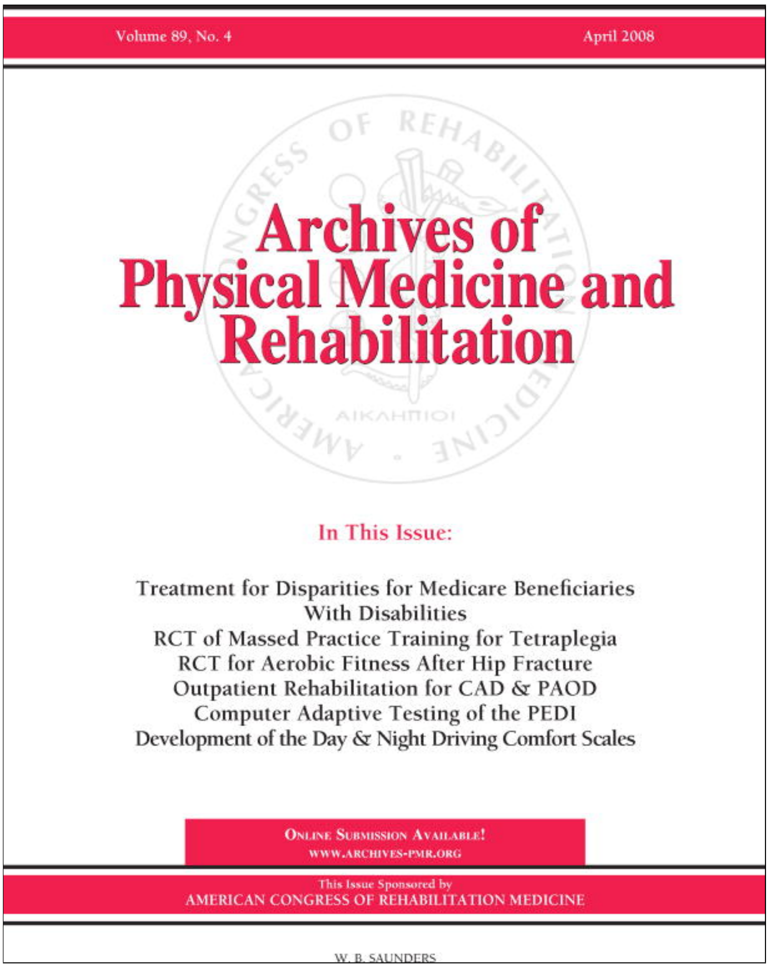
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ORIGINAL ARTICLE

Cardiovascular and Metabolic Responses During Functional Electric Stimulation Cycling at Different Cadences

Ché Fornusek, PhD, Glen M. Davis, PhD

ABSTRACT. Fornusek C, Davis GM. Cardiovascular and metabolic responses during functional electric stimulation cycling at different cadences. Arch Phys Med Rehabil 2008; 89:719-25.

Objective: To determine the influence of pedaling cadence on cardiorespiratory responses and muscle oxygenation during functional electric stimulation (FES) leg cycling.

Design: Repeated measures.

Setting: Laboratory.

Participants: Nine subjects with T4 through T10 spinal cord injury (SCI) (American Spinal Injury Association grade A).

Interventions: FES cycling was performed at pedaling cadences of 15, 30, and 50 revolutions per minute (rpm).

Main Outcome Measures: At each cadence, heart rate, oxygen uptake, and cardiac output were recorded during 35 minutes of cycling. Near infrared spectroscopy was used to quantify quadriceps muscle oxygenation.

Results: All pedaling cadences induced similar elevations in cardiorespiratory metabolism, compared with resting values. Higher average power output was produced at 30rpm (8.2±0.7W, $P<.05$) and 50rpm (7.9±0.5W, $P<.05$) compared with 15rpm (6.3±0.6W). Gross mechanical efficiency was significantly higher ($P<.05$) at 30 and 50rpm than at 15rpm. Quadriceps muscle oxygenation did not differ with pedaling cadences.

Conclusions: Cardiorespiratory responses and muscle metabolism adjustments during FES leg cycling were independent of pedal cadence. FES cycling at a cadence of 50rpm may not confer any advantages over 30 or 15rpm for cardiovascular fitness promotion in persons with SCI.

Key Words: Efficiency; Electric stimulation; Exercise; Rehabilitation; Spinal cord injuries.

