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# Cycling exercise with functional electrical stimulation improves postural control in stroke patients

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The aim of this study is to determine whether short term functional electrical stimulation (FES)-assisted cycling training can affect the postural control of stroke patients, and whether the application of FES can enhance the effect of cycling training. 20 stroke patients were randomly assigned to the FES-cycling group (FES-CG) or the cycling group (CG). Measurements were completed before and immediately after each 20 min training sessions. The measurements included a balance test (to quantify the postural control ability), a Hoffmann's reflex/motor response ratio (H/M ratio) test and a pendulum test (to quantify the muscle tone). In the balance test, some parameters in all directions exhibited significant intervention effects between the FES-CG group and the CG group. The H/M ratios ($p$ = .014; .005, FES-CG and CG respectively) and relaxation index ($p$ = .005; .047, FES-CG and CG respectively) revealed significant difference between FES-CG and CG group. The change ratios of directional control in the forward direction and H/M ratio revealed significant difference ($p$ = .022; .015) between FES-CG and CG among subjects with higher muscle tone. The stroke subjects' postural control was improved while their muscle tone was reduced after the 20 min cycling training program both with and without FES. We conclude that cycling training, with or without FES may reduce spasticity in stroke patients. The application of FES in cycling exercise was shown to be more effective in stroke patients with higher muscle tone.



## 1. Introduction

The various deficits in sensation, muscle strength, muscle tone and synergistic movement in the hemiplegic limbs of stroke patients often affect activities of their daily life. Walking, one of the most important and effective means of rehabilitation training [1], is often time-consuming and requires extensive assistance because of potential risk of falls. Cycling exercise completed using a bicycle ergometer is usually used to supplement functional ambulatory training. The kinematic pattern of cycling exercise is very similar to that of walking; yet cycling exercise requires less balance capacity. Both walking and cycling exercise are cyclic and require the alternate muscle activation of antagonists of lower extremities in a well-coordinated manner. The intensity of cycling exercise can be controlled, and has been suggested to improve functional mobility of stroke patients [2–4]. Other studies have reported that repetitive passive movement of spastic muscles can increase range of motion and reduce stiffness in the hypertonic joints of stroke patients [5,6]. The aforementioned studies also suggest that cyclic leg movement may provide a potential therapy for reducing hypertonia, one of the factors that prevent functional activity in stroke patients.

Functional electrical stimulation (FES) is used in physical therapy to assist paretic limbs in performing functional tasks [7–9]. Previous studies have reported that functional tasks performed by hemiplegic hands show improvement after electrical stimulation treatment [10,11]. FES has also been used to improve walking ability in stroke subjects [12,13]. The benefits of FES-assisted cycling exercise include enhanced muscle strength and endurance, increased bone density, cardiopulmonary improvement, spasticity relief, and many other physiological and psychological advantages [14–16].

Recently, similar FES-assisted cycling devices have been used for stroke patients [1,2]. Clinical studies on central motor neuroplasticity have revealed that active, repetitive movement for paretic limbs can enhance motor recovery and increase aerobic

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**Fig. 1.** Functional electrical stimulation (FES)-cycling device.

capacity and functional performance in stroke patients [1]. However, in the aforementioned studies, functional performance was evaluated by clinical scales; which cannot granulate training induced changes (such as neurophysiologic changes) in the affected limbs [1,2]. The improvements demonstrated by these clinical scales may come from the efforts of the unaffected limbs. Additionally, a previous study [2] concluded that the use of FES during cycling exercise has no additional effect on subjects with chronic stroke. The influence of FES on the affected limbs may not be easily identified by the clinical scale used. Therefore, whether the application of FES during cycling exercise has any additional effect is also worth investigating.

