Preliminary Tests of a Prototype FES Control System for Cycling Wheelchair Rehabilitation

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***Abstract*—The cycling wheelchair "Profhand" developed by our research group in Japan has been found to be useful in rehabilitation of motor function of lower limbs. It is also expected for rehabilitation of paraplegic subjects to propel the cycling wheelchair by lower limbs controlled by functional electrical stimulation (FES). In this paper, a prototype FES control system for the cycling wheelchair was developed using wireless surface stimulators and wireless inertial sensors and tested with healthy subjects. The stimulation pattern that stimulated the quadriceps femoris and the gluteus maximus at the same time was shown to be effective to propel the Profhand. From the analysis of steady state cycling, it was shown that the cycling speed was smaller and the variation of the speed was larger in FES cycling than those of voluntary cycling. Measured angular velocity of the crank suggested that stimulation timing have to be changed considering delay in muscle response to electrical stimulation and cycling speed in order to improve FES cycling. It was also suggested that angle of the pedal have to be adjusted by controlling ankle joint angle with FES in order to apply force appropriately.**

Keywords—cycling wheelchair; Profhand; lower limb; functional electrical stimulation; FES

I. INTRODUCTION

In Japan, cerebrovascular disease is the 4th leading cause of death, and the number of patients with cerebrovascular disease is more than 1.3 million. Most of the patients suffer from the aftereffects of cerebrovascular disease, in which, especially, motor paralysis deteriorates activities of daily living (ADL). A wheelchair has been an effective transportation device for the patients whose motor function of lower limbs has been affected severely by the disease. However, it is sometimes difficult to propel the wheelchair with both upper limbs for hemiplegic patients. In addition, traveling with the conventional wheelchair do not need movements of lower limbs, which leads disuse syndrome of lower limbs that causes muscle weakness, decrease of range of motion (ROM) of joint, joints ossify, deterioration of peripheral circulatory function, and so on.

The cycling wheelchair "Profhand" (TESS Co., Ltd.) [1], which was developed by our research group in Japan (Fig. 1), has a possibility of solving the above problems of conventional wheel chair [2, 3]. Profhand is a pedaled wheelchair, that is, it is not propelled by upper limbs like conventional wheelchairs, but by lower limbs. A hemiplegic patient, whose one-side lower limb have been paralyzed due to a stroke, can propel the cycling wheelchair by moving mainly the non-paralyzed side. Furthermore, even if the patients can hardly walk without assistance, they can propel the wheelchair with their own lower limbs. Therefore, it makes possible for patients who have severe motor paralysis to undergo rehabilitation of lower limbs with the cycling wheelchair. In a previous study, from electromyogram (EMG) measured during driving the cycling wheelchair with severe hemiplegic patients, it was suggested that training with Profhand could be effective in motor rehabilitation, in which the measured EMG showed cycling wheelchair could induce muscle activities of the paretic leg after the training [4]. It is expected that the subjects can perform rehabilitation training of lower limbs using Profhand without assistance of a therapist, because the cycling wheelchair has an advantage of decreasing significantly the risk of falling as a rehabilitation device.

Because of no risk of falling, it is considered that the cycling wheelchair can be applied to paraplegic patients as a rehabilitation tool in combination with FES for developing movement of pedaling the cycling wheelchair. Then, it is expected that rehabilitation with the cycling wheelchair brings about effects such as muscle strengthening, improvement of joint movement and range of motion, and improvement of peripheral circulation. There are several studies on FES cycling: bicycle ergometer combined with FES [5-7], and

Fig. 1 Cycling wheelchair "Profhand" (TESS Co., Ltd.) developed by our research group in Japan.

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experimental system of cycling wheel chair incorporated a rotary encoder [8, 9] or a motor assistance with an encoder [10]. Recumbent tricycle with ankle orthosis was also studied for mobile cycling [10, 11]. Cycling with FES has also been shown to be effective in rehabilitation [8, 9]. However, the bicycle ergometer system aimed only at rehabilitation training. On the other hand, FES control for mobile cycling depends on cycling system. In addition, if extensive modifications are required for the cycling wheelchair in order to incorporate FES control system, then it is difficult to use commercially available wheelchair with FES control. Therefore, this study focused on a simple FES control system that does not need extensive modifications of the cycling wheelchair "Profhand".

