PAPER

Comparison of Muscle Stimulation Groups for Simplified Practical FES Cycling Control with Cycling Wheelchair: An Experimental Test with Healthy Subjects

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SUMMARY The cycling wheelchair "Profhand" was developed in Japan as locomotion and lower limb rehabilitation device for hemiplegic subjects and elderly persons. Functional electrical stimulation (FES) control of paralyzed lower limbs enables application of the Profhand to paraplegic subjects as a rehabilitation device. In this paper, simplified muscle stimulation control for FES cycling with Profhand was examined for practical application, because cycling speed was low and not stable in our preliminary study and there was a difficulty in setting stimulation electrodes for the gluteus maximus. First, a guideline of target cycling speed to be achieved by FES cycling was determined from voluntary cycling with healthy subjects in order to evaluate FES cycling control. The cycling speed of 0.6m/s was determined as acceptable value and 1.0m/s was as ideal one. Then, stimulation to the gluteus maximus and that to the dorsiflexor muscles in addition to the quadriceps femoris were examined for simple FES cycling control for Profhand with healthy subjects. Stimulation timing was adjusted automatically during cycling based on muscle response time to electrical stimulation and cycling speed, which was shown to be effective for FES cycling control. Simple FES cycling control with Profhand removing stimulation to the gluteus maximus was found to be feasible. Stimulation to the dorsiflexor muscles with the quadriceps femoris was suggested to be effective for practical, simple FES cycling with Profhand in case of removing the gluteus maximus stimulation.
key words: *cycling wheelchair, Profhand, FES, cycling speed, gluteus maximus, dorsiflexor*

1. Introduction

A wheelchair is an effective mobility device for the patients whose motor function of lower limbs was affected severely by the spinal cord injury or the cerebrovascular disease, and for elderly subjects. However, it is sometimes difficult to propel the wheelchair with both upper limbs for hemiplegic subjects. In addition, traveling with the conventional wheelchair does not need movements of lower limbs, which has a possibility of increasing risks of 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.

A cycling chair was studied as a novel mobility device for elderly persons, hemiplegic subjects and persons with difficulty in walking [1], [2]. Cycling wheelchair "Profhand" (TESS Co., Ltd.) was developed in Japan (Fig. 1) based on results of those studies. Profhand is a pedaled wheelchair and not a motorized one, which is not propelled by upper limbs, but by lower limbs. A hemiplegic patient, whose one-side lower limb have been paralyzed due to the 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.

The cycling wheelchair also makes it possible to undergo rehabilitation of lower limbs for patients who have severe motor paralysis, because it has an advantage of decreasing significantly the risk of falling. In a previous study [3], measurement of electromyogram (EMG) during driving the cycling wheelchair with severe hemiplegic patients showed that the cycling wheelchair training could induce muscle activities of the paretic leg. This suggests that training with cycling wheelchair is effective in motor rehabilitation.

Functional Electrical Stimulation (FES) makes it possible to use the cycling wheelchair "Profhand" as a rehabilitation and locomotion device for paraplegic subjects. This is well known as FES cycling. Mobile cycling with FES has been studied to develop locomotion device mainly for paraplegic subjects [4]–[7]. Integration of electric motor assist and FES has also been studied for this purpose [8], [9]. In addition to using the FES cycling as a mobility device, application of FES cycling to motor rehabilitation has been studied [10]–[12]. For the rehabilitation purpose, many studies have used stationary FES cycling system such

Fig. 1 Cycling wheelchair "Profhand" (TESS Co., Ltd.) used in the experiments.

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as bicycle ergometer combined with FES [13]–[20]. From these studies, FES cycling has been shown to be effective in fitness or rehabilitation training mainly for stroke patients [10], [14], [17]–[19], [21].

FES control system for Profhand has to be developed for FES cycling, because different cycling devices for mobile cycling are considered to have different FES control system. In oder to achieve widespread use of FES cycling, an FES cycling system easy to use for a user is desired. Current systems for FES mobile cycling use mainly a recumbent tricycle with ankle orthosis, and with or without electric power assist [6], [8]. Cycling wheelchairs incorporated a rotary encoder [10] or a motor assistance with an encoder [9] was also developed as experimental systems. Not requiring significant modification to a cycling wheelchair or not using dedicated device for FES cycling makes it possible to test FES cycling easily for cycling wheelchair users, which is expected to lead its widespread use.

