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MAXIMIZING MUSCLE FORCE VIA LOW-CADENCE FUNCTIONAL ELECTRICAL STIMULATION CYCLING

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Objective: **This study investigated the effect of pedal cadence upon torque production, power output and muscle fatigue rates during functional electrical stimulation evoked cycling in spinal cord injured individuals.**

Subjects: **All subjects had complete thoracic spinal cord injuries T4–T9 (ASIA A) and had been functional electrical stimulation training regularly for at least 6 months.**

Methods: **One trial ($n = 8$) examined a low vs high pedal rate (20 and 50 $\text{rev} \cdot \text{min}^{-1}$) upon isolated muscle fatigue over 5 minutes. A second trial ($n = 9$) investigated the effect of cadence (15 vs 50 $\text{rev} \cdot \text{min}^{-1}$) upon performance during 35-minutes of functional electrical stimulation evoked cycling.**

Results: **Peak torque produced by left quadriceps decayed significantly faster at the higher pedal cadence, indicating a higher rate of muscle fatigue. Functional electrical stimulation cycling over 35 minutes also revealed that peak and average torques were significantly greater at the lower cadence. From 15 minutes onwards, power output was significantly higher at 50 $\text{rev} \cdot \text{min}^{-1}$ FES-cycling, compared with 15 $\text{rev} \cdot \text{min}^{-1}$.**

Conclusion: **The higher muscle forces observed during low cadence functional electrical stimulation cycling should offer improvements over traditional pedalling velocities for training leg strength in individuals with spinal cord injury.**

Key words: electrical stimulation, leg cycle ergometer, spinal cord injury, exercise therapy, rehabilitation, muscle fatigue.

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INTRODUCTION

Besides muscle paralysis, spinal cord injury (SCI) leads to the other degenerative sequelae including reduced cardiorespiratory fitness, muscle atrophy, osteoporosis, pressure sores and poor circulation in the affected limbs (1). Functional electrical stimulation (FES) exercise has been used for individuals with SCI to ameliorate or reverse these degenerative changes (2), as well as to provide strength and/or endurance training for the paralysed limbs (3, 4).

Leg cycling exercise is a common FES exercise modality, whereby computer controlled electrical stimulation elicits contractions in the quadriceps, hamstrings and gluteal muscles in an appropriate sequence to pedal an ergometer (5). Cycling is a popular FES exercise because it is safe, familiar to subjects and recruits a large lower-limb muscle mass (6, 7).

FES cycling training has been shown to produce a number of physiological benefits in the paralysed limbs of individuals with SCI. The benefits include increases in muscle mass and tone (7, 8), increased blood flow (9) and improved body composition (8). After FES cycling the muscle fibre composition and properties of paralysed muscles revert towards normal becoming more fatigue resistant (10). FES cycling also elicits beneficial metabolic and cardiorespiratory responses (11) and when performed regularly can result in improved aerobic fitness (12).

Despite these positive outcomes, FES cycling has not gained widespread use for the ongoing rehabilitation of those with SCI. For many patients with SCI, the expense and the training time required outweigh any benefits gained. Typically, individuals make progress during the first 3 months of training, but subsequently performance plateaus thereafter (13). The training intensity of current FES cycling systems may not be high enough to produce continual training gains over long periods. The main problem limiting FES exercise training is the rapid muscle fatigue that is associated with electrical stimulation of muscle (14). Rapid fatigue restricts the exercise load that can be applied to the stimulated muscles and the cardiovascular system.

