The use of functional electrical stimulation assisted cycling in adolescents with cerebral palsy

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Abstract
Cerebral palsy (CP) is a non-progressive disorder of the brain that results in decreased strength, abnormal muscle tone and difficulty with gradation of movement which results in decreased independence with functional mobility. Exercise is often difficult for individuals with CP due to the balance and coordination required to exercise at the levels necessary to improve cardiovascular function. Functional Electrical Stimulation (FES) assisted cycling has been proposed for individuals with CP as it does not require standing balance and FES can be used to supplement the individual’s volitional effort and improve cycling performance. This paper seeks to provide an update on the use of FES assisted cycling in children with CP. Five subjects participated in pilot work assessing the feasibility and efficacy of FES assisted cycling. FES assistance to the quadriceps was tolerated well and resulted in increased cadence, torque and power and decreased variability in cycling performance. FES assistance also allowed subjects to work at sufficient levels to achieve increased heart rate and peak VO2. Considerations for FES-assisted cycling in CP including the use of an auxiliary motor to control cadence and allow for valid cycling tests are discussed. Future work will focus on optimizing stimulation settings and further development of a closed-loop control system for the application of FES assisted cycling in individuals with CP.

1 Introduction
Cerebral palsy (CP) is a non-progressive disorder of the brain that occurs during development and results in motor impairment. It is the most prevalent neuromotor diagnosis and has the highest lifetime economic cost and net cost of medical care. Children with CP present with decreased strength, abnormal muscle tone and difficulty with gradation of movement in the affected muscle groups. These impairments result in decreased independence with functional mobility and decreased physical activity. Lack of involvement in physical activity is one of the leading indicators reflecting major health concerns in the United States. Consequences of inactivity or sedentary lifestyles include obesity, cardiovascular disease, diabetes and other chronic diseases and conditions.

The need for activity and exercise is especially acute for youth with physical disabilities, who participate in less physical activity compared to their typical developing peers and thus are more at risk for declines in health. Unfortunately, many children with disabilities are unable to meet activity and exercise recommendations due to functional impairments that limit the type of exercise in which they can participate.

Stationary cycling is suggested as an exercise method for individuals with CP because it does not require the dynamic balance or mobility that exercise in a standing position requires. Previous work in our lab examining the biomechanics of cycling in individuals with CP has demonstrated difficulties attaining threshold heart rates and cycling intensities necessary to achieve musculoskeletal changes and cardiorespiratory training effects. Thus, additional means may be necessary to improve the cycling ability in this population. For individuals with spinal cord injuries, functional electrical stimulation (FES) cycling has led to cardiorespiratory gains and musculoskeletal gains. Although fundamentally a different task in children with CP who have varying degrees of volitional ability, we hypothesize that FES assisted cycling could be used to produce higher heart rates, power output and cadences than children with CP are able to achieve on their own. This purpose of this paper is to discuss recent progress in the development of a FES assisted cycling system for use in individuals with CP.

2 The Feasibility of Applying FES Assisted Cycling in Individuals with CP

There are certain considerations that need to be made when applying the technology developed for individuals with spinal cord injuries to those with CP. Six subjects with CP participated in pilot work assessing the feasibility and efficacy of FES assisted cycling. (Table 1) FES assistance was provided to the quadriceps through surface electrodes.

Table 1- Description of pilot study subjects; “Functional Mobility” describes the devices required for subjects to walk (Subjects 1-3) or the necessity of using a wheelchair for mobility (Subjects 4,6)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Sex</th>
<th>Functional Mobility</th>
<th>Prior Cycling?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>F</td>
<td>Anterior Walker</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>M</td>
<td>Posterior Walker</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>M</td>
<td>Crutches</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>F</td>
<td>Wheelchair</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>M</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>F</td>
<td>Wheelchair</td>
<td>No</td>
</tr>
</tbody>
</table>
Subjects completed constant load and incremental tests with and without the application of FES to assess their cycling ability as measured by cadence, torque and power output. Cycling performance was also analyzed by calculating the coefficient of variability in power output (averaged over each minute during the cycling trial).

A tricycle-based FES-cycling system fitted with a stimulator capable of 8 channels of FES was used for this study. The cycle, previously described by McRae and colleagues, is instrumented with a torque sensor and crank encoder and data is collected using custom software. (MatLab, The Mathworks, Inc.)

