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ORIGINAL REPORT

# COMPARISON OF ENERGY COSTS OF LEG-CYCLING WHEELCHAIRS WITH OR WITHOUT FUNCTIONAL ELECTRICAL STIMULATION AND MANUAL WHEELCHAIRS FOR PATIENTS AFTER STROKE

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***Objective:*** **To determine whether, for patients after stroke, propelling a functional electrical stimulation (FES)-assisted leg-cycling wheelchair requires less energy than propelling a manual wheelchair, and whether leg propulsion with FES has lower energy costs than without FES.**
***Design:*** **Within-subject comparison.**
***Subjects*****: A total of 16 patients after stroke were recruited from the university hospital.**
***Methods:*** **Subjects propelled 2 leg-cycling wheelchairs (a FES-leg-cycling wheelchair and a leg-cycling wheelchair) and a manual wheelchair for 200 m as quickly as possible. Cardiopulmonary responses (heart rate, oxygen consumption, carbon dioxide production, minute ventilation, and respiratory exchange ratio) and energy costs (physiological cost index and oxygen cost) data for each wheelchair-type were compared for each subject.**
***Results:*** **The cardiopulmonary responses were significantly higher, and energy costs significantly lower for propelling the FES-leg-cycling wheelchair and leg-cycling wheelchair compared with the manual wheelchair. No significant difference was found between the FES-leg-cycling wheelchair and the leg-cycling wheelchair.**
***Conclusion:*** **Propulsion of a leg-cycling wheelchair with or without FES yielded significantly higher cardiopulmonary responses and required less energy than propulsion of a manual wheelchair. The energy costs of cycling with FES was comparable to the energy costs of cycling without FES.**

*Key words:* wheelchair; physiological cost index; oxygen cost; functional electrical stimulation; stroke.

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## INTRODUCTION

Physical inactivity after stroke may contribute to unilateral limb muscle weakness as well as cardiovascular and metabolic deconditioning (1, 2). A lack of adequate exercise due to asymmetrical movement patterns may lead to progressive atrophy of muscles and decreased cardiopulmonary fitness (3, 4). Use of a manual wheelchair for locomotion is common for patients in the recovery stage after stroke. Most patients with hemiplegia use their unaffected arm and leg to propel their wheelchair, which causes the wheelchair to deviate toward the affected side. This asymmetrical propulsion pattern consumes a lot of energy in order to correct direction, which contributes greatly to fatigue (5, 6). In addition, some patients try to propel the wheelchair faster by rocking their upper bodies forwards and backwards, which is a further contributing factor for fatigue.

Leg-propelled devices may be a viable alternative for alleviating the problems of early onset of fatigue and limitation of exercise capacity stemming from use of manual wheelchairs (7–10). A comparison of leg-propelled wheelchairs equipped with electric stimulation on both legs and manual wheelchairs for patients with spinal cord injuries showed that significantly less effort was required for wheelchairs with electric stimulation (8). A more recent evaluation (10) of a similar device used by healthy subjects in a cardiopulmonary exercise also showed that leg propulsion was more efficient than hand propulsion. Functional electrical stimulation (FES)-induced leg exercise, which has generally been used in clinical practice to assist functional movement for patients with lesions of the central nervous system, such as spinal cord injuries and stroke, may solve the problem of insufficient and inadequate muscle fibre activation (8, 11–14). Applying FES to paralysed legs during cycling not only induces high levels of aerobic and cardiac responses, but also positive central nervous system (15, 16) and haemodynamic responses (17, 18). The peak heart rate and power output were also found to be significantly lower during leg-cycling than voluntary hand exercise for patients with spinal cord injuries (12, 19). Although previous studies reported positive effects on FES-assisted leg movements, there are few studies on the energy consumption of FES-assisted leg movements for patients with hemiplegia.

Focusing on the unilateral paralysed limbs of patients after stroke, some specialized wheelchairs have been developed recently. Tsai et al. (20, 21) proposed a 2-leg-propelled

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wheelchair and showed their controllability and physiological responses were significantly better than those of a hand-rim-propelled wheelchair. Makino et al. (22), proposed a foot-pedalled wheelchair propelled by both legs, which was faster and yielded lower energy costs than the manual wheelchair. These new designs assisted patients after stroke to regain mobility, but the user's affected leg was either fixed on the footrest (20, 21) or passively driven (22) during wheelchair propulsion. Lacking adequate exercise, a stroke patient's affected leg will become progressively weaker (8) and the patient's cardiopulmonary fitness will decrease (3, 4). If the affected leg contracts actively (e.g. with the assistance of FES) during wheelchair propulsion, the paralysed muscles may be protected from atrophy and the patient's cardiopulmonary function may be improved.