A new FES-cycling device (Fig. 1), modified from our previous prototype [17], was utilized for this study. This device combines FES and a cycling system with ankle-foot orthosis. FES stimulates the quadriceps and hamstring to assist cycling movements. This study sought to assess how cycling exercise and electrical stimulation affect balance control and hyper muscle tone in stroke patients. The first hypothesis of the study was that balance control ability would be improved and muscle tone would be reduced after cycling exercise with FES. The second hypothesis was that FES-assisted cycling exercise would improve balance ability and muscle tone more than cycling alone. Therefore, the aims of this study were to determine if a short-term FES-cycling program can improve the postural control of stroke subjects, and to verify that the application of FES in cycling programs is more effective than without such application.

## 2. Methods

### 2.1. Subjects

20 stroke patients were recruited for the study. Clinical details of the subjects are shown in Table 1. Inclusion criteria were as follows: (1) single stroke with unilateral hemiplegia (Brunnstrom stage $\geq$3); (2) hypertonia in the affected leg, modified Ashworth scale (MAS) grade $\geq$1; (3) able to follow verbal instructions; (4) no significant perceptual, cognitive, or sensory deficits; (5) no history of osteoarthritis, severe cardiopulmonary disease, or vascular disease in lower limbs; and (6) lack of a fixed contracture in the affected lower limbs. All subjects were fully informed of the details of the experimental procedure and provided written informed consent as required by the ethics committee of the medical university hospital. The subjects were randomly assigned to the FES-cycling group (FES-CG) to perform cycling training with FES, or to the cycling group (CG) to perform the same training without FES.

**Table 1**
Demographics of the FES-CG and CG.

| Variable | FES-CG (*N* = 10) | CG (*N* = 10) |
|---|---|---|
| Gender (M/F) | 7/3 | 9/1 |
| Age (years) | 47.62 ± 3.28 | 51.64 ± 3.41 |
| Height (cm) | 165.61 ± 3.26 | 164.74 ± 2.67 |
| Type of stroke (H/I) | 6/4 | 5/5 |
| Time since stroke (months) | 25.54 ± 12.95 | 29.64 ± 10.36 |
| Side of hemiplegia (R/L) | 5/5 | 6/4 |

FES-CG: FES-cycling group; CG: cycling group; H: haemorrhage/I: ischaemia.

### 2.2. Training protocol

The duration of each training program was 20 min. The target cycling cadence was set at 45 rpm. In the FES-CG group, FES was applied to the affected leg via surface electrodes over the quadriceps and hamstrings. The positions of the legs were detected by an angular encoder (MES-30-360P; Microtech Laboratory Inc. Kanagawa, Japan). The zero degree position was defined as when the crank was parallel to the ground and the position of the foot pedal was closest to the subject. The protocol of FES stimulation was similar to that of a previous study [7]. The intensity of stimulation was increased until a gross muscle contraction was visible while maintaining the subject's comfort. Subjects in the CG group received a 20 min program of cycling training without FES. The training protocol and application of stimulation electrodes were undertaken by a senior therapist.

Postural control (balance test) and muscle tone (Hoffmann's reflex/motor response ratio, H/M ratio and pendulum test) of the affected legs were measured before and immediately after each training program.

### 2.3. Postural control measurement

The Smart Balance Master system (NeuroCom International, Inc. USA) was applied to measure the limits of stability (LOS) for each subject. The test procedure was based on the Limits of Stability protocol, one of the standardized assessment protocols of Smart Balance Master. All subjects were instructed to stand on both legs according to a standardized position on the force plate, with their arms held in a relaxed posture. The subjects were asked to move the center of gravity (COG) cursor from the target center to eight peripheral targets demonstrated on the computer screen as quickly and accurately as possible within 8 s. Each subject had 6–8 min to familiarize him or herself with the system on the day before the trial. The evaluation parameters in each trial included reaction time (RT) (s), movement velocity (MVL) ($^\circ$/s), directional control (DCL) (%), endpoint excursion (EPE) (%), and maximum excursion (MXE) (%) [18]. RT was defined as the duration between the movement request and the subject's first movement. MVL was defined as the average velocity of COG movement in degrees per second. DCL was defined as the comparison between the amount of movement in the intended direction (toward the target) and the amount of extraneous movement (away from the target). EPE was defined as the distance of the first movement toward the designated target, which is presented as a percentage of maximum LOS distance. The endpoint was defined as the point at which the initial movement toward the target ceases. MXE was defined as the maximum distance achieved during the trial.

