Physiologic Responses During Functional Electrical Stimulation Leg Cycling and Hybrid Exercise in Spinal Cord Injured Subjects

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ABSTRACT. Mutton DL, Scremin E, Barstow TJ, Scott MD, Kunkel CF, Cagle TG. Physiologic responses during functional electrical stimulation leg cycling and hybrid exercise in spinal cord injured subjects. Arch Phys Med Rehabil 1997;78:712-8.

Objectives: (1) To determine if a hybrid exercise (leg plus arm) training program performed immediately after functional electrical stimulation (FES) leg cycle exercise (LCE) training would further improve aerobic capacity when compared with FES leg cycle training alone, and (2) to compare the submaximal responses occurring during both FES-LCE alone and hybrid exercise in the same SCI subjects.

Design: Nonrandomized control trial whereby subjects act as their own control.

Setting: Outpatient rehabilitation in a primary care hospital.

Patients: A volunteer sample ($n = 11$) of men 20 to 50 years old with complete spinal cord injury, free from cardiovascular and metabolic disease with spasticity.

Interventions: Three phases of exercise training: phase I, progressive FES-LCE to 30 minutes of exercise ($n = 11$); phase II, 35.2 ± 16.2 sessions of FES-LCE ($n = 11$); phase III, 41.4 ± 17.7 30-minute sessions of hybrid exercise ($n = 8$).

Main Outcome Measures: (1) Aerobic capacity—a further increase after hybrid exercise when compared with FES-LCE alone; (2) submaximal physiologic parameters (oxygen uptake [$\dot{V}O_2$], heart rate [HR], blood lactate [BLa^-])—measurement of these during constant work rate exercise and a training effect.

Results: $\dot{V}O_2$ (the body's ability to utilize oxygen) significantly improved ($p < .05$) after both FES-LCE and then further after hybrid training. Hybrid exercise training resulted in significantly ($p < .05$) greater work rates and $\dot{V}O_2$ values than both FES-LCE at baseline and training work rates.

Conclusion: These subjects demonstrated that hybrid exercise performed twice a week provided sufficient intensity to improve aerobic capacity and provide a medium whereby patients with SCI can burn more calories than via FES-LCE alone. This has important implications for improving the health and fitness levels of individuals with SCI and may ultimately reduce their risk of cardiovascular disease.

SPINAL CORD INJURY (SCI) results in decreased physical activity, negatively affecting the body's ability to utilize oxygen (aerobic capacity). This decrease in aerobic capacity is exemplified by low values for peak oxygen uptakes ($\dot{V}O_2$)[1] and slow oxygen uptake kinetics[2] for persons with SCI. It has been postulated that the physical inactivity caused by SCI is responsible for reduced oxidative capacity in skeletal muscle[3] and a conversion of slow-twitch fibers to fast-twitch fibers.[4] These two factors contribute to the decrease in peak $\dot{V}O_2$. Persons with SCI experience a significant decline in their physical fitness levels after injury and are at greater risk to develop cardiovascular disease.[3,5]

Various exercise programs have been developed that focus on improving the health and physical fitness levels of persons with SCI and reducing cardiovascular disease risk. These include arm exercise,[6] functional electrical stimulation leg cycle ergometry (FES-LCE)[7-10] and hybrid exercise (FES-LCE combined with arm ergometry).[11] The most dramatic improvements in cardiorespiratory endurance, an important indicator of health and physical fitness, have been demonstrated with the use of hybrid exercise.[11] Peak oxygen uptake levels after 6 weeks of FES-LCE plus 6 weeks of hybrid exercise training are greater (1.49L/min)[11] than corresponding peak $\dot{V}O_2$ values after FES-LCE training programs ranging from 12 to 26 weeks (1.0L/min).[7-10]

Previous studies evaluated the cardiorespiratory fitness levels of SCI either acutely[12,13] or after FES-LCE training programs of 12 to 26 weeks.[7-10] Improvements in aerobic capacity using FES-LCE as a training medium ranged from 20% to 35%. Peak $\dot{V}O_2$ values after training were approximately 1.0L/min. This is equivalent to an O_2 cost for an able-bodied 70-kg man walking at a pace of 3.5mph or cycling at 50 watts (W). Although activity of this nature may not be maximal for the able-bodied individual, it has been shown to be near maximal or maximal for an individual with SCI.[7-10] The only other study that evaluated the effects of hybrid exercise on maximal aerobic capacity used a shorter training period (6 weeks) immediately following 6 weeks of FES-LCE training.[11] No other research to date has evaluated the effects of long-term (6 months or longer) FES-LCE plus hybrid exercise training on the cardiorespiratory endurance of SCI individuals. In addition, there has been no research to evaluate the submaximal responses during hybrid exercise after hybrid training or to compare these responses to those occurring during FES-LCE in the same subjects. Therefore, the purpose of this study was twofold: (1) to determine whether a long-term training program utilizing hybrid exercise would further improve aerobic capacity over that initially

