hemiplegic subjects. As seen in table 1, SI was 3–5 cycles, ME was less than 1° for all trials and MV was approximately 1°. The evaluation indices for the hemiplegic subjects showed similar values as those for the neurologically intact subjects.

The developed system performed well in the knee extension control with all subjects. However, there were some cases that the value of S-OAF did not change dynamically to the change in the sensitivity. Figure 5 shows relationship between the sensitivity and the S-OAF of each cycle after reaching the target in the knee extension angle control. The value of sensitivity was about between 20° and 50°/s in the hemiplegic subjects and about between 50° and 90°/s in the neurologically intact subjects. The value of sensitivity in the hemiplegic subjects was small compared to those of neurologically intact subjects, because muscle responses to electrical stimulation were weak with the hemiplegic subjects. The controller used in the experiments adjusted output values (TB) by the S-OAF for subject A (0.7–1.0) and C (1.2–1.5). For Subjects B and D, values of the S-OAF were about 1.0, which shows little adjustment by the S-OAF. The role of the S-OAF is to compensate variation of the muscle properties between subjects, change in muscle response and muscle fatigue. In the control tests, parameter values for the S-OAF were determined based on the previous results [8]. That is, for paralyzed subjects, considering weak muscle responses to electrical stimulation, values of sensitivity for the input membership function (M) were set between 10°/s and 70°/s with 40°/s for the center. Those sensitivity values were similar to those for a neurologically intact subject whose muscle responses were considerably weak [8]. Since the adjustment of the S-OAF was little with one hemiplegic subject and one neurologically intact subject compared with

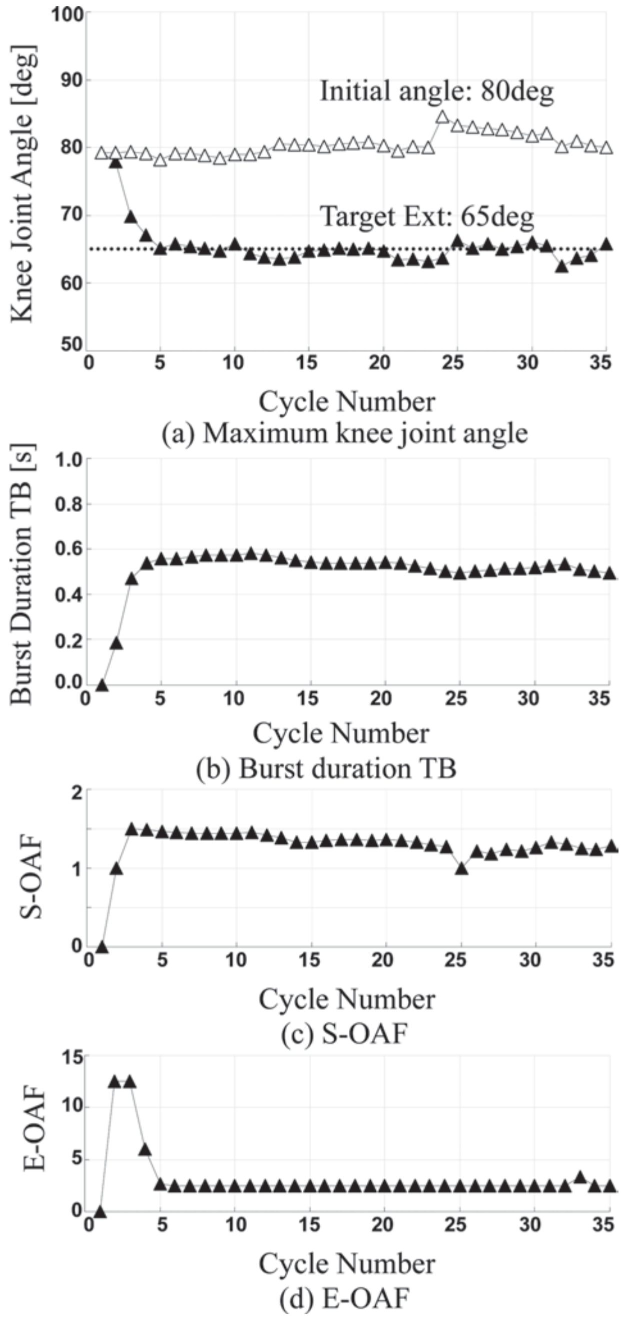


Figure 4. An example of control results of the maximum knee extension angles (Subject C trial 2).

