Department of Veterans Affairs

JRRD Volume 45, Number 6, 2008
Pages 819–830
Journal of Rehabilitation Research & Development

Effects of modified electrical stimulation-induced leg cycle ergometer training for individuals with spinal cord injury

Thomas W. J. Janssen, PhD;[1–2*] D. Drew Pringle, EdD[2]
[1]Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, the Netherlands, and Duyvensz-Nagel Research Laboratory, Rehabilitation Center, Amsterdam, the Netherlands; [2]Wright State University School of Medicine, Dayton, OH

Abstract—Computer-controlled electrical stimulation (ES)-induced leg cycle ergometer (ES-LCE) exercise can be beneficial for individuals with spinal cord injury (SCI), but exercise performance is often insufficient for eliciting continuous gains in cardiopulmonary training adaptations. The first purpose of this study was to determine whether a modified ES-LCE improved exercise performance and responses compared with the standard ES-LCE. Modifications to the ES-LCE included increased ES current amplitude (140–300 mA), added shank muscle activation, and increased ES firing angle ranges (+55°). The second purpose was to evaluate the effects of a 6-week interval training program (ITP) with this modified methodology on ES-LCE exercise performance, peak metabolic and cardiorespiratory responses, and muscle strength in experienced and novice riders. No significantly different peak values for power output and stroke volume were found for the two systems, but the modified ES-LCE elicited significantly higher peak values for oxygen uptake (+22%), carbon dioxide production (+51%), pulmonary ventilation (+37%), cardiac output (+32%), heart rate (+19%), and blood lactate concentration (+50%). Power output, metabolic rate, and lower-limb muscle strength increased significantly following training. This study showed that an ITP with the modified ES-LCE can elicit marked improvements in ES-LCE performance (peak power output), peak metabolic and cardiorespiratory responses, and muscle strength in men with SCI, even in those subjects whose performance has plateaued during training on the standard ES-LCE.

Key words: cardiopulmonary response, electric stimulation therapy, exercise therapy, leg cycle ergometer, metabolic response, muscle performance, paraplegia, rehabilitation, spinal cord injury, tetraplegia.

INTRODUCTION

Computer-controlled electrical stimulation (ES)-induced leg cycle ergometry (ES-LCE) technology was developed in the early 1980s to permit individuals with spinal cord injuries (SCIs) to pedal via rhythmic induced contractions of the paralyzed quadriceps (Q), hamstring (H), and gluteal (G) muscle groups. This original ES-LCE technology, which became commercially available in 1984, has been shown to provide physiological and psychological benefits in individuals with SCI [1–7] that may be unattainable with conventional arm exercise modes [8]. However, a problem frequently encountered with long-term ES-LCE therapy relates to the person's

Abbreviations: CO = cardiac output, ECG = electrocardiogram, ES = electrical stimulation, ES-LCE = ES-induced leg cycle ergometry, FI = fatigue index, G = gluteal, GS = gastrocnemius-soleus, GXT = graded exercise test, H = hamstring, HR = heart rate, ITP = interval training program, LA = blood lactate concentration, PO = power output, PO_{max} = maximum PO, PP = paraplegia, Q = quadriceps, SCI = spinal cord injury, SV = stroke volume, TA = tibialis anterior, TP = tetraplegia, $\dot{V}CO_2$ = carbon dioxide production, $\dot{V}e$ = pulmonary ventilation, $\dot{V}O_2$ = oxygen uptake.

*Address all correspondence to Thomas W. J. Janssen, PhD; VU University, Faculty of Human Movement Sciences, Van der Boechorststraat 9, 1081 BT Amsterdam, the Netherlands; +31-20-5988586; fax: +31-20-5988529. Email: t.janssen@fbw.vu.nl
DOI: 10.1682/JRRD.2007.09.0153

inability to exercise at sufficiently high intensity levels to elicit continuous gains in exercise performance and corresponding cardiopulmonary training adaptations. Typically, individuals initiate training at a power output (PO) of 0 W, progress to 6 to 12 W after several weeks, and plateau at this level for long periods. This mediocre exercise performance results in limited exercise responses and training effects, which can discourage individuals and healthcare providers from using this therapy.

However, the efficacy of the original ES-LCE technology may be markedly improved by appropriate modifications of ES parameters and muscle groups activated. For instance, results show that a combination of upper-body and ES-LCE exercise, so-called hybrid exercise, can markedly enhance exercise responses [9–11]. Even though this technique appears very useful for promoting central cardiovascular and metabolic responses, it will not improve exercise and integrity of the paralyzed legs. In contrast, increasing maximal ES current from the original 140 to 300 mA was shown to notably improve ES-LCE exercise responses, including significant increases in PO and cardiorespiratory and metabolic variables [12–13]. Also, several studies have shown that stimulation parameters and cycling cadence can affect cycling performance [14–17]. Studies further found that augmented metabolic and cardiorespiratory responses could be obtained when shank muscle groups were additionally activated [18]. In addition, Schutte et al. predicted, based on a biomechanical modeling technique, that ES firing angle ranges could be substantially widened from those originally used to provide a smoother and more continuous propulsive action by increasing the contraction duty cycle [19]. Thus, a modified ES-LCE system using combinations of these modified parameters could provide greater overload capability that enhances muscular and cardiopulmonary adaptations.

