Metabolic and hemodynamic responses to concurrent voluntary arm crank and electrical stimulation leg cycle exercise in quadriplegics

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Abstract—This study determined the metabolic and hemodynamic responses in eight spinal cord injured (SCI) quadriplegics (C5–C8/T1) performing subpeak arm crank exercise (ACE) alone, subpeak functional electrical stimulation leg cycle exercise (FES-LCE) alone, and subpeak FES-LCE concurrent with subpeak ACE (hybrid exercise). Subjects completed 10 minutes of each exercise mode during which steady-state oxygen uptake (\(\dot{V}_\text{O}_2\)), pulmonary ventilation (\(V_E\)), heart rate (HR), cardiac output (CO), stroke volume (SV), mean arterial pressure (MAP), arteriovenous oxygen difference (a-v O\(_2\) diff), and total peripheral resistance (TPR) were determined. Although mean \(\dot{V}_\text{O}_2\) for both ACE alone and FES-LCE alone was matched at 0.66 l/min, individualized power outputs ranged from 0–30 W (\(\bar{x} = 19.4 \pm 1.3\)) and 0–12.2 W (\(\bar{x} = 2.3 \pm 0.6\)), respectively. Hybrid exercise elicited significantly higher \(\dot{V}_\text{O}_2\) (by 54 percent), \(V_E\) (by 39–53 percent), HR (by 19–33 percent), and CO (by 33–47 percent), and significantly lower TPR (by 21–34 percent) than ACE or FES-LCE performed alone (\(P \leq 0.05\)). Stroke volume was similar between hybrid exercise and FES-LCE alone, and these two exercise modes evoked a significantly higher SV (by 41–56 percent) than during ACE alone. These data clearly demonstrate that hybrid exercise creates a higher aerobic metabolic demand and cardiac-volume load in SCI quadriplegics than either subpeak levels of ACE or FES-LCE performed separately. Therefore, hybrid exercise may provide more advantageous central cardiovascular training effects in quadriplegics than either ACE or FES-LCE alone.

Key words: aerobic metabolism, cardiopulmonary, exercise, functional neuromuscular stimulation, rehabilitation, spinal cord injury, therapy.

INTRODUCTION

Traditional rehabilitation programs have prescribed upper-body exercise (i.e., arm crank ergometry, wheelchair propulsion, and weight training) for the improvement of health, fitness, and functional capacity in patients with lower limb disabilities. However, upper-body exercise modes utilize relatively small muscle groups that are not capable of stressing the central circulatory cardiovascular system at high enough magnitudes for long enough durations to stimulate marked training adaptations (1,2). Therefore, physiologic benefits derived from upper-body exercise/rehabilitation programs are primarily peripheral (localized within the trained muscles) rather than central circulatory in nature (1,3). It has been suggested that deconditioned lower limb disabled patients may incur some beneficial central cardiovascular effects from chronic upper-body aerobic exercise training (3).
This suggestion may not be applicable to spinal cord injured (SCI) quadriplegics due to their limited use of upper-body muscles. In addition, peripheral vascular insufficiency and inactivity of the skeletal muscle venous pump associated with SCI quadriplegia results in excessive lower limb venous pooling during upright upper-body exercise (4-8). The diminished capacity for facilitating venous return to the heart limits left ventricular stroke volume (SV) and cardiac output (CO), lowering the cardiac-volume load placed upon the heart (9). In combination, deficient arm muscle function and marked venous pooling may hinder SCI quadriplegics from obtaining high levels of physiologic benefits from upright upper-body aerobic exercise training.