Pedalling cadence is one parameter of FES cycling that has not received much previous attention. Recently, a new FES cycle ergometer of isokinetic design (iFES-LCE) has been described (15) that permits a wide range of cadences (5–60 $\text{rev} \cdot \text{min}^{-1}$). The core components of the iFES-LCE consist of a motorized ergometer, a laptop PC and a custom-designed 6-channel transcutaneous neuromuscular stimulator (for further details see Methods section). The force–velocity relationship of muscle (16, 17) may apply to muscle contractions evoked during FES cycling, leading to higher forces being generated as the pedal cadence is decreased. Additionally, muscle fatigue rates may be lower at a slower pedal cadence during FES cycling. If fatigue rate does decrease at slower pedal cadences, then low cadence cycling should produce higher muscle forces

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Table I. *Physical characteristics of the subjects*

Number	SCI level	Gender	Mass (kg)	Height (metres)	Post injury (months)	Age (years)	Prior training (per week, months)
1	T4	F	53	1.67	56	36	2/week, 12
2	T9	M	66	1.74	48	23	3/week, 18
3	T5	M	49	1.67	97	36	3/week, 72
4	T8	M	70	1.73	102	48	2/week, 6
5	T8	M	70	1.70	208	38	3/week, 24
6	T4/T5	M	60	1.67	41	27	2/week, 6
7	T4	M	60	1.64	37	55	3/week, 12
8	T4	F	80	1.65	45	27	2/week, 12
9	T10	M	75	1.76	54	47	2/week, 12

during FES-cycle training. Higher muscle forces may, in turn, lead to improved muscle strength training outcomes (4).

The purpose of this study was to determine the effect of varying the FES-evoked pedalling cadence upon the rate of muscle fatigue, muscle force and power output. To achieve this purpose, FES cycling was performed at 2 different cadences for both a 5 minute isolated muscle "fatigue test" and a 35-minute "typical" FES training session.

MATERIAL AND METHODS

Subjects

All subjects had complete thoracic spinal cord injuries T4–T9 (ASIA A) and were in the age range 23–55 years (37.8±10.4 years). The physical characteristic of each individual subject are shown in Table I. All subjects were experienced with FES cycling and had been FES training regularly for at least 6 months.

iFES-LCE ergometer

A recently-developed isokinetic FES leg cycle ergometer (iFES-LCE) was used for this study (15, 18). The iFES-LCE system consisted of the following components: a laptop computer system, cycling control software, a microcontroller driven 6-channel transcutaneous neuromuscular stimulator (DS2000) and a motorized cycle ergometer module (MOTOmed Viva, Reck, Germany). The motorized cycle ergometer module possessed speed control circuitry to maintain a user preset pedalling cadence up to 60 $\text{rev} \cdot \text{min}^{-1}$ in 1 $\text{rev} \cdot \text{min}^{-1}$ steps. The cycle ergometer module sent data (i.e. crank position, crank velocity and motor current) to the computer via RS-232 serial transfer at ~60 Hz. Using the ergometer data, the computer system directed the DS2000 muscle stimulator to stimulate muscle contractions at the appropriate crank angles and specified intensity to produce leg cycling exercise. From the motor current and crank velocity data the computer accurately calculated the pedal torque and external power output exerted by the subjects.

Neuromuscular stimulation

Neuromuscular electrical stimulation consisted of mono-phasic rectangular pulses at a frequency of 35 Hz and pulse width of 250 μs. Stimulation amplitude was fixed (Trial 1, 80 mA) or varied according to a set time protocol (Trial 2, 70–140 mA). Since muscle stimulation angles were fixed, the stimulation duty cycle was constant and all muscles received the same total stimulation time regardless of the pedalling cadence employed. Stimulation was delivered via Empi gel-backed self-adhesive surface electrodes that were placed over the bellies of the quadriceps (SE6350 3″×5″ oval electrodes), hamstrings (SE6350) and glutei muscles SE5240, 2″×3.5″ rectangular electrodes). Electrode placement was measured during the first session of each trial and kept consistent to ensure that muscle fibre recruitment was similar within trials.

