

Maximizing muscle forces during FES-LCE via low pedalling cadence

Ché Fornusek, Glen M Davis.

Rehabilitation Research Centre, Faculty of Health Sciences, University of Sydney, Sydney, Australia.

Introduction

Functional electrical stimulation leg cycle ergometry (FES-LCE) training has been shown to induce physiological benefits in the paralyzed limbs of spinal cord injury (SCI) patients. These benefits include increased muscle mass and tone, increased blood flow, improved wound healing, reduced occurrence of pressure sores and decreased risk of deep vein thrombosis in the affected limbs.

In the past, research to improve FES-LCE training focused on improving stimulation patterns, training protocols, control algorithms, and biomechanical modeling. Pedalling cadence is one parameter that has received very little attention until recently. Recent research from our laboratory has shown that the fatigue rate of electrically stimulated muscle decreases as pedalling cadence decreases. This recent research only tested fatigue rate over a 5-min period. If lower cadence cycling produces decreased fatigue compared to traditional cycling cadences (35-50 rev·min⁻¹) for the duration of a typical FES-LCE session, higher muscle forces will be generated at the lower cadences throughout the training session. The higher forces at lower cadences could lead to an improvement in FES-LCE training.

The aim of this research was to determine whether the fatigue rates seen at different pedalling cadences have an effect upon the torque and exercise power produced over a typical FES-LCE session. To achieve this goal, power and torque measurements were recorded during FES-LCE sessions at two different pedalling cadences and compared.

Method/Design

The subjects (n=9) had complete thoracic spinal cord injuries (ASIA A). All of the subjects were experienced with FES-LCE and had been training regularly prior to testing. A specially designed isokinetic FES leg cycle ergometer (iFES-LCE) was used for these experiments [1]. The iFES-LCE ergometer relies upon a motor control system instead of muscle stimulation contractions, as is the usually the case, to control pedalling cadence. The iFES-LCE can perform cycling between cadences of 5-60 rev·min⁻¹.

This experiment involved two 35-min FES-LCE training sessions, one at 15 and the other at 50 rev·min⁻¹. Session order was randomized and each was performed on a different day. Gel-backed self-adhesive surface electrodes were used to deliver the stimulation to the quadriceps, hamstrings, and gluteal muscles.

Subjects began by performing FES-LCE at the selected cadence with 50% (70mA) stimulation applied. The stimulation was then linearly increased to reach 100% (140mA) at exactly 5 min. The stimulation applied at each cadence was identical except for the period (duration of the contraction-relaxation cycle) of the stimulation protocol, which is inversely proportional to the pedalling cadence.

Every 5 minutes during the training session, current and velocity samples were recorded from the ergometer. These measurements allowed the calculation of the torques and powers the subjects were exerting on the motor through the pedal cranks. Measurements were made during bilateral cycling (quadriceps, hamstrings, and gluteals stimulated on both legs), left quadriceps cycling (alone), and passive cycling (no stimulation).

Brief pauses in stimulation while cycling continued allowed measurement of the gross left quadriceps data and the passive cycling data. Overall, due to pauses in stimulation the breakdown of a session was 92% bilateral cycling, 4% left quadriceps cycling, and 4% passive cycling.

Each data sample was ensemble averaged to generate torque versus crank angle and velocity versus crank angle curves. Net torque versus crank angle curves were calculated by subtracting the passive torque curves from the respective active curves. Power versus crank angle curves were calculated by multiplication of the net torque curve with the corresponding velocity curve. Peak torque (left quadriceps only), average torque, and power measurements were calculated from these curves. Descriptive statistics, repeated measures ANOVA and Pair T-tests were then used to analyze the data. Statistics were taken to be significant if $p < 0.05$.

