Functional electrical stimulation elliptical stepping versus cycling in spinal cord-injured individuals

Nur Azah Hamzaid a,b,c,*, Karla R. Pithon d, Richard M. Smith b,1, Glen M. Davis a,b,2

a Clinical Exercise and Rehabilitation Unit, Faculty of Health Sciences, The University of Sydney, Australia
b Exercise, Health and Performance Faculty Research Group, Faculty of Health Sciences, The University of Sydney, Australia
c Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Malaysia
d Orthopaedics Department, Faculty of Medical Sciences, State University of Campinas, Brazil

ARTICLE INFO

Article history:
Received 15 July 2011
Accepted 15 March 2012

Keywords:
Isokinetic
Exercise
Functional electrical stimulation
Spinal cord injury

ABSTRACT

Background: The cardiorespiratory responses and mechanical efficiencies of two modalities of functional electrical stimulation augmented leg exercises – isokinetic cycling and isokinetic elliptical stepping – were compared amongst individuals with spinal cord injury.

Methods: Five subjects performed seated isokinetic evoked cycling and elliptical stepping leg exercise at 10, 20 and 30 rev·min−1 pedal cadences. 3-D motion analysis and force transducers attached onto the foot pedals quantified the external forces and power outputs developed by each lower extremity. Hip, knee and ankle joints power were derived via inverse dynamics analysis. The subjects’ cardiorespiratory responses during exercise were measured by respiratory gas analysis.

Findings: Ensemble-averaged oxygen uptakes across pedal cadences were higher during stepping (448 (75) ml·min−1) compared to cycling (422 (54) ml·min−1). External power outputs and metabolic efficiencies during stepping (9.9 (8.3) W, 2.9 (3.2) %) were double those observed during cycling (5.3 (6.3) W, 1.6 (1.9) %). Cumulative internal and external leg joint powers during stepping were twice higher than cycling, but the stepping mechanical efficiencies derived from inverse dynamics analysis were comparable to cycling (76.3 (21.2) % and 63.6 (12.3) % respectively). Heart rate responses were similar between cycling and stepping, while carbon dioxide production and expired ventilation were slightly higher during elliptical stepping.

Interpretation: Both exercise modalities could deliver appropriate training stimuli for improving the aerobic fitness and leg pedalling strength of spinal cord-injured individuals. However electrical stimulation-enhanced elliptical stepping might provide greater exercise dose-potency for leg muscle strengthening than electrically-enhanced cycling due to the higher power outputs observed.

* Corresponding author at: Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail addresses: azah.hamzaid@um.edu.my (N.A. Hamzaid), kpithton@fcm.unicamp.br (K.R. Pithon), richard.smith@sydney.edu.au (R.M. Smith), glen.davis@sydney.edu.au (G.M. Davis).

1 Faculty of Health Sciences, The University of Sydney, Lidcombe 2141, NSW, Australia. Tel.: +61 2 9351 9462; fax: +61 2 9351 9204.
2 Faculty of Health Sciences, The University of Sydney, Lidcombe 2141, NSW, Australia. Tel.: +61 2 9351 9466; fax: +61 2 9351 9204.

0288-0033/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2012.03.005

1 Isokinetic exercise: exercise performed with a specialised apparatus that provides variable resistance to a movement, so that no matter how much effort is exerted, the movement takes place at a constant speed. Such exercise is used to test and improve muscular strength and endurance, especially after injury. In: EDITORS (ed.) The American Heritage® Dictionary of the English Language. Fifth Edition copyright ©2000, updated in 2011. ed.: Houghton Mifflin Harcourt Publishing Company.
This trainer facilitates elliptical stepping by users who perform the movement in a seated position with their legs positioned forward from the body. Elliptical stepping is mechanically aided by the combination of a slider and crank mechanism, in which the resulting movement pattern at the foot pedal forms an elliptical shape comprised of a horizontal linear component and a circular component (Fig. 1).