Hence, applying FES to the affected leg during cycling may be a promising approach to increase cardiopulmonary fitness for patients after stroke. We recently developed a FES-assisted leg-cycling wheelchair (FES-LW) that patients after stroke can propel using both the affected and unaffected legs. The FES-LW was reported to provide more mobility (23) and positive effects on reducing spastic leg muscle tone (24) for patients with hemiplegia; however, the cardiopulmonary responses after propelling FES-LW were not clear. The aims of this study were to determine whether propelling the FES-LW in patients after stroke has lower energy costs than propelling the manual wheelchair, and whether the leg propulsion with FES has lower energy costs than without FES.

## METHODS

### *Subjects*

A total of 16 patients after stroke (11 men and 5 women, age range 35–72 years) with hemiplegia were recruited from the university hospital. Inclusion criteria included the following: (*i*) the patient had sustained a single, unilateral cerebrovascular accident; (*ii*) the affected leg ability was in the range Brunnstrom's Motor Recovery Stage II~IV; and (*iii*) the patient had sufficient cognitive function to understand the instructions and potential risks of this study. Exclusion criteria included: (*i*) visuospatial impairment; (*ii*) a diagnosis of heart failure, arrhythmia, or angina; and (*iii*) orthopaedic or neurological diseases impairing the patient's ability to propel a wheelchair. For all subjects, time after lesion detection was 2–10 weeks. Nine subjects had right-side hemiplegia and 7 had left-side hemiplegia. Ten of the 16 hemiplegic subjects had strokes caused by cerebral haemorrhage; the other 6 had strokes caused by cerebral ischemia. The characteristics of patients who participated in this study are shown in Table I. The purpose and procedures of the clinical evaluation were fully explained to all subjects, their informed consent obtained, and the study was approved by the ethics committee of the university hospital.

Table I. *Characteristics of study participants (*n = *16)*

| Variables | |
|---|---|
| Gender, men/women, *n* | 11/ 5 |
| Age, years, mean (SD) | 53.6 (9.3) |
| Time after stroke, weeks, mean (SD) | 4.0 (2.2) |
| Side of stroke, right/left, *n* | 9/7 |
| Pathology, haemorrhage/ischaemia, *n* | 10/6 |
| Brunnstrom stage, I/II/III/IV/V/VI | 0/6/4/6/0/0 |

SD: standard deviation.

### *Wheelchairs*

The leg-cycling wheelchair (LW) was equipped with a cycling system and 2 ankle-foot orthoses. The cycling system allowed the user to propel the wheelchair using both legs. The 2 ankle-foot orthoses were attached to the cycling system, which prevented accidental disengagement of the subject's legs from the cycling system. The FES-LW added a 2-channel FES controller with a shaft encoder (MES-30-360P; Microtech Laboratory Inc., Kanagawa, Japan) to the LW. The shaft encoder was attached to the shaft of the cycling system to continuously measure the current position of the affected leg. The FES controller only stimulates the affected leg when it sweeps through specific ranges (50–180° for quadriceps and 200–290° for hamstring, respectively). The frequency of stimulation was 20 Hz with a pulse width of 300 μs, and the current amplitude was fixed for the duration of each exercise at different levels ranging from 0 to 100 mA. The stimulation intensity was adjusted by the therapist on an individual basis for each subject in order to elicit muscle contraction without introducing pain. Finally, a commercial manual wheelchair (MW, KM-8520; Karma Medical Products Co., Ltd, Chia-Yi, Taiwan) was used in this study, which can be propelled by the unaffected arm and leg of the subject.

