Functional Electrical Stimulation Cycling Wheelchair for Stroke Patients: Design and Preliminary Evaluation Results

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Abstract

People with post-stroke neurological damage may be left with physical impairments deeply affecting their daily life. Using a manual wheelchair is a common manner of locomotion for stroke patients in recovery stage. However, this kind of wheelchair is poor clinical considered and difficult for them to use. A functional electrical stimulation system with cycling system wheelchair (FCW) for hemiplegic patients was designed and proposed in this study. Hemiplegic patients can propel the FCW using both the unaffected and affected legs and can steer the wheelchair efficiently. A clinical evaluation was conducted to assess both the chair’s maneuverability and user-satisfaction with the chair. A total of 12 participants were recruited to evaluate the FCW by comparing with a commercially available manual wheelchair (MW). The results inducted that the FCW was more maneuverable than the MW. In addition, participants were more satisfied with the FCW than with the MW. Therefore, we concluded that it is easier and more efficient for hemiplegic stroke patients to operate the FCW than the MW.

Keywords: Stroke, Hemiplegia, Functional electrical stimulation, Wheelchair, Maneuverability

1. Introduction

People who survive a stroke or cerebrovascular accident may be left with physical impairments that bring about numerous life style changes, including the loss of activities, abilities, characteristics and independence [1-3]. These losses can cause depression, a decreased subjective feeling of well-being, changes in self-concept and a decrease in the quality of life [4]. The loss of mobility is of paramount importance to hemiplegic stroke patients, about 85% of whom have impaired mobility three months after a stroke, and almost half of whom need mobility aids [5]. Use of a wheelchair is a common way of locomotion for hemiplegic patients in recovery stage because it provides the greatest degree of mobility and stability [4].

Asymmetrical functions between the affected and unaffected limbs, which are commonly observed in hemiplegic patients [6,7], can have several causes: decreased muscle strength, inappropriate muscle contraction patterns, and limited ranges of joint motion [8,9]. Most of them use their unaffected arm and leg to propel a manual wheelchair. Clinically, this can cause them some embarrassments. First, they use only the unaffected arm to propel the hand rim on a single wheel. Single-handed propulsion produces a relatively excessive strain on the shoulders and lower back, which leads to high energy consumption, and may quickly cause exhaustion [10,11]. Second, using only the unaffected leg to stamp the ground to steer the wheelchair requires coordinating the leg-stamping speed and hand-rim pushing speeds. This unilateral propulsion pattern often causes the wheelchair to wander toward the affected side [4,12]. Third, to extend propulsion distance, users have to swing their trunk forward and backward. This unstable propulsion pattern induces their posture to become unbalanced, which may consume even more energy. The above inconveniences may result from using an unsuitable mobility aid, because the manual wheelchair was designed to be propelled by two healthy arms, not just one. Therefore, a well-designed mobility aid for the hemiplegic patients is necessary to facilitate their safety and mobility.

Propelling a wheelchair with one’s legs instead of one’s arms should be more effective because of the legs’ larger and stronger muscle groups. Some innovative wheelchairs that can be propelled by hemiplegic patients have been proposed [13-15]. Bloswick et al. designed knee-extension wheelchairs that can be propelled using residual leg function for elderly, which might be able to be operated with the unaffected leg by...
stroke patients [13]. Recently, Tsai et al. developed two types of unilaterally leg-propelled wheelchairs for hemiplegic patients [14,15]. Propelling these wheelchairs requires no use of the affected leg. In addition, long-time sitting on the chair with flexed hip and knee frequently may make users’ joints contract. Since some hemiplegic patients still have preserved leg function, propelling a wheelchair using both legs might be a feasible way to benefit both mobility and rehabilitation.

Functional electrical stimulation (FES) has been described as “electrical stimulation of muscle deprived of nervous control with a view of providing contraction and providing a functionally useful movement” for people with upper motor neuron lesions [16]. It is used primarily to control shallow muscles and major functional motions, which are more suitable for muscle strengthening and exercise purposes such as standing, walking, and cycling [17]. FES-induced leg exercise may solve the problems of insufficient muscle activation, which has generally been used in clinical practice to assist functional movement for patients with stroke and spinal cord injuries [18-20]. In addition, FES-induced leg exercise has other advantages, such as increasing muscle strength and endurance, preventing paralyzed muscle from atrophying, and improving cardiopulmonary function, among other physiological and psychological effects [21,22]. Despite the number of studies on providing mobility to patients whose muscles may still be stimulated [19,20,23], very few have dealt with using FES for hemiplegic patients to propel a wheelchair. Therefore, the purpose of this study was to design a new wheelchair which combined a cycling system with FES system for hemiplegic patients. In addition, we conducted a clinical evaluation to evaluate the maneuverability of and user satisfaction with the newly designed wheelchair compared with a manual wheelchair.