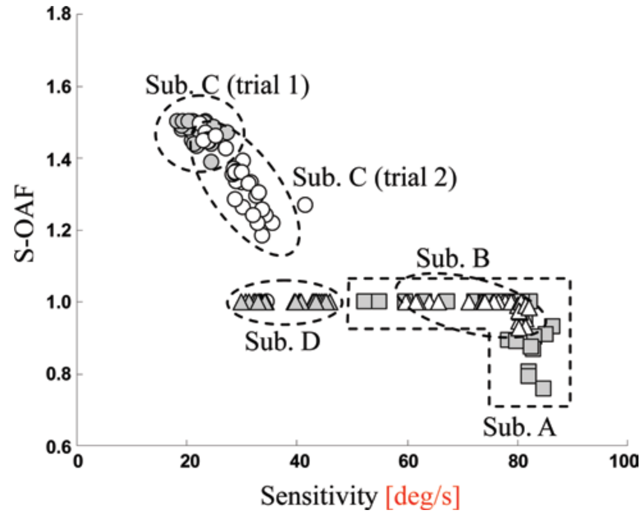


Figure 5. Evaluation results of sensitivity and S-OAF in knee extension angle control.

Table 1. Evaluation results of knee extension control.

| Subject range of extension | Max. knee extension control | | |
|---|---|---|---|
| | SI (cycle) | ME (deg) | MV (deg) |
| A 35° | 5 | 0.8 (1.2) | 1.0 (1.4) |
| B 35° | 3 | 0.7 (0.7) | 0.9 (1.0) |
| C 10° (trial 1) | 3 | 0.6 | 0.8 |
| C 15° (trial 2) | 4 | 0.8 | 0.8 |
| D 15° | 3 | 0.9 | 1.0 |

The number in parentheses shows the result for the first 35 cycles that is the same evaluation condition as the hemiplegic subjects.

the change in sensitivity, the modification of the S-OAF will be necessary.

## Knee flexion and extension control with neurologically intact subjects

Based on the results of the previous section, the range of values of input and output membership functions of the S-OAF were expanded, and the number of terms were increased in order to adapt to changes in these muscle responses. The maximum knee flexion and extension angle control was examined as a sequence of movements stimulating two muscles with neurologically intact subjects because of safety for hemiplegic subjects in positioning during control.

### Experimental methods

The maximum knee flexion and extension angles were controlled in one cycle stimulating the hamstrings and the vastus muscles by the surface electrical stimulation system with 7 neurologically intact subjects (figure 6). Subject's consent to participate in the experiment was obtained. The subject sat on the equipment keeping his position by his upper limbs. The initial knee joint angle (neutral position) was approximately 30° and target angles were 45–70° for knee flexion and 10° for extension (the maximum angle of knee extension is defined as 0°). Starting condition for each control cycle was when the difference of knee joint angle between two consecutive cycles is less than 0.3° for the 20 consecutive samples after 6 seconds from the time when the maximum extension angle was detected in the previous control cycle. The hamstrings were stimulated first and then the vastus muscles were stimulated after detecting the maximum flexion angle.

Pulse width was fixed at 0.2 ms. Other electrical stimulation condition and the measurement method of knee joint angle were same as the experiment of knee extension control. Initial value of TB is 0 s and 35 cycles were performed in each control session. Three control sessions were performed for each subject with the time interval between 20 min and 30 min.