### *Procedures*

A physical therapist instructed subjects how to propel the FES-LW using their legs and to propel the MW with the unaffected arm and leg. They practiced with each wheelchair for 1 h a day, every other day, for 2 weeks. In the field test, participants were instructed to propel each wheelchair for 200 m as quickly as possible (Fig. 1). First, subjects propelled themselves forward clockwise around an oval pathway for 100 m. After turning around, they propelled themselves counterclockwise on the same pathway for another 100 m. There was no rest period during test trial. Subjects completed 3 test trials (FES-LW, LW, and MW) separated by at least 1 day of rest during the span of 10 days to ensure similar physiological characteristics. Before each trial, the resting heart rate and respired gases were recorded for 3 min, after which the subjects started their propulsion task. For their safety, the subject's heart rate was recorded after each trial for another 3 min while their heart rate returned to the resting value. The rating of perceived exertion was obtained after each trial according to the Borg 6–20 scale elicited directly from the subjects. The test was terminated according to the guidelines of the American College of Sports Medicine (25).

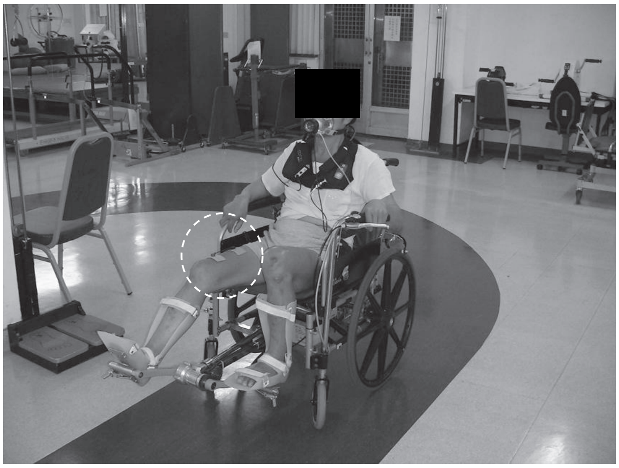

*Fig. 1.* The field test. A patient with right-sided hemiplegia propelled the functional electric stimulation assisted leg-cycling wheelchair (FES-LW). Two sets of surface electrodes are attached to the quadriceps and hamstrings of the right-hand affected leg.

*Data collection*

The heart rate (HR, beats/min) was recorded in real-time using an HR monitor (PE 4000 Sport Tester; Polar, Kempele, Finland). Respired gases were collected and analysed using a breath-by-breath metabolic test system (Cortex Metamax 3B; Leipzig, Germany) to determine oxygen consumption ($\dot{V}O_2$, l/min), carbon dioxide production ($\dot{V}CO_2$, l/min), min ventilation ($\dot{V}E$, l/min), and respiratory exchange ratio (RER). The cardiopulmonary responses (HR, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, and RER) were the mean of values recorded during the last 30 sec of the test. The energy costs, physiological cost index (PCI) and oxygen cost (OC), were compared for each wheelchair. The PCI was calculated with MacGregor's formula (8, 26):

$$\text{PCI (beats/m)} = \frac{\text{HR} - \text{resting HR}}{\text{average speed}}$$

The OC was calculated as follows (8, 27):

$$\text{OC (l/m)} = \frac{\dot{V}O_2}{\text{average speed}}$$

*Statistical analysis*

Descriptive statistics are expressed as means (standard deviations). The exercise cardiopulmonary responses, average speed (m/min), and energy costs were compared using a one-way analysis of variance (ANOVA) with repeated measures. A Scheffe *post-hoc* test was used to detect statistically significant differences in the dependent variables across the tests. Analyses were performed using the Scientific Package for the Social Sciences (SPSS), version 12 (SPSS, Chicago, IL, USA). A *p*-value $<0.05$ was considered statistically significant.

## RESULTS

All subjects completed the test trials using the FES-LW, LW and MW, and no subjects reported adverse reactions to the tests. Table II presents the summarized ANOVA results for the 3 wheelchair types. The cardiopulmonary responses of the users, including HR, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, and RER, were significantly affected ($p<0.05$) by the type of wheelchairs. Propelling the FES-LW and the LW induced significantly higher ($p<0.05$) cardiopulmonary responses than the MW, but no significant differences were found between the FES-LW and the LW. The average wheelchair speed at which the subjects travelled was significantly affected ($p<0.001$) by the type of wheelchair. The average speeds of FES-LW (37.32 m/min) and LW (38.30 m/min) were significantly higher ($p<0.05$) than those of the MW (23.35 m/min). There was no significant difference in speed between the clockwise and counterclockwise pathways in each wheelchair.