2. Wheelchair design

2.1 Empirical study

Surveys of user opinion and clinical observation were conducted in this stage. A total of 20 stroke patients (14 men, 6 women; age range: 45-65 years old) participated in the empirical study. All participants had asymmetrical limb functions and unilateral limb weakness, but the range of motion of their unaffected upper and lower limbs was sufficient to propel a manual wheelchair. The patients were required to operate a commercially available manual wheelchair (KM-8520; Karma Medical Products Co., Ltd., Chia-Yi, Taiwan) in the empirical study. Since hemiplegic patients typically propel a manual wheelchair with the unaffected arm and leg, the foot rest of the wheelchair on the unaffected side was removed and the seat height was decreased to 40 cm. Patients could therefore produce propulsive force and steer the chair by stamping the unaffected foot on the ground. An observation survey was conducted using a digital video camera, and the results were shown as follows. In general, participants propelled the wheelchair by pushing the hand rim with the unaffected hand. To counteract the single-handed propulsion forces, they stamped the unaffected foot on the ground. Those who used only the unaffected arm to propel the wheelchair often complained that they were easily fatigued because of insufficient arm strength. Some participants with poor coordination had to stop their arm or leg propulsion movements when the unaffected leg or arm was correcting the chair’s direction. After the wheelchair had been guided back to the right direction, the propulsion task would resume. Our observations indicated that an asymmetrical propulsion pattern forced the user’s trunk toward the affected side, and the user’s posture became unbalanced. Therefore, it is difficult and possibly unsafe for a hemiplegic patient to propel a manual wheelchair over a long distance. An interview survey with the participants was conducted, most of them expressed that they wanted to be able to push the wheelchair by themselves rather than be moved by caregivers. They reported that self-propulsion made them feel independent and self-confident; however, difficulties with maneuvering and pushing the wheelchair forced them to rely on their caregiver. From the empirical study, we found that the suitable wheelchair for hemiplegic patients would be easily self-propelled, easy to operate, and might allow the user to travel greater distances than with a manual wheelchair.

2.2 FES cycling wheelchair design

The new FES cycling wheelchair (FCW) was designed to combine a cycling wheelchair with an electrical stimulation controller (Fig. 1). A wheelchair with a cycling system is expected to be a practical device for locomotion (Fig. 2). Ankle foot orthoses were attached to the pedals to prevent abduction of the hip joint of the affected leg. The leg-generated forces are transmitted to the rear wheel by a transmission system. Hemiplegic patients can use their legs with the cycling system to propel the wheelchair. A steering lever connected to a caster of the unaffected side controls driving direction of wheelchair.

![Electrical stimulation controller](image)

**Figure 1.** Configuration of the FES cycling wheelchair (FCW). Channel 1: for the quadriceps; Channel 2: for the hamstrings.
height between the hip joint (H) and the rotation center of the crank (C) can be ignored, the dead spots just cross the pedal cycling locus and the line that connects points H and C. Three assumptions are proposed for the model: points H and C are fixed, the knee joint (K) has only one degree of freedom, and the lengths of thigh (HK) and shank (KP) are invariable. According to the cosine theorem in geometry, the relationship between the knee angle (θ) and the triangle KHP can be expressed as

$$H P^2 = H K^2 + K P^2 - 2 \times H K \times K P \cos \theta$$

(1)

Eq. (1) can be further simplified as:

$$\theta = \cos^{-1}\left(\frac{H P^2 - H K^2 - K P^2}{2 \times H K \times K P}\right)$$

(2)

and

$$H P = \sqrt{H C^2 + C P^2 - 2 \times H C \times C P \cos \lambda}$$

(3)

In the upper cycle, the angle variation of ranges from 0° to 180°; thus, the length variation of HP in Eq. (3) is an increasing function. Therefore, \(\cos \theta\) in Eq. (2) must be a decreasing function. In addition, the sum of HK and KP must be larger than HP; and the value of \(\theta\) will increase in the upper cycling exercise.