The efficacy of iFES-LST was tested with SCI individuals and the system was shown to perform safely and effectively (Hamzaid et al., 2009). Following the initial development and efficacy trial of the iFES-LST, the current study investigated their physiological and biomechanical responses during elliptical stepping exercise. Specifically, we sought to explore the potential of the novel pedaling pattern of the iFES-LST system to provide equivalent or better exercise ‘dose potency’ for training leg strength (Fornusek et al., 2004) compared to existing isokinetic FES leg cycling ergometers (iFES-LCE).

The purpose of this investigation was to compare the biomechanical and physiological responses during iFES-LST exercise (elliptical stepping) versus iFES-LCE exercise (cycling). The exercise responses of interest included biomechanical data such as the subjects’ external and internal power productions, as well as their physiological responses, including heart rates and oxygen consumptions during each exercise mode.

2. Methods

2.1. Subjects

Five individuals with spinal cord lesions between the 4th and 10th thoracic vertebra, American Spinal Injury Association classification (ASIA, 1992) A or B participated in this study (Table 1). Prior to their participation, planar radiographs of the lower limbs were recorded to exclude any subject with pre-existing bone injuries or advanced osteoporosis. The study was approved by the Human Research Ethics Committee of the University of Sydney and all individuals underwent written informed consent. Before commencing the current protocol, all subjects had trained with the iFES-LCE or iFES-LST for at least 2 months, and they had performed stepping and cycling at 15 rev·min⁻¹ at least twice, to provide familiarisation with each exercise mode.

2.2. Exercise devices

The iFES-LST is a new FES elliptical stepping trainer recently developed in our laboratory based on the Biodex BioStep (Biodex Medical System Inc., NY, USA). The efficacy and safety of iFES-LST system had previously been tested with SCI users (Hamzaid et al., 2009) and

Fig. 1. (a) Stimulation pattern for LST (top ellipse) and LCE (bottom circle). (b) Isokinetic cycling (left) and isokinetic elliptical stepping (right).
it had been used thereafter in the gymnasium amongst SCI users for their weekly training sessions.

The iFES-LCE was a FES cycle ergometer developed in our laboratory based on the Motomed Viva system (Motomed Viva 1, Reck Medizintechnik GmbH, Betzenweiler, Germany) (Fornusek et al., 2004). Both the iFES-LST and iFES-LCE were safety-tested by a licensed Biomedical Engineer employed by the Faculty of Health Sciences at the University of Sydney and were approved for research studies.

Both systems were motorised which allowed constant-velocity passive elliptical stepping and cycling respectively. However, one significant postural and biomechanical difference between the two systems, was that the iFES-LST had 11 cm greater leg elevation of the ankle joint with respect to the hip. Whether this higher leg elevation would introduce any metabolic or biomechanical advantages or disadvantages was unknown at the study outset.

2.3. Experimental design and study protocol

Subjects were prepared for FES electrode placement before commencing biomechanical investigation of iFES-LCE versus iFES-LST. Oval 2.75 × 5 inches gel-backed self-adhesive surface electrode pairs were placed over the quadriceps, hamstrings and rectus pairs of 1.9 × 3.5 inches gelled electrodes on the gluteal muscles.

In the motion analysis lab, subjects sat on either the iFES-LST system with their feet strapped to plantar-dorsi flexible ankle orthoses for lower-limb stability. As the seat height was not modifiable, the seat-to-pedal distance was adjusted to be the same between both exercise devices by altering the anterior-posterior seat position to near-maximum hip and knee extension.

Before beginning an exercise session, the subject’s resting heart rate (HR) and oxygen uptake (VO2) were recorded at rest during 5 min using a breath-by-breath computerised metabolic gas analysis system (CPX Dia, Medical Graphics Corporation, St. Paul, Minnesota, USA).

The external motor driving the iFES-LCE or iFES-LST was then engaged to passively move the legs at the intended cadence. During these passive movements, 5 min of baseline measurement was recorded including HR, VO2, carbon dioxide production (VCO2) and expired ventilation (Ve), as well as their passive power output production. The passive movement was performed to control for segment inertial and gravitational effects and friction at the joints and ankle orthoses (Fornusek et al., 2004; Hunt et al., 2004), as well as permitting range-of-motion during a “warm-up” period.