Study design

Two separate trials were conducted to investigate a slow (15–20 $\text{rev} \cdot \text{min}^{-1}$) vs a fast (50 $\text{rev} \cdot \text{min}^{-1}$) pedal cadence upon torque production and power output during FES cycling. Torque and power output were calculated by the iFES-LCE. Two trials were used because it was not possible to make all of the desired measurements in a single trial. The first trial examined the effect of pedalling cadence upon isolated muscle fatigue over a short duration. The torque and power output produced by the left quadriceps muscle was measured during 5- minutes of FES cycling. Five minutes of iFES-LCE exercise was chosen because our pilot data and previous research studies (19, 20) had suggested that during FES training the majority of fatigue occurs within the first 5 minutes. The second trial investigated torque and power output produced by the left quadriceps alone and by the quadriceps, hamstrings and glutei during prolonged FES-cycling (35 minutes). This 35-minute trial was designed to assess whether different pedal cadences, conducted over a "typical" FES training session, might confer different benefits to the SCI individual.

Trial 1: isolated muscle fatigue vs pedal cadence during 5-minute iFES-LCE

Five-minute iFES-LCE tests were performed with the left quadriceps muscle alone at cadences of 20 and 50 $\text{rev} \cdot \text{min}^{-1}$ ($n = 8$). Cadence testing order was randomized. Each cadence was tested on a different day with a maximum of 7 days between tests. Stimulation was applied to the left quadriceps muscle between the angles of 300–30°. For the iFES-LCE, zero degrees was defined when the respective crank was at top dead centre. Only 1 muscle group was used to allow calculation of meaningful peak torques from the iFES-LCE (15). Stimulation amplitude was ramped up to 110 mA within the first 10 seconds of the trial and maintained constant over 5 minutes. Crank torque and velocity data were recorded from the ergometer at a sample rate of 60 Hz. Passive cycling data, i.e. when no stimulation was applied, was recorded before and after left quadriceps FES cycling for the purpose of calculating "true" crank torques and power outputs (15). Every 0.5 min, a 10-second segment of data was analysed to provide a representative measurement at that time point. Analysis of the data segments has been described in subsequent section.

Trial 2: muscle fatigue vs pedal cadence over 35-minute iFES-LCE

The second trial investigated the effect of pedalling cadence on crank torque and power output over 35 minutes of iFES-LCE at cadences of 15, 30 and 50 $\text{rev} \cdot \text{min}^{-1}$ ($n = 9$). The torque and power data of the 30 $\text{rev} \cdot \text{min}^{-1}$ trial lay between those of 15 and 50 $\text{rev} \cdot \text{min}^{-1}$, and for the purpose of simplicity and clarity these data were not displayed in the results. This trial explored the potential benefits that training at different FES-cycling cadences might confer. Cadence testing order was randomized. Each cadence was tested on a different day with a maximum of 7 days between tests. Stimulation amplitude was closely controlled for subject comfort, reproducibility and to mimic stimulation

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levels during a "typical" FES-training session. Stimulation amplitude was initially set to 70 mA, then linearly increased to reach 140 mA by 5 minutes. During the session the quadriceps (300–30°), hamstrings (60–160°) and gluteal (6–73°) muscle groups of both legs were stimulated to produce FES cycling. Every 5 minutes, 12-second torque and crank velocity samples were recorded from the combined muscles, the left quadriceps and passive cycling (no stimulation). To measure left quadriceps data, stimulation to all other muscles was temporarily suspended. Similarly, for passive cycling measurements it was necessary to suspend stimulation to all muscles. The passive torque measurements from the iFES-LCE were used to calculate the net torque generated by the muscles as has been previously described (15). Passive torques were measured regularly during each test, since changes in leg tone or seating position might have altered the passive data, and this would have been reflected in the net torques generated by leg muscles over 35 minutes.

For both trials, instantaneous peak torques (Nm) and average torques (Nm) during one complete pedal revolution were measured. Power outputs (W) were calculated as the product of instantaneous torque and pedal velocity, ensemble-averaged over a single pedal revolution. Total work (kJ) over 5 minutes or 35 minutes of FES cycling was calculated from power output and time.

Statistical analyses

Time-series data for torque production and power output were plotted and descriptive statistics were subsequently derived. Repeated measures ANOVA were used to determine whether the time main effect and time × cadence interactive effects were significant for both the 5-minute and 35-minute trials. *A posteriori* within-subjects Reverse Helmert contrasts were employed to determine which time points were significantly different from their predecessors during each trial.