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Table 1: Training and Testing Protocol

Pre-Training
- Phase I—pedalling progression to 30min continuous × 2 sessions
- Pre-testing* completed
  1. Graded arm (GRA)
  2. Graded FES leg (GRL)
  3. Constant WR (CWR)
     Leg baseline (CWR leg-b)

Mid-Training
- Phase II—minimum of 24 30-min sessions of FES-LCE only
- Mid-testing* completed
  - Tests 1, 2, 3, and
  4. CWR leg relative (CWR leg-r)
  5. Graded Hybrid (GRH)
  6. CWR Hybrid (CWR-h)

Post-Training
- Phase III—minimum of 24 30-min sessions of hybrid exercise
- Post-testing* completed
- Tests #1-6

* Pre-testing, testing performed after completion of Phase I (accomodation, progressive cycling); mid-testing, testing performed after completion of Phase II (FES-LCE cycle training); post-testing, testing performed after completion of Phase III (Hybrid exercise training).

achieved with FES leg cycle training alone, and (2) to compare submaximal physiologic responses to both FES leg cycle ergometry and hybrid exercise in the same group of patients with SCI.

METHODS

Subjects. Eleven male volunteers (ages 25 to 46yrs) with SCI (C5-6 to T12-L1) participated in phase I and phase II of the study (table 1). Eight subjects also completed phase III (hybrid training). Each subject gave written informed consent prior to participation. The study was approved by the Research and Development Committee at our Veterans Administration Medical Center. Subjects underwent the following medical screening: physical exam including sensory/motor neurological assessment, blood chemistry and urinalysis, x-rays of the chest, spine, and lower limbs, 12-lead resting electrocardiogram (ECG), and arm ergometer stress test with 12-lead ECG. All subjects were American Spinal Injury Association (ASIA) Class A (ie, complete sensory and motor block below the level of injury[14]). None of the subjects had been involved in an aerobic training program before the study. All subjects used manual wheelchairs. Subject characteristics are listed in table 2.

Training program. All FES-LCE was performed on the REGYS1[a] ergometer and computer system. FES-LCE was achieved by applying carbon-filled silastic surface electrodes to the quadriceps, gluteal, and hamstrings to achieve a sequential, rhythmical cycling motion. Stimulation frequency was 30Hz and current was varied (10 to 132mA) by the computer to maintain a pedalling frequency of 50rpm. Subjects started by pedalling against a resistance load of 0W for a period of 5 to 15 minutes or until they were unable to maintain 35rpm. Each session began and ended with technician-assisted warm-up and cool down periods lasting 2 minutes. Rest periods of at least 2 minutes were incorporated between exercise bouts. The training program consisted of three phases. Table 1 is a summary of the training and testing protocols used in the study. Pre-exercise testing was performed after phase I (completion of accommodation phase). Mid-testing was after phase II (FES-LCE training) and post-testing after phase III (hybrid training). Phase I, the accommodation phase, involved successive sessions whereby the exercise duration was progressively increased until the subject was able to complete two separate 30-minute sessions of FES-LCE at 0W. Phase II, FES-leg cycle ergometry, consisted of a minimum of 24 30-minute sessions of FES-LCE performed two times per week. The training protocol started with a resistive load of 0W. The work rate (WR) was progressively increased by 6.1W when the subject was able to complete three 30-minute sessions at the previous WR. If the subject was unable to complete 30 minutes of FES-LCE at the higher WR, the WR was reduced to the previous level (without a rest period) and a total of 30 minutes were completed. Phase III (hybrid exercise) incorporated the simultaneous performance of FES-LCE, as described in phase II, combined with arm exercise using a Monark[b] arm ergometer. Every effort was made by the investigators to maintain the phase II FES-LCE work rate and to add a work rate for the arms that the subjects could maintain for 30 minutes. Subjects performed a minimum of 24 30-minute sessions of hybrid exercise two times per week.

Exercise test procedures. The following tests were performed to determine peak and submaximal physiologic responses during arm ergometry, FES-LCE, and hybrid exercise (table 1): (1) graded arm ergometry (GRA) to fatigue, (2) graded FES-LCE (GRL) to fatigue, (3) constant work rate (CWR-b) FES-LCE baseline (0W), (4) constant work rate (CWR-r) FES-LCE relative/training WR, (5) graded hybrid (GRH) (graded arm performed simultaneous with graded FES-LCE), and (6) CWR hybrid exercise (CWR-H) at relative WR. Subjects performed tests 1 through 3 pre-testing and tests 1 through 6 mid- and post-testing, after phases II and III of the training program (table 1).

