Elliptical FES Stepping: Effect of Varying Stimulation Angles

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Abstract

A novel isokinetic functional electrical stimulation (FES) leg stepping trainer (iFES-LST) was trialled upon 5 individuals with spinal cord injury (4 ASIA A / 1 ASIA B, T5 – T11). A biomechanics evaluation was conducted to provide insights into the optimal stimulation angles at 15 rev•min⁻¹ during elliptical stepping. The stimulation angles of three primary agonists to evoke seated elliptical stepping (i.e. quadriceps, hamstrings and glutei) were based on a FES cycling paradigm, which might not be optimal for elliptical limb movements. During iFES-LST exercise, quadriceps muscles produced the greatest torque production with stimulation angles based on an able-bodied EMG-derived (AB EMG) strategy (p = 0.009), which was also highest when all muscles were stimulated (p < 0.001). Glutei stimulation only evoked greatest torque when an empirically-derived able-bodied FES paradigm (AB FES) was employed (p = 0.040), while hamstrings-only torque was not significantly different amongst stimulation angle sets. This study revealed that stimulation angles could be optimized to produce greatest torque during isokinetic FES elliptical stepping exercise.

1 Introduction

The optimal functional electrical stimulation (FES) ‘firing’ angles to elicit the greatest muscle forces during FES-cycling in spinal cord injured (SCI) population may be monitored through changes in torque production. Several studies have investigated varying these stimulation angles during FES leg cycling exercise [1-6]. However, when the leg movements are of a different pattern to cycling, such as during seated elliptical stepping, there is no empirical evidence to predict the “best” muscle stimulation patterns for optimal torque production. In this study, FES-evoked elliptical stepping was produced via a crank and slider mechanism in a commercial system (Biodex BioStep) (see Fig. 1).

A pilot study of muscle activation patterns in able-bodied subjects performing seated elliptical stepping had been previously concluded [7]. The results suggested a set of likely muscle activation timings for this exercise modality (AB EMG-derived). These, however, did not exclude possible effects of primary agonist co-contractions during the movement. An FES pilot study was undertaken with a well-habituated able-bodied individual to derive a set of stimulation patterns when voluntary muscle co-contractions were eliminated (AB FES-derived). The two sets of muscle activation patterns from the pilot studies were then evaluated against traditional stimulation angles employed during SCI FES-cycling.

To investigate the effect of varying muscle activation angles, the torque of the isokinetic driving motor was monitored as the primary outcome measure. This reflected the responses of the pushing and pulling forces at the pedal produced by each muscle group. This study investigated which combination of stimulation patterns might optimize power production during isokinetic FES-evoked elliptical stepping (iFES-LST).

2 Methods

2.1 Experimental Setup

Five paraplegic individuals participated in this study (4 ASIA-A / 1 ASIA-B, T5 – T11), who had been FES-cycling regularly (2-3 times/week, for at least 20 weeks). Written informed consent, approved by the Human Research Ethics Committee of The University of Sydney, was obtained before their participation.

Fig. 1 Subject seated on stepper with three muscles groups on each leg connected for FES. Reflective markers were positioned on the machine and the subject’s body.
A five-camera 3D motion analysis real time system was employed to capture leg and angular positions (100Hz) synchronized with motor torque (1000Hz). Retro-reflective markers were positioned on the subject’s shoulder, hip, knee, ankle and toe; on the trainer the markers were positioned on the rotating crank and the pedal (see Fig. 1). Subjects’ position on the trainer was mechanically constrained except the seat to pedal distance was adjustable based on subject’s anthropometric measures so their legs were near full extension with slight knee flexion to avoid hyperextension.

Three sets of stimulation patterns (i.e. muscle activation angles) were investigated based on, (i) FES-cycling paradigm, (ii) able-bodied (AB) EMG data during elliptical stepping, and, (iii) an AB FES muscle activation pattern developed by ‘trial and error’ torque optimization (n=1). As the elliptical stepping exercise system was isokinetic, the cadence was set by the investigators at 15 rev•min⁻¹. Low cadence was selected as it is the appropriate cadence to elicit highest torque with slowest fatigue [8].