All subjects were able to tolerate the application of FES to bilateral quadriceps muscles without requiring anesthetizing cream. The thresholds for sensory-level stimulation (the amount of stimulation required for the tactile sensation of the electrical stimulation), motor-level stimulation (the amount of stimulation required to move the legs through a portion of the cycling revolution) and the maximum tolerated level of stimulation while the subject’s legs are being passively moved at the individual-specific cycling cadence were determined. All subjects were able to complete this testing without difficulty.

The application of FES in an individual that is able to contribute to the cycling effort also required the development of a feedback system. Unlike in paralyzed individuals, our subjects were able to cycle volitionally, although inefficiently, and were provided with visual feedback on the computer screen in order to encourage cycling at a target power output. (Figure 1)

Figure 1: Visual feedback provided during cycling tests and training sessions. Subjects are asked to cycle at a target power level. If they are successful, the ball stays within the box and turns green (A). If they cycle at a higher (B) or lower power level (C), the ball moves out of the box and turns red.

3 The Use of an Auxiliary Motor to Control Cadence in FES Assisted Cycling in Individuals with CP

In initial pilot work, the volitional and FES assisted tests were attempted without the use of the auxiliary motor. The auxiliary motor is located on the rear wheel of the trike and allows for cadence control during cycling tests. The data from Subject 2 led us to conclude that not all individuals with CP have the strength and coordination to complete a standard constant load or incremental test without the use of a motor to assist with propulsion.

Subject 3 was also unable to cycle consistently without assistance from the motor. His spasticity and poor motor control led to highly variable performance. Without the ability to consistently cycle at a target cadence, we are unable to perform a valid constant load or incremental test. Figure 2 illustrates the performance of the subject when cycling at a target cadence of 40 RPM. He was unable to achieve this cadence and his cycling performance was quite variable without the motor (Fig. 2A); however, the motor assistance allowed him to cycle at a consistent cadence (Fig. 2B).

Although motor assistance controls pedal cadence, useful tests can be performed by analyzing power output, which is derived from the positive volitional torque exerted on the crank.

Figure 2: Cycling cadence for an individual with CP (Subject 3) that was asked to cycle at 40 rpm without (A) and with (B) the use of motor assistance to control cadence. (Subject 3)

Likewise, the use of the auxiliary motor assist allows us to run an exercise test at clearly defined power increments. The work of Johnston and colleagues and our own pilot work have demonstrated the erratic cycling patterns used by children with CP. By using the motor-assist, we can collect measurements of performance in individuals with poor cycling ability. (Figure 3) A valid exercise test is difficult or impossible to gather without the use of the motor assistance due to the inability of these subjects to maintain a constant cadence during cycling tests.

Figure 3: Valid cycling tests can be performed by using an auxiliary motor to control cadence. The plots in this figure show the power output during a constant load test with motor-controlled cadence (A) and an incremental test with motor-controlled cadence (B). The vertical dotted line in the plots delineates the transition from passive cycling to active cycling. The blue traces are cycling performance while the horizontal dotted lines represent the target power output for the constant load and incremental tests.
4 The Efficacy of Applying FES Assisted Cycling in Individuals with CP

All subjects were able to attain higher levels of power output and modest increases in heart rate in the cycling trials with FES vs. volitional trials. Figure 4 illustrates the data from a typical subject. In addition, the variability in cycling performance decreased when FES was applied. (Figure 5)

![Graph](image)

Figure 4: Power output for an individual with CP that was asked to cycle at 40 rpm volitionally (A) and with FES assistance to bilateral quadriceps (B). The auxiliary motor was used to volitionally with a motor assisting to dampen the variability in cadence. The vertical dashed line indicates the end of passive cycling and beginning of active cycling phase.

![Graph](image)

Figure 5: Coefficient of variation of cycling power output during incremental cycling tests with (solid line) and without FES assistance (dotted line) in a child with CP well adept at cycling (Subject 1).

5 Discussion and Conclusions

The pilot work described in this paper demonstrates the feasibility of applying FES-assisted cycling technology in children with intact sensation. In previous work, we observed that cycling movement is likely impaired by deficits in motor control. Electrical stimulation is the only modality available that can elicit muscle contractions at appropriate times during functional tasks to enhance performance.

FES assisted cycling with electrical stimulation applied to the quadriceps was tolerated well and resulted in increased cadence, torque and power and decreased variability in cycling performance. FES assistance also allowed subjects to work at sufficient levels to achieve increased heart rate and peak VO2. That data was not presented in this paper in the interest of brevity. The use of an auxiliary motor to control cadence allowed for valid constant load and incremental testing. Future work will focus on optimizing stimulation settings and further development of a closed-loop control system for the application of FES assisted cycling in individuals with CP.

6 Literature


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