Graded exercise tests. Eleven subjects performed GRA and GRL testing pre- and mid-training while eight subjects additionally performed GRA, GRL, and GRH mid- and post-training. The graded arm ergometry test (1) consisted of an initial warm-up phase at 0W for 3min, followed by an increase in WR of 5W every minute until fatigue. The graded FES-LCE test (2) consisted of 2min of technician-assisted pedalling warm-up, following by 5-min stages of increasing work rates to fatigue. The initial WR of 0W was increased by 6.1W every 5min. Fatigue occurred when FES cycling could no longer be maintained at 35rpm. Graded hybrid testing (5) consisted of an initial warm-up with FES-LCE and arms followed by increases in WR every 5min; WR for the legs started at 0W and was increased by 6.1W every 5min, while the arm work rate started at 0W and was increased by 10 to 25W every 5min depending on the subject's peak arm tolerance, as previously determined from test 1.

Constant WR exercise tests. Eleven subjects performed constant WR tests with legs only (FES-LCE) pre- and mid-training, while eight subjects performed CWR FES-LCE pre-,

Table 2: Subject Characteristics

Subject	Age (yrs)	Ht (cm)	Wt (kg)	Lesion Level	TSI (yrs)	Cause of Injury
1	33	188.0	62.6	C5-6	15	Diving
2	37	182.9	104.4	C6-7	3	MVA
3	33	177.8	72.6	T4	11	MVA
4	45	172.7	95.3	T4-5	8	MVA
5	25	177.8	81.7	T5	3	GSW
6	42	175.3	79.4	T6-7	9	MVA
7	46	180.3	99.4	T9	12	MVA
8	29	182.9	63.5	T12-L1	11	MVA
9	31	177.8	62.6	T6	13	Infection
10	37	172.7	68.1	T9	12	GSW
11	33	172.7	61.3	T4	10	MVA
Mean	35.6	178.3	77.4		9.7	
±SD	6.6	4.9	16.0		3.8	

Subjects 1-8 participated in all phases of training, whereas subjects 1-11 completed FES leg cycle training only.
Abbreviations: TSI, time since injury; MVA, motor vehicle accident; GSW, gun shot wound.

mid-, and post-training and hybrid testing mid- and post-training. Constant WR tests included an initial resting period (2 to 3min), a warm-up period of 2 to 3min, 10 minutes of constant WR exercise, and finally, 10 minutes of recovery. The CWR FES-LCE tests, baseline (3) and relative (4), were performed at WRs of 0W and at each subject's training WR, respectively. The CWR hybrid test (6) was performed at a WR for legs and arms that the patient could maintain for 10 minutes. WRs were determined from peak WRs during GRA and GRL tests as well as the WR from CWR FES-LCE relative tests.

Measurements. Pulmonary gas exchange was measured breath-by-breath during each test using a Medical Graphics CPX metabolic cart.[c] Gas analyzers and pneumotach were calibrated before each test. Periodic validations were performed using a Gas Exchange Calibrator.[c,15] The highest $\dot{V}O_2$ over the last 60-sec interval was considered peak $\dot{V}O_2$ for each graded test. Values for $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), ventilation ($\dot{V}_E$), respiratory exchange ratio (RER), and heart rate (HR) were averaged for the last minute of graded testing and for the last 2 minutes of CWR exercise. HR was measured continuously using a six-lead configuration, printed out every 30sec and stored in the Medical Graphics file on a breath-by-breath basis. Blood pressure was taken before and after each test by auscultation. Arterialized blood lactate (BLa^-) samples were obtained via a finger-prick before and within 2 minutes after end-exercise and immediately analyzed using a 1500 Sport Lactate Analyzer.[d]

Statistical analysis. Two different modes of analysis of variance (ANOVA) were used to analyze the data. A randomized block ANOVA with repeated measures was used to compare pre- to mid-training changes in physiological responses during GRA and GRL for the 11 subjects participating in the FES-LCE training. A randomized block ANOVA was used to compare pre- and mid-training differences in metabolic responses between CWR FES-LCE baseline and relative tests. The same analysis was performed for the group of eight subjects but the GRH and CWR-H tests were included as well as the third time point (post-training). When significant *F* values ($p < .05$) were observed, a Scheffe post hoc was used to determine significant differences between means. All data are presented as mean ± standard deviation (SD).

RESULTS

Training

Eleven subjects completed 17.1 ± 8.0 sessions of the accommodation phase I (pedalling progression) over 8.2 ± 3.9 weeks, averaging 2.3 ± .59 times per week. During phase II, FES-LCE training only, subjects completed 35.2 ± 16.2 sessions over 18.2 ± 11.1 weeks, averaging 2.1 ± .41 times per week. When we calculated the number of training sessions for the eight subjects who completed the hybrid exercise training (phase III), in addition to phases I and II, the results were as follows: phase I, 14.0 ± 5.9 sessions over a period of 7.0 ± 3.5 weeks, averaging 2.3 ± 0.6 times per week; phase II, 38.3 ± 17.1 sessions in 20.4 ± 11.7 weeks, averaging 2.0 ± 0.4 times per week; and phase III, 41.4 ± 17.7 sessions in 24.5 ± 10.6 weeks, averaging 1.75 ± .36 times per week. Over the entire training period (phases I, II, and III, inclusive) these eight subjects trained for a total of 93.6 ± 28.1 sessions over a period of 51.9 ± 21.5 weeks, averaging 1.9 ± .30 times per week. There were no reported episodes of autonomic dysreflexia or other complications during any of the training sessions.