The plateau in training effects may also be related to the commonly used protocol for ES-LCE training, which requires up to 45 min of continuous exercise at a constant PO level during each session. This protocol does not appear to provide the continuous overload necessary to markedly improve exercise performance. Thus, developing a training program in which each session consists of several bouts of shorter duration but higher intensity exercise may be desirable.

Therefore, the first purpose of this study was to determine whether a modified ES-LCE improved ES-LCE exercise performance and peak metabolic and cardiorespiratory responses compared with the standard ES-LCE. The second purpose was to evaluate the effects of a new short-term interval training program (ITP) with this modified methodology on ES-LCE exercise performance, peak metabolic and cardiorespiratory responses, and isolated muscle group performance of experienced and novice riders.

METHODS

Subjects

Twelve men with chronic SCI (six with tetraplegia [TP] and six with paraplegia [PP]) volunteered to participate in this study. Subjects were medically screened for contraindications to ES-LCE exercise, such as severe leg muscle tightness or orthopedic problems (e.g., heterotopic ossification) that impede cycling exercise, pressure sores in the G region, occurrence of autonomic dysreflexia after ES, and severe cardiopulmonary problems. Each subject signed an informed consent form approved by Wright State University's Institutional Review Board prior to participation. Relevant subject characteristics are shown in **Table 1**. The subject group included four subjects (age 44 ± 14 yr, time since injury 13 ± 8 yr) who had trained on the standard ES-LCE during the previous 6 ± 1 yr (all data presented as mean ± standard deviation unless otherwise noted). These subjects had been in a regular training program, the goal of which was to cycle at the highest exercise intensity and load resistance possible for 30 min, which is the commonly used program. Hence, in spite of efforts to exercise at a higher intensity level, they did not succeed but had plateaued with no further improvement possible with the standard ES-LCE. The remaining eight subjects were considered novice users.

ES-LCE Instrumentation

ES-LCE was performed on a modified ERGYS 1 system (Therapeutic Alliances, Inc; Fairborn, Ohio). A custom-built, 10-channel, current control system [20], which had the capability to boost maximal current output from the original 140 mA (monophasic pulses) to 300 mA (biphasic rectangular wave, pulse duration 300 µs, frequency 35 Hz) was retrofitted to the ERGYS. Before exercise, two active and one reference rectangular carbonized electrodes were placed over motor points of not only the Q, H, and G muscle groups but also the gastrocnemius-soleus (GS) and tibialis anterior (TA) muscle groups. The current control

Table 1.
Relevant subject characteristics.

Subject	Age (yr)	Lesion Level	Motor Complete	Time Since Injury (yr)	ES-LCE Experience
1	24	C4–5	No	8	Novice
2	41	C5–6	No	11	Experienced
3	20	C6	Yes	2	Novice
4	42	C6	Yes	23	Experienced
5	63	C6	Yes	15	Experienced
6	23	C6–7	No	7	Novice
7	30	T5–6	Yes	15	Novice
8	70	T5–8	Yes	29	Novice
9	34	T6	Yes	2	Novice
10	29	T6	Yes	6	Experienced
11	29	T9	Yes	0.75	Novice
12	32	T10–11	Yes	14	Novice
Mean ± SD	36 ± 16	—	—	11 ± 9	—

C = cervical, ES-LCE = electrical stimulation-induced leg cycle ergometer, SD = standard deviation, T = thoracic.

system essentially receives the 6 channels of ES output from the ERGYS and provides 10 channels of output. The additional four channels of ES were used to activate the right and left TA and GS muscles. ES to these muscles was configured so that they would cocontract with the Q and H, respectively. ES firing angles were widened by 55° (20° before and 35° after each standard ES firing) from the standard ERGYS settings using a custom, erasable, programmable, read-only memory chip plugged directly into the ERGYS. Thus, contraction times were increased from about 0.07 to 0.2 s. Based on the results by Schutte et al., these increments were considered not to hinder cycling and would provide a smoother and more continuous propulsive action by increasing the contraction duty cycle [19]. A separate front panel permitted us to set the current limit for each muscle group before as well as during exercise periods. Maximal current amplitude was set to 300 mA for the G and thigh muscles and 110 mA for the shank muscles. Two subjects (2 and 6) who had partial sensate skin could only tolerate up to 180 mA.

A retrofit load resistance controller [20] for the ERGYS incorporated the standard ERGYS load cell and particle brake to provide a continuous and immediate setting of flywheel braking force by the turn of a dial, eliminating the need to discontinue exercise to reset the resistance. With this system, load resistance could be varied at will during continuous or intermittent exercise protocols. In addition, maximal resistance was increased from the original 7/8 kp (8.6 N) to 2 kp (19.6 N), which allowed maximal attainable PO to increase from 43 to 98 W. **Figure 1** illustrates the modified ES-LCE system.