IN ADDITION TO MUSCLE paralysis, spinal cord injury (SCI) leads to secondary degenerative changes that may include reduced cardiorespiratory fitness, muscle atrophy, osteoporosis, pressure ulcers, and poor circulation in the affected limbs.[1-3] These changes are often exacerbated by the reduced physical activity of persons with SCI.[4]

Functional electric stimulation (FES)−evoked leg exercise has ameliorated some of the degenerative changes associated with chronic SCI. Some established benefits from regular FES exercise include increased muscle mass or lean body mass, augmented blood flow, and lowered risk of pressure ulcers.[5] Additional benefits may also include improvements in bone density[6] and enhanced glucose metabolism.[7]

The most common forms of FES leg exercise are static contractions, knee extension,[8] and cycling.[9] FES-evoked cycling, which uses bilateral stimulation of the quadriceps, hamstrings, and gluteal muscles to pedal an ergometer, elicits the highest metabolic and cardiorespiratory responses. When performed regularly, FES-evoked cycling may result in improved aerobic fitness in very deconditioned persons with SCI.[10]

Traditionally, FES-evoked cycling is performed at pedal cadences of about 50 revolutions per minute (rpm). Improvements in performance from FES-cycle training have been primarily the result of endurance improvements and not muscle strength increases.[11,12] The magnitude of strength and hypertrophy gains after such exercise is small and more slowly developed compared with gains induced by FES-evoked knee extension. Much greater levels of muscle hypertrophy have been observed after 12 weeks of FES knee extension[8] compared with 1 year of FES cycling.[13] Moreover, the forces developed at 50rpm are low compared with those generated during FES knee extension.[11,12] The neuromuscular stimulation patterns used to evoke FES knee extension,[8] that is, moderate duty cycles and long contraction-relaxation periods combined with slow contraction velocities, are associated with low fatigue rates[14] and high forces. Analogous to voluntary training, greater muscle forces during FES training generally have led to enhanced strength[15] and muscle adaptations.[16]

Recently, we[17] found greater pedal forces but reduced power outputs during FES-evoked cycling at slower pedaling cadences (ie, 15rpm). Therefore, FES-evoked cycle training at slow pedal cadences may result in improved leg muscle strength and hypertrophy compared with training at higher pedal cadences. Muscular endurance and aerobic fitness, however, might not be enhanced at the modest power outputs elicited during slow cadence training. Certainly, in studies of voluntary exercise[18] and FES-evoked cycling,[19,20] the magnitude of cardiorespiratory adjustments was strongly associated with the exercise power output. Accordingly, both the magnitude and duration of the cardiorespiratory adjustments compared with resting levels might be important factors in promoting aerobic fitness through FES exercise. Thus, FES-evoked cycle training at the traditional cadence (50rpm), with its associated higher power outputs, should generate greater improvements in cardiorespiratory fitness than would be generated at slower cadences.

The relation between aerobic metabolism during FES-evoked cycling and power output or cadence may be more complicated, however. The cardiorespiratory adjustments of SCI subjects performing FES-evoked cycling obviously differ from those of able-bodied subjects doing voluntary exercise.[9,21] Additionally, FES recruits the muscle fibers in a non-

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physiologic "reverse" order,[22] and chronically paralyzed muscle comprises predominantly type II fibers.[13]

No previous research has compared the physiologic effects of prolonged FES-evoked cycling at different pedal cadences. Given the close association between aerobic metabolism and power output during voluntary exercise, a greater cardiorespiratory stimulus might be expected during FES-evoked leg cycling at high pedal cadences than with low cadences.

Therefore, our purpose in this study was to investigate the effect of pedaling cadence on the cardiorespiratory and muscle oxygenation responses during FES-evoked cycling in persons with SCI. Our hypothesis was that higher pedaling cadences would result in a greater aerobic response. We sought to enhance our understanding of FES-evoked cycle training and to see whether pedal cadence is an important consideration in cardiorespiratory fitness training in this population.

METHODS

The data presented in this study were collected simultaneously with torque and power data in an earlier study.[17] The data presented here represent the cardiorespiratory and metabolic responses that matched the torques and powers produced in the earlier study.

Participants

Seven men and 2 women (mean age ± standard deviation, 37.4±10.9y; mass, 64.8±10.2kg; height, 169±4cm; postinjury, 76±55mo) with complete T4 through T10 SCI (American Spinal Injury Association grade A) participated in this experiment. All were experienced with FES-evoked cycling exercise and had been training regularly 2 to 3 times a week for 6 months. The University of Sydney's Human Research Ethics Committee approved the study and written informed consent was obtained from all subjects.