Graded Testing

Phase II—FES leg cycle training. Values for peak $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, HR, O_2 pulse ($\dot{V}O_2$/HR), and WR for graded arm and graded FES-LCE tests before and after FES leg cycle training for the 11 subjects are displayed in table 3. In response to FES-LCE training, both peak $\dot{V}O_2$ and peak WR during GRL but not GRA testing improved with training. No other physiologic variables were significantly different as a result of the training. Peak WR and HR for GRA exercise were significantly higher than for GRL exercise, both before and after training. Peak O_2 pulse was significantly lower during GRA than during GRL both before and after FES-LCE training.

Table 3: Peak Physiologic Responses During Graded Arm and Graded FES Leg Cycle Testing Before and After FES Leg Cycle Training (Phase II) (N = 11)

Variable	Pre–FES-LCE (PRE)	Post–FES-LCE (MID)
WR (W)		
GRA	55.5 ± 17.6	55.5 ± 24.0
GRL	10.5 ± 4.8†	14.4 ± 4.9*†
$\dot{V}O_2$ (mL/min)		
GRA	1,350 ± 387	1,355 ± 503
GRL	1,295 ± 271	1,424 ± 339*
$\dot{V}CO_2$ (mL/min)		
GRA	1,549 ± 499	1,557 ± 640
GRL	1,447 ± 317	1,546 ± 324
$\dot{V}_E$ (L/min)		
GRA	56.6 ± 17.0	57.3 ± 13.5
GRL	55.8 ± 16.4	59.0 ± 14.0
HR (beats/min)		
GRA	161.8 ± 20.2	153.8 ± 21.5
GRL	13.1 ± 26.3†	132.5 ± 22.2†
O_2Pulse (mL O_2/beat)		
GRA	8.3 ± 2.0	8.7 ± 2.8
GRL	9.8 ± 1.2†	10.6 ± 2.2†

Abbreviations: GRA, graded arm; GRL, graded FES leg.
* Significantly ($p \leq .05$) different pre- to post-training.
† Significant ($p \leq .05$) difference between modes (GRA and GRL).

Hybrid training. Values for peak physiologic responses during GRA, GRL, and GRH both before and after hybrid training are displayed in table 4. As a result of the hybrid training, peak $\dot{V}O_2$, $\dot{V}CO_2$, and O_2pulse were significantly increased during graded hybrid testing, but not during graded arm or graded FES leg testing alone. Hybrid exercise training resulted in a 13% improvement in peak $\dot{V}O_2$ during hybrid exercise, but no further increases in either peak arm or peak FES-LCE $\dot{V}O_2$ were noted. Legs responded to hybrid training without significant changes in any of the physiologic variables except WR, which increased 28% (from 13.7 ± 5.4 to 17.5 ± 6.9W). Arms did not respond with any significant changes in any physiologic variables as a result of the hybrid training. Comparisons were also made between GRA, GRL, and GRH tests. After hybrid training, GRH peak $\dot{V}O_2$ and $\dot{V}CO_2$ were significantly higher than GRA and GRL values. Before training, peak $\dot{V}O_2$ and $\dot{V}_E$ during GRH were significantly higher than those obtained during GRA but not GRL testing. Before hybrid training peak HR during GRL testing was significantly lower than during both GRA and GRH; after training there was no significant differences between peak HR for any of the tests.

Constant Work Rate Exercise

Phase II—FES leg cycle training. Table 5 identifies the physiologic responses occurring during constant work rate FES leg cycle testing at the baseline (0W) and relative (training WR) before and after FES-LCE training. In response to the FES-LCE training, there were no significant changes in any physiologic variables during the baseline CWR tests at unloaded cycling (0W). In contrast, values for $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, HR, O_2pulse, and blood lactate during the CWR-relative test were significantly higher than CWR-baseline test. This was expected due

Table 4: Peak Physiologic Responses During Graded Arm, FES Leg Cycle, and Hybrid Testing Before and After Hybrid Training (Phase III) (N = 8)