In this paper, first, in order to test a simple FES control, the FES control system that triggered electrical stimulation by signals from the accelerometer attached on the crank was developed. Then, in order to find simple, effective stimulation patterns for FES cycling with Profhand and to determine a suitable timing to switch stimulation from one leg to the other, two stimulation patterns and various stimulation timings were tested with healthy subjects. Finally, in order to benchmark where the current method stands as compared to voluntary cycling by healthy subjects, the FES cycling was evaluated in comparing to voluntary cycling under steady state cycling.

II. Outline of FES Control System

Fig. 2 shows outline of the cycling wheelchair with FES control system. A wireless inertial sensor (WAA-010, Wireless Technology) was fixed firmly to the center of the right crankshaft of the cycling wheelchair with adhesive tape. Acceleration and angular velocity signals were measured with the inertial sensor and recorded on a PC through Bluetooth network. Stimulation timing was determined by the crank angle calculated from the measured gravitational acceleration. The clank angle θ was calculated from x and y axis acceleration components of the sensor, a_x and a_y :

$$\theta = \tan^{-1} \frac{a_x}{a_y} \tag{1}$$

Electrical stimulation was automatically applied to muscles at the determined timing through surface electrodes with wireless electrical stimulator that was developed based on our previous stimulator [13]. The stimulation data are transmitted to the stimulator via a 2.4 GHz wireless transceiver module (MK72660-01, LAPIS Semiconductor Co., Ltd.) from a portable PC. The stimulator generates electrical stimulation pulses immediately after receiving the stimulation data. The data is composed of stimulus voltage, stimulus pulse width and type of stimulation pulse (monophasic or biphasic). The stimulation system can output up to 4 channels together. The size of the stimulator is 61×100×18.5 *mm*. The stimulator is powered by 2 AAA batteries.

III. Test of Stimulation Pattern and Timing

A. Stimulation Pattern and Timing

In this paper, the following 2 stimulation patterns were tested focusing on the quadriceps femoris that develops knee extension combining with stimulation to the hamstrings or the gluteus maximus that have major role in the cycling.

1) Patten A: The quadriceps femoris was stimulated with the hamstrings of the contralateral side. This stimulation develops knee extension with knee flexion of the contralateral lower limb. That is, repeated stimulation to the combination of the left quadriceps femoris and the right hamstrings, or that of the right quadriceps femoris and the left hamstrings were applied alternately.

2) Pattern B: The quadriceps femoris was stimulated with the gluteus maximus of the ipsilateral side. This stimulation develops knee extension with hip extension of the ipsilateral lower limb. That is, repeated stimulation to the combination of the left quadriceps femoris and the gluteus maximus, or that of right quadriceps femoris and the gluteus maximus were applied alternately.

The combination of stimulated muscles was changed based on the crank angle θ. The crank angle was defined to be 0 deg at the position that the right crank was located forward under the condition of that the right and left crank was in the

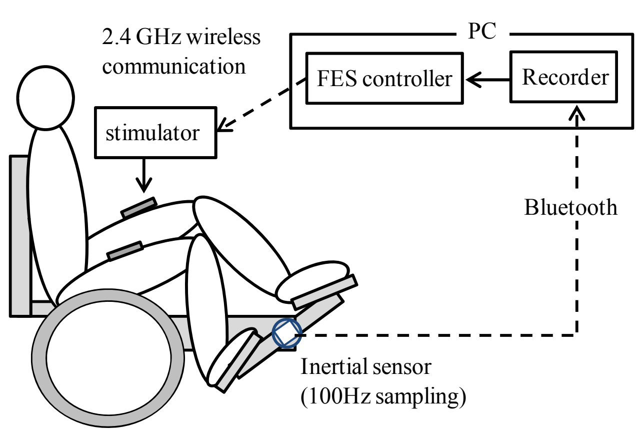


Fig. 2 Outline of FES control system for cycling wheelchair "Profhand".

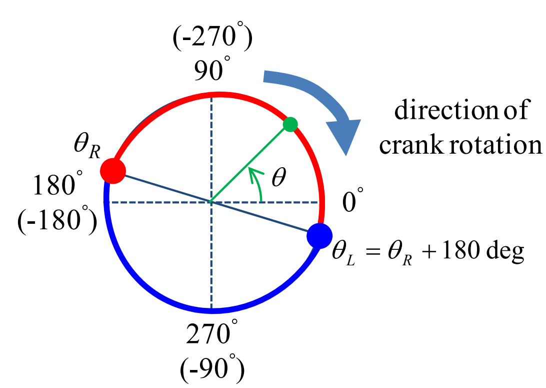


Fig. 3 Definition of the crank angle θ and direction of crank rotation. Stimulation switching angles θ_R and θ_L are also shown on the figure. The red line means that stimulation is applied to the right quadriceps femoris and the blue line means that the left one is stimulated.