In our previous study [22], a prototype of FES control system for the Profhand was developed, in which an wireless acceleration sensor was only used to detect stimulation timings considering practical application without greatly modifying the Profhand. Although neurologically intact subjects could propel the Profhand with the FES control system applying electrical stimulation to the quadriceps femoris and the gluteus maximus, average cycling speeds were low (less than about 0.4m/s) and fluctuation of the cycling speed during FES cycling was larger than voluntary cycling. From this previous study, it was pointed out that constant stimulation timing determined only by crank angle was inadequate in FES cycling. Inappropriate ankle plantar flexion during FES cycling was suggested to be one of reasons of low cycling speed and large fluctuation of the cycling speed. It was also pointed out that stimulation to the gluteus maximus was not practical because of difficulty in electrode setting for motor disabled subjects.

From the above points of view, preliminary tests were performed stimulating different muscle groups using stimulation timing adjusted automatically during cycling [23]. Although FES control without stimulation to the gluteus maximus was suggested to be possible, its evaluation criteria was not clear and effectiveness of stimulation to the dorsiflexor muscles was not shown. Therefore, the purpose of this paper was, first, to determine a guideline of appropriate cycling speed to be achieved by FES cycling in order to make clear the evaluation criteria for FES cycling control. Second was to make it clear whether FES cycling without stimulation to the gluteus maximus can be practical or not, and to validate effectiveness of stimulation to the ankle dorsiflexor muscles for FES cycling with Profhand.

2. FES Control System for “Profhand”

2.1 System Configuration

Experimental setup of FES control for the cycling wheelchair used in this study is shown in Fig. 2. 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 signals were measured at sampling frequency of 100Hz with the inertial sensor and recorded on a portable computer through Bluetooth network.

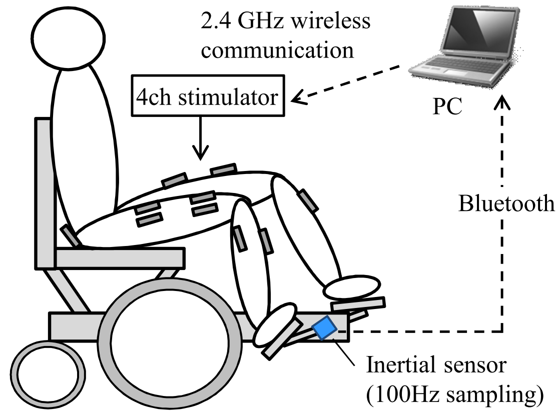

Fig. 2 Experimental setup of FES cycling control tests with the cycling wheelchair “Profhand”.

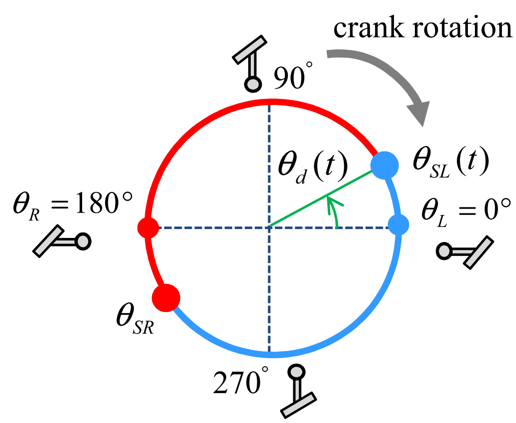

Fig. 3 Definition of crank angle and direction of crank rotation. Stimulation switching angles θ_{SL} and θ_{SR} are also shown in the figure. Electrical stimulation is switched at θ_{SL} from the right side muscles to the left side muscles and at θ_{SR} from the left to the right.