Study Design

FES-evoked cycling was done at pedaling cadences of 15, 30, or 50rpm for 35 minutes during each trial. Cadence order was randomized, with each trial performed on a different day. The consecutive trials were performed less than 1 week apart. Cardiorespiratory responses and muscle oxygenation adjustments during exercise were recorded during each trial. Subjects did 10 minutes of passive cycling at the tested cadence before doing the FES-evoked cycling. Neuromuscular stimulation was closely monitored for the subjects' comfort, for reproducibility, and to mimic stimulation levels that might occur during a typical FES-evoked training session in a clinical practice. Stimulation amplitude was initially set to 70mA, and then linearly ramped to 140mA by the fifth minute of exercise. During each trial, the quadriceps (30°–300°), hamstrings (60°–160°), and gluteal (6°–73°) muscle groups of both legs were bilaterally stimulated to produce the cycling pattern. For the muscle stimulation angles, 0° was defined as when the respective crank was at top dead center.

Equipment

Isokinetic FES leg cycle ergometer. In this study, we used a recently-developed isokinetic FES leg cycle ergometer (FES-LCE).[23] In brief, the isokinetic FES-LCE system consisted of a laptop computer running specific cycling control software, a microcontroller 6-channel transcutaneous neuromuscular stimulator (DS2000)[a] and a motorized cycle ergometer.[b] The cycle ergometer had pedal cadence control circuitry to maintain a preset cadence up to 60rpm in 1-rpm increments. The ergometer's controller sent instantaneous performance data (eg, crank position, crank velocity, motor current) to the computer through RS-232 interface at approximately 60Hz. The laptop software directed the neuromuscular stimulator to produce muscle contractions at the appropriate crank angles and intensity to elicit isokinetic (constant velocity) leg cycling exercise. The computer also calculated from the motor current and crank velocity data the instantaneous pedal torque and external power output generated by the subjects. The ergometer can calculate the internal power (inertial and gravitational forces) required for cycling from measurements taken during passive cycling. For each subject and particular cadence, the measured internal power was subtracted from the external power to obtain the exercise power output. It is important to correct for internal power when comparing different FES cycling cadences because the power outputs developed are very low.

Neuromuscular stimulation. Neuromuscular electric stimulation comprised monophasic rectangular pulses at a frequency of 35Hz and pulse width of 250μs. Because muscle stimulation angles were fixed, the stimulation duty cycle was constant and all muscles received the same total stimulation time regardless of the pedaling cadence. Stimulation was delivered through gel-backed self-adhesive surface electrodes[c] that were placed over the bellies of the quadriceps, hamstrings, and gluteii muscles. Electrode placement was measured during the first session of each trial and kept consistent to ensure that muscle fiber recruitment was similar between trials.

Cardiorespiratory responses and exercise metabolism. Cardiorespiratory responses were assessed continuously with an open-circuit metabolic gas analysis system.[d] We used a Portoscope CR55[e] to measure electrocardiographic activity and heart rate. Stroke volume was measured through transthoracic impedance cardiography.[24] Cardiac impedance was measured for 30 seconds while subjects were at rest, during passive cycling, and every 5 minutes during FES-evoked cycling. Systolic blood pressure (SBP) and diastolic brachial blood pressure were measured with a manual sphygmomanometer at rest and at 5-minute intervals during passive cycling and FES-evoked cycling.

Muscle oxygenation (near infrared spectroscopy). We used near infrared spectroscopy (NIRS) to calculate the hemoglobin saturation in small blood vessels by measuring the absorption and scattering of near infrared light at different wavelengths. We used a 2-wavelength frequency-domain tissue oximeter[f] to measure the oxygenation within the left quadriceps muscle group at rest and during FES cycling. The NIRS sensor was placed on the middle of the left quadriceps muscle (over the rectus femoris). To calibrate the muscle oxygen saturation levels,[25] NIRS measurements were made at rest during super-systolic arterial occlusion of the thigh (≈290mmHg) with an inflatable pressure cuff.[g] Arterial occlusion was maintained for up to 12 minutes or until the decreasing thigh muscle oxygen saturation had stabilized.