Variable	Pre–Hybrid (MID)	Post–Hybrid (POST)	Comments
WR (W)			
GRA	55.6 ± 28.3	59.4 ± 23.5	
GRL	13.7 ± 5.4†	17.5 ± 6.9†*	GRL < GRH, GRA (pre, post)
GRH	36.6 ± 23.4	45.4 ± 24.2	
$\dot{V}O_2$ (mL/min)			
GRA	1,319 ± 585	1,441 ± 547	
GRL	1,504 ± 330	1,567 ± 451	
GRH	1,691 ± 635†	1,911 ± 485†*	GRH > GRA (pre); GRH > GRA (post)
$\dot{V}CO_2$ (mL/min)			
GRA	1,517 ± 736	1,642 ± 620	
GRL	1,633 ± 291	1,713 ± 403	
GRH	1,884 ± 608	2,125 ± 502*†	GRH > GRA, GRL (post)
$\dot{V}_E$ (L/min)			
GRA	57.2 ± 15.0	61.5 ± 17.2	
GRL	63.0 ± 10.1	73.2 ± 16.4	
GRH	73.3 ± 19.9†	78.4 ± 19.1†	GRH > GRA (pre, post)
HR (beats/min)			
GRA	150.6 ± 23.0	147.5 ± 22.4	
GRL	138.5 ± 16.7†	144.8 ± 20.3	GRL < GRA, GRH (pre)
GRH	151.6 ± 11.3	151.9 ± 16.0	
O_2Pulse (mL O_2/beat)			
GRA	8.6 ± 3.3†	9.6 ± 3.0†	GRA < GRL, GRH (pre, post)
GRL	10.8 ± 1.5	10.7 ± 2.1	
GRH	11.0 ± 3.7	12.7 ± 3.4*	

Abbreviations: GRA, graded arm; GRL, graded leg; GRH, graded hybrid (arm + leg).
* Significantly ($p \leq .05$) different pre- to post-training.
† Significant ($p \leq .05$) difference between modes. See comments.

to the consistent increase in training WR from unloaded cycling to a mean of 11.4W.

Phase III—Hybrid exercise training. Table 6 identifies the physiologic responses for CWR exercise during CWR baseline and relative, and CWR hybrid tests before and after hybrid exercise training for eight subjects. In response to the hybrid training, the subjects were able to achieve a significantly higher WR during hybrid CWR testing (22.2W vs. 32.4W). The only change in physiologic variables as a result of the hybrid training was a significant decrease in HR during unloaded FES-LCE (CWR-b). However, several of the physiologic variables were significantly lower during unloaded cycling (CWR-b) than during either CWR-r or CWR-H exercise. This was expected because the WR during unloaded cycling was significantly lower (0W) than either CWR-r (11.4W) or CWR-H (32.4W) after training. WR and $\dot{V}O_2$ during CWR-H testing were significantly greater than during FES-LCE CWR-r testing after hybrid training. None of the other variables was significantly different. The latter is not surprising because both were performed at similar relative percentages of peak $\dot{V}O_2$ representing 95% and 89% of GRL and GRH exercise, respectively. After hybrid training, FES-LCE CWR-b was performed at 54% of peak GRL $\dot{V}O_2$, accounting for the significantly lower values for physiologic variables.

DISCUSSION

Peak Physiologic Responses During FES-LCE Training (Phase II)

Subjects improved their aerobic capacity 10%, from 1.29 to 1.42L/min, which was statistically significant but not as dramatic as that found by other investigators. Improvements in aerobic fitness levels of 22% to 92% have been reported in subjects with SCI after FES-LCE training. These FES-LCE training programs ranged from 6 to 26wks.[7-10] Our subjects participated in 35 sessions of FES-LCE over a period of 18 weeks, at a frequency of 2.1 times per week. This difference in training improvement may be due to the training protocol we instituted, which required subjects to complete two 30-minute sessions of FES-LCE (phase I) before starting the 24 sessions of FES-LCE training. Pre-training peak $\dot{V}O_2$ was measured after phase I, which ranged anywhere from 2 to 14 weeks (mean = 8 weeks; 17 sessions) and probably resulted in improvements in the subject's aerobic capacity above entry baseline that were not measured. Subjects in our study also obtained higher peak $\dot{V}O_2$ values (1.42L/min) than other studies during post–FES leg testing after FES-LCE training. Other investigators have reported post-training peak values of approximately 1.0L/min after FES-LCE training programs of 6 to 26 weeks.[7-10] In line with the improvements in $\dot{V}O_2$ peak, our subjects exhibited significant improvements in peak WR, from 10.5W to 14.4W. This is expected because increases in peak $\dot{V}O_2$ are normally accompanied by improvements in peak WR. Other researchers have reported comparable significant improvements in peak WR with improvements in peak $\dot{V}O_2$ to only 1.0L/min.[7,11] It is possible that the higher peak $\dot{V}O_2$ values at similar peak WR of our subjects is a function of the type of ergometer used. Our subjects trained on the REGYS I cycle ergometer, which has an upright cycle ergometer design allowing more upper body movement and may result in higher $\dot{V}O_2$ values. Conversely, both Hooker et al[7] and Krauss et al,[11] who reported lower peak $\dot{V}O_2$ values, trained their subjects on the ERGYS cycle ergometer, which has a recumbent design.