To test the hypothesis that quadriceps peak torque and power decay rate was significantly affected by pedal cadence, the following steps were performed on the 5-minute data. First, for each subject and at each cadence (20 and 50 rev·min^{-1}), the time series data were fit to an exponential decay equation of the form:

$$Y = Y0 + Ae^{(-Bx)}$$

Y0, A, and B were exponential decay coefficients describing the "shape" of each subject's time-series peak torque and power data. B was the decay constant which described the non-linear decay rate of the curve. Subsequently, the decay coefficients, the R^2 and SE estimates of the regression were contrasted between 20 rev·min^{-1} and 50 rev·min^{-1} using paired *t*-tests.

Statistical results were taken to be significant if $p < 0.05$. Data are shown as mean ± SE. All analyses were undertaken using SPSS 11.5 statistical package.

RESULTS

Trial 1: isolated muscle fatigue vs pedal cadence during 5-minute iFES-LCE

At both cadences, instantaneous peak torque production demonstrated an exponential decay that fitted to the form described above (Fig. 1). Initially, peak crank torques were similar at 20 rev·min^{-1} (10.5 ± 3.1 Nm) and 50 rev·min^{-1} (9.7 ± 3.2 Nm). Peak crank torque at 20 rev·min^{-1} decreased less than that at 50 rev·min^{-1} from the first minute onwards. The torque decay constant (B) was significantly greater for 50 rev·min^{-1} compared with 20 rev·min^{-1} (0.96 vs 0.55), supporting our hypothesis that peak torque decayed faster at the higher cadences. The exponential decay equations fit the torque decay data well (average $R^2 = 0.96$), but the SE estimates for the regression were significantly greater for the 50 rev·min^{-1} torque curves (0.59 vs 0.32 Nm).

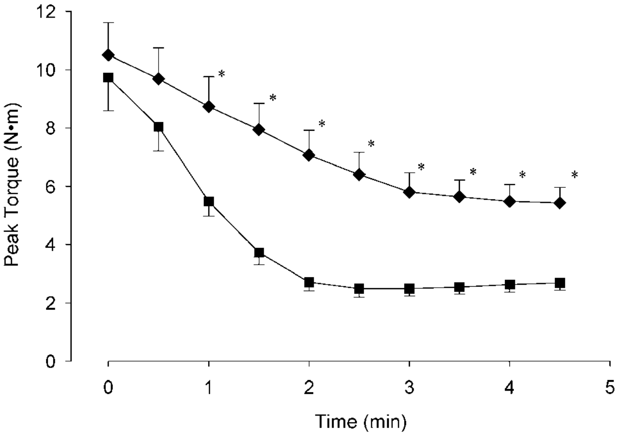

Fig. 1. Peak crank torque generated by L. quadriceps (110 mA) at cadences of 20 (diamond, $y = 3.99 + 6.71e^{-0.38t}$) and 50 rev·min^{-1} (square, $y = 2.16 + 8.02e^{-0.95t}$) over 5 minutes. The values plotted are means ± SE. *Significant difference between means ($p < 0.05$).

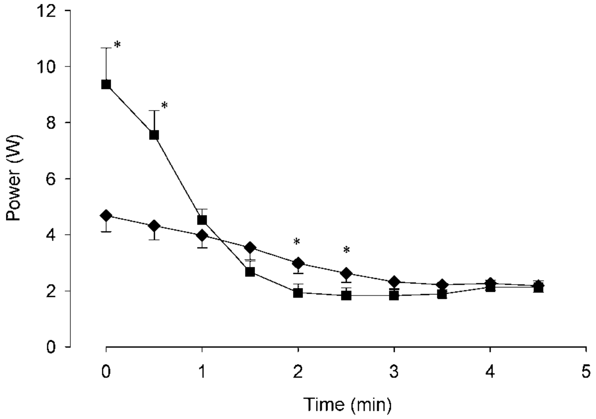

Fig. 2. Power generated by L. quadriceps (110 mA) at cadences of 20 (diamond, $y = 1.30 + 3.53e^{-0.35t}$) and 50 (square, $y = 1.60 + 8.25e^{-1.07t}$) rev·min^{-1} over 5 minutes. The values plotted are means ± SE. *Significant difference between means ($p < 0.05$).