Results

Torque

Throughout the exercise session the peak crank torques generated by left quadriceps muscles at $15 \text{ rev}\cdot\text{min}^{-1}$ were significantly greater than those generated at $50 \text{ rev}\cdot\text{min}^{-1}$ (Figure 1). At each time point, the left quadriceps average torque was significantly greater at $15 \text{ rev}\cdot\text{min}^{-1}$ than at $50 \text{ rev}\cdot\text{min}^{-1}$. Bilateral cycling followed the same pattern with significantly more average torque produced at $15 \text{ rev}\cdot\text{min}^{-1}$ than at $50 \text{ rev}\cdot\text{min}^{-1}$ (Figure 2). When averaged over the whole session, significantly more torque was produced at $15 \text{ rev}\cdot\text{min}^{-1}$ ($3.8 \pm 0.3 \text{ Nm}$) than at $50 \text{ rev}\cdot\text{min}^{-1}$ ($1.5 \pm 0.3 \text{ Nm}$).

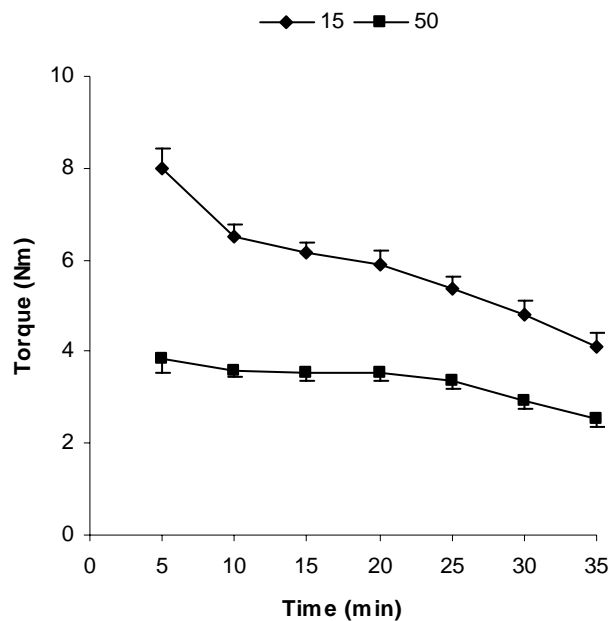


Figure 1. Peak crank torque generated by L. quadriceps during FES-LCE sessions at cadences of 15 (diamond), and $50 \text{ rev}\cdot\text{min}^{-1}$ (square). Stimulation amplitude reached 100% at 5 min. Peak torque was significantly higher ($p < 0.05$) at 15 than at $50 \text{ rev}\cdot\text{min}^{-1}$ throughout the session.

Power

The power produced with bilateral cycling during the training sessions at 50 rev·min⁻¹ (7.9W) was greater on average than at 15 rev·min⁻¹ (6.3W) but this difference was not significant. However, after the fifteenth minute power became significantly greater at 50 rev·min⁻¹ compared to 15 rev·min⁻¹.

Discussion

Pedalling cadence had a significant effect on the crank torques generated in FES-LCE with the lower cadence cycling producing significantly greater peak and average torques over the whole 35-min session. After 5 min it appears that the majority of fatigue had already occurred at 50 rev·min⁻¹ and little fatigue occurred during the rest of the training session. In contrast, at 15 rev·min⁻¹, fatigue was more gradual and continued throughout the training session. The stimulation delivered at the two different cadences was identical except for the stimulation-relaxation period of the stimulation protocol.

Past research has shown that when comparing stimulation protocols with similar duty cycles but different periods, the protocols with longer periods fatigue slower[2]. Research in our laboratory showed that this fatigue rate observation also applies to FES-LCE, where the stimulation period is inversely proportional to pedalling cadence. Our previous research also showed that the effect of the force-velocity relationship was of secondary importance compared to the difference in fatigue rates. Leg velocity also differed between cadences, which may also have increased fatigue at the higher cadences.

Therefore, the increased torque levels seen at 15 rev·min⁻¹ are most likely the result of decreased fatigue rates at lower FES-LCE cadences. Since stimulation timing was identical between cadences, the greater torque levels seen imply that greater muscle forces were maintained at 15 rev·min⁻¹.