As to stimulation patterns, Channel 1 was used to increase the muscle strength of the quadriceps to increase the knee angle (extension) in the upper cycle. The Channel 2 was used to increase the strength of the hamstring to decrease the knee angle in the lower cycle. Two pairs of surface electrodes were positioned on the quadriceps and hamstrings of the affected side (Fig. 4). The negative electrode was placed on the motor point of the quadriceps and hamstrings, and the positive electrode was placed 3-5 cm distally to the negative electrode. The physical therapist adjusted the stimul intensity individually for each patient to elicit muscle contraction without causing pain. Stimulus patterns with 15° starting and ending ramps were used to prevent a jerky cycling movement caused by abrupt turn-ons and turn-offs of stimulated muscles.

Figure 2. Design of the cycling wheelchair. (a) ankle foot orthosis, (b) transmission system, (c) angular encoder, (d) steering lever, (e) caster.

Figure 3. The simplified five-bar linkage mechanical system consists of the thigh and lower leg, and the crank of the cycling system.

All the joints in the linkage are assumed to be pin-joints that allow only one degree of freedom. Two of the joints, the hip joint and the rotation center of the crank, are assumed to be fixed. The zero degree of the crank angle is defined as the proximal point of the crank when it is parallel to the ground. The quadriceps and hamstrings muscles, the power sources for pushing the pedals, were stimulated. For complete cycling, there are two pedal positions, dead spots, at which the net moment referred to crank rotation center is zero. The dead spot is defined as the point of transition between the knee extension (α) and the flexion (α’) movement. If gravitational effects of the differential
3. Clinical evaluation

3.1 Participants

The clinical evaluation was conducted with 12 stroke patients (7 men and 5 women; age range: 42-68 years old; 3-10 weeks post-stroke) from a medical university hospital (Table 1). Participants were selected from the patients who were admitted to receive medical rehabilitation in the hospital, based on the following criteria: (1) hemiplegia caused by initial onset of a stroke; (2) stage 1 or 2 evaluated by Brunnstrom’s test for the affected leg; (3) no walking ability by the time the experiment was performed; (4) no remarkable joint contractures found in affected leg; (5) had sufficient cognitive function to participate; (6) use a little; 6, he as. A Wilcoxon signed-rank test was applied to compare the differences in maneuverability measurement as well as user satisfaction questionnaire between the FCW and the MW. Analysis was performed using the Statistical Package for the Social Sciences (version 12; SPSS, Chicago, IL). Statistical significance was set at p < 0.05.

Table 1. Participant characteristics (n = 12).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Gender</th>
<th>Age (years), mean (SD)</th>
<th>Time post-stroke (weeks), mean (SD)</th>
<th>Side of stroke</th>
<th>Pathology</th>
<th>SD: standard deviation.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>55.2 (5.3)</td>
<td>5.8 (3.2)</td>
<td>Right</td>
<td>Ischemia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>5</td>
<td>8</td>
<td>Left</td>
<td>Hemorrhage</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

3.2 Test protocol

There were two stages in the clinical evaluation: maneuverability measurement and user-satisfaction questionnaire. For maneuverability measurement, participants had to perform the following selected tasks on a flat floor: (1) propel a wheelchair forward along a counterclockwise 1-meter-wide oval-shaped pathway; (2) make a 180° rotation maneuver; and (3) propel the wheelchair clockwise on the same pathway. The total distance of the propulsion task was 60 meters. Participants were instructed to comfortably propel the wheelchair and to keep it within the boundary lines of the pathway. A video record was made while the participants were performing the tasks. These videotapes were later carefully viewed by the testers to determine propelling time, deviation frequency, and deviation time periods in the straight and curved regions for the two wheelchairs. The speed can be calculated by dividing the total distance by the total propulsion time. Deviations occurred when both the caster and rear wheels of one side ran over the pathway boundary.

After completing the maneuverability measurement, a user-satisfaction questionnaire was made to collect user satisfaction information of the new wheelchair. It consisted of 3 items which were measured on a 7-point Likert scale with verbal anchors: 1, strongly disagree; 2, disagree; 3, disagree a little; 4, neither agree nor disagree; 5, agree a little; 6, agree; and 7, strongly agree (Table 2).

Table 2. User-satisfaction information questionnaire.