The initial power outputs (Fig. 2) at 50 rev·min^{-1} were twice those produced at 20 rev·min^{-1} (9.4 ± 3.6 W vs 4.7 ± 1.6 W, respectively). The power output was significantly higher at 50 rev·min^{-1} for the first minute, but significantly lower between 1.5 and 2.5 minutes. The decay constants of the power output time-series data were significantly different between 20 and 50 rev·min^{-1}. This was not surprising, considering the earlier torque decay results and that power output is directly related to torque production. The total work of FES-cycling over 5 minutes was 15% greater at 50 rev·min^{-1} compared with 20 rev·min^{-1} (1.07 ± 0.09 vs 0.93 ± 0.10, $p < 0.05$).

Trial 2: muscle fatigue vs pedal cadence over 35-minute iFES-LCE

Throughout the 35-minute trial, the peak crank torques generated by the left quadriceps at 15 rev·min^{-1} were

Table II. *Peak crank torque and crank power generated by L. quadriceps (LQ) during functional electrical stimulation (FES) cycling sessions at cadences of 15 and 50 rev · min^{-1}. The values plotted are means ± SE*

Measure	Cadence	5 minutes	10 minutes	15 minutes	20 minutes	25 minutes	30 minutes	35 minutes
LQ torque	15 rev · min^{-1}	*8.0 ± 0.4	*6.5 ± 0.3	*6.1 ± 0.2	*5.9 ± 0.3	*5.4 ± 0.3	*4.8 ± 0.3	*4.1 ± 0.3
	50 rev · min^{-1}	3.8 ± 0.3	3.6 ± 0.1	3.5 ± 0.2	3.5 ± 0.2	3.4 ± 0.2	2.9 ± 0.2	2.6 ± 0.2
LQ power	15 rev · min^{-1}	2.7 ± 0.2	*2.1 ± 0.1	*1.9 ± 0.1	*1.7 ± 0.1	*1.6 ± 0.1	*1.3 ± 0.1	*1.1 ± 0.1
	50 rev · min^{-1}	3.0 ± 0.4	2.6 ± 0.1	2.7 ± 0.1	2.5 ± 0.2	2.4 ± 0.1	1.9 ± 0.1	1.7 ± 0.1

*$p < 0.05$.

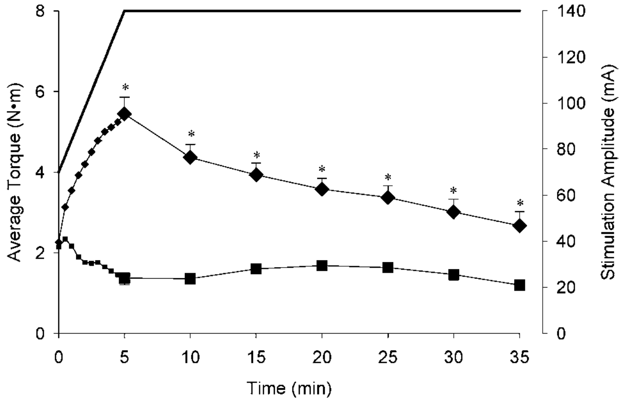

Fig. 3. Average crank torque sampled during FES cycling training sessions at cadences of 15 (diamond), and 50 rev · min^{-1} (square). The smaller points represent data sampled every 30 seconds. The larger points represent data sample every 5 minutes. The thick line represents the stimulation amplitude (mA). The values plotted are means ± SE. *Significant difference between means ($p < 0.05$).