Following the brief warm-up, the leg muscles were stimulated to elicit extra forces through the pedals. These forces were monitored through a set of 3 piezoelectric force transducers attached to and arranged along each foot pedal to measure directly the applied 3D normal and shear foot forces (Kistler, Type 9602).

Electrical stimulation was applied to the subject’s quadriceps, hamstrings and gluteal muscles via pairs of pre-gelled electrodes, deploying a pattern of neuromuscular stimulation and angular leg movements (for iFES-LST; quadriceps: 330° to 90°, hamstrings: 90° to 110°; with 0° as the top dead centre) (Fig. 1(a)). The electrical stimulation intensity was increased from 40 mA up to~75% of each subject’s pre-determined maximum within 2 to 3 min, and was then kept constant at~75% maximum stimulation for the remaining exercise time. Stimulation current was monophasic 400 μs at 35 Hz. The maximum current intensity (between 110 mA and 140 mA) that evoked peak muscle forces was pre-determined from the usual levels for each subject during the preceding 2 months of FES training.

Movement produced solely by electric motor was defined as ‘passive motion’ and the lower limb action produced by the FES-evoked muscle contractions on top of motor assistance was referred to as “active pedaling”. The difference between the two movement profiles was regarded to be due to FES-evoked contraction. The maximum FES current applied for each subject was determined from their previous training activities. Subjects then performed iFES-LCE or iFES-LST exercise while their power production, bilateral lower extremity kinematic movements and cardiorespiratory responses were monitored throughout three bouts of short (15 min) steady-state exercise.

Each individual’s external power output, HR, VO2, VCO2 and Ve were recorded during a pedal cadence on both the iFES-LCE and iFES-LST systems. Gross and net metabolic efficiencies were calculated from power output and VO2 (Garby and Astrup, 1987).

Cardiorespiratory data and metabolic efficiencies were averaged during rest, passive-cycling, and during iFES-LCE or iFES-LST exercise in minutes 0–2, 2–4, and 4–6, as well as into post-exercise recovery, for each pedal cadence. Subjects were allowed 15 min of recovery before commencing the next bout of leg exercise at a higher pedal cadence. Heart rate during FES was not collected due to interference-effects of the neuromuscular stimulation, so immediate post-exercise values were taken as representative of the heart rate during exercise.

The procedure was repeated for three trials of constant pedaling speeds: 10, 20 and 30 rev·min⁻¹. The whole session was repeated for the same subject on another day, at least 2 days after the first session, with the iFES-LCE system.

3. Study limitations

Exercise trials were conducted over 2 different days, with iFES-LST presented on day 1 and iFES-LCE on day 2. Since a direct comparison of the two systems needed to ensure bioequivalence of the stimulation ramp and maximum stimulation currents deployed, the presentation orders of the two exercise devices could not be randomised.

The presentation order of iFES-LST (day 1) followed by iFES-LCE (day 2) also ensured that any experimental procedures made to accommodate the subjects’ responses during iFES-LST exercise were exactly copied onto the traditional iFES-LCE device. As fatigue is accelerated at higher pedalling cadence (Fornusek et al., 2004), each exercise was performed at three cadences of incremental rate to eliminate any possible fatigue effects on the physiological measurements. Each exercise session lasted about 75-min on each day.

3.1. Biomechanics and inverse dynamics analysis

Kinetics and kinematics data were extracted, and each subject’s leg joint moments, angular velocities and power outputs were derived via inverse dynamics analysis (Fig. 2). The applied external forces on each pedal, pedal velocity and external powers (torque by angular velocity at motor; and force by velocity at pedal) during passive and FES-enhanced training were derived to also calculate the mechanical and metabolic efficiencies.

The 10-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, California) recorded each joint marker bilaterally (malephalangeal toe, ankle, knee, hip, and pelvis). A 3D 10 camera
system was used instead of 2D analysis because the movement requires capturing of both legs, and even though they are all in sagittal plane, the exercise machine setup (moving handles bars, paraplegic subjects body trunk and arm movement which was inevitably moving for subjects’ comfort and body stabilizing) did not allow full view of all markers during movement without disturbances.