Electrical stimulation was applied to muscles through surface electrodes at the timing that was detected by the crank angle calculated from the measured gravitational acceleration. The crank angle θ was defined to be 0 degrees at the position that the right crank was located forward under the condition of that the right and the left crank was in the horizontal plane (Fig. 3). The crank angle was calculated from x and y axis acceleration components of the sensor, a_x and a_y. That is,

$$\theta(t) = \tan^{-1} \frac{a_x(t)}{a_y(t)} \quad (1)$$

Two wireless electrical stimulators were used in experiments, which were developed based on our previous study [24]. The stimulation data are transmitted to the stimulator via a 2.4GHz wireless transceiver module

(MK72660-01, LAPIS Semiconductor Co., Ltd.) from the portable computer. The data are composed of stimulus voltage, stimulus pulse width and type of stimulation pulse (monophasic or biphasic). The stimulator generates electrical stimulation pulses immediately after receiving the stimulation data. Each stimulator can output up to 4 channels simultaneously, powered by 2 AA batteries.

2.2 Stimulation Timing

Electrical stimulation was applied to the right side or the left side muscles based on the crank angle. The switching of electrical stimulation is outlined in Fig. 3. Basically, the electrical stimulations to the right lower limb muscles and that to the left side muscles were switched at the crank angle θ_R and θ_L, respectively. Here, θ_L was set at 0 degrees and θ_R was 180 degrees, which were determined based on our previous study [22]. However, since there is delay in muscle response to electrical stimulation, stimulation switching timing was adjusted automatically based on muscle response time to electrical stimulation and cycling speed.

First, mean angular velocity $\omega_m(t)$ was calculated by

$$\omega_m(t) = -\frac{\theta(t) - \theta(t-n)}{n} \tag{2}$$

where $\theta(t)$ and $\theta(t-n)$ shows crank angle at time t and $t-n$, respectively. In this paper, n was set at 200ms. Then, using muscle response time T_r, crank angle change in the muscle response to electrical stimulation $\theta_d(t)$ can be calculated by

$$\theta_d(t) = \omega_m(t) T_r \tag{3}$$

Finally, stimulation switching angles $\theta_{SR}(t)$ and $\theta_{SL}(t)$ were determined at each time by using the initial switching angles θ_R and θ_L as follows:

$$\theta_{SR}(t) = \theta_R + \theta_d(t) \tag{4}$$

$$\theta_{SL}(t) = \theta_L + \theta_d(t) \tag{5}$$

The crank rotates in the clockwise direction in the cycling in Fig. 3. The left side muscles are stimulated so as to develop the left knee extension at the timing when the crank angle reached the stimulation switching angle $\theta_{SL}(t)$, and the right side muscles are stimulated to develop the right knee extension at when the crank angle reached the stimulation switching angle $\theta_{SR}(t)$.

3. Experimental Method of Evaluation of Steady State Cycling

FES cycling with Profhand was tested in 20m cycling on the level floor with 6 neurologically intact subjects (male, 21–23 y.o.) using the FES control system shown in the previous section. Physical characteristics of the subjects are shown in Table 1.

First, measurements of voluntary cycling were performed under different conditions of cycling speed: slow, moderate and fast. The cycling speeds were determined by subjects themselves. After that, FES cycling tests were performed, in which the following muscle groups were stimulated:

Table 1 Physical characteristics of the subjects.

	Sub.1	Sub.2	Sub.3	Sub.4	Sub.5	Sub.6
Height [m]	1.84	1.68	1.72	1.74	1.79	1.73
Weight [kg]	75	70	61	50	62	70

- Q: the quadriceps femoris (the rectus femoris muscle and the vastus lateralis muscle)
- QG: the quadriceps femoris and the gluteus maximus
- QD: the quadriceps femoris and the dorsiflexor muscles (the tibialis anterior muscle and the common peroneal nerve)
- QGD: the quadriceps femoris, the gluteus maximus and the dorsiflexor muscles

The muscle group QG was used in our previous study [22]. Electrical stimulation to the muscles of the same side were applied simultaneously at the detected switching angle. Measurements were performed in 3 sets of the above 7 trials, in which several minutes of rest was inserted between measurement sets. In the FES cycling tests, stimulation muscle group was selected randomly and the information was not given to subjects. The subjects were instructed not to contribute to the cycling voluntarily during FES cycling.