horizontal plane (Fig. 3). The electrical stimulation to the right and that to the left quadriceps femoris was switched at the crank angle θ_R and θ_L , respectively. Here, θ_L was set as $\theta_L = \theta_R + 180\,\text{deg}$ for simplicity in this paper. Since the crank rotates in clockwise direction, the crank angle decreased in the cycling as shown in Fig. 3. The right quadriceps femoris was stimulated to develop the right knee extension at the timing when the crank angle reached the stimulation switching angle θ_R, and the left quadriceps femoris was stimulated to develop the left knee extension at when the crank angle reached the stimulation switching angle θ_L .

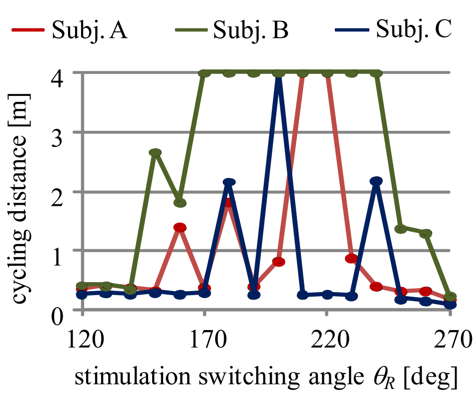
B. Experimental Method

The 2 stimulation patterns were tested in FES cycling with the cycling wheelchair "Profhand" changing stimulation switching angle θ_R between 120 deg and 270 deg every 10 deg (θ_L was between 300 deg and 90 deg). The cycling wheelchair was propelled by lower limbs with FES to the goal set at 4 m length for each stimulation switching angle. The initial crank angle was set at between 240 deg and 260 deg and the left quadriceps femoris was stimulated first. In case of the FES cycling did not reach the goal, cycling distance was measured from the beginning of cycling to the stop of its movement. The cycling distance of the wheelchair was calculated from the crank angle as 0.27 cm/deg. The beginning of the cycling was detected by acceleration signal measured with the inertial senor using the threshold of motion acceleration of 10 mG.

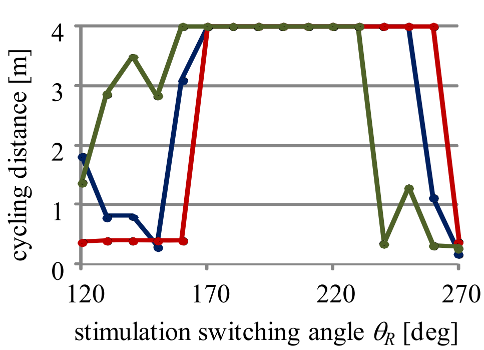
The subjects were 3 healthy males. The subject was instructed not to do cycling voluntary, but to relax his lower limbs during measurement with FES cycling. Electrical stimulation pulses, which were biphasic pulses with the frequency of 30 Hz and pulse width of 0.3 ms, were applied to muscles through surface electrodes (SRH5080, Sekisui Plastic Co., Ltd.) using 2 stimulators. Stimulus pulse intensity was determined to produce enough muscle force without pain.