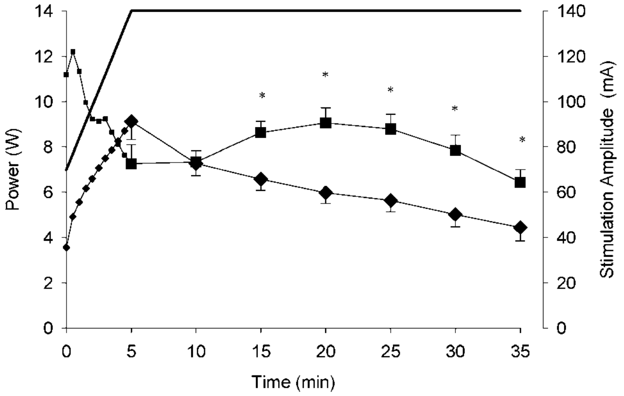

Fig. 4. Crank power during FES cycling training sessions at cadences of 15 (diamond), and 50 rev · min^{-1} (square). The smaller points represent data sampled every 30 seconds. The larger points represent data sample every 5 minutes. The thick line represents the stimulation amplitude (mA). The values plotted are means ± SE. *Significant difference between means ($p < 0.05$).

significantly greater than those generated at 50 rev · min^{-1} (Table II). Average torque for cycling with the isolated left quadriceps (data not shown) and for all muscle groups (Fig. 3) was significantly higher at 15 rev · min^{-1} than 50 rev · min^{-1} at every time point during the 35-minute session. The mean torque produced by all muscle groups over the whole session was significantly greater at 15 rev · min^{-1} (3.8 ± 0.3 Nm) than 50 rev · min^{-1} (1.5 ± 0.3 Nm).

From 10 minutes onward left quadriceps power (Table II) at 50 rev · min^{-1} was significantly greater ($p < 0.05$). Over the 35-minute session the left quadriceps produced an average of 2.4 W at 50 rev · min^{-1}, which was significantly more than the 1.8 W produced at 15 rev · min^{-1}.

Power data from FES cycling with all muscles (Fig. 4) showed a similar pattern to cycling with left quadriceps only. Power output became significantly greater at 50 rev · min^{-1} from the 15th min. The total work produced over 35 minutes of iFES-LCE was 26% significantly higher at 50 rev · min^{-1} than at 15 rev · min^{-1} (16.61 ± 1.14 kJ vs 13.21 ± 1.16 kJ, $p < 0.05$).

DISCUSSION

The 5-minute trial demonstrated that pedalling cadence had a significant effect upon torque production during iFES-LCE exercise, with torque at the lower cadence decaying more slowly. Based on the comparative torque data between cadences at $t = 0$ the results suggest that the fatigue rate had a much more significant effect on torque levels than the force-velocity relationship. The reduced fatigue rate also impacted on the 35-minute session torque data with much higher peak and average torques generated at the lower cadence by both the isolated quadriceps and all muscles combined. During the 35-minute session, at 50 rev · min^{-1} the muscles were already severely fatigued after 5 minutes, whereas at 15 rev · min^{-1} the leg muscles were relatively fresh and continued to demonstrate a slow rate of fatigue throughout the session. However, greater power outputs and work levels were observed at the higher cadences, especially towards the end of the session. The subjects tested in this study were well trained and most likely possessed some fatigue resistant muscle fibres. Nonetheless, we would have expected the trend of these results to hold if untrained SCI muscle was used.

Fatigue rate

The reason that muscle fatigue rate increased at the faster pedalling cadences was most likely the stimulation period, but may also have been related to differences in limb angular velocity. A significant difference in the muscle stimulation delivered at different pedalling cadences is the length of the contraction-relaxation period, which for FES cycling is inversely related to the pedalling cadence (i.e. high cadences have a short contraction–relaxation periods). For intermittent isometric contractions, shorter contraction–relaxation periods result in more rapid force decline (21, 22). The only other difference between the experimental trials performed in the current study was leg angular velocity. Timing considerations and the force rise times of muscle mean that the contraction angles and distance of sarcomere shortening would have been slightly affected by cadence, but this should not have greatly affected the results. A previous study (23) that investigated the relationship between knee velocity and FES fatigue rate observed that fatigue increased in proportion to the velocity. The relative contributions of stimulation period vs leg angular velocity to the different fatigue rates cannot be delineated within the current study.

