A Pilot Study of Lower-limb FES Cycling in Paraplegia

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Abstract

The aim of this work was to develop the engineering methods and apparatus for FES cycling, and to achieve regular periods of mobile FES cycling over significant distances with paraplegic subjects. The study utilised a commercial recumbent tricycle, which was instrumented for stimulation control. Three subjects with a complete spinal cord lesion at level T7-T10 were recruited for the study. After four months of participation in the study the subjects were able to cycle outdoors for distances of up to 3km in a single session. The subjects are also able to cycle continuously and reliably on an indoor cycle trainer for periods of up to 1 h. We conclude that mobile FES cycling over useful distances outdoors is a realistic option for the paraplegic population, even with a low-intensity training regime. Future work will involve FES cycling exercise tests to document changes in cardio-pulmonary fitness in SCI subjects.

1. Introduction

FES cycling promises to offer a highly attractive exercise modality for people with spinal cord injury. Our approach is based upon instrumentation of commercially available recumbent tricycles. Our systems are mobile, thus opening the way for recreational use of FES cycling technology. We believe that FES cycling is likely to bring significant improvements in cardiopulmonary fitness, helping to reduce the risk of the secondary medical conditions which commonly accompany the disability [1]. A pilot study of mobile FES cycling has been carried out in parallel at two cooperating centres: Glasgow and London. The results of the London study have been reported elsewhere [2,3]; this paper reports the results of the work done in Glasgow.

2. Methods

Three subjects with a complete spinal cord lesion at level T7-T10 were recruited for the study. Details of the subjects are given in the table (TPI = Time Post-Injury).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Level</th>
<th>Age [years]</th>
<th>TPI [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>T10</td>
<td>57</td>
<td>3</td>
</tr>
<tr>
<td>S2</td>
<td>T7/8</td>
<td>38</td>
<td>7</td>
</tr>
<tr>
<td>S3</td>
<td>T8/9</td>
<td>28</td>
<td>3</td>
</tr>
</tbody>
</table>

The subjects initially carried out a programme of muscle strengthening using a portable electronic stimulator at home on a daily basis, for a period of 6-8 weeks. During this time subjects attended the Spinal Unit at the Southern General Hospital one day per week, for progress monitoring and preparation for FES cycling. When the cycling muscles (quadriceps, hamstrings and gluteal muscles) were judged to be sufficiently strong, subjects began a programme of “static” FES cycling with the tricycle mounted on a cycle trainer. At this stage subjects attended the Spinal Unit once per week for a cycling session, while continuing daily muscle training at home on all other days. When each subject became proficient in cycling on the trainer, they began sessions of mobile cycling outside. Again, cycling sessions took place once per week.

Fig 1: Shaft encoder and ankle orthosis arrangement.

The cycle used in this study is a standard recumbent tricycle, which has been adapted for FES cycling. The trike is equipped with a shaft encoder, which is driven by a short chain attached to the left crank (Fig. 1). This allows measurement of the crank angle; crank speed is...
obtained by differentiation of the angle. Customised ankle orthoses are fixed to the pedals. These stabilise the ankle and constrain the legs to movement in the sagittal plane.

The shaft encoder is interfaced to a stimulation control program, running either on a laptop computer (with Matlab/Simulink and the Realtime Toolbox), which controls a multi-channel stimulator, or within the multi-channel stimulator itself. During the experiments reported here the stimulator operated at constant frequency (20Hz), constant current, adjustable in 10mA increments up to a maximum of 120mA, and the pulsewidth was varied online in the range 0-800\,\mu s. Surface electrodes were attached to six muscle groups, i.e. the left and right quadriceps, hamstring and gluteal muscles. The crank angle measurement was used to switch each muscle group on and off during each cycle according to a pre-specified pattern (this is schematically illustrated in Fig. 2). To simplify the control structure a common pulsewidth variable was applied to all muscles; the effect of this is to reduce the structure to a single-input (pulsewidth) single-output (crank speed) system as shown in Fig. 3. The stimulation intensity (i.e. the pulsewidth) is continually adjusted by the cyclist using a throttle installed on the right-side hand grip.