Table III shows that both the FES-LW and LW had significantly lower energy costs than the MW ($p=0.008$ in PCI and $p=0.007$ in OC, respectively). The PCI and OC of the FES-LW and LW were significantly lower ($p<0.05$) than those of MW. Finally, the rating of perceived exertion revealed significant differences ($p<0.001$) among the 3 wheelchair types. The rating of perceived exertion of FES-LW (9.67) and LW (10.40) were significantly lower ($p<0.05$) than those of the MW (12.47). The results showed that there were no significant differences between the FES-LW and the LW.

Table II. *Analysis of variance (ANOVA) results of cardiopulmonary responses in the last 30 sec of test (*n = *16)*

| | FES-LW | LW | MW | *p*-value |
|---|---|---|---|---|
| HR (beats/min) | 110.35 (12.83)† | 109.65 (12.37)‡ | 98.18 (8.44) | 0.006* |
| $\dot{V}O_2$ (l/min) | 0.575 (0.103)† | 0.585 (0.100)‡ | 0.476 (0.076) | 0.004* |
| $\dot{V}CO_2$ (l/min) | 0.646 (0.110)† | 0.653 (0.122)‡ | 0.489 (0.069) | 0.000* |
| $\dot{V}E$ (l/min) | 25.53 (4.38)† | 25.35 (5.43)‡ | 20.62 (4.04) | 0.006* |
| RER | 1.13 (0.13)† | 1.12 (0.08)‡ | 1.03 (0.07) | 0.012* |

* Significance level at $p<0.05$.
†Significant difference between the FES-LW and the MW.
‡Significant difference between the LW and the MW.
HR: heart rate; $\dot{V}O_2$: oxygen consumption; $\dot{V}CO_2$: carbon dioxide production; VE: minute ventilation; RER: respiratory exchange ratio; FES-LW: functional electrical stimulation assisted leg-cycling wheelchair; LW: leg-cycling wheelchair; MW: commercial manual wheelchair.

## DISCUSSION

This study, comparing the cardiopulmonary responses and energy costs of leg-cycling and manual wheelchairs propelled by patients after stroke, produced 3 significant findings. First, both of the leg-cycling wheelchairs induced significantly higher cardiopulmonary responses than the MW. Secondly, the energy costs were significantly lower for both of the 2 leg-cycling wheelchairs than for the MW, which indicates that leg-cycling wheelchairs consume less energy than the MW. Thirdly, the leg-cycling wheelchairs with or without FES induced similar cardiopulmonary responses and required similar energy costs in the test.

The higher cardiopulmonary responses of the leg-cycling wheelchairs compared with the MW can easily be explained, since 2 legs are used to propel leg-cycling wheelchairs, but only one arm to propel the MW. The major muscles of the legs, which are normally active in locomotion, are usually larger and stronger than those of the arms. Therefore, the maximal workload for leg exercise is greater than that for arm exercise (28, 29). Cardiopulmonary responses depend on the response of the increase in energy demanded from the exercised muscles (12). The relatively larger muscle groups in the legs have greater oxidative capacity, and motor unit recruitment (30) explains the higher leg-cycling-wheelchair cardiopulmonary responses in this study.

In the present study, we conducted the field test for 3 wheelchairs to measure the cardiopulmonary responses and average speed, and then calculated the energy costs. The results for

Table III. *Analysis of variance (ANOVA) results of energy costs of each wheelchair (*n = *16)*

| | FES-LW | LW | MW | *p*-value |
|---|---|---|---|---|
| PCI (beats/m) | 0.440 (0.120)† | 0.470 (0.200)‡ | 0.670 (0.300) | 0.008* |
| OC (l/m) | 0.016 (0.004)† | 0.017 (0.006)‡ | 0.022 (0.006) | 0.007* |

* Significance level at $p<0.05$.
†Significant difference between the FES-LW and the MW.
‡Significant difference between the LW and the MW.
PCI: physiological cost index; OC: oxygen cost; FES-LW: functional electrical stimulation assisted leg-cycling wheelchair, LW: leg-cycling wheelchair; MW: commercial manual wheelchair.

cardiopulmonary responses revealed that both the FES-LW and the LW were significantly higher in each parameter than the MW. With regard to the FES-LW and LW, although the FES-LW has higher HR, $\dot{V}E$, RER and lower $\dot{V}O_2$, $\dot{V}CO_2$ than the LW, no significant difference was found between them. The RER values for these 3 wheelchairs are higher than 1.0. This phenomenon indicates there is a larger anaerobic component. However, the $\dot{V}O_2$ of the FES-LW and LW were significantly higher than that of the MW. This indicates that the $O_2$ consumption was higher in FES-LW and LW, even though they have larger anaerobic energy components (Table II). However, the propelling speed of leg-cycling wheelchairs was significantly higher than that of MW. We normalized the HR and $\dot{V}O_2$ by the average speed to represent the energy costs, PCI and OC, respectively. We found that the energy costs were significantly lower in the leg-cycling wheelchairs compared with the MW, but no significant difference was found between FES-LW and LW. In addition, the changes in HR and $O_2$ consumption in the FES-LW and LW were lower than those of the MW when propelling a constant distance.