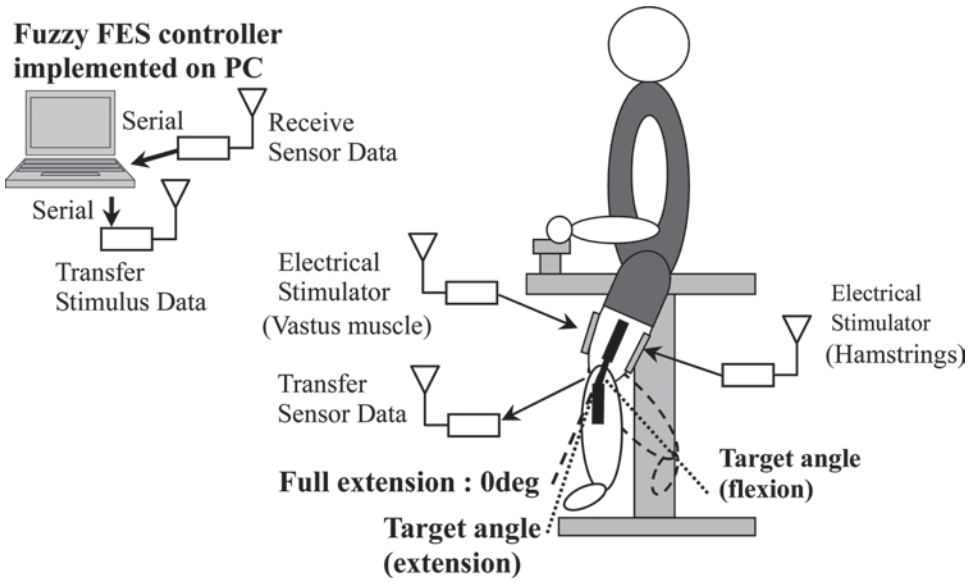


Figure 6. Experimental setup of the knee flexion and extension control.



For the hamstrings, the fuzzy model of the S-OAF was changed to have 7 linguistic terms for input membership function and 7 singletons for the output variable. For the vastus muscles, the fuzzy model of the S-OAF was changed to have 4 linguistic terms for input membership function and 4 singletons for the output variable.

### Results

Both maximum joint angles were controlled with five subjects, but sufficient knee flexion angle was not produced by the electrical stimulation with two subjects. One example of control results is shown in figure 7. The maximum flexion and extension angles reached their targets with small number of cycles (3 for the flexion and 4 for the extension, respectively) and were controlled stably during the stimulation cycles after reaching the target. As shown in the case of knee extension control, the E-OAF worked effectively in early cycles and the burst duration was adjusted appropriately by regulating the value of S-OAF (about 1.2 for flexion and about 0.8 for extension, respectively) to compensate for different muscle responses.

For evaluating control results, SI, ME and MV were calculated (table 2). SI was 3–5 cycles, ME was less than 4° for flexion control and less than 2° for extension control. MV was less than 5° for flexion and less than 2.5° for extension.

## Discussions

The developed wireless surface electrical stimulation system combined with the fuzzy controller performed well in the knee angle controls. The system realized reaching the target within about 5 cycles. In most of trials, the mean error after reaching the target was less than about 3°, and the mean variation after reaching the target was less than about 3°. These control results were similar to the results in our previous reports [9], which were obtained by using previous wired stimulation system. In addition, under the condition of the longer control cycles than the previous report [9], the maximum knee extension angle was controlled stably with neurologically intact subject. Therefore, the wireless surface electrical stimulation system combined with the fuzzy controller was considered to function effectively as a closed-loop controller.

The developed system worked well with hemiplegic subjects in the knee extension control. Although the muscle response produced by the electrical stimulation with the hemiplegic subjects was weak compared to those of neurologically intact subjects, the ability of fuzzy FES controller based on the cycle-to-cycle control is considered to be appropriate to reach the target angle and to compensate difference in muscle properties between subjects. Therefore, the developed system is expected to be practical in clinical applications.

Stimulation burst duration (TB) was adjusted appropriately, and the knee joint angle was controlled stably by the fuzzy controller with two parameters of the E-OAF and the S-OAF in both control tests. For large error between the control angle and the target angle in early cycles, the E-OAF worked effectively to reach the target with small number of cycles in all subjects. After reaching the target angle, the E-OAF was small because the error of the obtained knee joint angle was small. In contrast, the S-OAF worked to compensate for the different muscle responses during all the stimulus cycles automatically based on the value of sensitivity. These results showed that both of the E-OAF and S-OAF would be effective in controlling the repetitive execution of similar movements for rehabilitation.

In the knee extension angle control, the value of S-OAF did not change dynamically to the change in sensitivity with some subjects. Therefore, the range of values of input and output membership functions of the S-OAF was expanded and the number of terms was increased, and then the knee flexion and extension angle control was examined. Figure 8 shows the sensitivity and the S-OAF of each cycle after reaching the target obtained in the knee flexion and extension angle control. The value of the S-OAF changed dynamically as the sensitivity changed. It may be better to expand the range of the

Table 2. Evaluation results of knee flexion and extension control.