C. Results

It was necessary to find appropriate electrode position for

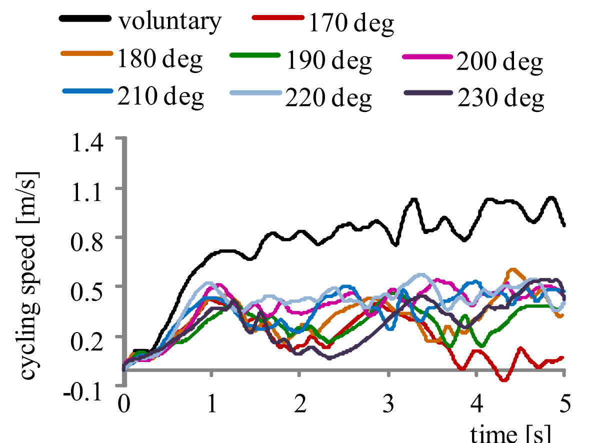


(a) Pattern A

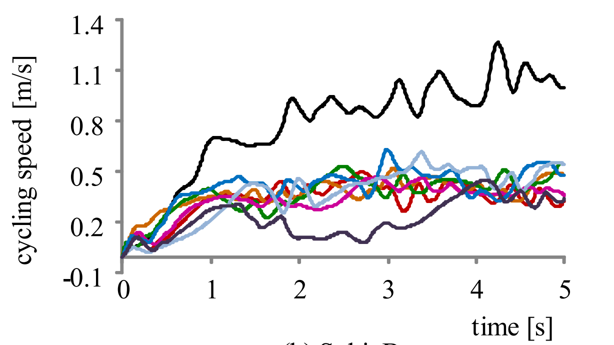


(b) Pattern B

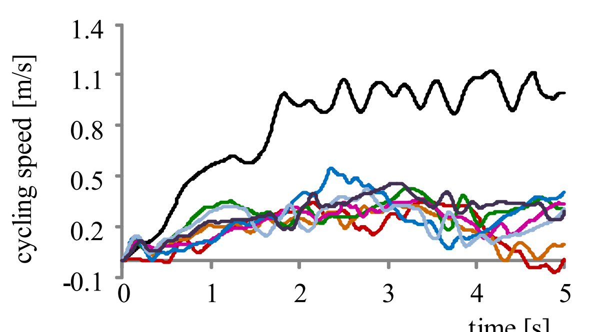
Fig. 4 Cycling distance for different stimulation switching angles by FES cycling for 2 different stimulation patterns.



(a) Subj. A



(b) Subj. B



(c) Subj. C

Fig. 5 Cycling speeds for 5 s from the beginning of the cycling (Voluntary cycling and FES cycling with stimulation pattern B).

electrical stimulation to the hamstrings for each subject, because it was different largely between subjects. Many electrodes were attached on the hamstrings and various combinations of electrodes were tested in producing knee flexion force before cycling test.

Fig. 4 shows the cycling distance of each stimulation switching angle for all the subjects. With the Pattern A, although each subject reached the goal with some switching angles, there was no switching angle that all the subjects reached the goal by FES cycling. On the other hand, with the Pattern B, all the subjects reached the goal with the switching angle between 170 deg and 230 deg. These results suggest that the Pattern B is appropriate to propel the cycling wheelchair "Profhand".

Cycling speeds of the wheelchair with stimulation pattern B for 5 s from the beginning of the cycling are shown in Fig. 5. In case of voluntarily cycling, the speed increased smoothly and sustained large value during the cycling. On the other hand, although FES cycling increased the speed at the beginning of the cycling, the speed was not increased or was decreased after that. There is no large difference in the cycling speed between stimulation switching angles.

IV. EVALUATION OF STEADY STATE CYCLING

A. Experimental Method

FES cycling was compared to voluntary cycling with 3 healthy subjects under steady state cycling. Each cycling was performed on the level floor for more than 20 s and analyzed removing the first 5 s. For FES cycling, stimulation pattern B was used with the stimulation switching angle of $\theta_R = 180\,\text{deg}$ ($\theta_L = 0\,\text{deg}$). One trial was performed for each subject.

B. Results

Mean cycling speed (v_{ave}) and coefficient of variation (CV) were calculated for the term of 15 *s* from 5 *s* after the beginning of cycling to 20 *s*. In order to evaluate difference in cycling between the right and the left sides, cycling of each side was defined by the crank angle for applying electrical stimulation. That is, the right side cycling was when $180\,\text{deg} \geq \theta > 0\,\text{deg}$ in clockwise direction, at when the right side muscles were stimulated, and the left side cycling was $360\,\text{deg} \geq \theta > 180\,\text{deg}$ at when the left side muscles were stimulated.

Table 1 summarizes v_{ave} and CV for 3 subjects. There were no differences in the cycling speed and the CV between the left and the right sides both for the voluntary cycling and FES one. It is found that values of v_{ave} of the FES cycling were about from 0.3 to 0.4 m/s, which were smaller than those of voluntary cycling for all the subjects. The values of CV during the FES cycling were larger than voluntary cycling with all the subjects, which ranged from 2-fold to 3.5-fold compared to the voluntary cycling. That is, the variation of velocity of FES cycling was larger than that of voluntary cycling. The value of CV was different largely between subjects in FES cycling, while the difference between subjects was small in voluntary cycling.