Electrical stimulation pulses, which were biphasic pulses with the frequency of 30Hz and pulse width of 0.3ms, were applied to muscles through surface electrodes (SRH5080, Sekisui Plastic Co., Ltd.) using 2 stimulators. Pulse amplitude was determined in order to develop enough joint movement or enough muscle force without uncomfortable feeling. In the measurements, muscle response time T_r was set at 300ms.

In order to analyze steady state cycling, the first 2 cycles and the last 2 cycles were removed from analysis. Angular velocity at each time was calculated from crank angle measured with accelerometer. That is,

$$\omega(t) = -\frac{\theta(t) - \theta(t-\Delta t)}{n} \tag{6}$$

Where Δt shows sampling period (10ms). The cycling speed was calculated from the angular velocity at each time by 0.27cm/deg of moving distance of Profhand. That is,

$$v(t) = 0.0027\omega(t)\ [\text{m/s}] \tag{7}$$

4. Results

4.1 Voluntary Cycling

Average cycling speed of each trial is shown in Fig. 4. For all subjects, cycling speeds of all the 3 trials of the moderate speed condition were higher than those of the slow speed condition, and lower than the fast speed condition. The average values of cycling speed, the minimum and the maximum values of cycling speed of 18 trials of all the subjects were

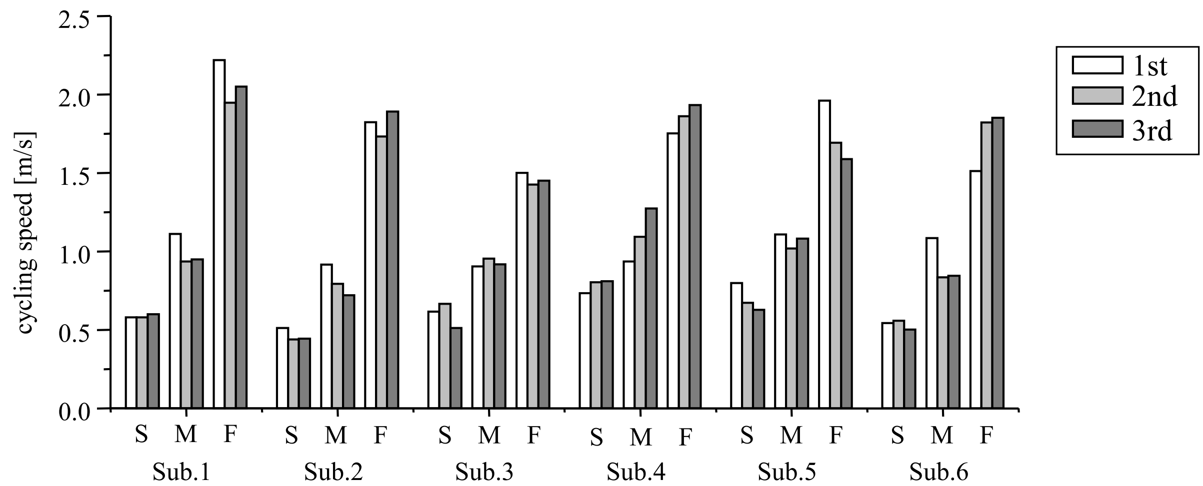

Fig. 4 Average cycling speed of each trial during voluntary cycling under different 3 cycling speed conditions. S, M, and F mean slow, moderate and fast speed cycling conditions, respectively.

Table 3 Coefficient of variation (CV) of cycling speed in voluntary cycling.

	slow			moderate			fast		
Sub.1	0.09	0.08	0.07	0.07	0.08	0.07	0.26	0.21	0.20
Sub.2	0.14	0.11	0.10	0.06	0.06	0.09	0.12	0.12	0.13
Sub.3	0.09	0.08	0.09	0.06	0.06	0.06	0.12	0.15	0.13
Sub.4	0.10	0.10	0.09	0.09	0.06	0.07	0.16	0.20	0.18
Sub.5	0.09	0.11	0.10	0.08	0.09	0.08	0.20	0.17	0.18
Sub.6	0.13	0.09	0.11	0.12	0.06	0.10	0.21	0.20	0.20
average	0.10 ± 0.02			0.07 ± 0.02			0.17 ± 0.04		