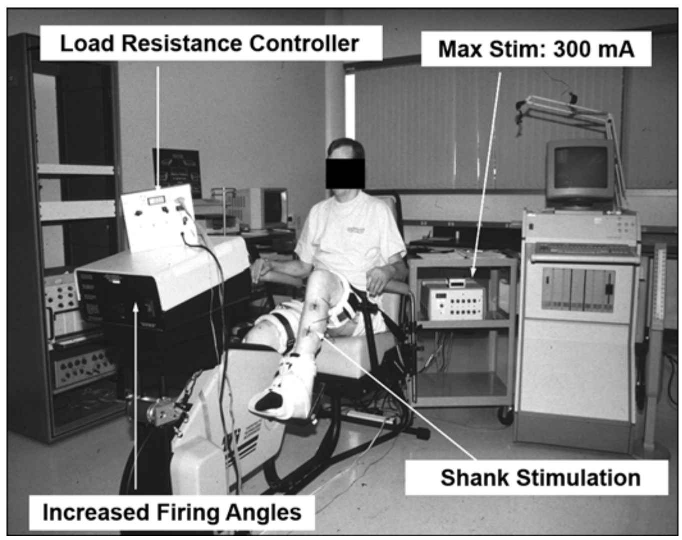

Figure 1.
Subject on modified electrical stimulation-induced leg cycle ergometer system, showing load resistance controller, shank stimulation, and 10-channel current control system. Max Stim = maximum stimulation.

We recorded resistance and crank rate continuously and used the values to calculate PO.

ES-LCE Exercise Performance and Metabolic and Cardiorespiratory Responses

Before the training period, each subject performed two graded exercise tests (GXTs) with at least 2 days between tests to determine maximum PO (PO_{max}) and peak metabolic and cardiopulmonary responses. One test was performed on the standard ES-LCE system and the other on the modified system. After the training period, all subjects performed one GXT on the modified system. A continuous progressive-intensity exercise protocol was designed. This protocol, enabled by the new resistance controller, is essentially different from the commonly used discontinuous protocol. The protocol was initiated with exercise without resistance applied. Subsequently, resistance was increased every 2 min by 1/16 kp (3 W at 49 rpm) until cadence dropped from 49 to below 35 rpm, at which time exercise was ended.

During the GXT, metabolic and cardiorespiratory responses were determined noninvasively. We measured oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and pulmonary ventilation ($\dot{V}e$) using open-circuit spirometry (System 2001, Medical Graphics Corp; St. Paul, Minnesota). Maximal 30 s average values for $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}e$ were determined. Heart rate (HR) was continuously monitored via electrocardiogram (ECG) signals. During the 10 s immediately after exercise cessation (during end-expiratory apnea), we noninvasively assessed central hemodynamic responses, i.e., stroke volume (SV), and cardiac output (CO) by impedance cardiography [21] using a Minnesota impedance cardiograph (Model 304B, Surcom Inc; Minneapolis, Minnesota). The impedance cardiogram was recorded from four aluminized tape electrodes positioned on the neck and trunk [22]. We used semiautomated software to digitize and analyze analog recordings of the impedance cardiogram, ECG waveforms, and phonocardiogram. Five minutes after exercise, a fingertip blood sample was analyzed for blood lactate concentration (LA) (YSI, Inc; Yellow Springs, Ohio) to estimate the anaerobic energy supplementation. Because of technical problems, valid impedance cardiography data were collected in only 10 subjects and LA data in only 8 subjects.

Muscle Performance

We evaluated muscle performance of the right leg using a system that consisted of a custom-built ES unit, a dynamometer (Kin-Com II, Chattanooga Group Inc; Hixson, Tennessee), a data acquisition computer, and appropriate software. The system linked the Kin-Com embedded signal processing board output signals of force, position, and velocity through buffer amplifiers to the computer. The ES unit, interfaced with the computer and the Kin-Com, allowed for variability in current amplitude range from 0 to 300 mA, pulse frequencies from 10 to 100 Hz, pulse duration from 50 to 600 µs, and various waveforms through the waveform generator. For this study, the stimulator was set at a frequency of 35 Hz and pulse duration of 500 µs, with a balanced biphasic square waveform. Bipolar surface electrodes (EMPI Inc; St. Paul, Minnesota) were placed over motor points of the muscle group being tested (G, Q, H, TA, GS). The motor points, determined with a handheld motor point locator, were defined as the site producing the greatest muscle twitch for a fixed current.

To evaluate H and Q force development, we seated subjects in an upright position on the Kin-Com at a hip flexion angle of 80° and a knee flexion angle of circa 100° (resting position). The lateral femoral condyle was aligned along the lever arm's axis of rotation. The leg was attached to the lever arm by a Velcro™ strap, and the center of the shin pad (attached to the force transducer) was placed approximately 1 inch proximal to the malleolus. To evaluate plantar and dorsiflexion performance, we positioned subjects in a supine posture with legs fully extended. The right foot was attached to a specially designed device that allowed only ankle rotation. The lateral malleolus was aligned to the axis of rotation of the transducer. Velcro straps placed on the upper thigh, around the hips, and across the chest provided additional support and prevented extraneous movement. To evaluate G performance, we positioned subjects in a supine posture with the right hip in 90° flexion. The greater trochanter was aligned with the transducer's axis of rotation. The leg was attached to the lever arm with a Velcro strap, and the pad was placed on the dorsal thigh just proximal of the knee joint. The hips were stabilized with a wide strap placed across the iliac crests.