Each joint data point in space was connected to form four segments; foot, shank, thigh, and pelvis. The relative angles between each segment were derived at the ankle, knee and hip joints. The angular velocities of the ankle, knee and hip joints were then derived through the time series. Pedal positions were used to derive translational velocity of the foot to calculate external power output.

Inverse dynamics analysis were performed using Matlab 7.1 software by solving for each joint’s moment, velocity and power (Payton and Barlett, 2008; Robertson et al., 2004). Anthropometric data of each subject; i.e. their height and weight, were fed to the program to calculate their lower limbs centre of mass, weight, moment of inertia and density of each segment (Winter, 1979).

The joint moments were solved starting from the known external force at the pedals and foot segment through the shank to the thigh segment. The relative angular velocities of each joint were multiplied by their moments to get each joint internal power. The absolute force at the pedals and foot segment through the shank to the thigh segment. The relative angles between each joint were multiplied with its corresponding joint velocity.

Joint Power (W) = Joint Moment (N.m) × Joint Angle Velocity (rad·s⁻¹)

External power and internal joint power were corrected by the passive power, i.e. the power required to overcome any resistance to isokinetic movement and to passively move the legs.

3.3. Statistical analyses

Statistical analyses were performed on all the stepping versus cycling outcome measures, irrespective of the stepping or cycling cadence. Paired t-tests were performed on physiological measures during rest, passive and active movements and into recovery. The mechanical and joint power variables were statistically analysed only during FES-enhanced stepping or cycling. Statistical significance was set to the 95% confidence limit (P≤ 0.05).

4. Results

The findings have been presented in two parts; the first part portrays the cardiorespiratory responses of HR, VO₂, VCO₂, and V̇E (Table 2) during iFES-LST or iFES-LCE, and second part reports the biomechanical performance, focusing on the participants’ external and joint kinematics, joint moments, angular velocities, powers and metabolic and mechanical efficiencies (Table 4). The respiratory exchange rate (RER = VCO₂/VO₂) were reported to represent the ratio of glucose to fat oxidation, with RER > 1.0 usually suggesting anaerobic metabolism (Table 3).

4.1. Cardiorespiratory responses

The HR, VO₂, VCO₂ and V̇E increased significantly (P<0.05) from passive to FES-augmented cycling or elliptical stepping. During the onset of either exercise mode, the subjects’ heart rate displayed an expected exercise-induced tachycardia, but the differences between iFES-LCE and iFES-LST were not significant.

The subjects’ metabolic responses were similar during rest and passive cycling and stepping, but when FES was switched on, the VO₂, VCO₂ and V̇E became greater during elliptical stepping compared to cycling during the first 4-min of FES-augmented exercise. However
4.2. Biomechanical performance

The hip and knee angles during both exercise modes were comparable. The mean joint moments indicated that the hip, knee and ankle joints had greater variation of moments throughout stepping cycle compared to the joint moments when cycling (Fig. 3). The ankles however were more neutrally positioned during stepping (between −15 and +18°) compared to cycling; in which the ankle tended to be more planar-flexed throughout cycling (between +31 and +60°).

Joint moments were also directly affected when each muscle group were stimulated. Fig. 3 illustrates that the FES active moments were greater compared to passive moments during the stepping exercise. These greater rotational moments of the joints indicated that the activity could only have originated from the FES-augmented stepping of the foot onto the pedals.

As the muscles crossing the ankle joint were not stimulated, both ankles were affected only by the forces applied to the feet. Therefore, the ankle joint moment profile during passive and FES followed a very similar pattern to that of the knee joint moment profile, both during stepping and cycling.

Active power profiles over multiple cycling or stepping revolutions were less consistent. However the overall effects were greater during stepping compared to cycling. Table 4 portrays the overall power production during the FES-augmented exercise, during which the biomechanical performance was maximal during the first 2 min only, but decreased thereafter due to neuromuscular fatigue.

Ankle powers were more dynamic during stepping compared to cycling, due to the constant change in moment through applied forces and greater range of ankle movement, which resulted in greater angular velocity than cycling at the same cadence. For cycling, a clear and greater range of ankle movement, which resulted in greater ankle moment was greater compared to the passive profile all throughout the cycle.

