Cardiorespiratory and Metabolic Responses during FES-Leg Cycling and Hybrid FES-Gait in SCI Individuals

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Abstract

This study compared metabolic and cardiorespiratory responses between functional electrical stimulation-evoked leg cycling exercise (FES-LCE) and functional electrical stimulation-induced walking (FES-Gait) in individuals with spinal cord injury (SCI). Both forms of exercise were contrasted with maximal effort arm cranking exercise (ACE) to compare the relative physical challenges of the different exercise modes. Four male subjects (T4-10 ASIA-A SCI) undertook FES-evoked exercise training to improve their muscle strength and endurance in preparation for FES-gait. After completion of training, the subjects performed maximal effort ACE, a submaximal treadmill FES-Gait task and a peak FES-LCE test. Oxygen uptake, heart rate and ventilation were increased significantly over rest during FES-LCE, FES-Gait and maximal-effort ACE. FES-LCE evoked 64% of ACE VO2max, but FES-Gait elicited 95% ACE VO2max. Exercise heart rate was also significantly higher during FES-Gait than FES-LCE. Cardiac output and arteriovenous oxygen extraction were increased significantly over rest during FES-LCE and FES-Gait, and exercise cardiac output was also higher during FES-gait compared to FES-LCE. Interestingly, stroke volume did not increase significantly during FES-LCE (6%) and even decreased during FES-Gait (-14%). Both modalities of exercise elicited sufficient metabolic responses, as indicated by %VO2max during ACE, to be beneficial for fitness training, but FES-LCE demonstrated lower exercise intensity for cardiorespiratory benefits. Increased aerobic fitness may facilitate every day activities in individuals with SCI and may reduce risk factors for secondary complications such as cardiovascular disease.

1 Introduction

To slow the onset and reduce the burden of cardiovascular disease, the individual with spinal cord injury (SCI) must increase their physical activity level in order to improve their level of cardiorespiratory fitness [1]. There is convincing evidence that individuals with SCI who participate in regular physical exercise have improved cardiorespiratory reserve and possess a higher exercise capacity [2]. Generally, upper body exercise has been used to augment fitness after SCI. Yet, despite the positive effects reported after upper body exercise [2, 3] such training elicits smaller physiological responses than leg exercise, and excessive arm exercise may contribute to the early development of upper extremity degenerative conditions.

Functional electrical stimulation (FES) leg exercise has been recommended to maintain optimal physical fitness and health in individuals after SCI [4]. FES-leg exercise is generally performed as FES-induced weight training or FES-evoked cycling exercise (FES-LCE). Even greater exercise benefits may be achieved through ‘hybrid’ exercise – a modality of exercise whereby simultaneous FES-leg exercise is combined with voluntary arm effort [4]. Potential advantages of hybrid exercise over upper body effort alone or FES-leg exercise might include; (i) exercise capacity is augmented through increased active working musculature of arms and legs, (ii) FES-leg exercise may raise upper body blood flow and thereby facilitate whole-body exercise performance, and, (iii) compared with FES-leg cycling alone, hybrid exercise with its voluntary upper body component may elicit greater sympathetic cardiovascular activity and induce a more “normal” exercise response.

FES-evoked walking (FES-Gait) is a particular form of hybrid exercise that seeks to improve the upright mobility of paraplegic subjects in daily life – currently with limited functional success. Yet despite the limited benefits of FES-gait for functional outcomes, the increase of active muscle mass during upright ambulation may be efficacious for promoting improved cardiorespiratory fitness.

The aim of this study was to compare the physiologic responses elicited during FES-Gait (as a hybrid form of whole-body exercise) with involuntary FES-LCE exercise. Both modalities of exercise were contrasted with maximal effort arm cranking exercise (ACE) to compare the relative physical challenges of the different exercise paradigms.