Twenty ES-induced isometric contractions were performed with a ramped linear increase in current from 0 to 300 mA in 12 s, followed by an identical ramped decrease in current from 300 to 0 mA. Rest intervals between contractions were set to 5 s. Either the current amplitude was permitted to increase if force output was less than 150 N or current was automatically reversed when 150 N was reached. This maximal force limit was set as a safety factor to prevent injury. The 150 N maximal force limit has been used in our research laboratory for the past 25 years with no incidence of orthopedic injury or other problems. We adjusted the recorded force to account for limb weight, and we calculated peak torques for the first and twentieth contractions. To estimate fatigue resistance, we calculated a fatigue index (FI) by calculating a ratio between peak torque and the current amplitude needed to achieve this peak torque, dividing this ratio of the last contraction by that of the first contraction, and multiplying by 100 percent. Just calculating a FI based on a ratio between peak torques of the last and first contraction was not valid because it was not clear in many cases what the real peak torque was as a result of the 150 N safety limit.

Training Program

Subjects trained two to three times a week over 6 weeks for a total of 18 sessions using the modified ES-LCE. The goal of each training session, consisting of at least three exercise bouts, was to achieve 25 to 30 min of cumulative exercise. Target time for each progressive exercise bout was between 5 and 10 min. Each bout was followed by a 5 min rest interval. The systematic increase in resistance during the exercise bout at each of 26 training levels is illustrated in **Figure 2**. The initial level was established by the pretraining exercise test. If subjects were able to exercise between 5 and 10 min on this test, they would start at level 3, which had the same load progression as the exercise test. If they were unable to exercise for 5 min, they started at a lower level, and if they exercised longer than 10 min, they started at a higher level. The level was adjusted subsequent to each bout to maintain the 5 to 10 min target, ensuring continuous overload as exercise ability increased. This pattern was followed throughout the training period.

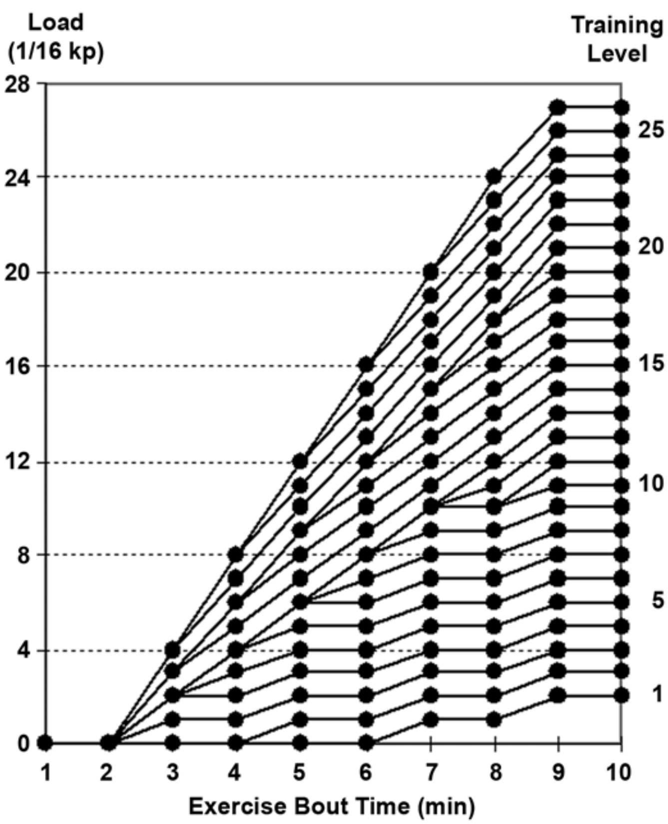

Figure 2.
Systematic increase in resistance load during each exercise bout for 26 training levels.

Data Analysis

We used a general linear model with repeated measures to evaluate exercise responses on the standard versus the modified system. Two-way interaction effects were studied for the between-subjects factors lesion level (PP vs TP) and ERGYS experience level (novice vs experienced). We used the same model to compare exercise responses and muscle performance parameters before and after the training program on the modified system. The significance level was set at $p = 0.05$.

RESULTS

Standard Versus Modified Before Training

Table 2 shows the results from the two GXTs and compares the standard with the modified system before the training program. PO levels achieved before training were not significantly different for the standard versus the modified systems. A tendency toward interaction effects was noted ($p < 0.1$), suggesting that those with PP and the experienced users performed worse on the modified system, while those with TP and the novice users performed better on the modified system.

No significant differences in SV were found for the two systems before training. In contrast, the modified ERGYS elicited significantly higher peak values for $\dot{V}O_2$ (+22%), $\dot{V}CO_2$ (+51%), $\dot{V}e$ (+37%), CO (+32%), HR (+19%), and LA (+50%) than the standard system. A significant interaction effect was found for HR and LA, suggesting that compared with the subjects with PP, those with TP showed larger differences between the systems for these two variables. For the remaining variables, no significant interactions between subject groups and system effects were found. Even though for all variables a general trend toward higher values in those with PP was noted, no statistical significance was reached.

Table 2.
Results (mean ± standard deviation) from graded exercise tests for four subject groups: tetraplegia (TP) (n = 6), paraplegia (PP) (n = 6), experienced (Exp) (n = 4), and novice (Nov) (n = 8) and for all subjects combined (Total) (n = 12) comparing standard with modified system and comparing responses before and after training.