For manoeuvrability, patients after stroke are able to use the MW by propelling the hand-rim with the unaffected hand and pushing the ground with the unaffected leg. The most severe problem with the MW is that asymmetrical forces may cause the wheelchair to stray towards the affected side. This ergonomic shortcoming of the MW makes it difficult and dangerous for patients with hemiplegia to propel manual wheelchairs over a long distance, go up a slope, or change direction. Hemiplegic patients using the FES-LW and LW moved faster than those using the MW. This indicates that leg propulsion is more efficient than the MW, probably because muscles in both the lower and upper legs are used for the FES-LW and LW. It was easier for patients with hemiplegia to control the FES-LW and LW using a steering lever than using the unaffected arm and leg to control wheel speeds and direction adjustment while propelling the MW. The brake on the lever handle was also beneficial for control. Because the speed of the FES-LW and LW was higher than that of the MW, the brake was necessary to ensure user safety.

Better propulsion pattern may have contributed to the lower energy costs. Previous studies indicated that subjects propelled the leg-cycling wheelchairs using a continuous and circular motion, which is inherently more efficient than the intermittent movement of hand-rim propulsion (8). In addition, the hand-rim propulsion pattern of MW is a complex and intermittent motion that consumes extra energy because of the acceleration and deceleration of the hand (30–33). The energy costs of FES-LW tended to be lower than the LW in our study, but did not yield a significant difference. Our findings were similar to the previous studies (14), in that applying electrical stimulation to the affected leg during cycling had no additional effects on improving aerobic capacity of patients with chronic stroke. This may be explained by the relatively small muscle mass that was additionally activated by the stimulation currents. Patients after stroke still have some preserved sensation in their affected limbs. We used low stimulation intensities in this study to prevent causing our subjects unnecessary pain. Although the patients recruited in our study were in the sub-acute stage, a limited number of motor neurones were stimulated by low intensities to induce muscle contraction.

Alternative mobility devices, such as powered wheelchairs and scooters, are frequently used for patients after stroke in the recovery stage. These devices are comfortable, easy to operate, and convenient. However, the consequent lack of adequate exercise when using powered mobility devices may lead to decreased cardiopulmonary fitness and muscle atrophy (8, 22). Using a leg-cycling wheelchair may have advantages, such as providing greater activity in the *vastus medialis* and *vastus lateralis* muscles of the affected leg (34). It has been demonstrated that exercising the unaffected leg can facilitate a selective muscular contraction in the affected leg, which may be a beneficial technique for re-education of selective muscle activation. These reciprocal effects from the contralateral limb might contribute to facilitate selective and phasic muscle activities during leg cycling (35). In addition, we used electrical stimulation to induce paralysed muscle contraction with the FES-LW. FES can actively contract the muscle during cycling, which can improve blood circulation of the affected leg. Since muscle stiffness can decrease, depending on increased blood flow to the stimulated area (36), FES may provide additional rehabilitation effects.

Propulsion of the leg-cycling wheelchairs was proved to have significantly lower energy cost than that of the MW in this study. The effect of FES on cardiopulmonary response was not obvious and could be attributed to the relatively small subject group and low intensity of the FES in a short-term experiment. The small subject group may have resulted in relatively low power intensity for FES. To prevent inducing muscle pain, the stimulation intensity of the FES was adjusted per subject. Because of this, only a limited number of nerves could be stimulated, therefore reducing the effect of FES. In order to determine the effects of FES on reducing the energy cost of LW, more subjects and a long-term training exercise are suggested for future research.

In conclusion, the FES-LW was designed as a locomotion aid to provide autonomy for patients after stroke. We conclude that propulsion of the FES-LW and LW yielded significantly higher cardiopulmonary responses and had lower energy costs than propulsion of the MW. The application of FES to the affected leg during cycling has comparable energy costs to cycling without FES.

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