<table>
<thead>
<tr>
<th>Item</th>
<th>Decreases</th>
<th>Increases</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) I am satisfied with the wheelchair’s propulsion pattern.</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>(2) I am satisfied with the wheelchair’s steering pattern.</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>(3) The wheelchair meets my needs.</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Results

The stimulus pattern differed for each subject. From our records, Channels 1 and 2 were triggered to stimulate quadriceps when sweeping from 158° to 197° and hamstrings when sweeping from 185° to 240°, respectively. The two types of wheelchairs were evaluated in the clinical evaluation: the FCW was propelled by both unaffected and affected legs, and the MW was propelled only by the unaffected arm and hand. The FCW significantly (p < 0.05) outperformed the MW in all categories (Table 3). The FCW was faster than the MW on straight regions, on curves, and on average. The FCW deviated less frequently than the MW on straight regions, on curves, and on average. Finally, the FCW had significantly lower deviation percentages than the MW on straight regions, on curves, and on average.

Table 3. Maneuverability measurement of the two types of wheelchairs in clinical evaluation. (n = 12).

<table>
<thead>
<tr>
<th>Speed (m/min)</th>
<th>FCW</th>
<th>MW</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td>36.25 (4.60)</td>
<td>22.28 (3.04)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Curves</td>
<td>24.58 (4.33)</td>
<td>16.83 (3.60)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Average</td>
<td>30.42 (3.77)</td>
<td>19.71 (2.88)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Deviation frequencies (times)</td>
<td>5.25 (1.09)</td>
<td>6.88 (1.83)</td>
<td>0.020*</td>
</tr>
<tr>
<td>Straight</td>
<td>5.78 (1.71)</td>
<td>9.50 (2.93)</td>
<td>0.008*</td>
</tr>
<tr>
<td>Curves</td>
<td>6.42 (1.02)</td>
<td>8.17 (1.94)</td>
<td>0.005*</td>
</tr>
<tr>
<td>Average</td>
<td>12.26 (2.98)</td>
<td>18.29 (3.50)</td>
<td>0.003*</td>
</tr>
<tr>
<td>Deviation percentages (%)</td>
<td>17.31 (5.26)</td>
<td>24.39 (5.19)</td>
<td>0.004*</td>
</tr>
<tr>
<td>Average</td>
<td>14.78 (3.73)</td>
<td>21.34 (3.26)</td>
<td>0.002*</td>
</tr>
</tbody>
</table>

*p < 0.05
All values are means (SD).
FCW: FES cycling wheelchair; MW: manual wheelchair.

On the user satisfaction questionnaire, participants rated the FCW significantly (p < 0.05) higher than the MW in all aspects (Table 4): “I am satisfied with the wheelchair’s propulsion pattern”; “I am satisfied with the wheelchair’s steering pattern”; and “The wheelchair meets my needs”.

...
Table 4. User satisfaction with the two types of wheelchairs in clinical evaluation (n = 12).

<table>
<thead>
<tr>
<th></th>
<th>FCW</th>
<th>MW</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I am satisfied with</td>
<td>5.50 (0.78)</td>
<td>3.50 (0.70)</td>
<td>0.007*</td>
</tr>
<tr>
<td>the wheelchair’s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>propulsion pattern.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am satisfied with</td>
<td>5.58 (0.78)</td>
<td>3.25 (0.78)</td>
<td>0.003*</td>
</tr>
<tr>
<td>the wheelchair’s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>steer pattern.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The wheelchair</td>
<td>6.17 (0.69)</td>
<td>4.17 (0.90)</td>
<td>0.002*</td>
</tr>
<tr>
<td>meets my needs.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.05
All values are means (SD).
FCW: FES cycling wheelchair; MW: manual wheelchair.

4. Discussion

Achieving early post-stroke independence may improve the quality of life for stroke patients and increase their self confidence [2]. The FCW allows hemiplegic stroke patients to propel themselves with the affected leg assisted by FES. The maneuverability measurements showed that the FCW had a higher average speed, a lower deviation frequency, and lower deviation percentage than the MW, which agrees with previous studies [14,15]. The subjective user-satisfaction questionnaire results showed that the FCW had higher mean scores in propulsion pattern and steering pattern, which were in agreement with the maneuverability measurements.