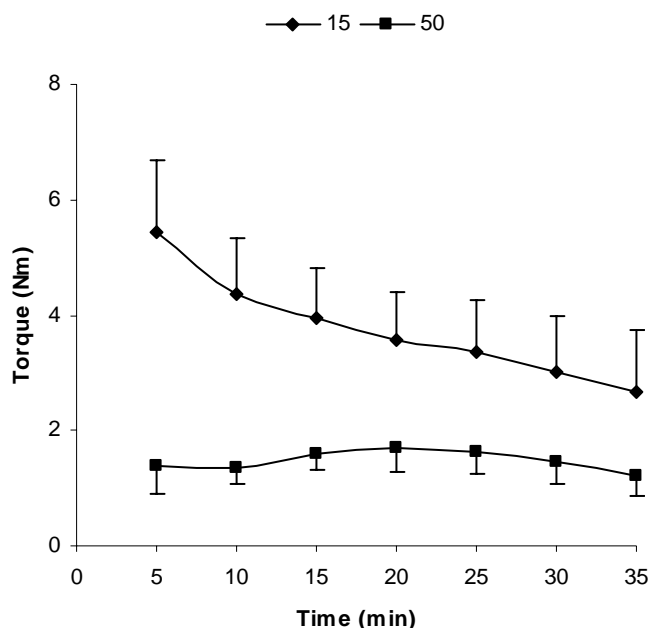


Figure 2. Average crank torque sampled at 5 min intervals during FES-LCE training sessions at cadences of 15 (diamond), and 50 rev·min⁻¹ (square). Stimulation amplitude reached 100% at 5 min. Average crank torque was found to be significantly higher ($p < 0.05$) at 15 rev·min⁻¹ than at 50 rev·min⁻¹ at all times during the training sessions.

Maintenance of higher muscle forces during FES training is expected to lead to improved strength training. Voluntary strength training advocates the use of high muscle forces to increase muscle strength and induce muscle hypertrophy. However, there is little experimental evidence that explicitly shows that higher electrically stimulated muscle forces result in greater strength gains or hypertrophy. Electrically stimulated muscle strength has been shown to increase more with high resistance training than low resistance training [3]. Research with able-bodied subjects or incomplete SCI subjects has shown that resulting voluntary isometric strength gains from FES training were related to the electrically evoked torque or force generated during the training sessions. A recent FES knee extension training study using stimulation protocols similar to those used during very low cadence FES cycling (i.e. 5 rev·min⁻¹) resulted in very effective training of knee extension strength and endurance in SCI[4]. To confirm the hypothesis that training at low cadences leads to improved electrically elicited strength gains compared to high cadence training it will be necessary to perform a long-term training study using multiple cadences.

Increased load on the lower limbs through low cadence training may provide other benefits, for example increased bone density. Evidence has shown that FES-LCE exercise can maintain bone density or reduce the loss rate but most studies show that FES does not increase bone density. Bone density increases were seen in a sub-population of subjects who were able to cycle at high resistance [5]. If it is necessary to produce higher forces for a prolonged period to increase bone density, low cadence FES-LCE cycling could allow a larger proportion of SCI to generate forces high enough to improve bone density.

On average subjects developed greater power outputs over the whole session at the high cadence. Although this average power was not significant, there was a significant difference in power generated over the last half of the training session where the slow but consistent fatigue of torque (Figure 2) at 15 rev·min⁻¹ reduced the power that was produced. It is not likely that all of the beneficial outcomes of FES-LCE are maximized under low cadence training. Perhaps training at a higher cadence, and with the resulting higher power outputs, would be best suited for cardio-respiratory fitness or increased muscle power. Further research measuring physiological and cardio-respiratory data is necessary to identify the potential advantages of training at the different cadences.

One of the limitations of this study was the necessity to include brief pauses in stimulation to measure the passive cycling and left quadriceps cycling data. However, these pauses did not appear to affect the results, with the brief rest periods resulting in no lasting recovery of power or torque during the testing sessions.

In conclusion, FES pedalling cadence significantly affects muscle force and power generated during FES-LCE training. The appropriate selection of pedalling cadence may lead to improvements in the benefits gained from FES-LCE. Long-term training studies are required to test the relative benefits that low cadence training offers over traditional FES-LCE cadences (35-50 rev·min⁻¹).

References

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