Stimulation of shank muscles during FES cycling to maximize ankle movement

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Abstract

This study investigated the stimulation of the shank muscles (tibialis anterior [TA] and triceps surae [TS]) on ankle joint range of motion (ROM) during functional electrical stimulation (FES) cycling in three persons with chronic spinal cord injury (SCI). The isokinetic cycle ergometer employed a free-moving ankle support whereby the pedal boot was free to rotate by up to 60°. The subjects were instrumented with retro-reflective markers and trials were recorded using a digital video camera. Ankle, knee, and hip movements were analyzed using 2D software biomechanical analyses. The optimal stimulation timings to induce ankle plantar- and dorsiflexion were investigated by systematically altering the stimulation angles of TA and TS. The ankle ROMs during passive cycling were 21.5 ± 7.6°. TA and TS stimulation resulted in ROM of up to 38.1 ± 10.9° and 28.1 ± 6.9°, respectively. In 2 of the subjects, standard FES cycling evoked via quadriceps, hamstrings, and glutei stimulation produced some increase in ankle ROM compared to passive cycling. These results suggested that appropriately timed neurostimulation of TA and TS may significantly increase the amount of ankle joint motion during FES cycling. This outcome might be of benefit for SCI individuals who seek increased ankle flexibility and shank muscle cosmesis by cycle FES-training.

1 Introduction

Functional electrical stimulation (FES)-evoked cycling elicits muscle contractions in paralyzed or weak muscles during exercise. FES cycling has been applied to persons with spinal cord injury (SCI) to counteract the secondary complications associated with paralysis and reduced physical activity (e.g., muscle atrophy, osteoporosis, pressure ulcers, reduced cardiorespiratory fitness, and poor circulation). The established benefits of FES cycling include increased muscle mass, augmented blood flow, and improved aerobic fitness in deconditioned individuals.

The movements and muscle activity produced during FES cycling may also be beneficial for joint health and flexibility. Contractures are common complication for persons with SCI with an associated loss of joint range of motion (ROM). Contractures are thought to result from disuse due to: i) increased stiffness of connective tissue within the joint capsule and muscles, and, ii) shortened muscle length from removal of sarcomeres and/or muscle fibres [1]. Intensive regular stretching of 30 min (3 times per week) for 12 weeks was found to have only a minimal effect on ankle mobility [2].

Most FES cycling systems utilize a fixed calf shell arrangement which provides leg stability and prevents ankle movement. However, since thigh guides establish leg stability in the anterior-posterior orientation, the calf shell joint can be safely adjusted to also allow ankle plantar- and dorsiflexion movements. The degree of ankle movement during recumbent cycling (FES or passive) for persons with SCI using a ‘free’ ankle setup have not been previously reported. During traditional FES cycling, stimulation is applied to the quadriceps, hamstrings, and glutei muscle groups. Stimulation of the shank muscles (triceps surae and tibialis anterior) with a free-moving ankle footplate might increase ankle ROM during FES cycling. Inclusion of stimulation to the shank muscles during FES cycling might increase the ankle flexibility of persons with paralysis by improving muscle condition and maximizing joint range of motion.

When using a free ankle footplate setup, the optimal angles to stimulate TA and TS to produce ankle movement during ES cycling have not been reported. Therefore the purpose of this research was to determine: 1) the crank angles at which the shank muscles should be stimulated to produce the greatest plantar- and dorsiflexion during FES cycling with a free-moving setup ankle, and, 2) the amount of ankle movement that occurs with a free-ankle setup during passive and traditional FES cycling.
2 Methods

Three persons with chronic SCI (2 ASIA-A / 1 ASIA-C, T5-T11) volunteered to participate in this pilot study. They had been previously FES cycle training (2-3x per wk) via quadriceps, hamstrings, and glutei muscle groups for a minimum of 12 weeks. For all trials, subjects were seated on an isokinetic FES cycle ergometer [3] and self-adhesive gel electrodes were placed over the leg muscles used.

Cycling cadence was fixed at 15 rev\cdot min\(^{-1}\) by the isokinetic ergometer regardless of muscle forces applied to pedals. Seating distance (axle to hip) was set to that preferred by the subject. Retro-reflective markers (toe, ankle, heel, knee, hip and shoulder joints) were placed on one side of the subject. A digital video camcorder (MV960, Canon) was used to record the movements during FES cycling.

2.1 Stimulation angle for TA and TS

To determine the effect of the stimulation of tibialis anterior (TA) and triceps surae (TS) on ankle movement, we stimulated the TA and TS muscles on one leg across a range of crank angles during isokinetic cycling at a cadence of 15 rev\cdot min\(^{-1}\).

During cycling, TA was repetitively activated for 20s (duty angle 90°) then rested for 20s (passive cycling). For the first period of stimulation the muscle contraction of TA was initiated at 0°, but after each rest period, stimulation window was delayed by 45°. Table 1 portrays the progression of the stimulation window interspersed with rest periods. After stimulation was applied across the complete range of crank angles, the procedure was then repeated using the TS muscles. Stimulation parameters were chosen to elicit strong contractions in the TA and TS muscles (Frequency 35 Hz, Pulse duration 300 \(\mu\)sec, Stimulation amplitude 70mA).

Table 1. Protocol to determine the best stimulation angles for tibialis anterior & triceps surae movements.