Clinical implications

When selecting a training cadence, there is a trade-off between power output and muscle force, i.e. lower cadence training will develop more muscle force but less power.

Higher torques imply higher muscle forces were generated. Higher muscle forces during FES exercise has been shown to increase electrically elicited muscle strength at a greater rate than low resistance exercise (24). Therefore, lower cadence training should offer improved “doses” of strength training. An increased load on the lower limbs, through low cadence training, may provide other benefits, for example improvements in bone density. Past evidence for FES cycling improving bone density is unclear. These previous FES cycling studies were performed at cadences around 50 $\text{rev} \cdot \text{min}^{-1}$ where our data suggest muscle forces are low. Some studies indicate no improvement (25, 26), while one has shown a bone density improvement in the proximal tibia (27). However, in Bloomfield et al. (25), a subset of subjects who were able to train at higher resistances (power output $\geq$18 W) significantly increased their bone density in the distal femur. If resistance level is the criteria for improving bone density then subjects not capable of generating the forces required to improve bone density at 50 $\text{rev} \cdot \text{min}^{-1}$ could possibly generate enough while training at a slower cadence.

Muscular endurance and cardiorespiratory fitness training may not necessarily be maximized under a low cadence training regime. Training at a higher cadence and the resulting higher power outputs may be best for training cardiorespiratory benefits or muscle power. In the 5-minute isolated muscle trial and the 35-minute “typical” FES exercise session, total work of cycling was 15–26% greater at the faster pedal cadence. It is important to recognize the direct relationship between mechanical total work (kJ) and physiological energy expenditure. A greater total work, implying higher energy expenditure, may be beneficial for exercise targeted to body weight reduction via fat loss. Ultimately, both the higher gross energy expenditure (i.e. total kJ) as well as the increased rate of energy utilization (i.e. oxygen consumption) that are associated with faster pedal cadences (28) may confer superior potency of cardiovascular training during FES-cycling.

To a certain extent the “optimal” training program, with respect to muscle vs muscle power training depends upon the needs of the each SCI individual. Theoretically large forces might develop better bone density and more hypertrophy giving resistance to fractures and pressure sores. Tetraplegics or those who cannot perform voluntary arm cranking might prefer to use high power FES cycling to improve cardiovascular fitness. However, due to the poor condition of SCI muscle, even FES trained muscle, we believe the muscle can be trained for both strength and endurance.

Further research measuring physiological and cardio-respiratory data, as well as long-term training studies are necessary to investigate the advantages of training at different cadences. Past FES training programs (7, 29) have often used a FES leg extension program for building strength followed by FES cycling training to build strength and endurance. The strength training potency of FES cycling at traditional cadences (35–50 $\text{rev} \cdot \text{min}^{-1}$) is probably reduced due an increased fatigue rate.

If both high muscle forces and powers are required for optimal training then FES cycling training at multiple cadences on the same or different days is a convenient way to achieve both strength and endurance training. Another alternative would be leg extension training and FES cycling but this would require additional cost and set-up time. FES cycling at low speed should offer equivalent strength training to leg extension but have the additional advantage of training the quadriceps, hamstrings and gluteal muscle groups. If multi-cadence training within the same session is employed, the order of training is important; low cadence training should be employed first to ensure that the high force strength training takes place before the muscle is fatigued.

CONCLUSION

In conclusion we have observed that FES pedalling cadence may be an important criterion in FES cycle training. Low cadence training may be optimal for strength training while higher cadences may be best for power training. To confirm the benefits that slow cadence-high force training offers over traditional FES cycling cadences (35–50 $\text{rev} \cdot \text{min}^{-1}$) a prospective training study would be required. Further investigation must also be made into the effect of FES cycling cadences on other physiological responses, such as cardiorespiratory response and fitness.

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