Variable	Before Training		After Training
	Standard	Modified	
Power Output (W)			
TP	4.4 ± 4.0	5.6 ± 2.5	10.8 ± 5.2
PP	12.8 ± 12.1	11.5 ± 13.7	16.2 ± 12.7
Exp	9.0 ± 6.8	6.3 ± 0.1	13.9 ± 7.6
Nov	8.4 ± 11.3	9.7 ± 12.2	13.3 ± 11.1
Total	8.6 ± 9.7	8.6 ± 9.9	13.5 ± 9.7*
Peak $\dot{V}O_2$ (mL/min)			
TP	603 ± 139	718 ± 134	956 ± 139
PP	738 ± 284	919 ± 417	1,174 ± 364
Exp	698 ± 167	765 ± 125	991 ± 147
Nov	657 ± 235	845 ± 347	1,101 ± 310
Total	670 ± 208	818 ± 287†	1,065 ± 264*
Peak $\dot{V}CO_2$ (mL/min)			
TP	709 ± 178	1,145 ± 226	1,328 ± 115
PP	820 ± 274	1,163 ± 532	1,481 ± 512
Exp	814 ± 180	1,164 ± 182	1,275 ± 108
Nov	740 ± 256	1,149 ± 473	1,470 ± 433
Total	765 ± 228	1,154 ± 390†	1,405 ± 363*
Peak $\dot{V}e$ (L/min)			
TP	28.9 ± 10.7	40.2 ± 11.4	46.3 ± 2.9
PP	31.4 ± 7.3	42.5 ± 14.7	52.4 ± 12.4
Exp	35.2 ± 12.7	42.4 ± 11.6	50.3 ± 7.4
Nov	27.1 ± 5.1	40.6 ± 13.6	48.4 ± 11.6
Total	30.1 ± 9.0	41.3 ± 12.3†	49.1 ± 9.1*
Max CO (L/min)			
TP	5.8 ± 1.1	8.5 ± 2.1	8.5 ± 2.0
PP	7.1 ± 1.6	8.7 ± 2.0	10.6 ± 2.3
Exp	5.7 ± 1.1	8.2 ± 2.2	8.8 ± 2.5
Nov	7.0 ± 1.5	8.9 ± 1.9	10.0 ± 2.2
Total	6.5 ± 1.4	8.6 ± 1.9†	9.5 ± 2.3
SV (mL)			
TP	84.0 ± 9.0	87.7 ± 24.2	80.6 ± 13.4
PP	81.2 ± 29.4	95.6 ± 24.8	101.9 ± 37.3
Exp	75.9 ± 12.5	82.8 ± 24.3	86.5 ± 11.9
Nov	87.1 ± 24.6	97.6 ± 23.1	94.4 ± 37.1
Total	82.6 ± 20.6	91.7 ± 23.5	91.2 ± 28.7
Max HR (bpm)			
TP	74.1 ± 16.2	99.1 ± 10.2‡	115.0 ± 25.4
PP	91.3 ± 14.8	95.4 ± 13.2	111.3 ± 22.6
Exp	77.0 ± 23.0	98.6 ± 11.3	109.3 ± 29.4
Nov	84.7 ± 14.5	96.8 ± 12.0	115.6 ± 20.8
Total	81.9 ± 17.3	97.4 ± 11.2†	113.3 ± 23.0*
LA (mmol/L)			
Exp	5.3 ± 1.8	7.5 ± 1.4	9.1 ± 0.9
Nov	3.5 ± 1.7	5.7 ± 2.1	8.3 ± 1.0
Total	4.4 ± 1.9	6.6 ± 1.9†	8.7 ± 1.0*

*Significant increase from before training.
†Significantly different from standard training.
‡Significantly higher increase than in PP.
CO = cardiac output, HR = heart rate, LA = blood lactate concentration, Max = maximum, SV = stroke volume, $\dot{V}CO_2$ = carbon dioxide production, $\dot{V}e$ = pulmonary ventilation, $\dot{V}O_2$ = oxygen uptake.

Effects of Training on Metabolic and Cardiorespiratory Responses

On the modified system, we found significantly higher peak values for PO (+57%), $\dot{V}O_2$ (+29%), $\dot{V}CO_2$ (+22%), $\dot{V}e$ (+19%), HR (+16%), and LA (+32%) after the training period compared with before training (**Table 2**). Peak SV values were not significantly different after training, nor were peak CO values, although a tendency toward an increase was seen ($p = 0.13$). No significant interaction effects were found, indicating that those with PP responded similarly to those with TP and that the experienced users improved in the same way as the novice users.

Muscle Performance

While stimulating the TA muscle during the muscle performance tests, we found that at higher stimulation amplitudes, spread of the electrical current to the GS muscles occurred, inducing cocontraction of these muscle groups. Since the GS muscles were generally stronger, a plantar flexion moment instead of the intended dorsiflexion moment was recorded, making TA strength with this system and setup impossible to determine.

Table 3 shows the peak torque and FI data for the four remaining muscle groups before and after the training period. Peak torques during the first contraction were significantly higher after training for the GS (+25%), the H (+19%), and the G muscles (+47%), but not for the Q muscle group. A tendency toward an interaction effect was found for the H muscles ($p = 0.098$), suggesting that the TP group improved more than the PP group. Peak torques during the last contraction were significantly higher after training for the GS (+33%), the H (+47%), the G (+89%), and the Q muscles (+65%). In addition, a significant interaction effect was found, which indicates that H muscles of the novice users had improved more than those of the experienced users. FI increased significantly only for the Q muscles, even though a tendency toward an increase was seen for the GS and H muscle groups ($p < 0.15$). In addition, a tendency toward an interaction for the H muscles was noted, suggesting that only the FI of the novice users had improved after training.