Recent advances in functional electrical stimulation (FES) technology have enabled the restoration of purposeful movement to the paralyzed lower limb muscles of SCI persons. One of the more complex FES systems is leg cycle exercise (LCE) which induces repetitive contractions in a relatively large muscle mass (10,11). This technology is now commercially available and has been shown to promote central hemodynamic responses in SCI quadriplegics superior to those observed during upright arm crank exercise (ACE). The superior central hemodynamics are evidenced by higher SV and CO levels during FES-LCE than ACE at the same submaximal oxygen uptake (12) and peak exercise capacity (5). However, the exercise capacity attained and cardiovascular responses to FES-LCE in SCI quadriplegics may be limited due to 1) the deteriorated condition of the paralyzed lower limb muscles, 2) inadequate organ-system adjustments resulting from peripherally-induced contractions and impaired autonomic sympathetic nervous system function, and 3) fixed stimulation characteristics of commercially available FES-LCE systems (13).

To improve cardiovascular training capability, it would be necessary to augment the active muscle mass, aerobic metabolic rate, autonomic sympathetic outflow, and cardiovascular responses in the SCI during exercise. Use of voluntary ACE with simultaneous FES-LCE (hybrid exercise) has been suggested (3,8,13). However, there has been little research evaluating the metabolic and cardiovascular responses in SCI quadriplegics during hybrid exercise. The only cardiovascular data published to date involved untrained quadriplegics performing maximal-effort ACE combined with 0 watt (W) FES-LCE (7). Peak values for aerobic metabolism, SV, and CO were significantly higher during hybrid exercise versus peak ACE performed without FES-LCE. This demonstrated that the cardiovascular system was not fully stressed with ACE alone. The authors speculated that hybrid exercise may promote greater central cardiovascular training benefits than ACE due to the higher peak aerobic metabolic rate elicited and cardiac-volume load generated during this mode of exercise.

Since endurance exercise is required to train the cardiovascular system, the appropriate combination of arm and leg power output should be selected to permit relatively high cardiovascular responses to be elicited for sufficiently long durations. The purpose of this study was to examine the metabolic, pulmonary, and central hemodynamic responses in SCI quadriplegics to subpeak ACE and subpeak FES-LCE performed separately and concurrently. The information derived from this study may be beneficial for establishing endurance training protocols that will optimize metabolic and cardiovascular responses in quadriplegics and provide improved cardiopulmonary (aerobic) training capability.

METHODS

Subjects

Eight quadriplegics (lesion levels C5–C8/T1) volunteered to participate in this study (Table 1). Each subject signed an informed consent document prior to participation in accordance with procedures established by the Institutional Review Board of Wright State University. Subjects underwent medical screening, which included the following: a 12-lead resting electrocardiogram (ECG); chest and lower limb radiographs; measurement of resting blood pressure; fasting blood chemistry and urinalysis; and neurologic (sensorimotor and autonomic) as well as functional, physical, and psychologic assessments. Total motor index scores were determined by a neurologist (14). Table 2 presents a description of the upper extremity neurologic status of each subject. Common denominators for this SCI group were: 1) they responded well to FES exercise; 2) they were able to comfortably tolerate the electrical current required to perform FES-LCE; 3) they were well habituated to ACE; and, 4) each subject had recently completed 36 FES-LCE training sessions over a 12–15 week period.
Table 1.
Subject characteristics.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>Lesion* (level)</th>
<th>Time Since Injury (yr)</th>
<th>SCI Motor Index Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>28</td>
<td>75</td>
<td>C5i</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>33</td>
<td>61</td>
<td>C5i</td>
<td>2</td>
<td>62</td>
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<td>3</td>
<td>M</td>
<td>34</td>
<td>91</td>
<td>C6i</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>26</td>
<td>66</td>
<td>C6i</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>34</td>
<td>70</td>
<td>C6-7</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>40</td>
<td>80</td>
<td>C6-7i</td>
<td>15</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>28</td>
<td>80</td>
<td>C7i</td>
<td>6</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>38</td>
<td>68</td>
<td>C8i</td>
<td>4</td>
<td>39</td>
</tr>
</tbody>
</table>

Means ± SE 32.6 ± 0.6 73.9 ± 1.2 7.6 ± 0.7

*i = incomplete lower-limb motor loss

Table 2.
Upper extremity neurologic status of subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Deltoid/ Biceps</th>
<th>Radial Wrist Extensors</th>
<th>Triceps</th>
<th>Flexor Profundus</th>
<th>Hand Intrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
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<td>4</td>
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</tr>
</tbody>
</table>