2 Methods

Four male subjects with SCI of traumatic aetiology (T4-10 ASIA-A; time since injury 2-11 y) participated in this study. After a verbal explanation of the research, the subjects gave their written informed consent according to Human Research Ethics Committee guidelines of the University of Sydney.

2.1 Training Protocol

Initially, each subject undertook a gait training program which involved three training sessions of 1-1.5 h per week comprising either: (i) initial leg strengthening and passive standing, (ii) FES-assisted standing training, or, (iii) FES-evoked over-ground and treadmill stepping training.

2.2 Assessments

On 3 separate days, the subjects performed a maximal effort arm crank exercise (ACE) test, a peak FES leg cycling exercise (FES-LCE) test and a submaximal, near-steady state FES-walking test (FES-Gait).

Maximal effort ACE is a common strategy to assess peak cardiorespiratory fitness in SCI individuals [2]. Cardiorespiratory measurements were collected at rest and during progressive-intensity ACE, starting at 0W for 2-min and increasing by 10-20W at 1-min intervals until volitional fatigue. Subjects were required to maintain an ACE cadence of 50 rev•min⁻¹.

The FES-LCE test was performed on an isokinetic cycle ergometer and laboratory-developed FES system [5]. Cardiorespiratory data were collected at rest and during an incremental FES-LCE test at 50 rev•min⁻¹, starting at 0W for 4 min, and then progressing at 2W increments every 2-min thereafter. Using a feedback mode provided by the cycle ergometer [5], the stimulation automatically increased to maintain the target power output, starting at 0mA and increasing up to maximum of 140mA. The test ceased when the stimulation reached maximum FES system output.

FES-Gait (‘Hybrid’ exercise), comprised motorized treadmill FES leg-stepping at a velocity of 0.04 m•s⁻¹ in combination with voluntary upper body muscle contractions using a ‘rollator’ frame for postural support. The treadmill was selected for the gait assessment and training because there was an overhead-suspended support harness for the subjects’ safety, a physiotherapist could place the subjects’ footfalls carefully, and the gait velocity could be accurately controlled. Cardiorespiratory data were collected at rest and during near steady-state stepping exercise at 5-min intervals until test termination. The test was terminated when one of the following events took place: (i) the subject requested to stop, (ii) HR reached age-predicted maximum, (iii) stimulation amplitude reached a maximum and knee buckle during stance phase could not be controlled.

Skin surface electrodes were placed on each leg over the neuromuscular motor points of the quadriceps and the glutei for standing, the quadriceps, the glutei and the hamstrings for FES-LCE and quadriceps, glutei and common peroneal nerve for FES-Gait. The neuromuscular stimulator used for this study was a pre-commercial 8-channel FES system (Neopraxis ExoStim™, Cochlear Medical Devices, Lane Cove, Australia), which delivered 150μs monopolar square wave pulses at a continuous frequency of 25Hz.

Computerized open circuit spirometry was used to derive oxygen consumption (VO₂; ml•min⁻¹) and expired ventilation (V̇e; l•min⁻¹) at rest and during exercise. Heart rate (HR; b•min⁻¹) was measured continuously via 3 lead ECG and interfaced with data from the metabolic measurement. CO₂-rebreathing was employed to estimate cardiac output (Q; l•min⁻¹), left ventricular stroke volume (SV; ml) and arteriovenous oxygen extraction (a•vO₂; ml•100ml⁻¹).

The primary outcomes were changes of exercise values over resting values for cardiorespiratory responses within the tests. Other primary outcomes were the % of the maximal effort ACE test reached in FES-LCE and FES-Gait for VO₂peak, highest HR and V̇epeak.

A one sample t-test was performed to determine the increase of exercise data over the rest data. One-way analysis of variance with Scheffe’s Post Hoc Test was used to contrast the differences in the cardiorespiratory responses at rest and during peak exercise for the test conditions. Results were expressed as mean ± SD and statistical significance was accepted when p ≤ 0.05.