<table>
<thead>
<tr>
<th>Period</th>
<th>TA/TS Stimulation window (angle)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None (passive)</td>
<td>0-20</td>
</tr>
<tr>
<td>2</td>
<td>0-90</td>
<td>20-40</td>
</tr>
<tr>
<td>3</td>
<td>None (passive)</td>
<td>40-60</td>
</tr>
<tr>
<td>4</td>
<td>45-135</td>
<td>60-80</td>
</tr>
<tr>
<td>5</td>
<td>None (passive)</td>
<td>80-100</td>
</tr>
<tr>
<td>6 ... 14</td>
<td>90-180 ... 270-360</td>
<td>100-120 ... 260-280</td>
</tr>
<tr>
<td>15</td>
<td>None (passive)</td>
<td>280-300</td>
</tr>
<tr>
<td>16</td>
<td>345-45</td>
<td>300-320</td>
</tr>
<tr>
<td>17</td>
<td>None (passive)</td>
<td>320-340</td>
</tr>
</tbody>
</table>

2.2 Ankle joint movement during traditional FES cycling

On another day the subjects performed FES cycling (using quadriceps, hamstrings, & glutei muscles) and the ankle joint movement was compared to passive cycling. Video recordings (20s) were made similar to passive cycling. For subject comfort, the stimulation amplitude was ramped up to 140mA for the prime agonists over 15 minutes and 20s of cycling was then video-recorded. The stimulation angles used for the quadriceps, hamstrings, and glutei activation were 300-30°, 90-190°, and 0-80°, respectively.

2.3 Data analysis

The 20s (5 revolutions) of data recorded from each trial was digitized and ensemble-averaged with respect to crank angle. 2D biomechanical analyses were performed using KAVideo digitization software and KA2D analysis software. The ankle ROM was then determined for each stimulation window and compared to the ROM observed during passive cycling.

3 Results

During passive cycling, the ROM measured was between 13.1° and 27.8° (Mean ± SD: 21.5° ± 7.6°). Maximum ROM induced by the stimulation of TA and TS muscles were from 26.4° to 48.0° (38.1° ± 10.9°) and 21.1° to 34.9° (28.1° ± 6.9°), respectively. For the three subjects, ankle joint ROM was affected by the angle at which the muscle stimulation was applied to the TA (Fig 1). Initiating stimulation of the TA between 270° and 45° resulted in dorsiflexion and a greater than 25% increase in ankle ROM for all subjects. When stimulation was applied, joint movement was rapid with the ankle quickly moving and settling at a more dorsiflexed aspect. Stimulation of the TA muscles at some angles reduced ankle ROM by opposing the natural passive plantarflexion motion around the ankle.

![Stimulation Angle](image)

Fig. 1 Stimulation angle of TA muscle and induced range of motion for three subjects. Percent change is portrayed relative to passive cycling.

Similarly, the stimulation angle of TS affected ankle joint ROM (Fig 2). Initiating stimulation of the TS at 180° or 225° resulted in plantarflexion and a greater than 20% increase in ankle ROM for all subjects. When stimulation was applied, joint movement was...
rapid with the ankle quickly moving and settling at a more plantarflexed position. Stimulation of the TS muscles at some angles reduced ankle ROM by pulling the joint into a more plantarflexed aspect.

The traditional FES cycling trial (employing quadriceps, hamstrings, and glutei stimulation) evoked greater ankle ROM than passive cycling in 2 out of 3 subjects (Fig 3). When there was an enhanced ankle ROM this was due to an increase in plantarflexion that coincided with the initiation of hamstrings stimulation.

4 Discussion

There was noticeable movement of the ankle during passive cycling, and in some cases this was increased during traditional FES cycling. However, our data reveal that appropriately timed muscle stimulation to TA and TS can generate substantially increased ankle dorsiflexion and plantarflexion. Recently, McDonald et al. [1] have suggested that besides regular stretching, muscle condition is important to prevent joint contractures in the paralyzed limbs. Thus, the addition of stimulation to the Shank muscles, thereby inducing ankle movements during FES cycling may be useful for both conditioning the muscles and moving the ankle joints of persons with SCI.

Prior research on Shank muscle stimulation during FES cycling has been restricted to simulations [4] or during FES with a fixed ankle setup [5]. Van Soest and colleagues [4] predicted that the power output exerted on the crank may be reduced when using a released-ankle setup. Power output is important for FES-based autonomous tricycle riding. Stimulating the triceps surae muscles [6, 5] with a fixed ankle has been shown to increase cardiovascular stress but did not alter power output [5].

Future research is required to confirm the validity and clinical efficacy of our results. The goal may be to maximise lower leg muscle condition and flexibility, but we must consider the technical practicality of stimulating the Shank muscles in addition to those of the thigh and buttocks; this will require a higher cost (electrodes), a longer setup time, and currently most muscle stimulators only have 8 channels. The stimulation of the hamstring muscles does tend to elicit plantarflexion in some subjects (i.e. Subject 1 & 2); whether this is due to overflow stimulation of the TS or the pull of the hamstrings on the pedals is unclear. However, some subjects develop significant triceps surae muscle hypertrophy after traditional FES cycle training which may mean that it is not necessary to evoke triceps surae muscle contractions in those subjects.

5 References