5. Discussion

It has been previously established that metabolic and biomechanical efficiencies can be independent of each other (Korff et al., 2007). In the current study, we established that the metabolic efficiencies of iFES-LST and iFES-LCE amongst SCI individuals were very low compared to those usually observed in able-bodied individuals performing leg exercise (Weinstein et al., 2004). However, the metabolic efficiencies were close to those of able-bodied people performing wheelchair propulsion (de Groot et al., 2008) and the subjects’ VO2 were comparable to their other SCI counterparts performing FES exercises (Hettinga and Andrews, 2008). This is probably due to the nature of neuromuscular recruitment when leg muscles are activated via electrical stimulation, and not the central nervous system.

Such neuromuscular activation has been described as “predominant fast-twitch fibre recruitment” (Crameri et al., 2000, 2002) in an “all or nothing” pattern, resulting in very low aerobic metabolism relative to power output production. This characterisation is often the explanation for low metabolic efficiencies observed during FES-enhanced leg exercise, although “predominant fast-twitch fibre recruitment” has never been directly observed in humans with SCI. Additionally, the relationship between FES stimulation current and the quality of muscle contractions in SCI individuals during such exercise has been limited to either; (i) the use of EMG (Estigoni et al., 2011; Graupe, 1989; Winslow et al., 2003) as direct feedback or, (ii) utilizing electronic motor or pedal sensor data as an indirect method of muscle performance (Fornusek et al., 2004). Otherwise, physiological measures would be an optional representative of muscle activity (Hunt et al., 2006; Jacobs et al., 1997).

To date, direct, practical and accurate quantification of muscle contraction is still lacking in the SCI population, making calculation of FES-exercise efficiencies somewhat imprecise and further confounded by fatigue issues that affect this exercise modality.

The inverse dynamics analysis used in the study clearly identified the significant contribution of the knee extensors and flexors to the difference in power output between the two types of exercise, as the knees were the main power production point during a seated cyclical movement (Broker and Gregor, 1994). In contrast, power production around the hip joint was not markedly different between iFES-LCE and iFES-LST, probably because the Hamstrings are also hip extensors shared with gluteii, and the stimulation electrodes used to produce gluteal muscle contractions were the smallest relative to muscle mass.

Passive cycling or stepping movements do not alter the peripheral circulation of subjects with SCI (Ter Woerds et al., 2006) due to their

---

**Table 2**

<table>
<thead>
<tr>
<th>Time series</th>
<th>HR (beats·min−1)</th>
<th>VO₂ (mL·min−1)</th>
<th>VCO₂ (mL·min−1)</th>
<th>VE (L·min−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iFES-LST</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>6.8 (1.7)</td>
<td>219 (43)</td>
<td>198 (50)</td>
<td>8.3 (1.6)</td>
</tr>
<tr>
<td>Passive (1-2)</td>
<td>6.7 (1.4)</td>
<td>227 (70)</td>
<td>200 (62)</td>
<td>8.3 (1.7)</td>
</tr>
<tr>
<td>Passive (4-5)</td>
<td>6.0 (1.1)</td>
<td>235 (71)</td>
<td>204 (62)</td>
<td>8.4 (2.0)</td>
</tr>
<tr>
<td>FES-evoked (0-2)</td>
<td>5.6 (0.5)</td>
<td>465 (74)</td>
<td>503 (118)</td>
<td>16.1 (3.4)</td>
</tr>
<tr>
<td>FES-evoked (2-4)</td>
<td>5.6 (0.5)</td>
<td>447 (78)</td>
<td>542 (129)</td>
<td>17.2 (4.0)</td>
</tr>
<tr>
<td>FES-evoked (4-6)</td>
<td>5.6 (0.5)</td>
<td>432 (73)</td>
<td>507 (122)</td>
<td>16.5 (3.9)</td>
</tr>
<tr>
<td>Recovery</td>
<td>7.9 (5.0)</td>
<td>370 (80)</td>
<td>434 (130)</td>
<td>14.2 (3.8)</td>
</tr>
</tbody>
</table>