Improvements in peak aerobic capacity are the result of central and/or peripheral changes. The central adaptations that can occur as a result of an endurance training program include increases in stroke volume and arteriovenous oxygen difference (a-v O_2 difference).[16] Since we did not measure cardiac output

Table 5: Steady State Physiologic Responses During Constant WR Exercise Testing for FES Leg Cycle at Baseline (0W) and Relative (Training) WRs Before and After FES Leg Cycle Training (N = 11)

Variable	Pre–FES-LCE (PRE)	Post–FES-LCE (MID)
WR (W)		
CWR—baseline	0	0
CWR—relative		11.4*
$\dot{V}O_2$ (mL/min)		
CWR—baseline	969 ± 208	910 ± 219
CWR—relative		1,358 ± 399*
$\dot{V}CO_2$ (mL/min)		
CWR—baseline	1,067 ± 211	978 ± 264
CWR—relative		1,506 ± 470*
$\dot{V}_E$ (L/min)		
CWR—baseline	39.8 ± 10.7	35.7 ± 11.7
CWR—relative		54.8 ± 14.3*
HR (beats/min)		
CWR—baseline	104.4 ± 16.4	103.4 ± 16.3
CWR—relative		124.6 ± 28.4*
O_2Pulse (mL O_2/beat)		
CWR—baseline	9.3 ± 1.5	8.8 ± 1.8
CWR—relative		10.9 ± 2.2*
Respiratory Exchange Ratio (RER)		
CWR—baseline	1.11 ± .12	1.07 ± .08
CWR—relative		1.11 ± .08
Blood Lactate (mM)		
CWR—baseline	6.3 ± 1.6	6.4 ± 2.5
CWR—relative		8.5 ± 1.6*

Abbreviations: CWR, constant WR; baseline, unloaded cycling (0W); relative training WR.
* $p < .05$ CWR—relative significantly greater than CWR—baseline both before and after training. No significant differences were noted between pre- and post-training for any variable during CWR baseline test.

Table 6: Steady State Physiologic Responses During Constant WR Exercise Testing for FES Leg Cycle and Hybrid Testing Before and After Hybrid Training (N = 8)

Variable	Pre–Hybrid (MID)	Post–Hybrid (POST)	Comments
WR (W)			
CWR-b	0.0 ± 0.0	0.0 ± 0.0	
CWR-r	11.4 ± 3.9	11.4 ± 3.9	
CWR-H	22.2 ± 13.0†	32.4 ± 14.3*†	CWR-H > CWR-b, CWR-r (pre, post) CWR-H (post) > CWR-H (pre)
$\dot{V}_2$ (mL/min)			
CWR-b	951 ± 207†	854 ± 168†	CWR-b < CWR-r, H (pre, post)
CWR-r	1,435 ± 423	1,486 ± 610	
CWR-H	1,623 ± 748	1,693 ± 534†	CWR-H > CWR-b, CWR-r (post)
$\dot{V}CO_2$ (mL/min)			
CWR-b	1,032 ± 246†	880 ± 162†	CWR-b < CWR-r, H (pre, post)
CWR-r	1,581 ± 496	1,632 ± 670	
CWR-H	1,659 ± 646	1,764 ± 517	
$\dot{V}_E$ (L/min)			
CWR-b	38.8 ± 11.1†	37.2 ± 10.6†	CWR-b < CWR-r, H (pre, post)
CWR-r	59.7 ± 12.0	67.0 ± 12.8	
CWR-H	67.0 ± 21.2	66.1 ± 14.9	
HR (beats/min)			
CWR-b	105.3 ± 15.1	93.3 ± 15.2*†	CWR-b < CWR-r, H (post)
CWR-r	130.0 ± 27.8	129.3 ± 29.4	CWR-b (post) < CWR-b (pre)
CWR-H	136.0 ± 25.7	135.1 ± 26.6	
O_2Pulse			
CWR-b	9.1 ± 1.8†	9.2 ± 1.4†	CWR-b < CWR-r, H (pre, post)
CWR-r	11.1 ± 2.6	11.1 ± 2.5	
CWR-H	11.5 ± 3.4	12.4 ± 2.7	
Respiratory Exchange Ratio (RER)			
CWR-b	1.09 ± .08	1.03 ± .05†	CWR-b < CWR-r (post)
CWR-r	1.10 ± .09	1.10 ± .04	
CWR-H	1.03 ± .10	1.05 ± .07	
Blood Lactate (mM)			
CWR-b	6.0 ± 3.2†	5.7 ± 1.1†	CWR-b < CWR-r, H (pre, post)
CWR-r	8.6 ± 1.9	10.8 ± 2.2	
CWR-H	9.5 ± 2.2	10.1 ± 3.2	

Abbreviations: CWR-b, constant WR—baseline (0W); CWR-r, constant WR—relative (training work rate); CWR-H, constant WR—hybrid (training work rate).
* Pre- to post-training significance, $p \leq .05$.
† Between-mode significance, $p \leq .05$.

in this study, it is not clear if the improvements in peak $\dot{V}O_2$ during FES-LCE exercise resulted from an increase in stroke volume. Oxygen pulse represents the amount of oxygen extracted by the tissues of the body with each heart beat. O_2 pulse values are dependent on the stroke volume and the a-v O_2 difference.[17] Our subjects demonstrated an increased peak $\dot{V}O_2$ with no change in peak HR (increased O_2pulse) during GRL testing after training, suggesting that stroke volume, a-v O_2 difference, or both increased.