Table 2 Summary of cycling speed [m/s] in voluntary cycling with healthy subjects.

	average	minimum	maximum
slow	0.61 ± 0.12	0.44	0.81
moderate	0.97 ± 0.14	0.72	1.27
fast	1.78 ± 0.22	1.43	2.22

shown in Table 2 for slow, moderate and fast speed cycling, respectively. Although the cycling speed varied between trials and between subjects, there were significant differences in cycling speed among 3 cycling speed conditions, slow, moderate and fast, respectively ($p < 0.001$, t-test with Bonferroni correction).

Values of coefficient of variance (CV) of cycling speed are shown in Table 3. Small values of CV shows that fluctuation of the cycling speed is small, which means the cycling speed is stable during cycling. The values of CV for slow speed cycling were less than 0.14 with all the subjects, although the values were larger than 0.12 for the fast speed cycling. Moderate speed cycling showed the smallest values of CV for all the subjects (less than 0.12). There were significant differences in variation of cycling speed among the 3 cycling speed conditions ($p < 0.001$, t-test with Bonferroni correction), which shows moderate speed cycling was most stable in voluntary cycling.

Considering moderate and slow speed cycling, target cycling speed of FES cycling can be 1.0m/s and acceptable slow cycling speed can be 0.6m/s. From the results of voluntary cycling of healthy subjects under the moderate speed condition, it is desirable for fluctuation of the cycling speed during FES cycling that the value of CV of cycling speed is less than 0.07. However, value of CV less than 0.1 would be accepted as its target value considering the slow speed cycling condition, because FES cycling speed usually fluctuates during cycling.

4.2 FES Cycling

Average cycling speeds obtained from FES cycling are shown in Fig. 5. The cycling speed was calculated at each time and the calculated speeds were averaged in each trial. Four of 6 subjects could complete 20m cycling in all the trials with all the stimulation muscle groups. Although other 2 subjects (Sub.3 and 6) could also complete it with all the muscle groups, Sub.3 could not complete it in the first and the last trial with muscle group Q, and Sub.6 could not complete it in the last trial with muscle group Q and QD.

Achievement rates of cycling speed of 0.6m/s or higher in FES cycling are shown in Table 4. These results show that stimulation to the gluteus maximus improves FES cycling. However, stimulating the muscle group QD could propel the cycling wheelchair with cycling speed larger than 0.6m/s with 5 of 6 subjects in at least 2 of 3 trials as shown in Fig. 5. Stimulation to the muscle group Q could also propel the cycling wheelchair with 4 subjects showing cycling speed larger than 0.6m/s in at least 2 of 3 trials. With one subject (Sub.3), cycling speed larger than 0.6m/s in 20m cy-