### 2.4. Muscle tone measurement

#### 2.4.1. H/M ratio test

During the H/M ratio test, the subjects sat with the affected knee straight and the affected ankle in a neutral position to measure the H reflex of the soleus. The H reflex and M response were elicited using a single rectangular 1 ms electrical pulse from an electrical stimulator (Model S88; Grass Technologies, Astro-Med, Inc., West Warwick, RI, USA) to stimulate the posterior tibial nerve over the popliteal fossa. Two 20 mm silver-silver chloride electrodes were attached along the soleus 2–3 cm below the head of the gastrocnemius muscle and one electrode above the lateral malleolus. The electrodes were connected to an amplifier (Model 7P511; Grass Technologies). The intensity of the stimulation current was adjusted to locate the maximal peak-to-peak amplitudes of the non-rectified M response ($M_{max}$). Subsequently, the amplitude of the small M response (10 ± 3% $M_{max}$) concurrent with the H reflex was monitored. The peak-to-peak amplitude of the H reflex was divided by the $M_{max}$ and expressed as the H/M ratio. A higher H/M ratio indicates higher muscle tone.

**Table 2**
Mean, standard deviation and $p$ value of parameters of balance tests in pre- and post- tests for FES-CG and CG.

| | Forward | | Backward | | Affected | | Unaffected | |
|---|---|---|---|---|---|---|---|---|
| | FES-CG | CG | FES-CG | CG | FES-CG | CG | FES-CG | CG |
| RT | | | | | | | | |
| Pre | 1.06 ± 0.42 | 1.42 ± 0.49 | 0.74 ± 0.65 | 0.78 ± 0.45 | 1.94 ± 1.71 | 1.32 ± 0.49 | 1.38 ± 0.64 | 1.13 ± 0.67 |
| Post | 0.60 ± 0.42 | 1.04 ± 0.26 | 0.71 ± 0.51 | 0.72 ± 0.35 | 1.42 ± 0.70 | 0.91 ± 0.28 | 1.50 ± 0.75 | 1.35 ± 0.26 |
| $p$ | 0.059 | 0.139 | 0.721 | 0.721 | 0.508 | 0.093 | 0.653 | 0.274 |
| MVL | | | | | | | | |
| Pre | 1.04 ± 0.50 | 1.24 ± 0.52 | 0.85 ± 0.41 | 1.85 ± 1.24 | 1.77 ± 0.96 | 2.02 ± 1.06 | 1.82 ± 0.91 | 1.96 ± 1.09 |
| Post | 1.19 ± 0.56 | 2.06 ± 1.09 | 1.25 ± 0.75 | 1.71 ± 0.96 | 2.81 ± 1.66 | 2.16 ± 0.91 | 3.31 ± 1.23 | 2.30 ± 0.85 |
| $p$ | 0.507 | 0.011* | 0.386 | 0.506 | 0.028* | 0.721 | 0.016* | 0.416 |
| EPE | | | | | | | | |
| Pre | 15.56 ± 4.81 | 25.7 ± 6.65 | 25.25 ± 7.59 | 40.5 ± 13.94 | 38.70 ± 18.66 | 32.40 ± 8.37 | 44.90 ± 21.42 | 52.40 ± 11.41 |
| Post | 19.81 ± 7.99 | 34.8 ± 9.46 | 25.56 ± 6.69 | 37.7 ± 9.44 | 52.40 ± 20.61 | 44.10 ± 11.91 | 57.40 ± 16.15 | 56.30 ± 11.58 |
| $p$ | 0.058 | 0.022* | 0.959 | 0.683 | 0.032* | 0.008* | 0.055* | 0.394 |
| MXE | | | | | | | | |
| Pre | 20.37 ± 8.99 | 46.8 ± 13.95 | 31.68 ± 9.52 | 49.62 ± 14.27 | 46.90 ± 20.91 | 44.60 ± 11.04 | 58.20 ± 19.26 | 64.00 ± 11.08 |
| Post | 29.62 ± 7.99 | 50.7 ± 12.16 | 36.37 ± 8.10 | 52.81 ± 10.42 | 64.80 ± 17.49 | 62.90 ± 8.71 | 70.10 ± 10.37 | 70.50 ± 8.29 |
| $p$ | 0.008* | 0.201 | 0.074 | 0.231 | 0.008* | 0.005* | 0.020* | 0.018* |
| DCL | | | | | | | | |
| Pre | 30.68 ± 15.42 | 65.02 ± 18.18 | 33.06 ± 13.92 | 57.30 ± 31.68 | 73.10 ± 11.80 | 71.70 ± 11.84 | 83.90 ± 5.28 | 84.50 ± 12.24 |
| Post | 41.62 ± 16.59 | 72.41 ± 18.60 | 39.56 ± 10.75 | 68.12 ± 17.21 | 85.60 ± 4.58 | 80.03 ± 12.48 | 85.70 ± 4.72 | 88.70 ± 6.09 |
| $p$ | 0.028* | 0.262 | 0.241 | 0.202 | 0.049* | 0.017* | 0.555 | 0.174 |