For this study, we developed a new wheelchair, the FCW, which hemiplegic patients can propel by affected leg with the assistance of FES, and the unaffected leg. A wheelchair propelled with both legs is generally faster than one propelled with both arms (e.g. MW) because the major muscles of the leg are larger and stronger than those of the arm [25,26]. In addition, the motions of leg cycling may consume less energy and yield more speed than the motions of hand rim-propulsion because the former are continuous while the latter are intermittent. The maneuverability measurement showed that the FCW was easier to control than the MW because its deviations in direction were smaller and less frequent than those of the MW. In the clinical evaluation, the participants steered the FCW with a steering lever connected to the castors and controlled by their unaffected hand. The unaffected hand was responsible for steering; therefore, the users were able to accurately and efficiently control the wheelchair’s direction. In contrast, using their unaffected arm and leg to propel a MW usually caused asymmetrical propulsion pattern that forced the wheelchair to deviate toward the affected side. To steer the MW, however, they had to coordinate the unaffected arm regulating wheel speed and the unaffected foot stamping the ground to change direction. It was difficult to control the direction of the MW on straight regions as well as on curves.

Leg propulsion, either voluntarily produced or electrically stimulated, is an alternative for wheelchair users. Stein et al. reported that people with spinal cord injuries could move their legs if surface electrodes were placed on the quadriceps and hamstrings to induce knee extension and flexion [19]. After evaluating the energy cost of their leg-propelled wheelchair, steinetal found that it was more physiologically efficient than an MW. But it had been designed for persons with two healthy arms, not for persons with hemiplegia. Bloswick et al. have proposed three types of knee-extension wheelchair propelled using residual leg function [13]. They reported that the maneuverability and usability of wheelchairs using a swing or sliding belt mechanism were better than those of wheelchairs using a sliding plate. Although hemiplegic patients may be able to propel the above two wheelchairs [13,19] using their residual limbs functions, their wheelchairs were not designed considering the physiological characteristic of persons with unilateral limbs functions. In recent years, only a few studies have focused specifically on hemiplegic patients operating a wheelchair with their unaffected limbs [14,15]. Tsai et al. evaluated the maneuverability of three wheelchairs (a two-hand rim-propelled MW, an ankle-propelled wheelchair, and a knee-propelled wheelchair) unilaterally propelled by hemiplegic users [14]. It was more efficient for hemiplegic patients to use the knee-propelled wheelchair than the two-handed rim-propelled wheelchair with only one arm and the ankle-propelled wheelchair with the unaffected hand and foot. Although they could propel unilaterally propelled wheelchairs using only the unaffected hand or leg, unilateral propulsion force may force the trunk to lean toward the affected side. This asymmetrical propulsion pattern may induce abnormal muscle tone in the affected leg [27]. In comparison, FCW can realize a partial active movement of the affected leg with the assistance of FES. The design of FCW considers the physiological characteristics of hemiplegic patients, and might promote independence and confidence in these patients. In addition, FCW have positive effects on increasing patients’ cardiopulmonary fitness and create no physiological complications such as abnormal muscle tone and unbalanced posture.

The FCW has other advantages. First, propulsion of an FCW with leg cycling movement can improve cardiopulmonary fitness and circulation [21,22] and functional performance of patients with stroke [28]. The cycling movement will also facilitate phasic and coordinated muscle activities, and may be an effective mode of muscle reeducation for the affected leg [29]. Second, paralyzed muscle fibers can be activated and contracted by electrical stimulation current, which will prevent paralyzed muscle fibers atrophying [30,31]. The electrical stimulation not only affects the nerve fibers going to the muscles but also those going to the brain, which may stimulate reorganization of neuromuscular activity to improve functional performance [16]. In addition, participants indicated that the design of FCW was closer to their needs than the design of the traditional manual wheelchair. However, there were some disadvantages of the FCW, such as cycling system may impede the transferring movement for patients with hemiplegia.

There are limitations to this study. First, the effect of cycling wheelchairs without FES was not evaluated. Further studies are needed to quantify the effects of FES on stroke patients during propelling FCW. Second, we studied propelling the FCW and MW on only a flat and relatively wide test field. There are other conditions in daily life, such as uneven ground, inclines, narrow corners, etc., which were not examined. Further investigation on the effectiveness of the FCW in daily use is needed.
5. Conclusions

In this study, we integrated the important ergonomics factors of post-stroke hemiplegic wheelchair users and the user-operated patterns into the design of the FCW design to achieve optimal wheelchair operation performance. None of the participants complained about musculoskeletal discomforts after propelling the FCW. Based on the clinical evaluation, we conclude that it is not only easier but also more efficient for hemiplegic stroke patients to operate the FCW than a manual wheelchair. The user-satisfaction survey also showed that participants preferred the FCW to the manual wheelchair.

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References