Data Analysis

Cardiovascular responses and exercise metabolism. Heart rate, expired ventilation ($\dot{V}$E), and oxygen uptake ($\dot{V}O_2$) were extracted from the raw metabolic cart data. Data from 5 minutes of rest were averaged to derive a pre-exercise value. During passive cycling and at 5-minute intervals during FES cycling, a 1-minute sample of cardiorespiratory data was ensemble-averaged. Respiratory exchange ratio (RER) and the ventilatory equivalent for oxygen ($\dot{V}O_2$/$\dot{V}$E) were calculated from the averaged values for each time period. Cardiac output was the product of stroke volume and heart rate.

At rest, during passive cycling, and at the end of every 5 minutes of cycling, 1 minute of NIRS data were averaged as a representative sample for the left quadriceps muscle oxygenation. In using NIRS to compare FES and passive cycling, there is a possibility that the muscle contraction induced by electric stimulation can change the position of the muscle fibers. We used measured variables, including hemoglobin (Hb) and oxyhemoglobin (Hbo_2) concentrations, to calculate the total Hb concentration and percent muscle Hb saturation. Percent Hb saturation was scaled to give relative muscle oxygen saturation (So_2); the minimum So_2 level attained during super-systolic arterial occlusion was assigned as 0% saturation and 100% saturation was assigned to the value of the pretrial resting data.[25]

Mechanical efficiency. Gross mechanical efficiency (ME) was calculated every 5 minutes during FES cycling from aerobic energy sources, with an assumed energetic equivalent of 21.1kJ/L of oxygen,[26] as power output divided by $\dot{V}o_2$.

Statistical Analyses

The time-series data were plotted and descriptive statistics were subsequently extracted. Thereafter, we used 1-way repeated-measures analysis of variance on the cardiorespiratory, leg oxygenation, efficiency, and cycling performance data to determine whether the time main effect and/or time by cadence interactive effects were significant. For all variables, where there was a significant main effect, a posteriori analyses were made among cadences using Duncan and Bonferroni pairwise comparisons. Statistical results were considered to be statistically significant at the 95% confidence limit ($P<.05$). Data were expressed as mean ± standard error (SE). All statistical analyses were made using the SPSS statistical package.[h]

RESULTS

Exercise power output was significantly affected by pedal cadence. The average power output (PO) during FES cycling was greater at 30 and 50rpm over 35 minutes than at 15rpm (PO_{15}, 6.3±0.6; PO_{30}, 8.2±0.7; PO_{50}, 7.9±0.5). In general, FES-evoked cycling elicited significant cardiorespiratory, hemodynamic, and muscle oxygenation adjustments above resting values at all 3 pedaling cadences. Neither the time courses nor the magnitude of these changes were significantly influenced by cadence. Passive cycling ($\dot{V}o_2$, 1.1±0.1 metabolic equivalents [METS]) did not cause an increase in any exercise response over resting values.

Cardiorespiratory and Hemodynamic Responses

Figure 1 shows the heart rate, cardiac output, and $\dot{V}o_2$ data across the 3 pedaling cadences over 10 minutes of passive cycling and 35 minutes of FES cycling. There were significant increases of heart rate (40%), $\dot{V}o_2$ (180%, 2.8±0.1 METS), cardiac output (52%) over the duration of each FES cycling trial. Both heart rate and cardiac output rose quickly within the first 5 minutes. Thereafter, heart rate continued to rise slowly throughout the remainder of the trial, while cardiac output achieved a steady state after 10 minutes. Table 1 shows the additional cardiovascular and cardiorespiratory responses during FES cycling for each cadence compared with resting values. Stroke volume did not change significantly from resting values. All 3 pedaling cadences induced significant and similar increases in RER, $\dot{V}E$, $\dot{V}E/\dot{V}o_2$, and SBP from rest to steady-state exercise. The $\dot{V}E/\dot{V}o_2$ and RER suggested a predominant reliance on anaerobic energy sources and/or blood lactate production.