* denotes significant difference between FES stepping and cycling, p < 0.05.
atrophied lower limbs and reduced circulatory network (Hopman et al., 1996). With FES-augmented cycling versus stepping, the slight elevation of the legs during the latter modality might have increased venous return to a greater extent (Makin, 1969). This might have had a profound impact on the metabolic responses reported herein, and clinically might be vital for the improvement of blood flow during FES exercise amongst SCI. Still, the metabolic load during both exercise modalities in our subjects was very low, suggesting that morphological and histochemical limitations within the muscles predominate over circulatory differences of posture imposed by iFES-LST or iFES-LCE. Metabolic responses (VO₂) were proportional to the subjects’ external and internal mechanical power outputs. As observed in this study, greater power output during FES-augmented elliptical stepping was always coupled with higher whole-body metabolism compared to FES cycling. In general, the higher metabolic responses and power outputs were related to the underlying mechanical advantage of elliptical stepping.

![Fig. 3. Mean joint moments of all subjects throughout full revolutions during (right) stepping with iFES-LST and (left) cycling with iFES-LCE. Top – hip joint moments; middle – knee joint moments; bottom – ankle joint moments. FES active (red); passive (black). Muscle stimulation bars for right leg are indicated for gluteal (yellow), hamstrings (blue) and quadriceps muscles (maroon). Contralateral leg (left leg) is stimulated 180° apart (bars not shown).](image)

<table>
<thead>
<tr>
<th>Table 4</th>
<th>External and internal powers during evoked stepping (iFES-LST) and cycling (iFES-LCE) exercise.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FES-evoked variables</td>
<td>FES-evoked stepping (iFES-LST) or cycling (iFES-LCE)</td>
</tr>
<tr>
<td></td>
<td>(Min 0–2)</td>
</tr>
<tr>
<td></td>
<td>iFES-LST</td>
</tr>
<tr>
<td>External power (W) †</td>
<td>9.9 (8.3)</td>
</tr>
<tr>
<td>Internal power (W) †</td>
<td>16.4 (17.2)</td>
</tr>
<tr>
<td>Hip power (W)</td>
<td>6.9 (8.1)</td>
</tr>
<tr>
<td>Knee power (W) †</td>
<td>7.9 (8.2)</td>
</tr>
<tr>
<td>Ankle power (W) †</td>
<td>1.6 (1.3)</td>
</tr>
<tr>
<td>Mechanical efficiency (%)</td>
<td>76.3 (21.2)</td>
</tr>
<tr>
<td>Gross metabolic efficiency (%) †</td>
<td>3.22 (2.64)</td>
</tr>
<tr>
<td>Net metabolic efficiency (%) †</td>
<td>3.42 (2.78)</td>
</tr>
</tbody>
</table>

† Indicates P<0.05.
‡ Indicates P<0.01, for all three time intervals (mins 0–2, 2–4, 4–6).
using the iFES-LST system (Fig. 4), perhaps combined with a postural advantage assisting venous return.

Even though this study demonstrated that iFES-LST exercise provided a greater mechanical and metabolic stimulus than does cycling, we have only investigated one mode of cycling — it is possible that concentric cycling (i.e. not motor-resisted constant-cadence) might have a different biomechanical or metabolic pattern. Other cycling exercise systems might have been used as a comparison in this study, but the body kinematics would not be equivalent.

6. Conclusion

This study demonstrated that FES-enhanced elliptical stepping using iFES-LST exercise system would have advantage over FES cycling. The cardiorespiratory responses during cycling and stepping at 15 to 30 rev·min⁻¹ were comparable, but power outputs and metabolic efficiencies were significantly higher during iFES-LST compared to traditional iFES-LCE exercise in SCI individuals.

Acknowledgement

The authors wish to thank Mr. Ray Patton and Mr. Ilhun Baek for their technical assistance during data collection. The first author received scholarship support from the Ministry of Higher Education Malaysia. This research was also supported by a NSW Office of Science and Medical Research Program Grant.

References