DISCUSSION

The goals of this study were to determine whether a modified ES-LCE improved ES-LCE exercise performance and peak metabolic and cardiorespiratory responses compared with the standard ES-LCE and whether a new short-term ITP with this modified methodology could improve ES-LCE exercise performance, peak metabolic and cardiorespiratory responses, and muscle performance in experienced and novice users. We found that the modified system indeed increases most exercise responses and that this short-term ITP with the modified ES-LCE can elicit significant improvements in exercise performance (PO), peak metabolic and cardiorespiratory responses, and muscle performance in individuals with SCI, even in those whose performance has plateaued during long-term training on the standard ES-LCE.

Standard Versus Modified ES-LCE

For the whole group of subjects, PO_{max} on the standard ES-LCE did not significantly differ from that on the modified ES-LCE. However, the experienced riders showed a tendency toward a decline in performance, whereas the novice riders showed the opposite. In contrast, using both experienced and novice users, Figoni et al. demonstrated a large (from 8.6 to 19.4 W, +124%) improvement when maximal current was increased from 140 to 300 mA [12]. This discrepancy might be partially explained by the fatiguing effects of the longer (+0.13 s) contraction duty cycle with wider firing angle ranges used in the present study. In addition, these wider firing angles might result in increased muscle activity without a marked contribution to the external PO. Also, the shank muscle activation may have interfered somewhat with the cycling exercise, even though movement around the ankle is very limited with the ERGYS system. The data suggest that especially those individuals trained on the standard system may be responsive to the increased firing angles.

Although PO_{max} was not always immediately improved with the modified system, higher metabolic and cardiovascular responses were obvious. In agreement with Figoni et al. [12], $\dot{V}O_2$, $\dot{V}e$, HR, CO, and LA were markedly higher with the modified system. In addition, $\dot{V}CO_2$ increased by 51 percent which, combined with the increased LA, indicates that anaerobic metabolism was noticeably higher with the modified system. The higher CO was mainly due to an increase in HR, while SV was not significantly different, a result also found by Figoni et al. [12]. These results may have been influenced to a certain extent by the fact that CO, HR, and SV were determined immediately after exercise cessation, which may have resulted in lower values than during actual exercise

Table 3.
Results (mean ± standard deviation) of muscle performance tests before and after training period for four subject groups: tetraplegia (TP) (n = 6), paraplegia (PP) (n = 6), experienced (Exp) (n = 4), and novice (Nov) (n = 8) and for all subjects combined (Total) (n = 12).

Muscle Group	Before Training			After Training		
	Peak Torque (N·m)		FI (%)	Peak Torque (N·m)		FI (%)
	First	Last		First	Last	
Quadriceps						
TP	42.7 ± 11.1	22.4 ± 14.0	42.6 ± 22.5	42.9 ± 10.5	32.5 ± 16.1	58.1 ± 25.3
PP	40.0 ± 12.3	12.7 ± 5.8	26.6 ± 10.2	46.9 ± 2.2	26.2 ± 10.8	39.8 ± 17.9
Exp	48.0 ± 0.0	25.6 ± 15.3	42.6 ± 30.5	48.0 ± 0.0	30.4 ± 12.0	44.6 ± 28.1
Nov	37.7 ± 12.7	13.6 ± 7.1	31.2 ± 9.5	42.9 ± 9.6	29.2 ± 15.5	52.8 ± 21.7
Total	41.4 ± 11.1	18.0 ± 11.7	35.3 ± 19.1	44.7 ± 7.8	29.6 ± 13.7*	49.8 ± 23.2*
Hamstring						
TP	15.6 ± 10.6	4.8 ± 3.8	29.5 ± 7.6	19.7 ± 10.4	7.7 ± 4.5	37.3 ± 11.5
PP	13.7 ± 9.1	5.1 ± 3.6	42.4 ± 17.9	14.9 ± 8.0	6.7 ± 3.6	47.4 ± 10.6
Exp	14.3 ± 11.3	4.8 ± 4.2	32.3 ± 2.3	17.4 ± 10.3	5.8 ± 4.2	29.8 ± 6.7
Nov	15.0 ± 9.3	5.0 ± 3.4	37.1 ± 18.0	17.6 ± 9.5	8.1 ± 3.8*	48.8 ± 7.4
Total	14.8 ± 9.5	4.9 ± 3.5	35.7 ± 14.2	17.5 ± 9.3*	7.3 ± 3.9*	41.9 ± 11.8
Gluteal						
TP	27.5 ± 12.6	12.7 ± 11.3	37.7 ± 12.5	39.7 ± 11.0	25.6 ± 13.5	54.2 ± 17.5
PP	14.1 ± 8.7	7.4 ± 5.2	49.8 ± 14.7	21.9 ± 10.4	11.5 ± 5.4	51.8 ± 12.6
Exp	30.4 ± 14.5	9.6 ± 2.8	37.0 ± 17.3	42.0 ± 14.4	22.4 ± 14.7	45.5 ± 14.8
Nov	18.6 ± 11.1	11.0 ± 11.3	44.9 ± 13.3	28.5 ± 12.1	18.9 ± 13.0	56.5 ± 14.9
Total	22.1 ± 12.7	10.6 ± 9.4	42.6 ± 14.1	32.6 ± 13.7*	20.0 ± 12.8*	53.2 ± 15.0
Gastrocnemius-Soleus						
TP	28.8 ± 11.8	14.0 ± 17.7	28.8 ± 23.4	34.2 ± 8.6	17.0 ± 16.5	29.5 ± 16.4
PP	16.2 ± 10.5	4.7 ± 3.1	30.0 ± 14.5	22.4 ± 15.0	8.2 ± 6.1	28.2 ± 21.4
Exp	27.6 ± 14.1	16.1 ± 21.5	35.6 ± 25.1	37.8 ± 9.4	21.2 ± 18.8	31.1 ± 24.8
Nov	20.5 ± 11.8	6.1 ± 5.8	25.8 ± 15.6	23.6 ± 12.0	8.3 ± 6.2	27.4 ± 15.8
Total	23.1 ± 12.5	9.8 ± 13.6	29.3 ± 19.0	28.8 ± 12.8*	13.0 ± 13.1*	28.8 ± 18.4