FES-CG: FES-cycling group; CG: cycling group; RT: reaction time; MVL: movement velocity; EPE: endpoint excursion; MXE: maximum excursion; DCL: directional control.
* Significance level at $p < 0.05$.

*2.4.2. Pendulum test*

During the test, affected limb dynamics were recorded by an electrogoniometer (S700 Joint Angle ShapeSensor; Measurand Inc., Fredericton, NB, Canada) attached to the knee joint. The output of the electrogoniometer was sampled and recorded using an analog-to-digital converter (USB-6008; National Instruments, Austin, TX, USA). The subjects were seated, and their affected leg was lifted to achieve maximum knee extension (defined as the starting angle) and then released. The leg was allowed to drop freely until it stopped naturally, and the stop position was defined as the resting angle. Two successive drop trials were analyzed. The relaxation index (RI) was expressed as a ratio equal to the first flexion angle, or the starting angle divided by 1.6× (resting position – starting angle) [19]. The mean value of RI is one for normal muscles and a lower RI value represented higher muscle tone.

*2.5. Data analysis*

The parameters of postural control and muscle tone measurements were compared before and after each test to determine the immediate effects from the two groups. The change ratios of the parameters concerning postural control and muscle tone measurements from both FES-CG and CG groups were compared to examine the effect of FES. The change ratios in postural control measurement included RT (*c*RT), MVL (*c*MVL), DCL (*c*DCL), EPE (*c*EPE), and MXE (*c*MXE). The change ratios in muscle tone measurement included the change ratios in H/M (*c*H/M) and RI (*c*RI). All of the ratio data was obtained by subtracting the pre-test value from post-test value divided by the pre-test value. Analysis was performed by using the Scientific Package for the Social Sciences (SPSS), version 12 (SPSS, Chicago, IL, USA). A $p$-value < .05 was considered statistically significant. The Wilcoxon signed-rank test was used to compare the pre- and post-test data from each group. The Mann-Whitney $U$ test was applied to compare the difference between each group. The differences between higher and lower muscle tone subjects in each group were also considered. Because comparisons were repeated, the error rate allowed in each significance test was adjusted to 0.025 according to Bonferroni adjustment.