L = left; R = right
Scores represent muscle grade based on the following observation:
0 Absent Total paralysis
1 Trace Palpable/visible contraction
2 Poor Full active range of motion, gravity eliminated
3 Fair Full active range of motion, against gravity
4 Good Full active range of motion, against resistance
5 Normal

Exercise test procedure
Each subject completed one exercise test session which consisted of the following sequence: 5 min seated rest; 10 min upright ACE; 10 min seated rest; 1 min passive (technician-assisted) LCE; 1 min FES-LCE at 0 W (unloaded flywheel); 1 min FES-LCE during which current output was gradually increased to the level required to maintain pedaling at 50 rpm (if the subject was able to perform subsequent FES-LCE at a power output (PO) higher than 0 W); 10 min FES-LCE; 10 min hybrid exercise (ACE added to ongoing FES-LCE);
Figure 1.
Exercise test protocol for one SCI quadriplegic subject using power outputs of 30 W during ACE alone, 12 W during FES-LCE alone, and 42 W during hybrid exercise.

Prior to testing, two active and one reference rectangular carbonized rubber surface electrodes were placed over motor points of the quadriceps, hamstring, and gluteal muscle groups. The subject was then transferred onto an ERGYS I FES leg cycle ergometer (Therapeutic Technologies, Inc., Tampa, FL). Arm crank exercise was performed using a Monark Rehab Trainer (Monark-Crescent AB, Varberg, Sweden) mounted on a specially designed platform that attached to the leg cycle ergometer (Figure 2). During ACE, the subjects were instructed to maintain a target cranking cadence of 50 rpm with visual feedback provided by a digital speedometer. The selected PO approximated 50 percent of the subject’s ACE peak PO (determined from a previously conducted graded ACE stress test). During FES-LCE, electrical stimulation was provided by monophasic rectangular-wave pulses of 0.375 msec duration at a frequency of 35 Hz. Cyclic patterning of muscle contractions at a target pedaling cadence exercise bouts. The hybrid exercise test protocol for one subject is displayed in Figure 1.

Figure 2.
Quadriplegic subject performing hybrid (concurrent ACE and FES-LCE) exercise.
of 50 rpm was controlled by a microprocessor within the leg cycle ergometer. Maximal current output was limited to about 130 mA. Subjects with incomplete spinal lesions and minimal lower limb motor function were instructed not to provide voluntary muscle contractions during FES-LCE. The selected PO for FES-LCE was the highest PO that could be maintained at 50 rpm for 20 min continuously.

**Physiologic variables**

During rest and throughout the test session, the subjects breathed through a two-way valve. Expired gas was continuously monitored for oxygen and carbon dioxide content and volume with a Medical Graphics Corp. 2001 metabolic cart. From these measurements, oxygen uptake ($\dot{V}O_2$), minute pulmonary ventilation ($\dot{V}E$), carbon dioxide output ($\dot{V}CO_2$), and respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) were calculated. Fifteen-second values for these variables were averaged for 2-min periods prior to the end of each rest and exercise stage.

Central hemodynamic responses of left ventricular SV and CO were determined noninvasively with impedance cardiography, as described by Kubicek, et al. (15). The $dZ/dt$ wave of the Minnesota Impedance Cardiograph Model 304B was recorded during end-expiratory apnea from four aluminized mylar tape electrodes positioned on the forehead, neck, and trunk (15). The CM$_4$ electrode placement was used to monitor the ECG. Ten-second recordings of the ECG and phonocardiogram were obtained on a Honeywell Model 1600 oscillographic recorder during rest periods and immediately preceding and following the end of each exercise stage. Heart rate (HR) was determined from the intervals between successive R waves of the ECG recorded during the final 5 sec of exercise. Artifact-free cardiac cycles obtained during the 10 sec immediately after exercise termination (during end-expiratory apnea) were used to calculate SV with previously described methods (15,16). Cardiac output was calculated by multiplying SV by exercise HR. This method of using exercise HR combined with immediate post-exercise SV to derive exercise CO has been proven valid and reliable, and is especially useful during ACE exercise where movement artifact could obscure the desired impedance signal (16).