### Table 1 Stimulation patterns of the current study

<table>
<thead>
<tr>
<th>Start / Stop Angle (º)</th>
<th>AB EMG [7]</th>
<th>AB FES (n=1)</th>
<th>SCI FES Cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps</td>
<td>300 / 90</td>
<td>250 / 80</td>
<td>330 / 90</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>130 / 250</td>
<td>90 / 210</td>
<td>90 / 190</td>
</tr>
<tr>
<td>Gluteus</td>
<td>0 / 80</td>
<td>250 / 60</td>
<td>30 / 110</td>
</tr>
</tbody>
</table>

NB: 0º was vertical position of the primary crank.

#### 2.1 Experimental Protocol

The experiment was a single-day trial for each subject. Prior to beginning, pairs of FES electrodes were affixed over subjects’ quadriceps, hamstrings and glutei muscles. Stimulation current was set to a constant 70mA, 400µs at 35Hz trains. Before commencing data collection, a single run of FES-evoked stepping was conducted at a low current intensity (40mA) for “warm-up” and habituation.

After a 3-min warm-up session, stepping cadences were set and a ‘passive trial’ (i.e. muscles produced no forces) was recorded for 30s. Twelve separate trials were recorded, whereby 3 trials were for all three muscles stimulated at each angle set, then each muscle group separately.

For data analysis, each trial comprising a muscle activation pattern was divided into multiple series of 360º revolutions. The torque values of each series were compared against the passive torque for each increment of angular resolution collected via motion analysis (see Fig. 2). The absolute value of each torque point deviation from the passive motor responses was ensemble-averaged to represent the average net torque production by the stimulated muscle groups.

The average net torque production elicited from stimulated muscles were analysed using one-way ANOVA (i.e. passive, all muscles, quadriceps, hamstrings, or glutei muscles) to determine whether active stimulated stepping torques were significantly higher than passive torque, i.e. the torque to move the leg’s mass without muscle contractions. Then, each muscle’s net torque production was contrasted to the others using 1-way ANOVA by stimulation patterns to identify any significant differences between muscle activation angles. Because the between-subjects variability was greater than within subjects-variability, a covariate of each subject’s muscle mean torque were introduced into analysis of covariance (ANCOVA) to statistically compare effects of stimulation angle sets amongst all subjects.

#### 3 Results

One-way ANOVA, through post-hoc analysis, confirmed that for every subject, net torque produced by any stimulated muscles produced significantly higher torque than passive stepping (p<0.05). The average net torque produced by all subjects (see Fig. 3) comprised net evoked torque output elicited by FES-evoked leg muscle contractions. Torque elicited by the different groups of muscles were: (i) all muscles, 0.737 (± 0.29) Nm, (ii) quadriceps, 0.744 (± 0.33) Nm, (iii) hamstrings, 0.44 (± 0.15) Nm, and, (iv) glutei, 0.49 (± 0.12) Nm. Average torque variation between subjects however was greater than within subjects variability amongst angle sets.

Univariate ANCOVA revealed that in general, the AB EMG-based angle set contributed towards greatest torque elicited (p = 0.006). When each muscle cases were analysed separately, all muscles stimulated together suggested highest torque production with the angle set derived from AB EMG stimulation (p<0.001). Individual muscle stimulation during stepping produced highest torque production of quadriceps with AB EMG stimulation (p = 0.009), hamstrings stimulation was not significantly different amongst angle sets (p = 0.764).
Average elicited torque suggested that greater power could be produced when the start and stop angles of stimulation were adapted to the exercise movement, whereby leg extension and flexion were extended throughout a longer linear motion. These adaptations included start and stop position of each stimulation angle and the length of each stimulation. However, the differences are more likely to be related to the angular position manipulation rather than to the length of stimulation.

Additionally, our results suggested that most of the torque, thus power production, of the evoked stepping was contributed by the quadriceps muscles. Post hoc analysis revealed that torque production of all muscles were not different from quadriceps muscles (\( p = 0.796 \)), while hamstrings and glutei muscles elicited significantly lower torque. Results are representative of all subjects, irrespective of subjects’ anthropometrical measures.

This suggested that stimulation quadriceps muscles are crucial in power production during FES elliptical stepping. While other muscles may not elicit large forces, it may contribute towards increasing overall net torque thus power. In addition, more muscles should also be stimulated to condition the muscles for the benefit of the SCI population. Future questions regarding muscle fatigue should be addressed by testing the angle sets performance over 30 minutes.

5 Conclusion

Manipulating the stimulation angles resulted in changes in muscle torque production. To maximize torque thus power production a stimulation paradigm combining quadriceps angles from AB EMG with glutei stimulation angles from AB FES could be employed.

6 References