**Table 3**
Mean, standard deviation and $p$ value of H/M ratio and RI in pre- and post- tests for FES-CG and CG.

| | FES-CG | CG |
|---|---|---|
| H/M ratio | | |
| Pre | 0.65 ± 0.25 | 0.62 ± 0.26 |
| Post | 0.44 ± 0.21 | 0.48 ± 0.26 |
| $p$ | 0.014* | 0.005* |
| RI | | |
| Pre | 1.36 ± 0.15 | 1.40 ± 0.25 |
| Post | 1.42 ± 0.16 | 1.49 ± 0.27 |
| $p$ | 0.005* | 0.047* |

FES-CG: FES-cycling group; CG: cycling group; RI: relaxation index.
* Significance level at $p < 0.05$.

## 3. Results

### 3.1. Immediate training effect

In the balance test, some of the parameters in the forward direction (MXE ($p$ = .008) and DCL ($p$ = .028)) were found to have significant interventional effect in FES-CG. Other parameters (MVL ($p$ = .011) and EPE ($p$ = .022)) in the forward direction were found to have significant interventional effect in CG (Table 2). The parameters in the backward direction showed no significant difference between the two groups. The results revealed that a session of cycling training can improve the postural control ability of stroke subjects with or without FES. After the cycling training, the postural control ability of the affected limb in the FES-CG group showed significant differences in MVL ($p$ = .028), EPE ($p$ = .032), MXE ($p$ = .008) and DCL ($p$ = .049), and in EPE ($p$ = .008), MXE ($p$ = .005) and DCL ($p$ = .017) of the CG group (Table 2).

The training effect on muscle tone is summarized in Table 3. The H/M ratios ($p$ = .014; .005, FES-CG and CG respectively) and RIs ($p$ = .005; .047, FES-CG and CG respectively) demonstrated significant differences between pre- and post- test results in the FES-CG and CG groups. The results indicated that a cycling training session can significantly reduce muscle tone regardless of FES application.

### 3.2. The effect of FES cycling exercise

The parameters of postural control measurement showed no significant differences between the FES-CG and CG groups. The *c*H/M of the FES-CG group was lower than that of the CG group, and the *c*RI of the FES-CG group was higher than that of the CG group; but *c*H/M and *c*RI demonstrated no significant difference between FES-CG and CG groups.

Subsequently, we divided the subjects into two groups: a lower muscle tone group (MAS 1+ and 2) and a higher muscle tone group (MAS 3 and 4). For the lower muscle tone group, there was no significant difference between the FES-CG ($N$ = 4) and the CG ($N$ = 3) groups concerning their parameters from the balance test. Only in subjects with higher muscle tone, were significant differences observed between the FES-CG ($N$ = 6) and the CG ($N$ = 7) groups concerning their forward *c*DCL ($p$ = .022). For muscle tone measurement, there was no significant difference between the FES-CG and the CG groups concerning their *c*H/M and *c*RI for lower muscle tone group. However, in the higher muscle tone group, the results of *c*H/M from the FES-CG group were significantly lower ($p = .015$) but no significant *c*RI difference was found between the FES-CG group ($p = .568$) and CG group. The results revealed that for higher muscle tone, FES may be more effective in reducing muscle tone than without FES.

## 4. Discussion

The first aim of our study was to determine whether short-term FES-cycling training can immediately improve stroke patients' postural control. Although there was only one cycling training session, some parameters from the postural control measurements were of great significance. The MXE and DCL for the forward direction from the FES-CG group were found to have increased significantly. The results indicated that the subjects were able to reach farther distances during the trial, along with a significant improvement in their movement accuracy. In the CG group, significant increases were also found for the MVL and EPE in the forward direction. These results show that the movement velocity during the trial was faster than the pre-exercise velocity, and the duration of the first movement toward the forward target was also longer than that of the pre-exercise. The results show that one cycling training session with or without FES can improve the postural control of stroke patients. Though no significant differences were found between the two groups concerning their other postural control parameters, all these parameters were improved after the cycling training. It would be worthwhile exploring the long-term effect of cycling exercise on motor control ability in the future.