Arteriovenous oxygen difference ($a-V$ $O_2$ diff) was calculated as $\dot{V}O_2/CO$. Discernible arterial blood pressures (BP) were obtained for five subjects via auscultation, and mean arterial pressure (MAP) was calculated as follows: ([systolic BP – diastolic BP]/3) + diastolic BP. Total peripheral resistance (TPR) for these five subjects was derived as MAP/CO.

**Statistical treatment**

Individual one-way repeated measures analysis of variance and Tukey’s post hoc tests were used to compare differences in physiologic responses elicited during rest, ACE alone, FES-LCE alone, and hybrid exercise. The criterion level of significance was $P \leq 0.05$. All data are presented as means ± standard error (SE).

**RESULTS**

Individual PO levels for ACE and FES-LCE ranged from 0–30 W and 0–12 W, respectively (Table 3). One quadriplegic with minimal arm function performed ACE against an unloaded flywheel (0 W) and five subjects executed FES-LCE against an unloaded flywheel. The mean subpeak ACE PO of 19.4 W equaled 55 percent of the subjects’ mean peak ACE PO and 91 percent of the total hybrid PO. The mean subpeak FES-LCE PO was 26 W.

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**Table 3.** Power output during ACE alone, FES-LCE alone, and hybrid exercise.

<table>
<thead>
<tr>
<th>Subject</th>
<th>ACE (W)</th>
<th>FES-LCE (W)</th>
<th>Hybrid (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>12</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>0</td>
<td>15</td>
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<tr>
<td>6</td>
<td>30</td>
<td>0</td>
<td>30</td>
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<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>6</td>
<td>26</td>
</tr>
</tbody>
</table>

Means ± SE: 19.4 ± 1.3, 2.3 ± 0.6, 21.7 ± 20

Amounts in parenthesis represent percent of total hybrid power output.
of 2.3 W equated to 16 percent of the subjects' mean peak FES-LCE PO and 9 percent of the total hybrid PO. Peak PO levels were determined from previous graded ACE and FES-LCE stress tests. The mean hybrid exercise PO of 21.7 W was equivalent to 44 percent of the combined mean peak ACE and peak FES-LCE PO levels of the subjects.

Mean steady-state values for physiologic responses to the three exercise modes are listed in Table 4. Except for MAP and SV, monitored variables were significantly increased above the value at rest during each of the three exercise modes. Stroke volume was not appreciably altered under conditions of ACE alone, but was significantly higher than rest during FES-LCE alone and hybrid exercise. There were no differences in MAP from rest during any exercise condition.

The $\bar{VO}_2$, $\bar{VE}$, HR, TPR, and $a-v$ $O_2$ diff responses elicited during FES-LCE alone and ACE alone were not significantly different. However, $\bar{VO}_2$, $\bar{VE}$, and HR were significantly higher and TPR significantly lower during hybrid exercise than both FES-LCE and ACE performed separately. Hybrid exercise and ACE resulted in similar $a-v$ $O_2$ diff values, and $a-v$ $O_2$ diff was significantly higher during hybrid exercise than FES-LCE alone. There was a trend for a higher $a-v$ $O_2$ diff during ACE than FES-LCE alone, but statistical significance was not achieved ($P<0.10$). Hybrid exercise and FES-LCE exhibited similar SV levels which were both significantly higher than SV determined during ACE alone. Cardiac output during hybrid exercise was significantly higher than during either FES-LCE or ACE performed individually. Although there was an apparent trend toward higher CO during FES-LCE than ACE alone, the difference was not significant ($P<0.10$). Mean arterial pressure remained relatively stable across exercise modes.