Mechanical Efficiency

Gross ME was also significantly altered by cadence and, when averaged over the whole session, was greater at 30 and

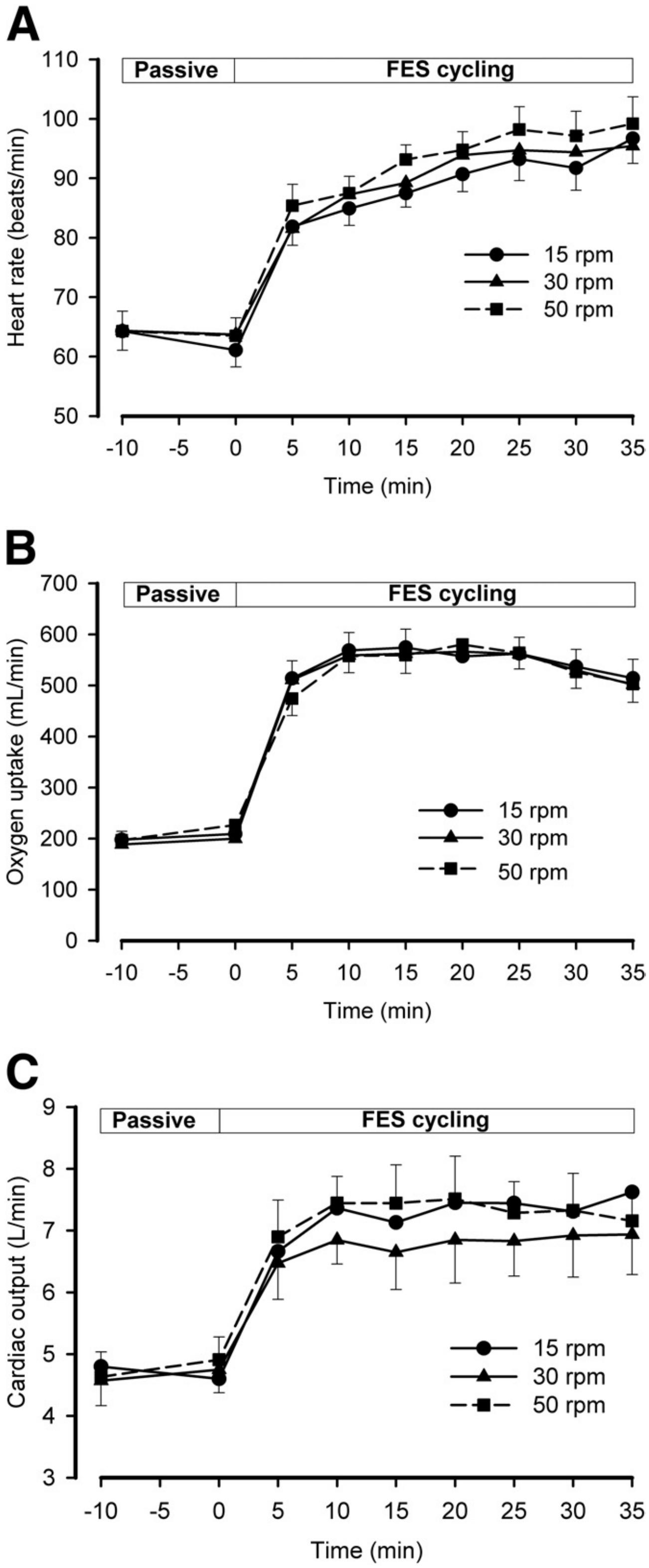

Fig 1. Performance and cardiorespiratory responses of the 9 subjects during passive and FES cycling at 3 pedaling cadences. Displayed are (A) heart rate, (B) $\dot{V}o_2$, and (C) cardiac output. Results are plotted every 5 minutes as means ± SE. Some SE bars have been omitted for clarity.

Table 1: Cardiovascular, Respiratory, and Hemodynamic Responses During FES Cycling at Different Pedal Cadences

Cadence (rpm)	Stroke Volume (mL)	$\dot{V}_E$ (L/min)	$\dot{V}_E/\dot{V}O_2$	RER	DBP (mmHg)	SBP (mmHg)
15						
Rest	74.5±4.8	7.0±0.5	36.4±2.0	0.83±0.02	83.9±4.3	121±6
Passive	75.2±4.9	7.7±0.4	37.9±2.3	0.87±0.02	85.6±4.2	124±6
FES-LCE	80.8±5.1	21.8±1.2*	40.2±1.1*	1.15±0.02*	85.5±4.8	133±7*
30						
Rest	70.8±5.0	6.7±0.4	35.8±2.0	0.79±0.02	82.4±4.3	117±6
Passive	74.6±5.2	7.2±0.4	36.1±2.2	0.82±0.02	84.5±4.5	121±6
FES-LCE	74.6±4.3	21.6±1.4*	40.1±1.2*	1.17±0.03*	80.6±5.5	129±5*
50						
Rest	73.2±4.9	7.1±0.4	36.0±2.0	0.86±0.02	80.6±4.1	123±6
Passive	78.5±5.0	8.5±0.5	37.8±2.2	0.86±0.02	88.2±4.4	129±6
FES-LCE	79.5±7.1	22.5±1.1*	41.8±0.9*	1.21±0.02*	82.3±4.2	134±6*

NOTE: Values are average over each trial.
Abbreviation: DBP, diastolic blood pressure.
*Significant change compared with rest ($P<.05$).