| Subject | Max. knee flexion control | | | Max. knee extension control | | |
|---|---|---|---|---|---|---|
| | SI ± SD (cycle) | ME ± SD (deg) | MV ± SD (deg) | SI (cycle) ± SD | ME ± SD (deg) | MV ± SD (deg) |
| E | 4.0 ± 1.0 | 2.3 ± 0.1 | 2.9 ± 0.2 | 3.7 ± 0.6 | 1.3 ± 0.2 | 1.2 ± 0.3 |
| F | 2.7 ± 0.6 | 3.3 ± 0.5 | 3.7 ± 1.1 | 3.3 ± 0.6 | 0.9 ± 0.1 | 1.1 ± 0.2 |
| H | 3.0 ± 0.0 | 1.3 ± 0.2 | 1.6 ± 0.4 | 3.0 ± 0.0 | 0.9 ± 0.2 | 1.3 ± 0.4 |
| J | 4.0 ± 1.0 | 2.3 ± 1.3 | 3.4 ± 1.6 | 2.7 ± 1.6 | 1.4 ± 0.5 | 1.7 ± 0.8 |
| K | 3.7 ± 0.6 | 2.1 ± 1.2 | 2.9 ± 1.7 | 3.0 ± 0.0 | 1.5 ± 0.1 | 2.0 ± 0.1 |
| Average | 3.5 ± 0.8 | 2.3 ± 0.9 | 2.9 ± 1.2 | 3.1 ± 0.5 | 1.2 ± 0.3 | 1.5 ± 0.5 |

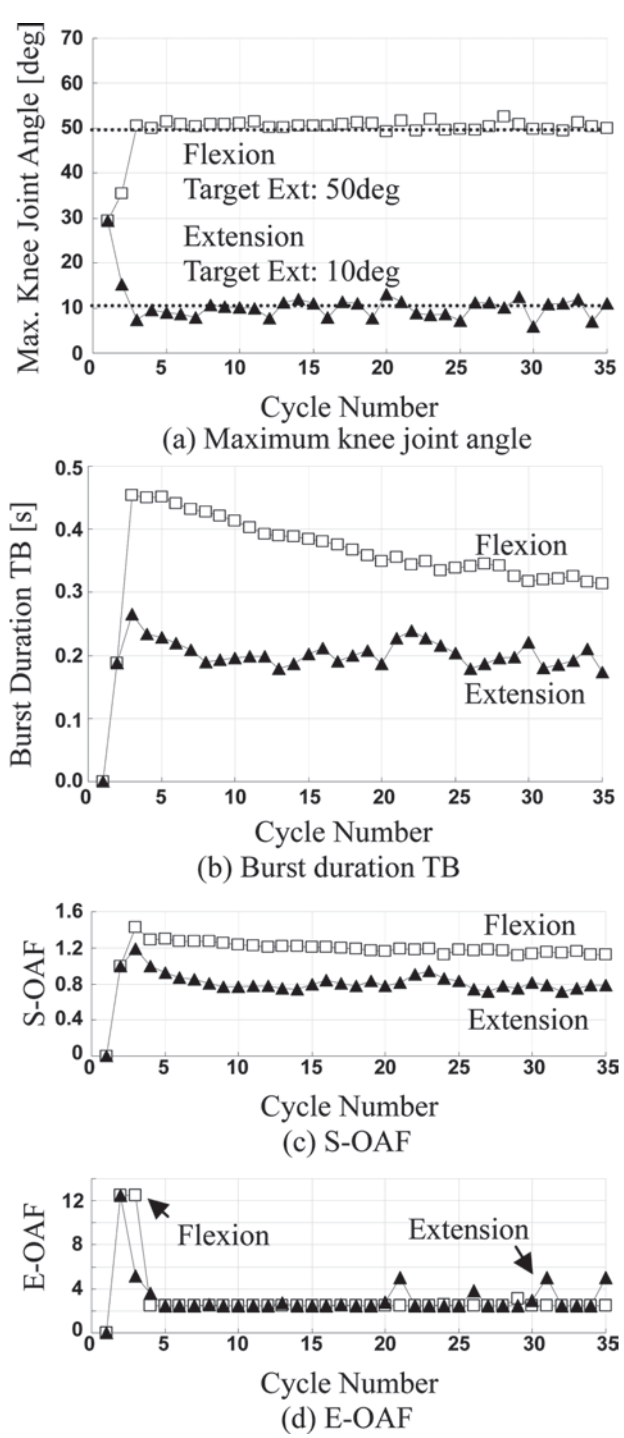


Figure 7. An example of control results of the maximum knee flexion and extension angles (Subj. K, 1st trial).