### Table 4.
Physiologic responses at rest and during ACE alone, FES-LCE alone, and hybrid exercise.*

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>ACE</th>
<th>FES-LCE</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen Uptake (l/min)</td>
<td>0.23 ± 0.01</td>
<td>0.66 ± 0.02</td>
<td>0.66 ± 0.02</td>
<td>1.02 ± 0.02a</td>
</tr>
<tr>
<td>Pulmonary Ventilation (l/min)</td>
<td>10.0 ± 0.2</td>
<td>25.9 ± 0.7</td>
<td>28.5 ± 0.7</td>
<td>39.7 ± 0.8a</td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>66 ± 2</td>
<td>99 ± 2</td>
<td>88 ± 2</td>
<td>117 ± 1a</td>
</tr>
<tr>
<td>Stroke Volume (ml/b)</td>
<td>63 ± 3</td>
<td>57 ± 3c</td>
<td>89 ± 3</td>
<td>80 ± 2</td>
</tr>
<tr>
<td>Cardiac Output (l/min)</td>
<td>3.9 ± 0.1</td>
<td>6.4 ± 0.2</td>
<td>7.6 ± 0.2</td>
<td>9.4 ± 0.2a</td>
</tr>
<tr>
<td>Arteriovenous Oxygen Difference (ml/100 ml)</td>
<td>6.1 ± 0.2</td>
<td>10.7 ± 0.3</td>
<td>8.8 ± 0.3</td>
<td>11.2 ± 0.3b</td>
</tr>
<tr>
<td>Mean Arterial Pressure (mmHg)</td>
<td>71 ± 2</td>
<td>72 ± 2</td>
<td>68 ± 2</td>
<td>71 ± 2</td>
</tr>
<tr>
<td>Total Peripheral Resistance (mmHg/l/min)</td>
<td>17.9 ± 0.2</td>
<td>10.9 ± 0.2</td>
<td>9.1 ± 0.1</td>
<td>7.2 ± 0.2a</td>
</tr>
</tbody>
</table>

*Means ± SE; N = 5.

**Hybrid exercise significantly different from FES-LCE and ACE alone ($P \leq 0.05$).

**Hybrid exercise significantly different from FES-LCE alone ($P \leq 0.05$).

**ACE alone significantly different from FES-LCE alone and hybrid exercise ($P \leq 0.05$).
DISCUSSION

The need to develop practical and effective exercise modes for SCI quadriplegics is emphasized by data revealing that this population is at the lower end of the aerobic fitness spectrum (2,3,17) and at an increased risk for secondary disabilities such as cardiovascular disease, diabetes, and hypertension (18,19,20). The proposed rationale for combining voluntary arm and electrical stimulation leg exercise in SCI quadriplegics is to 1) activate as much muscle mass as possible, 2) augment autonomic sympathetic outflow to induce appropriate cardiopulmonary responses, 3) reduce lower limb venous pooling to improve venous return to the heart and CO, 4) create a higher cardiac-volume load to promote central cardiovascular training benefits, 5) enable training at a higher VO₂ for more effective aerobic conditioning, and 6) provide training benefits for both upper-body and lower-body musculature. To date, combinations of intensities for the voluntary arm and FES-LCE modes during hybrid exercise have not been fully evaluated. The optimal combination of ACE and FES-LCE intensities would enable the SCI quadriplegic to exercise at relatively high magnitudes of cardiopulmonary responses and avoid the early onset of fatigue. To further our understanding of the potential effectiveness of hybrid exercise for stimulating cardiovascular training effects, this study compared the physiologic responses in SCI quadriplegics performing subpeak ACE and subpeak FES-LCE concurrently and independently.