50rpm than at 15rpm (ME_{15}, 2.0±0.2; ME_{30}, 2.6±0.2; ME_{50}, 2.5±0.2). Initially (ie, in the first 5–10min), gross efficiency was highest at 30rpm (fig 2). After 20 to 30 minutes of FES cycling, however, efficiency was highest at 50rpm, while at 15rpm it was significantly lower than at the other 2 cadences after 15 minutes.

Muscle Oxygenation

Normalized muscle SO_2 dropped rapidly after the start of FES cycling (fig 3), and both the Hb (87%–224%) and total Hb (12%–22.2%) increased significantly from rest values (table 2), suggesting an increase in oxygen utilization and metabolism. After 25 minutes of exercise, muscle SO_2 increased significantly ($P<.05$) for all cadences (9.7%–12% by 35min), but was still lower than resting values after 35 minutes. The increase in muscle oxygenation was accompanied by significant increases in HbO_2 (7%–10% from 20–35min), raised total Hb (2%–4% from 20–35min), and a significant decrease (7%–10% from 20–35min) in Hb. Notwithstanding the changes of NIRS parameters during FES cycling, there were no significant effects of pedaling cadence on muscle SO_2.

DISCUSSION

The cardiorespiratory adjustments during FES-evoked cycling exercise were independent of pedaling cadences, notwithstanding that different power outputs were produced. This is the first study to investigate the association between FES pedaling cadence, and the resulting cardiorespiratory, hemodynamic, and muscle oxygenation adjustments during such exercise in people with paraplegia. Our results were surprising because during voluntary exercise in able-bodied cohorts, the cardiorespiratory responses were closely linked to, and increased by, both power output[18] and pedaling cadence.[27] Therefore, the higher power outputs evoked at faster FES pedaling cadences were predicted to produce a greater cardiorespiratory and muscle metabolic activation. Our data pose some interesting questions about the traditional relationship between power output and exercise metabolism when the exercise is artificially induced and the paralyzed muscles comprise predominantly type II fibers.

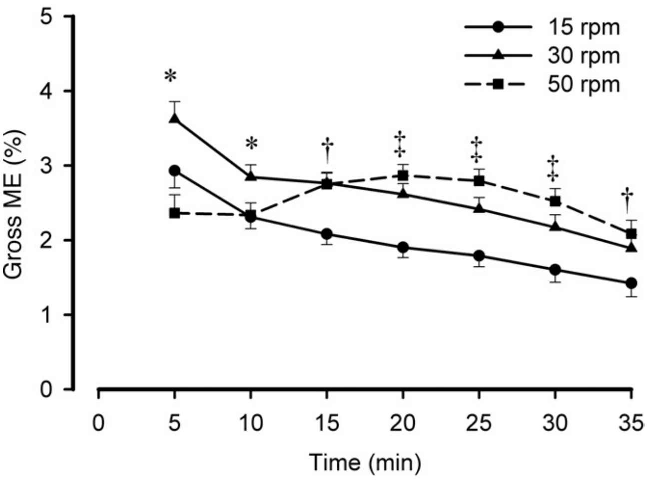

Fig 2. Gross ME during FES cycling by the 9 subjects at 3 pedaling cadences. Results were plotted every 5 minutes as means ± SE. *ME_{30} significantly greater ($P<.05$); †ME_{15} significantly lower; ‡significant difference between all 3 pedaling cadences.