In addition, visual inspection of the exercise time-series date for each test was investigated using a case-cohort methodology.

3 Results

Table 1 shows that VO₂, HR and V̇e were increased significantly over rest during FES-Gait (by 74%, 56% and 79%), as well as during FES-LCE (by 64%, 31% and 79%), and during ACE (by 81%, 58% and 85%). FES-LCE reached 64% of VO₂peak of the maximal ACE test, but FES-Gait elicited 95% of maximal ACE VO₂peak (Fig 1). Furthermore, VO₂ and HR were significantly higher during FES-Gait compared to FES-LCE.

Cardiac output and a•vO₂ both increased significantly over rest during FES-LCE (by 1.68 ± 0.75 l•min⁻¹ and by 2.66 ± 1.22 ml•100ml⁻¹ respectively) and during FES-Gait (by 4.43 ± 1.03 l•min⁻¹ and by 3.36 ± 1.30 ml•100ml⁻¹). Exercise Q was also higher during FES-
Table 1: Cardiorespiratory Responses during Arm Cranking, FES-Cycling and FES-Stepping Exercise

<table>
<thead>
<tr>
<th>Exercise</th>
<th>VO₂ (ml·min⁻¹)</th>
<th>HR (beat·min⁻¹)</th>
<th>Ve (l·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase over Rest</td>
<td>(steady-state exercise value − resting value)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>960 ± 159 *</td>
<td>89 ± 12 *</td>
<td>52.0 ± 9.8 *</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>472 ± 55 *</td>
<td>27 ± 9 *</td>
<td>30.0 ± 10.0 *</td>
</tr>
<tr>
<td>FES-Gait</td>
<td>822 ± 143 *</td>
<td>90 ± 27 *</td>
<td>34.5 ± 8.9 *</td>
</tr>
</tbody>
</table>

* Indicates a significant change during exercise over rest data (p<0.05). Abbreviations are described in text.

4 Discussion and Conclusions

This study demonstrated that FES-Gait, as a form of arm+leg ‘hybrid’ exercise, evoked a significantly higher metabolic demand than did FES-LCE (an involuntary form of legs-only exercise) in people with SCI. This was revealed by the greater oxygen consumption during FES-Gait. Submaximal FES-Gait VO₂ was significantly higher and similar to that reached during maximal effort ACE. The 33% higher oxygen consumption observed during FES-Gait was probably due to the larger muscle mass involved in hybrid exercise. Our data were similar to previous studies where a significantly higher VO₂ has been observed during FES-walking, FES-rowing or FES-cycling+arm cranking exercise when compared with other modes of involuntary FES-leg only muscle contractions.

Conversely, the findings of this study also suggested that FES leg-cycling by itself is not a strong “dose-potent” stimulus for improved cardiorespiratory fitness in individuals with SCI – VO₂ and heart rate were less than 65% of peak values observed during maximal ACE (Fig 1). This relatively modest cardiorespiratory stimulus during legs-only cycling was supported by much lower increases of cardiac output (1.7 vs. 4.4 l·min⁻¹) and arteriovenous oxygen extraction (2.7 vs. 3.4 ml·100ml⁻¹) for FES-LCE versus FES-Gait, respectively. Cardiac output represents the ‘central’ component of whole body oxygen consumption and arteriovenous oxygen extraction characterizes the ‘peripheral’ component of metabolism. Although the sample size for this study was small, all four subjects had been FES-leg training for at least three months previously before these assessments were performed, and all were leg-trained well enough to stand and walk on a treadmill.

In conclusion, both FES-cycling and FES-stepping elicited sufficient exercise responses, as indicated by %VO₂max exhibited during ACE, to be beneficial for fitness training, but FES-LCE demonstrated lower exercise intensity for cardiorespiratory benefits. Increased fitness may facilitate every day activities after SCI and may also reduce risk factors for secondary complications such as cardiovascular disease.

6 References