Peripheral adaptations in the muscle may also account for improvements in peak $\dot{V}O_2$ with exercise. These peripheral adaptations include increased mitochondria and capillarity, and increased muscle oxygenation and blood flow.[16] Our SCI subjects also demonstrated improvements in the rate of adjustment of $\dot{V}O_2$ following the onset, and in recovery from constant work FES-LCE.[18] This suggests that improvements in the muscle's aerobic capacity and blood flow, increases in type I fibers, and/or increases in mitochondria and capillarity may have occurred. Previous research has shown a predominance of Type II fibers in patients with SCI.[4] Increased proportions of Type I muscle fibers in the tibialis anterior muscles of SCI subjects after 24 weeks of FES were found by Martin et al.[19] It is possible that changes occurred in the muscle fiber composition (ie, increased Type I fibers) that may account for some of the improvement in peak $\dot{V}O_2$ and for enhanced muscle peripheral adaptations in our subjects.

A comparison was made between the peak physiologic responses occurring during graded FES-LCE and graded arm testing before and after FES-LCE training. The major differences were seen with HR and oxygen pulse (table 3). The heart rate during FES-LCE testing was significantly lower than during arm testing, both before and after training. This is consistent with findings reported by Krauss et al,[11] whose subjects demonstrated higher peak HR responses during arm exercise. Able-bodied individuals normally exhibit similar peak heart rates during graded leg exercise when compared with graded arm exercise, even though peak WR, $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}_E$ during arm exercise are significantly lower than peak leg responses.[20] In able-bodied individuals, the smaller muscle mass used in arm exercise places a greater strain on the small muscle group and muscular fatigue occurs at a lower power output and oxygen uptake level than leg exercise. This is not what was found in this study. Our subjects experienced muscular fatigue before the achievement of a high peak HR. SCI with complete paralysis below the level of the lesion results in extreme deconditioning of the leg muscles, thereby reducing their aerobic and oxidative capacity. This severely limits the SCI individuals's ability to generate the power output required to sufficiently challenge the cardiorespiratory system. Before any FES leg cycle training, the ability to achieve high peak HRs, oxygen uptake levels, and power outputs is severely limited in the SCI individual because of the extreme deconditioning of their leg muscles.

Peak Physiologic Responses During Hybrid Training (Phase III)

A major objective of this study was to determine whether an additional training phase of hybrid exercise, when performed immediately after the FES-LCE training, would result in further improvements in the subjects' aerobic capacities. In our study, peak $\dot{V}O_2$ increased from 1.69L/min to 1.91L/min (13%) during hybrid testing after hybrid training. This $\dot{V}O_2$ of 1.91L/min represents a 48% increase over the 1.29L/min attained during the pre-training FES-LCE testing. Furthermore, this is 28% higher than the peak $\dot{V}O_2$ reported by Krauss et al,[11] who trained SCI subjects for 12 weeks using 6 weeks of FES-LCE immediately followed by 6 weeks of hybrid exercise training. The greater $\dot{V}O_2$ values demonstrated by our subjects may be a result of a longer hybrid training program (24 weeks) and greater number (42) of sessions. The ability of our subjects to achieve higher peak $\dot{V}O_2$ values provides evidence that the capability exists for further improvement of aerobic capacity by SCI individuals who are willing to train for longer periods of time or with a greater whole-body training intensity (hybrid exercise).

As a result of the hybrid training, subjects were able to achieve higher peak WRs during GRL testing. This was not seen with GRA or GRH testing. The increase seen in the GRL WR but not the GRA WR is reflective of the training WR performed by the subjects during hybrid training. Graded leg WR increased 71% from 5.3W to 9.2W (3.9W), whereas graded arm WR increased only 26% from 16.9W to 21.3W (4.4W) after hybrid exercise training. The greater increase in GRL WR may have resulted from our efforts to maintain FES leg cycling endurance at a given WR and perform arm ergometry at one third of the peak arm WR. Krauss et al[11] reported similar results after 6 weeks of hybrid training.

Graded hybrid testing resulted in a significantly higher peak $\dot{V}O_2$ than did either graded leg (22% greater) or graded arm testing (33% greater). Peak $\dot{V}CO_2$ was also significantly greater during GRH when compared with GRA and GRL after training. These results are consistent with those found by Krauss et al[11] and are reflective of the greater total metabolic rate that results when an additional load (added arm ergometry) is put on the cardiorespiratory system during hybrid exercise. Although peak HR during GRL testing was significantly lower than GRA and GRH before hybrid training, this was not the case after the hybrid training. The power outputs achieved during post–GRL (17.5W) versus pre–GRL (13.7W) may have placed an additional stress on the patient's cardiorespiratory system to sufficiently increase the HR. The mechanism for the reduced HR response often seen with FES LCE is not understood.[2,3,18] The significantly lower O_2pulse seen with graded arm testing as compared with graded leg or hybrid testing was a function of the lower peak $\dot{V}O_2$ attained during GRA testing.