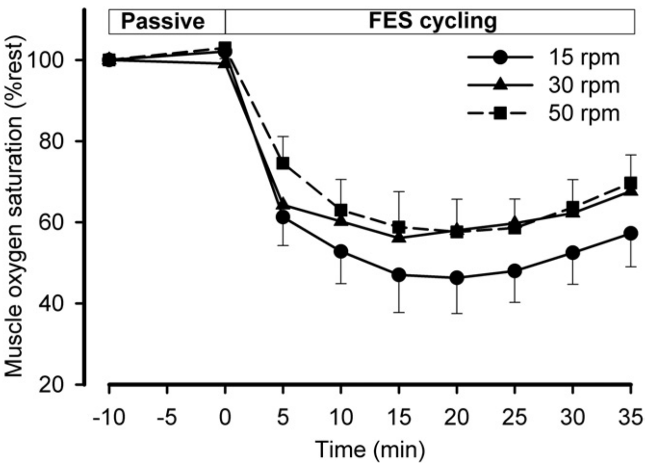

Fig 3. Left quadriceps SO_2 during passive and FES cycling by the 9 subjects at 3 pedaling cadences. Results were plotted every 5 minutes as means ± SE. Some SE bars have been omitted for clarity.

Table 2: Muscle Oxygenation During FES Cycling at Different Pedal Cadences

Cadence (rpm)	SO_2* (% rest)	Total Hb* (μM)	HbO_2 (μM)	Hb* (μM)
15				
Reset	100	40.5±5.4	31.7±3.7	8.7±1.8
Passive	102±2	39.1±5.4	30.2±3.7	8.9±1.9
FES-LCE	52±8	47.7±7.4	28.7±4.1	18.9±3.6
30				
Reset	100	40.1±5.5	30.7±3.7	9.5±2.0
Passive	99±2	39.2±4.9	30.5±3.2	7.7±1.8
FES-LCE	61±5	49.0±7.3	31.2±4.0	17.8±3.8
50				
Reset	100	44.6±5.4	36.9±4.8	5.7±2.0
Passive	103±1	42.8±5.9	31.7±4.0	8.8±2.0
FES-LCE	62±7	49.9±6.6	35.0±5.1	18.5±3.4

NOTE. Values measured from left quadriceps and represents average over each trial.
*Exercise induced a significant change compared with rest ($P<.05$).

Passive cycling. Passive limb movements (ie, passive cycling) did not result in significant changes in any of the variables measured. Our results are in agreement with those of 1 prior study[28] but are inconsistent with the results of another,[29] which found that not only did passive cycling increase cardiovascular and respiratory responses, but that an increase in pedaling cadence resulted in an increase in $\dot{V}E$ and $\dot{V}O_2$. Similar to the subjects in Ter Woerds et al,[28] our subjects performed the cycling in a recumbent chair and were told to relax during passive cycling. Muraki et al[29] used a standard bicycle ergometer seat that provided little back support. Activation of postural muscles may have contributed to the difference in results.[28] When examining the effects of passive exercise within or between exercise modes in SCI subjects, it is important to minimize muscle activation, for example, from muscle spasms or from the upper body.

Relation between power output and $\dot{V}O_2$ during FES cycling. The discrepancy between our results and those of previous studies that found a strong coupling of external power output and $\dot{V}O_2$[19,20] may be related to the duration of the FES cycling protocol and control of stimulation intensity.[9] Previous research[19,20] into FES-evoked cycling that used progressive short duration (<5min), intermittent graded protocols at a cadence of 50rpm found a tight coupling between power and $\dot{V}O_2$. Similar to our study, Theisen et al[9] held stimulation intensity (and fiber recruitment) constant over 40 minutes at 50rpm and found variations in FES-evoked cycling ME. Our results show that FES-evoked cycling efficiency is affected by both exercise duration and cadence.

FES-evoked cycling efficiency. The efficiencies we report here are fairly typical of values described in previous studies, for example, 3% to 4% for FES-evoked cycling.[9] Voluntary cycling at 50rpm and at a $\dot{V}O_2$ similar to our study usually shows mechanical efficiencies of approximately 13%.[30] Previous research has attributed such low ME during FES-evoked cycling to inadvertent muscle contractions[20] or enhanced respiratory activity, which do not contribute to external power output but add significantly to the overall energy cost. A significant amount of the energy metabolized during FES exercise may not be used to produce propulsive forces because of ineffective timing and coordination of muscle contractions.[31] Additionally, the $\dot{V}E/\dot{V}O_2$ during FES-evoked cycling is greater than during voluntary cycling,[32] so for a similar $\dot{V}O_2$, additional energy is also expended for the enhanced cardiovascular and respiratory activity that occurs during FES exercise.