In the present study, RI and H/M ratio showed significant reductions in muscle tone after one session of cycling exercise, whether with or without FES. The findings of the present study agree with previous studies [20–22]. Motl et al. [21], reported that H reflex of soleus was significantly suppressed after one bout of cycling exercise for normal subjects and subjects with multiple sclerosis. Rosche et al. [22], also indicated that spasticity in multiple sclerosis patients was decreased after a motorized cycling exercise. Singer et al. [23], pointed out that hypertonia contains two components, one is the reflex element, and the other is the non-reflex element. In the present study, the RI obtained by the pendulum test contains both reflex and non-reflex components of hypertonia. The changes in RI cannot be differentiated to determine which components were altered. The H/M ratio has previously been used to assess the excitability of the motor neurons [24]. The significant decrease in the H/M ratio in our study indicates that cycling exercise can significantly inhibit the excitability of the motor neurons. The results also verify the change in the reflex component of hypertonia after cycling exercise with or without FES.

One previous study [2] indicated that a 12-session training program on a semi-recumbent cycle ergometer can improve functional performance of stroke subjects. The other study [1] also reported that FES cycling training can significantly increase muscle strength and motor control in stroke patients. Both of the aforementioned studies did not describe how cycling training influences the affected side of patients. In the present study, the results show that there are significant differences in MVL, EPE, MXE and DCL of the FES-CG group and in EPE, MXE and DCL of the CG group. This indicates that range of motion and control of the affected side significantly improved in both groups, which verifies the therapeutic effect of cycling training. It is possible that exercising the affected limbs repetitively is crucial for stroke patient motor learning [12,25]. The inhibition of hypertonia is another possible mechanism which explains the improvement in the motor control of the affected limbs [6,12].

Janssen et al. [2], found that a short bout of leg cycling can improve functional performance, but electrical stimulation has no additional effect on the overall improvement. Lo et al. [20], found there was a significant decrease in muscle tone among higher muscle tone subjects in the cycling with FES group. In the present study, we also found a significant difference in *c*H/M among the higher muscle tone groups from both FES-CG and CG groups. The *c*RI of the FES-CG group was also higher, than that of the CG group, although not significantly. This result indicates that FES may enhance the effect of cycling exercise, and the influence of FES is more significant on the reflex component than on the non-reflex component of hypertonia. It is possible that, after training, the muscle tone of the soleus was lower for the FES-CG group compared to the CG group due to larger *c*H/M. The soleus muscle had less restriction on ankle joint movements and allowed the forward *c*DCL to be larger in the FES-CG group. Another possible mechanism would be that the reciprocal inhibition from the tibialis anterior was decreased due to the suppression of soleus muscle tone. The control of tibialis anterior in the FES-CG group would be better than that of the CG group. However, only the forward *c*DCL revealed significant differences in the present study. Bajd et al. [26], reported that electrical stimulation cannot only affect the nerve fibers of muscles, but also travel to higher brain centers and may have the potential to reorganize neuromuscular activity. In the present study, only 20 min training sessions were conducted, which may be insufficient time to change motor behavior.

## 5. Conclusions

According to the research results, it may be concluded that short term cycling training (with or without FES) is a useful therapeutic approach to reduce spasticity in stroke patients. After a 20 min cycling training program, the postural control of stroke patients was improved and their muscle tone was reduced, whether with or without FES. Furthermore, the application of FES to the affected leg during cycling training proved to have additional benefits for those with higher muscle tone. Further researches and long term studies are required to confirm the long term effect of FES-CG.

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## Conflict of interest statement

We would like to confirm that no known conflicts of interest associated with this publication and no significant financial support for this research work that could have influenced its outcome.

We also wish to confirm that this manuscript has been read and approved by all authors and no other persons who satisfied the criteria for authorship but are not listed.

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