**Fig 2:** Stimulation pattern for the right leg. The arcs show the crank angle ranges where each muscle group is stimulated. The pattern is shifted anti-clockwise as crank speed increases.

**Fig 3:** Open loop system.

During the muscle strengthening and static cycling phases we have developed and tested new feedback methods for robust control of knee-joint angle [4,5]. This is applied during quadriceps stimulation while the shanks are free to swing. The method is important because it provides safe and accurately-controlled knee extension, and can also be used to systematically monitor and assess progress in muscle conditioning.

We have also developed a new methodology for automatic control of FES cycling speed. Preliminary results have been published for intact subjects [6], and the method has also been applied to our paraplegic cyclists (unpublished). Automatic feedback control of cycling speed is important because FES cycling studies often require systematic and calibrated measurements to be made at a range of constant work rates.

3. Results

Subjects S1 and S3 improved progressively to the stage where they were able to cycle continuously and reliably on the trainer situated with the rehabilitation gymnasium for periods of 30-40 mins (Fig. 4), after approximately 3 months of participation in the programme. Currently, one year after starting the study, subjects S1 and S3 can cycle continuously for at least 1 hour on the trainer.

**Fig 4:** Indoor cycling on trainer set-up

Progress with Subject S2 was initially hindered by the appearance of spasms in the calf muscles (a clonus effect), which prevented him from cycling for more than a minute or two. However, persistence with the training regime and “tuning” of the mechanical arrangement of the apparatus has improved results. Subject S2 now carries out 15-20 minutes of standing in a standing frame prior to cycling, in order to stretch the calf muscles. This has been found to significantly retard the onset of clonus. Subject S2 is now able to cycle on the trainer for 30 minutes at a time.

Approximately 3-4 months after the subjects joined the programme we began mobile cycling sessions with all three subjects, on tarmac beside the sports track situated...
adjacent to the Spinal Unit (Fig. 5). Subjects S1 and S3 have completed up to 3km in a single session; and Subject S2 has done 1.4km (with partial assistance). Each outdoor “session” lasts approximately 30-40 mins and consists of 10-minute bouts of cycling, each followed by a 5-minute rest period. As noted above, Subject S2 became proficient in cycling later than S1 and S3. He is therefore significantly weaker and fatigues more rapidly. We believe however that he will continue to progress rapidly.

Fig 5: Outdoor cycling.

4. Summary and Conclusions

The aim of the first phase of the pilot project was to accomplish regular periods of FES cycling exercise in three volunteer paraplegic subjects. The pilot study to date has focused on the engineering development required to enable our subjects to cycle, and we have now achieved the original aim. In addition to achieving the goal of mobile FES cycling, an important scientific outcome of the work has been the development of novel methods of robust control of knee-joint angle (used during muscle strengthening and assessment), and for automatic control of FES cycling speed.

We are proceeding to a second phase of the pilot study. We have identified two main aims for Phase II: (i) to refine and systematically test our novel methods for automatic control of FES cycling; (ii) to carry out a preliminary series of physiological measurements on our subjects while cycling (using state-of-the-art monitoring and interpretation techniques) in order to establish a scientifically-validated methodology, tailored to the specific requirements of the SCI population during cycling exercise [7].

We conclude that mobile FES cycling over useful distances outdoors is a realistic option for the paraplegic population, even with a low-intensity training regime. In the longer term, we aim to carry out a systematic evaluation of the impact of a progressive and high-intensity FES cycling exercise programme on cardiopulmonary fitness, and susceptibility to pressure sore formation.

Acknowledgment

We would like to express our sincere thanks to the three cyclists who volunteered to take part in the study. We are grateful to the INSPIRE Foundation for the financial support which they awarded to the project.

References