During FES cycling, any metabolic variations caused by differences in power output among cadences may have been blunted by the energy expended on respiratory activity and isometric and antagonistic contractions. Although the pedaling cadences of 30 and 50rpm produced significantly greater power outputs than 15rpm, this difference was less than 2W, which may not have been great enough to produce an obvious change in whole-body $\dot{V}O_2$.

Contraction frequency and fiber type. Faster pedaling cadences of FES-evoked cycling, which are associated with higher contraction frequencies, should produce enhanced anaerobic and aerobic metabolism than with slower cadences. For electrically stimulated rhythmical contractions with a constant duty cycle, the energy requirements increase with the contraction frequency.[14,33,34] In contrast, our findings showed neither greater anaerobic (RER) nor aerobic ($\dot{V}O_2$) metabolism at higher pedaling cadences during FES cycling leg exercise. In persons with SCI, the predominance of fast-twitch fibers and their preferential recruitment may change the relation between $\dot{V}O_2$, power output, and pedaling cadence compared with voluntary exercise. Slow twitch fibers are most efficient at low contraction speeds, while fast twitch fibers are more efficient at higher speeds.[35] Perhaps there was little change in $\dot{V}O_2$ cadences, although greater power outputs were produced at higher cadence, because the enhanced efficiency of the fast-twitch fibers at the greater contraction speeds reduced the energy requirements and improved efficiency as the cadence was increased.

Muscle oxygenation and fatigue. The exact causes of an accelerated fatigue rate during FES exercise have not been previously identified, although impaired blood flow[36] and/or decreased muscle oxidative capacity[37] have been implicated. Poor circulation may contribute to accelerated fatigue during FES in persons with chronic SCI by affecting oxygen and substrate delivery or clearance of the metabolic byproducts of anaerobicosis. A recent study,[36] however, suggested that the magnitude of peak blood flow is not significantly less in SCI than in able-bodied subjects doing FES exercise, but the prolonged time required to reach peak blood flow in the SCI subjects may accelerate their fatigue.

Our data indicate that low muscle oxygenation levels were neither implicated nor were the main factor limiting muscle force output or the onset of fatigue during FES cycling. Notwithstanding that FES-evoked cycling muscle fatigue occurred more rapidly at higher pedaling cadences,[17] our data show that muscle oxygenation was not affected by cadence. The results of Bhambhani et al,[32] which demonstrated that muscle oxygen saturation dropped lower during maximal voluntary cycling than during FES-evoked cycling, also suggests that oxygen supply is not a limiting factor during FES exercise.

Practical Implications for FES-Evoked Cycle Training

The pedaling cadence selected for FES-evoked cycling does not influence the potency of aerobic fitness training or the benefits to be gained thereby. From results of previous studies,[19,20] we hypothesized that higher power outputs produced at faster cadences[17] would also promote greater exercise metabolism and cardiorespiratory responses. This study, however, demonstrated that slow-cadence FES-cycling evoked increases in cardiorespiratory responses and muscle oxygenation similar to those from faster pedaling cadences. These findings suggest that the selection of FES-evoked cycling training cadence may not be an important exercise prescription factor for SCI subjects who want to improve their aerobic fitness. Because of the larger muscle forces involved,[17] however, slow-cadence FES cycling should result in superior strength training outcomes.[15,16] Muscle strength and endurance are important determinants for FES activities such as standing and walking. Further long-term training studies are required to determine the general fitness, muscle strength, and muscle power benefits from training at different FES-evoked cycling cadences.

Study Limitations

The results of this study could be dependent on either the neuromuscular stimulation pattern used or the FES training history of the subjects involved. It is possible that there would have been different results had we used a different neuromuscular stimulation pattern. The stimulation pattern we used is typical of the stimulation patterns used during FES cycling. Our subjects were trained for 6 months in FES cycling at 50rpm. Research has shown that muscle fibers are not easily altered by FES cycling exercise. It is not known if or how the training of the subjects would have affected our results. Furthermore, the results may not be applicable to people with incomplete motor spinal injury that could generate substantial voluntary muscle contractions during FES cycling.

CONCLUSIONS

Pedaling cadence had little influence on the cardiorespiratory responses elicited during FES-evoked cycling. Low cadence training (15rpm) should be as equally effective as cycling at higher cadences (50rpm) to effect aerobic fitness gains. These results demonstrate that there is considerable differentiation between voluntary and FES-evoked exercise, which might be explained by differences in muscle fiber type composition, FES recruitment patterns, or other physiologic sequelae of spared neural innervation after SCI.

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