*Significant increase from before training.
FI = fatigue index.

and underlines the relatively high exercise responses found. These higher metabolic and cardiorespiratory responses are most likely due to the recruitment of additional muscle fibers and the longer duty cycle, which may provide greater metabolic overload and better elicit muscle and cardiopulmonary system training adaptations.

The apparent disagreement between the lack of change in PO and the increased metabolic responses suggests that the increased muscle activity was not contributing to cycling performance. Indeed, this apparent reduction in mechanical efficiency may be the result of inferior biomechanics [19]. Moreover, the activation of the shank muscles certainly augmented metabolism [18], while the restricted ankle movement probably prevented an actual contribution to the cycling performance [23]. Also, the higher current amplitudes may have resulted in some cocontraction of antagonistic muscle groups, which reduces cycling efficiency. Although a lower efficiency can be considered of little consequence for stationary cycling ergometry [24], it is not beneficial for outdoor cycle systems that have recently been developed.

The subjects indicated the perceived increase in exercise intensity by their comments about how much harder they had to work (predominantly as a result of higher ventilation) with the modified ES-LCE compared with the standard ES-LCE. The recovery time needed after the training session was extended accordingly. Because of the intense exercise and the added activation of the shank muscles, vasodilation in the legs appeared to be notably augmented. While essentially no problems in blood pressure regulation (extreme high or low blood pressure) were encountered during exercise, upon completion of exercise bouts, lower-limb blood pooling and hypotension probably occurred in some subjects, predominantly those with TP, because of cessation of the skeletal muscle pump that resulted in light-headedness. In such cases, the subject was placed in the recumbent position to facilitate venous return and reduce light-headedness. Continuing ES-LCE at zero resistance during rest intervals to maintain skeletal muscle pump activity may be advantageous and alleviate this situation. No other adverse events, such as autonomic dysreflexia, were noted with the modified system, indicating that this exercise can be performed without serious problems.

Effects of Modified Training

Exercise performance (PO_{max}) and metabolic and cardiorespiratory exercise responses in all subject groups (PP and TP, novice and experienced users) increased markedly after the relatively short training program on the modified ERGYS. These improvements were in agreement with previous training programs on the original system [25–27]. Even the subjects who had plateaued on the standard system improved markedly, indicating that the standard system is not capable of providing a continuous overload once a plateau has been reached.

The lack of a recorded change in CO after the training may be due to a lower total peripheral resistance as a result of a greater dilation of the lower-limb blood vessels and an increased vascular bed. These changes may have caused a decreased venous return immediately after exercise, the time at which CO was determined, which was also indicated by the light-headedness of some subjects after exercise. As a matter of fact, the lack of a decreased CO may actually suggest that CO during exercise was increased. With the current measuring technique, longer training periods at the higher PO levels may be required to elicit adaptations for improving this response. Still, we are not entirely certain that this ES-LCE exercise was able to sufficiently stress the heart to induce changes in the cardiac system. However, since this type of exercise on the standard systems has been shown to (partially) reverse myocardial atrophy in those with TP [28], longer training periods with the modified system and the higher CO levels may ultimately lead to even more structural cardiac adaptations.

Generally, the highest PO achieved during the first and last training sessions was higher than the PO achieved during the GXTs. This discrepancy may be explained by two factors. First, as a result of the GXT protocol, which started at a low PO level, some subjects had to exercise for a longer period than 10 min, which could have resulted in premature fatigue. Second, we noted that several subjects performed markedly better during a second or third training bout (within the same session), which could be explained by a fatigue-induced reduction in spasticity or muscle stiffness, whereas the GXT consisted of only one exercise period. Hence, an underestimation of the PO levels achieved during this exercise when only data from the GXTs were used may have occurred. As a practical consequence, when a GXT is being administered, having a subject perform a fatiguing exercise bout before the actual test could be considered. Although this exercise would increase the PO levels achieved, the "real" maximal PO would not be attained in this way. Hence, we need an optimized GXT that can really determine peak PO levels.

Postexercise LA values increased considerably after the training period. These values were similar to values reported for sedentary nondisabled individuals performing maximal voluntary exercise [29] but higher than most values found for regular ES-LCE exercise [25,30]. Since $\dot{V}O_2$ peak values were markedly lower than in nondisabled individuals, the high LA values indicate that ES-LCE exercise not only has a large absolute but also a markedly high relative anaerobic component, even though this exercise is supposedly mainly aerobic in nature. Exercise on the modified system appears to depend even more on the anaerobic energy system.