Steady state cycling speeds of the FES cycling were smaller and the variations of the cycling speed were larger than those of the voluntary cycling. Fig. 6 shows spatially-smoothed characteristics of the relationship between the crank angle and angular velocity measured with the inertial sensor attached on the crank. That is, the angular velosity plot with respect to the crank angle, which were measured between 5 s and 20 s after the beginning of the cycling, were low-pass filtered (moving average). As seen in this figure, the angular velocity during the voluntary cycling was almost constant to different crank angles, although the angular velocity showed small increase and decrease at around -60 deg and -240 deg. The small variations were different between subjetcs. On the other hand, the angular velocity during the FES cycling showed larger decrease and increase than voluntary cycling, which were different between subjects and between the left and the right sides. The angular velocity decreased largely at around -280 deg for the right side stimulation with all the subjects and at around -80 deg for the left with 2 subjects, which were 80 to 100 deg changes from the beginning of aplying stimulation. All the subjects also showed the decrease in the angular velocity for the range of angle change from 20 to 40 deg from the beginning of applying electrical stimulation, although its decrease was small with Subject B.

Table 1 Comparison of cycling speed of the cycling wheelchair between voluntary cycling and FES cycling. Mean cycling speed and coefficient of variation (CV) of the speed are shown.

		cycling speed [m/s]		CV	
		Left	*Right*	*Left*	*Right*
Subj. 1	***voluntary***	0.62±0.09	0.62±0.10	0.15	0.16
	FES	0.32±0.17	0.33±0.15	0.53	0.45
Subj. 2	***voluntary***	0.88±0.14	0.85±0.12	0.16	0.14
	FES	0.43±0.11	0.41±0.10	0.26	0.24
Subj. 3	***voluntary***	1.17±0.25	1.09±0.23	0.21	0.21
	FES	0.32±0.24	0.35±0.23	0.75	0.66

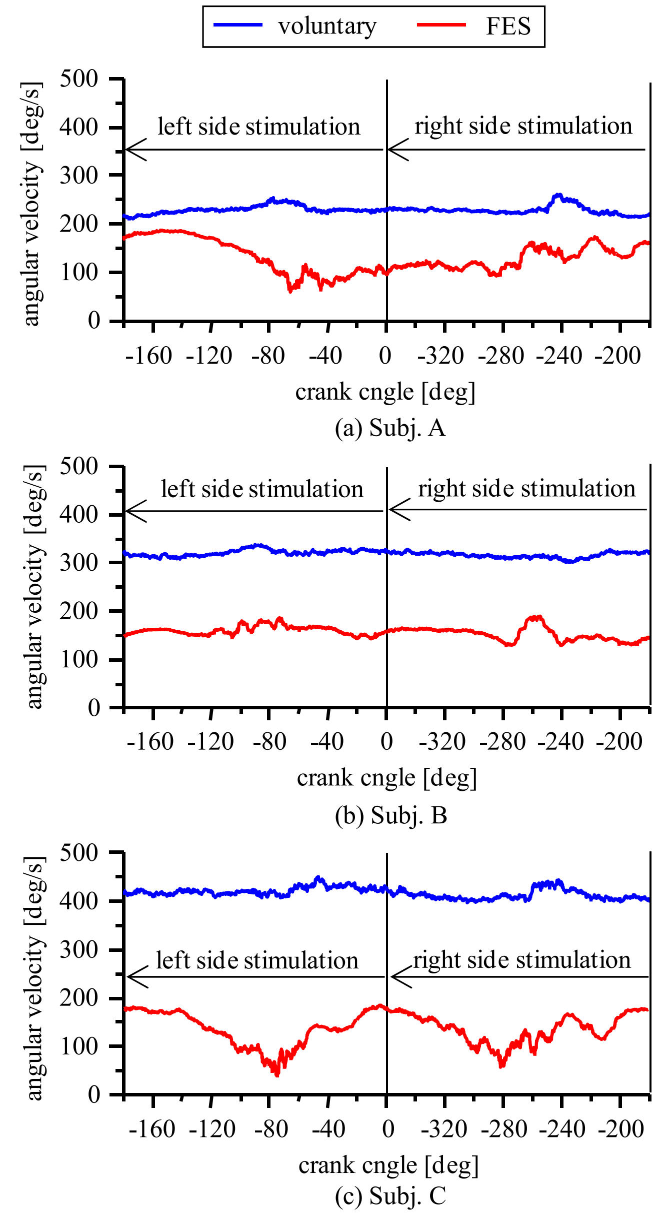


Fig. 6 Spatially-smoothed relationship between the crank angle and angular velocity during steady state cycling. The crank angle is shown by negative value.