Physiologic Responses During Phase II and III Training: Constant WR FES Leg Cycle Testing and Hybrid Exercise Testing

As expected, blood lactate (BLa^-) levels were significantly lower during the unloaded FES cycling (0W) as compared with the relative WR for FES cycling and hybrid testing after FES-LCE and hybrid exercise training (tables 5, 6). These lower blood lactate values were in line with the significantly lower $\dot{V}O_2$ values during unloaded FES cycling. The high lactate values are consistent with values reported by others who have conducted FES leg cycling programs with SCI subjects.[11,12] When compared with able-bodied individuals performing upright cycling, these BLa^- values are extremely high for the low power outputs performed by the patients. It is possible that the high BLa^- values experienced by subjects during FES cycle exercise are a function of the type of muscle fiber recruited (Type II vs. Type I), the decrease in the oxidative fibers associated with SCI,[4,19] and the effect of FES on the recruitment of motor units in a synchronous pattern.[4] The precise impact of FES cycle training on muscle aerobic capacity and fiber composition is still unknown.

HR during the CWR baseline test was significantly lower after hybrid training, indicating improvements in cardiorespiratory fitness.[16] The subjects exhibited a significant improvement in their training WR during hybrid exercise from 22.2W to 32.4W, demonstrating that a greater demand was put on the cardiovascular system during hybrid exercise training. Some previous researchers have attributed the ability to pedal at higher power outputs during longer durations of FES-LCE (ie, 30min vs. 5min) to increases in muscle strength and endurance.[21] In the present study, the high HR experienced by our subjects during hybrid exercise (135 beats/min) were associated with greater WR and metabolic rates. The hybrid exercise HR was 89% of maximal HR during the post-training GRH test. Using a FES-LCE training program similar to our Phase I program, Faghri et al[21] found significant reductions in submaximal exercise BP and HR and increases in SV and cardiac output in SCI subjects. He suggested these improvements in cardiorespiratory fitness were due to activation of the venous muscle pump and facilitation of venous return, and that the increases in SV and cardiac output were an indicator of improved cardiac volume loading.[21] It is also possible that the decrease in submaximal HR in our subjects during FES leg cycling at the same WR (0W) was a result of facilitated venous return and increased stroke volume. However, this was specific to FES-LCE exercise only, suggesting that the improvement in SV under these conditions may have resulted from improved control of the peripheral circulation affecting venous return (vasoconstriction and redistribution of blood flow) and not from a primary increase in heart size.

Aerobic exercise results in energy expenditure at the rate of approximately 5 kilocalories per liter of oxygen consumed.[22] Our subjects experienced a caloric expenditure of approximately 150 to 200kcal/session or 300 to 400kcal/week during FES-LCE training and a twofold increase during hybrid exercise to 250 to 300kcal/session or 500 to 600kcal/week. The energy expenditure experienced with aerobic exercise has also been attributed to more favorable levels of high density lipoprotein cholesterol (HDL-C) as seen in SCI wheelchair athletes versus sedentary SCI subjects.[23,24] Many researchers have postulated that high HDL-C levels represent a reduced risk for cardiovascular disease.[5,23-25] The optimum intensity and duration of physical activity necessary to reduce cardiovascular risk in patients with SCI remains unknown. The extent to which FES-LCE and hybrid exercise training reduce the risk of cardiovascular disease in SCI subjects requires further study.

CONCLUSION

The ability of our subjects to significantly increase (22%) their peak aerobic capacity ($\dot{V}O_2$ 1.91L/min) with hybrid exercise over that achieved during FES leg cycling (1.57L/min) is an important finding in this study. Not only did the hybrid exercise training enable the subjects to attain greater improvements in their aerobic capacity, but it allowed them to burn additional calories during training. Increases in the level of physical activity, either by increasing exercise duration or intensity, are vital for improving aerobic capacity. FES leg cycling and hybrid exercise have been shown to produce the highest levels of oxygen uptake and the greatest energy expenditure in these patients. Providing an exercise that can improve the leg muscle's aerobic capacity and provide an avenue for high energy expenditure may help reduce the risk of cardiovascular disease in SCI patients. Other researchers have related increases in physical activity to changes in risk factors (lipid profiles, obesity, insulin sensitivity, physical inactivity, etc).[25] Spinal cord injured athletes have demonstrated significantly higher total HDL cholesterol levels and HDL subfractions when compared with their sedentary counterparts.[24] Future studies are needed using FES leg cycle and hybrid exercise programs to determine the upper limit for improvements in aerobic capacity, the peripheral mechanisms accounting for the changes in aerobic capacity, the changes occurring in muscle fiber composition and oxidative capacity, and the amount of exercise training required to substantially reduce the risk of cardiovascular disease.

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