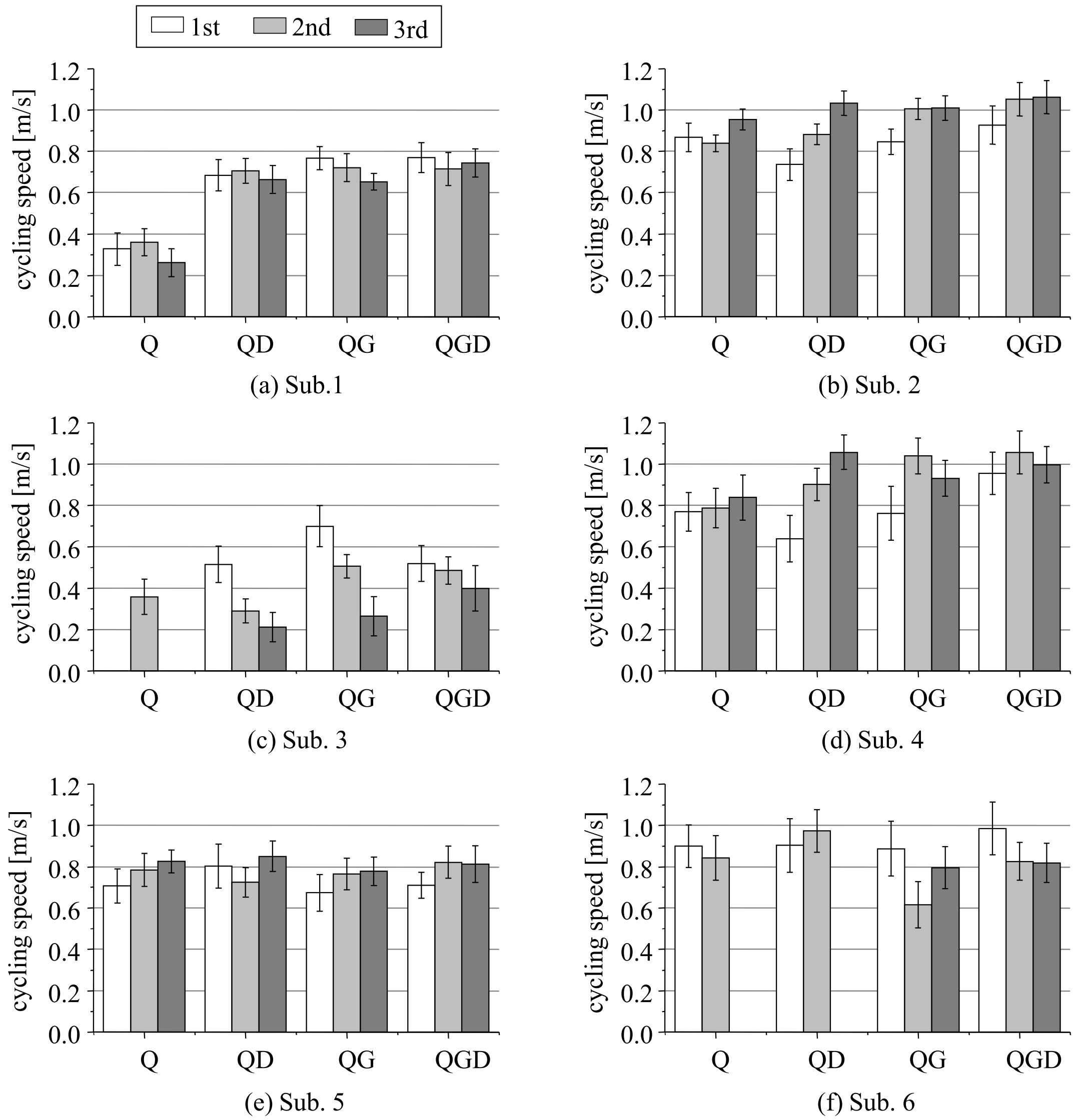

Fig. 5 Average cycling speed of each subjetcs during FES cycling under different stimulation muscle groups.

Table 4 Achievement rate of cycling speed of 0.6m/s or higher in FES cycling.

group	Q	QD	QG	QGD
rate	11/18 (61.1%)	14/18 (77.8%)	16/18 (88.9%)	15/18 (83.3%)

cling was not achieved except for the 1st trial of stimulation to the muscle group QG.

Values of CV of cycling speed during FES cycling are shown in Fig. 6. Most of stimulation muscle groups showed values of CV less than 0.15. However, for subject 1, the value of CV for the stimulation group Q was larger than other stimulation muscle groups, and the values of subject 3 were large especially in the 2nd and the 3rd trials in comparison to other subjects. These large values of CV show cycling speed fluctuated largely during FES cycling.

In cases of stimulation muscle groups showing large values of CV, cycling speeds were low as seen in Fig. 5. Figure 7 shows relationship between the cycling speed and the value of CV during FES cycling. The result shows there is negative correlation between cycling speed and value of CV during FES cycling ($r = -0.80$).