Aerobic metabolism

An important result was that the VO₂ during hybrid exercise was significantly higher than the VO₂ elicited during either ACE alone and FES-LCE alone. This demonstrated the additive effect of these arm and leg exercise modes on aerobic energy expenditure in quadriplegics. These results are in agreement with VO₂ data reported for one paraplegic subject performing simultaneous subpeak ACE (25 W) and FES-LCE (6 W) (8). The results further demonstrate that hybrid exercise involving FES-LCE can increase VO₂ to a much greater extent than subpeak ACE supplemented with either FES knee extension (21) or pulsatile static FES leg contractions (4,22). The marked elevation of aerobic metabolism during hybrid exercise in this study is probably due to a larger activated muscle mass and/or an increased frequency of contraction with FES-LCE versus the lower limb FES activities of previous studies. The rise in VO₂ during hybrid exercise was paralleled by an increase in \( \dot{V}_E \) suggesting that pulmonary function was well regulated with respect to the aerobic metabolic rate.

The absolute VO₂ attained during hybrid exercise in this study was either higher than or similar to levels achieved by SCI quadriplegics during maximal-effort ACE (5,23,24,25), wheelchair ergometry (WERG) (4,17), FES knee extension exercise (21), and FES-LCE (5,23,26), and peak ACE combined with 0-W FES-LCE (7) (Figure 3). The present hybrid exercise VO₂ levels were also higher than the VO₂ elicited by SCI quadriplegics exercising at subpeak PO levels associated with ACE (9), WERG (27), and FES-LCE (28) training.

Central hemodynamics

By doing a rearrangement of the Fick equation (\( \dot{V}O_2 = CO \times a-\dot{V} O_2 \text{ diff} \)), it is apparent that the higher VO₂ during hybrid exercise compared with ACE alone was supported by augmented central hemodynamics (CO) rather than peripheral mechanisms of oxygen extraction (a-\( \dot{V} O_2 \text{ diff} \)). The
relatively high $a\bar{\nabla}O_2$ diff during submaximal upright ACE alone is most likely a function of circulatory hypokinesis present in SCI quadriplegics (6). This circulatory hypokinesis is characterized by lower limb venous pooling, diminished venous return to the heart, and subnormal SV and CO values at a given VO$_2$ (6). Adding subpeak FES-LCE to subpeak ACE did not significantly alter $a\bar{\nabla}O_2$ diff (+5 percent), but resulted in a considerably higher CO (by 24-47 percent) than observed during ACE or FES-LCE alone. Therefore, hybrid exercise is characterized by an increased blood flow and oxygen delivery to active muscle to support the elevated aerobic metabolism.

The absolute increments in hybrid exercise VO$_2$ and CO above resting levels were nearly additive functions of the values achieved above rest during subpeak ACE and FES-LCE performed alone. These data substantiate that the pumping capacity of the heart was able to adequately meet the combined oxygen demands of the arms and legs at the PO levels used. We found that SCI quadriplegics were able to maintain hybrid exercise continuously for 10 minutes of testing without excessive arm or leg muscle fatigue. It is desirable to perform this exercise for 30 minutes or more during aerobic training sessions.

It has been our experience that relatively high-intensity voluntary ACE diminishes FES-LCE performance. The nature of the limitation may be mechanical (ACE interfering with FES-LCE), circulatory (competition of arms and legs for blood exceed the pumping capacity of the heart), humoral (increased metabolic acidosis from the arms influencing leg metabolic capacity), or a combination of the above or other unknown causes (3). Regardless of the potential mechanism(s) for this impediment, the combined exercise intensities in the present study appeared to have been complementary for enabling hybrid exercise to be performed without circulatory limitations.