The finding that CO showed no increase and $\dot{V}O_2$ did increase suggests that the arterio-venous oxygen difference was improved. This improvement may be the result of either an improved distribution of blood to the active muscle fibers; an improved uptake capability from the muscle fibers as a result of factors such as a higher capillary density, more and larger mitochondria, and more aerobic enzymes; or both. Studies from Hopman et al. [31], Gerrits et al. [32], and Thijssen et al. [33–34] have indeed shown that ES-LCE can improve peripheral circulation.

In contrast to the commonly used training protocol of 30 min of continuous submaximal exercise at a predetermined load resistance, this study used a protocol where resistance was increased every 2 min, resulting in maximal performance and subsequent fatigue occurring between 5 and 10 min. The advantage of this protocol is that maximal exercise responses are reached at least three times per session and that total work performed is greater, potentially providing more overload and better adjustment to improved performance capabilities than the regular training protocol. In addition, not only is the aerobic energy system stressed but also the anaerobic system, which provides a training stimulus of all energy systems.

Muscle Performance

As a result of the ES-LCE training, muscle performance of all muscle groups studied markedly improved. Peak torques during the first contraction improved significantly in all muscle groups except for the Q. The latter can be explained by the fact that, as a result of the safety limit of 150 N, maximal muscle force was not reached in many contractions, especially during the first few contractions of the Q muscles. This result is in agreement with a study by Gerrits and colleagues, who found that at a similar pulse duration of 250 µs (compared with 300 µs in the present study), the current amplitude needed to achieve a force of approximately 143 N in the Q of a group of six subjects with SCI was on average 142 mA [35]. The current needed to induce maximal contractions resulting from 20 Hz stimulation was 347 ± 95 mA,* leading to forces of 451 ± 75 N. In the present study, it was obvious for all muscle groups that an ES current amplitude of 140 mA and a pulse duration of 300 µs (the combination is called the pulse charge), which is the maximum limit in the current amplitude of the original ERGYS, was not sufficient to recruit all motor units, since stronger contractions were induced by the 300 mA. This limitation in pulse charge could to a certain extent be countered by increasing pulse duration.

Not only did the peak torques improve but also fatigue resistance improved considerably in all muscle groups, which is in agreement with other studies involving ankle or knee extension [36–37] or leg cycling exercise [38] induced by ES in individuals with SCI.

To our knowledge, this study is the first to report G muscle performance in SCI; physiological data have mainly focused on shank and Q muscle groups [37–42]. As a result of the 6-week training, G muscle strength increased significantly. This increase was to be expected, since Baldi et al. showed that ES-LCE not only prevents G muscle atrophy in individuals with recent SCI but even induces a marked hypertrophy of this muscle group [1]. Apparently, the G muscles are in better condition after ES-LCE training, stronger and more resistant to fatigue, and probably have better circulation. These factors combined may reduce risk of pressure sores as well.

Clinical Implications

The improved exercise and training responses with the modified system indicate that the standard ES-LCE is not optimal in providing continuous overload. Although in novice users the standard system may be sufficient for achieving overload, in experienced users who have plateaued at a certain exercise level, the modified system seems necessary to provide further sufficient overload.

The higher PO after training on the modified system may result in higher loading of the long bones of the legs, which may be helpful in the prevention or counteraction of osteoporosis. Bloomfield et al. showed that bone mineral density changes might be related to exercise load [43]. In a small group of subjects who were able to cycle at or above 18 W, they found an 18 percent increase in bone mineral density of the proximal femur after 3 months of cycle training. In the present study, four subjects were able to cycle at that PO level after the 6-week period, suggesting that training on this modified system might be helpful in reducing the risk of bone fractures. However, since the relation between bone density, bone strength, and related bone fracture is not yet entirely clear in this population, more research is needed to confirm this hypothesis.

Activation of the shank muscles during ES-LCE exercise resulted in improved muscle performance, probably because of improved circulation, enzyme activity, and fiber hypertrophy. Hence, the additional activation of these muscles not only augments metabolic responses but may also be beneficial for shank muscle and skin integrity and improved muscle bulk and appearance.

CONCLUSIONS

The results of this study show that a modified ES-LCE system clearly can increase subjects' metabolic and cardiopulmonary response magnitudes and that the ITP appeared to appropriately adjust the load resistance to the progressively increasing exercise capabilities. Finally, we can conclude that a short-term ITP with the modified ES-LCE can elicit significant improvements in ES-LCE exercise performance (PO_{max}), peak metabolic and cardiorespiratory responses, and muscle performance in individuals with SCI, even in those whose performance has plateaued during long-term training on the standard ES-LCE.

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*Janssen, Thomas W. J. (Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, the Netherlands). Conversation with: Karin Gerrits, PhD (Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, the Netherlands). 2007 Mar.

ACKNOWLEDGMENTS

The assistance of Traci Rackett-Humble and José Almeyda with the data collection is much appreciated. We would also like to thank William Couch for building all necessary modifications to the ERGYS system as well as the ES unit for evaluating muscle performance. Most importantly, we would like to thank Prof Dr. Roger Glaser (deceased) for initiating this project and for his stimulating thoughts.

This material was based on work supported by the Department of Veterans Affairs Rehabilitation Research and Development Service, grant B433-2RC.

The authors have declared that no competing interests exist.

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Submitted for publication September 21, 2007. Accepted in revised form February 6, 2008.