5. Discussions

The guideline of target cycling speed to be achieved by FES cycling is determined as cycling speed of 1.0m/s ideally, and 0.6m/s is adopted as the acceptable cycling speed. These were obtained from voluntary cycling with healthy subjects. In our previous study [22], instability of FES cycling was pointed out because of large values of CV. However, there was negative correlation in FES cycling between cycling speed and value of CV as shown in Fig. 7. That is, in FES cycling, instability of cycling speed is considered to be improved if the cycling speed is increased. The values

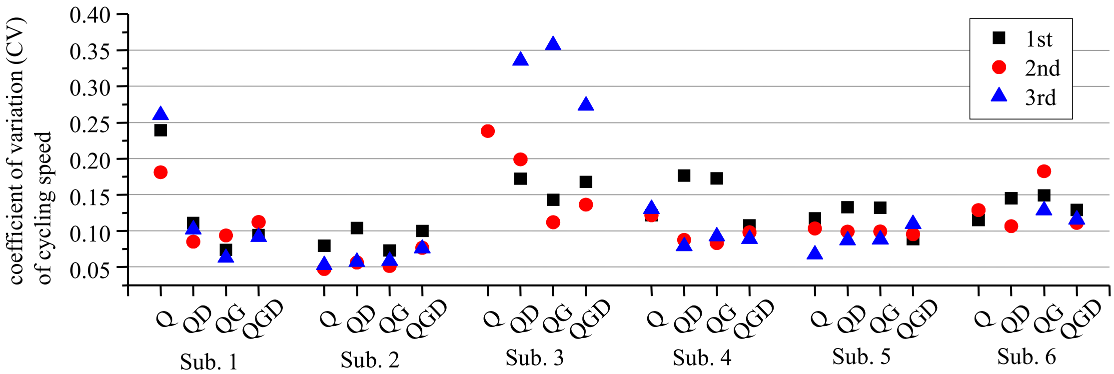

Fig. 6 Coefficient of variation (CV) of cycling speed during FES cycling under different stimulation muscle groups.

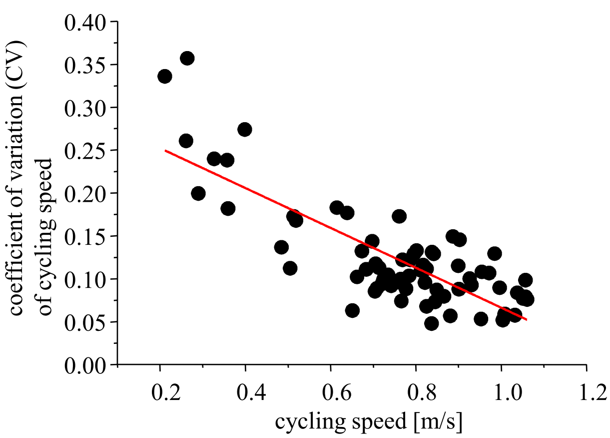

Fig. 7 Relationship between cycling speed and its coefficient of variation during FES cycling.

of CV were less than 0.15 in 95% of the trials that the cycling speed was larger than 0.6m/s. 0.6m/s with the value of CV of 0.15 shows that FES cycling speed varies between 0.424 ~ 0.776m/s in a trial. On the other hand, the minimum cycling speed of slow cycling condition in voluntary cycling was 0.44m/s in average, which was almost same as the lower value of the variation of cycling speed of 0.6m/s with the value of CV of 0.15. Therefore, the value of CV of 0.15 is considered to be acceptable by achieving FES cycling speed of 0.6m/s or higher.

The target FES cycling speed of 0.6m/s is a guideline for evaluation of FES cycling control. Target speed for each subject can be changed from 0.6m/s for the purpose of rehabilitation considering force production ability or muscle fatigue resistance of the subject. As described in [25], achieving walking speed over 0.3m/s is considered to require a lot of effort and to have a risk of falling for paraplegic subjects. In such case, the target FES cycling speed can be lowered from 0.6m/s, but higher than 0.3m/s, for paraplegic subjects. On the other hand, cycling speed of 0.6m/s is considered to be achieved by hemiplegic subjects and elderly persons in their voluntary cycling. Table 5 shows an example of cycling speed and its coefficient of variation (CV) in voluntary cycling of a hemiplegic subject (male, 60 y.o., 1.7m, 63kg, right hemiplegia) under his moderate speed cycling. Although the values of CV under the moderate speed condition were larger than those of healthy subjects (Table 3) because of motor paralysis, the subject achieved cycling speed higher than 0.7m/s in all 3 trials and the maximum speed was 1.04m/s. The subjects achieved similar cycling speed as healthy subjects. In this case, decreasing the value of CV is considered to be another target in rehabilitation.