V. Discussion

Stimulation pattern B was found to be appropriate for cycling wheelchair "Profhand". The subjects could reach the goal in FES cycling with wide range of stimulation switching angle with pattern B. For propelling the wheelchair, hip extension movement was effective in combination with knee extension. In addition, stimulation to the hamstring was difficult a little bit to find appropriate electrode position. In this paper, stimulation to three muscles, the quadriceps femoris, the gluteus maximums and the hamstrings, was not tested in order to find effective muscles for FES cycling wheelchair. Since it is also possible to propel the cycling wheelchair applying electrical stimulation with Pattern A, it is expected to propel the wheel chair appropriately by stimulating the 3 muscles. The muscles to be stimulated can be determined considering muscle force output, muscle fatigue, purpose of muscle training and so on.

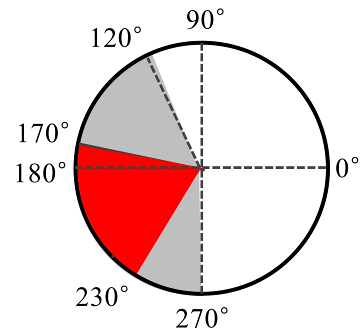


Fig. 7 Stimulation switching angle that all the subjects could reach the goal with the FES cycling (red) using stimulation pattern B obtained from Fig. 4. The gray area shows the tested switching angles.

The decrease of the angular verocity just after the beginning of stimulation is considered to be caused by the delay in muscle response to electrical stimualtion. For example, the delay in muscle response of 0.3 s causes about 44 deg change of crank angle before beginning muscle force production in FES cycling with the cycling speed of 0.4 m/s (148 deg/s). Therefore, it is considered that the angular velocity decreased from the beginning of applying electrical stimulation as seen in Fig. 6. In addition, time constant in force increase (for example, 0.2 s) causes further change of 30 deg in the crank angle before producing enough large muscle force in the FES cycling. Because of the time constant, it is considered that large increase of the angular velocity from around -80 deg and -280 deg was produced as seen in Fig. 6. As shown in Fig. 7, the stimulation switching angles θ_R that all the subjects could perform FES cycling were between 230 deg and 170 deg. Since the crank rotates in clockwise direction during cycling, it is considered that enough muscle force is produced between 96 deg and 156 deg. These angles to apply force to propel the wheelchair can be considered to be reasonable. It is required to measure the delay in muscle response to support the above consideration.

Muscle response to electrical stimulation is different between the left and the right sides, and between subjects. Therefore, the angle range that the angullar velocity decreased and the angle that the velocity increased after that were different between the sides and between subjects. In addition, those angle range and the crank angle also depends on cycling speed. Therefore, it is necessary to adjust the stimulation timing considering the muscle respose time and cycling speed.

The large increase of the angular velocity was seen from around -80 deg and -280 deg, which were 80 to 100 deg changes from the beginning of applying stimulation. These angle changes might be larger a little bit than those caused by the delay in muscle response and the time constant of force production. It is considered that angle of the pedal at around the crank angle of 90 deg was inappropriate to apply the force to propel the wheelchair, because ankle dorsiflexion is required to change the pedal angle at around 90 deg. It is expected that joint angles and angle of the pedals are measured during cycling and that controlling ankle joint angle during FES cycling is tested.

It is expected to apply Profhand with the FES control to paralyzed subjects. Although the results of this paper were obtained with neurologically intact subjects, stimulation pattern and switching timing was common for all the subjects. FES cycling under the steady state cycling was also similar for all the subjects. It is considered that the FES control method tested in this paper is, basically, effective for propelling Profhand. However, muscle force of paralyzed subjects produced by electrical stimulation is usually smaller than healthy subjects. Robotics technology would be effective to assist the FES cycling in that case.

VI. CONCLUSION

In this paper, a prototype FES control system for the cycling wheelchair (Profhand) was developed and tested in stimulation pattern and stimulation timing with healthy subjects. The stimulation pattern that the quadriceps femoris and the gluteus maximus of the ipsilateral side were stimulated at the same time was found to be effective to propel Profhand, and was able to propel the wheelchair with various stimulation switching angles. Then, FES cycling and voluntary cycling was compared in steady state cycling. The cycling speed was smaller and the variation of the speed was larger in FES cycling than those of voluntary cycling. It was considered that in order to improve FES cycling, stimulation timing have to be changed considering muscle response to electrical stimulation and cycling speed. It was also suggested that angle of the pedal to apply force to propel the wheelchair have to be adjusted by controlling ankle joint with FES.

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