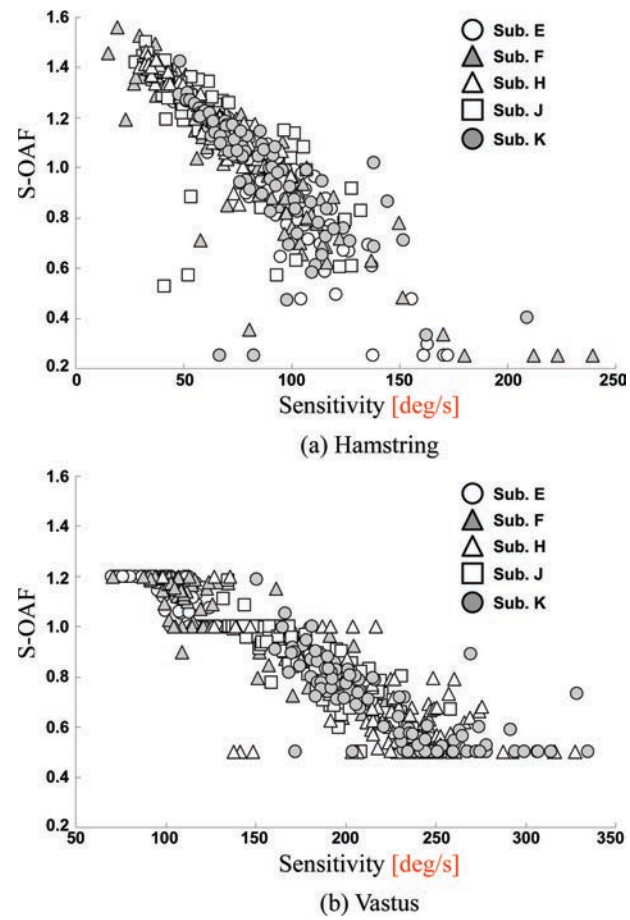


Figure 8. Evaluation results of sensitivity and S-OAF after reaching the target in knee flexion and extension angle control.

input and output membership functions of the S-OAF for the vastus muscles because of the slight saturation of the S-OAF of the vastus muscles in both the lower and higher sensitivity, if necessary.

The S-OAF using the sensitivity, which is the ratio of joint angle change to stimulation burst duration, worked effectively in both hemiplegic subjects and neurologically intact subjects. However, the sensitivity obtained by this method may contain other effects such as movements of other parts of the body or gravitational effect. For optimal movement control, it is required to modify by using directly measured muscle activity such as surface electromyogram elicited by electrical stimulation (M-wave).

The developed wireless surface FES system by using the wireless transceiver module is expected to improve ease of use.

However, the wireless communication has problems such as delay and interference. The delay of wireless communication between the wireless modules used in the developed system was small (2 ms) enough compared to the sampling period of ADC (25 ms) and the stimulus period (50 ms). Therefore, it is considered that the influence of the delay of the wireless communication on the performance of the cycle-to-cycle controller was small in this system. The interference in wireless communication was not caused in the experiments using the wireless transceiver module for the 2.4 GHz (Industrial, Scientific and Medical: ISM) band. However, the interference problem does not always cause in the wireless communication. It is necessary to deal with the problem of the wireless communication by modifying the communication software including time management within each module, the retransmission processing and so on.

The setting of the goniometer for movement measurements is not so easy for rehabilitation training because of limited attachment position and requirement of complicated calibration process. The measurement of movement using wearable sensor such as a gyroscope and accelerometer [14] would be suitable for clinical application of feedback FES control system.

## Conclusion

In this study, the small surface electrical stimulator was designed, and then the wireless surface FES system combined with the fuzzy controller based on the cycle-to-cycle control was developed. In order to show the effectiveness of the wireless FES system implemented the fuzzy cycle-to-cycle control for repetitive movement control, the developed wireless FES system was examined in knee joint controls with neurologically intact and hemiplegic subjects. The developed system performed well in the knee joint angle controls adjusting stimulation burst time appropriately as a closed-loop controller with both hemiplegic subjects and neurologically intact subjects, which shows that the wireless FES system can realize stable control. The wireless surface electrical stimulation system would be practical in clinical applications of repetitive execution of similar movements of the limbs for motor rehabilitation with FES.

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