Table 5 Cycling speed and its coefficient of variation (CV) in voluntary cycling of a hemiplegic subject.

	1st	2nd	3rd	average
cycling speed [m/s]	0.79	0.95	1.04	0.93
CV	0.13	0.10	0.11	0.12

Subject 3 could not achieve the cycling speed of 0.6m/s in most of trials of FES cycling. This was considered to be caused by lack of propulsive force or small muscle force produced by electrical stimulation. Since the cycling speed decreased as the number of trials increased, muscle fatigue is also considered as one of the reasons. On the other hand, size of the Profhand was fixed. Although it is considered that the cycling was affected by body size of subject, there was no another size of Profhand. However, as shown in Table 1, height and weight of Sub.3 who could not achieve the target cycling speed were not different largely from other subjects. Measurement of lower limb position, their angles and force or torque applied during cycling would be necessary for evaluation and improvement of FES cycling control.

FES cycling without stimulation to the gluteus maximus was found to be feasible with cycling wheelchair “Profhand”. This shows that FES cycling with Profhand can be practical realizing simple muscle stimulation control and easy of use by eliminating stimulation to the gluteus maximus. On the other hand, as seen in Fig. 5, subjects 3 and 6 who could not complete 20m cycling in some trials showed higher cycling speed or achievement rate by stimulating the gluteus maximus. It is considered that this is because muscle fatigue or low muscle force produced by electrical stimulation affected FES cycling. Stimulation to the gluteus maximus can be one option in order to increase the number of subjects who use FES cycling with Profhand.

Stimulation of the ankle dorsiflexor muscles is considered to be effective for practical FES cycling without stimulation to the gluteus maximus. Removing subject 3 and 6, who showed muscle fatigue or small muscle force production, average cycling speeds for Q, QG, QD and QGD were 0.69 ± 0.24m/s, 0.83 ± 0.13m/s, 0.81 ± 0.14m/s and 0.89 ± 0.14m/s, respectively. There were no significant differences in cycling speed among muscle groups (one-way ANOVA). However, cycling speed and the achievement rate of cycling speed of 0.6m/s or higher of the stimulation muscle group QD were both higher than those of the group Q. Although stimulation to the dorsiflexor muscles did not show significant differences in the parameters relating to cycling speed in this paper, other studies showed usefulness of stimulation to the shank muscles [26], [27]. Further studies would be required for effective stimulation control of the ankle dorsiflexors.

Stimulation timing based on muscle response time and cycling speed improved the cycling speed and the value of CV in comparison to our previous results [22]. Although the cycling speeds were less than 0.4m/s with 2 of 3 subjects and one subject was less than 0.5m/s in our previous study [22], the cycling speeds obtained in this paper were larger than 0.6m/s with 5 of 6 subjects and larger than 0.4m/s with all the subjects with variable stimulation switching angle based on muscle response time and cycling speed. However, it is considered that muscle response time set at 300ms for all the subjects in this study was not optimal, because different subjects and different muscles have different muscle response times. In addition, FES control used in this paper applied electrical stimulation simultaneously to all the muscles, and electrical stimulation was applied to either the right side or the left side during FES cycling. Stimulation timing based on cycling movement or muscle activity during cycling is expected to be examined.

6. Conclusion

Considering practical application, simplified muscle stimulation control for FES cycling with cycling wheelchair "Profhand" was examined based on a guideline of target cycling speed to be achieved by FES cycling. The guideline of the target cycling speed was determined from voluntary cycling with healthy subjects, which were 0.6m/s as acceptable value and 1.0m/s as ideal value. Stimulation timing based on muscle response time and cycling speed was effective for FES cycling control. Simple FES cycling control with Profhand removing stimulation to the gluteus maximus was found to be feasible. Applying stimulation to the ankle dorsiflexor muscles with the quadriceps femoris was suggested to be effective for practical, simple FES cycling control with Profhand in case of removing stimulation to the gluteus maximus.

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