The higher CO during hybrid exercise than ACE alone was due to the combined effect of significantly larger increases in HR and SV and decrease in TPR. The gains in CO (+47 percent) and SV (+23 percent) above ACE alone during hybrid exercise in this study are higher than and similar to the increases in CO (+23 percent) and SV (+22 percent), respectively, above ACE during another form of hybrid exercise utilizing static pulsatile FES leg contractions (4). The likely reasons for differences in CO are those previously discussed in reference to VO$_2$ differences observed between exercise modes for each study. In the current study, the heightened SV during hybrid exercise and FES-LCE alone compared to ACE alone supports previous speculations that FES-induced leg exercise will prevent or reverse venous pooling in the legs and improve venous return to the heart (3,4,8,13). Toner, et al. (29), reported that SV and HR were sustained in able-bodied subjects when arm exercise accounted for 75 percent of the total combined arm-leg VO$_2$ compared to levels observed during 100 percent voluntary leg exercise. However, significantly lower SV and higher HR were elicited during 100 percent ACE than during the other two combinations. The data presented by these authors demonstrated that minor involvement of voluntary leg cycling during upright ACE of low intensity facilitated venous return by the added lower limb skeletal muscle pump (29). In a similar manner, circulatory hypokinesis in SCI quadriplegics during ACE could potentially be ameliorated by activation of an otherwise dormant lower limb skeletal muscle pump with FES-LCE.

The fact that SV during ACE alone was not significantly altered from resting SV, agrees with previous reports that SV remains unchanged or is slightly increased during upper-body exercise (30). The lack of increase in SV during ACE likely reflects lower limb venous pooling (29), increased HR, and an increased intrathoracic pressure (30). An increased cardiac afterload is evident by the higher TPR during ACE alone than FES-LCE alone and hybrid exercise. In this study, simultaneous ACE and FES-LCE resulted in a 10 percent decline in SV compared to the SV exhibited during FES-LCE alone. Considering a markedly lower TPR during hybrid exercise than FES-LCE alone, it seems improbable that an increased afterload contributed to the diminished SV during hybrid exercise. However, hybrid exercise resulted in a substantially higher HR (+33 percent) than FES-LCE alone. Due to impaired sympathetic efferent outflow in SCI quadriplegics, the cardioacceleration during hybrid exercise reduced the diastolic filling time that may not have been compensated for with an adequate increase in myocardial contractility. As a result, SV would not be maintained at the same level during hybrid exercise compared to FES-LCE alone.
The greater cardioacceleration during hybrid exercise may be attributed to greater withdrawal of autonomic parasympathetic (vagal) tone and/or enhanced activation of the autonomic sympathetic nervous system. However, considering the relatively low HR levels achieved, the elevated HR response during hybrid exercise was probably more strongly influenced by diminished vagal tone. It has been speculated that the addition of voluntary ACE to FES-LCE would augment sympathetic outflow and improve FES-LCE capability (3,8,31). Further clarification of these mechanisms may be established by examining concentrations of circulating catecholamines during hybrid exercise, ACE alone, and FES-LCE alone.

Greater arterial vasodilation and a corresponding decrease in TPR will occur as more muscle mass is activated during exercise. A significantly lower TPR was observed during hybrid exercise than during either ACE or FES-LCE alone. This corroborates the earlier contention of an increased active muscle mass during hybrid exercise. The decline in TPR decreases cardiac afterload which favors more complete left ventricular emptying during myocardial contraction and, therefore, greater SV and CO. The augmented CO will not only elevate blood and oxygen delivery to exercising muscle, but will also help maintain MAP. The level of MAP was found to be similar across exercise modes as a function of changes in CO. Traumatic SCI quadriplegics are prone to orthostatic and exercise-induced hypotension due to the impairment of efferent sympathetic pathways responsible for arterial vasoconstriction in the periphery and metabolically inactive regions (32,33). However, we did not observe any episodes of hypotension, suggesting that the hybrid exercise implemented in this study is a relatively safe exercise mode.

Implications for exercise training
To facilitate improved central cardiovascular fitness, the exercise utilized during training should be performed at intensities and durations that are well beyond those normally encountered by the SCI person ("Overload" Principle). For reasons discussed previously, it is unlikely that SCI quadriplegics can maintain concurrent high-intensity ACE and FES-LCE for sufficient durations to promote central cardiovascular training effects. However, in the current study, combined subpeak arm and FES-induced leg exercise resulted in similar or greater VO₂ responses reported for SCI quadriplegics during maximal-effort ACE alone and FES-LCE alone, respectively (Figure 3). A major advantage of this hybrid exercise versus voluntary ACE is that the aerobic metabolic load is spread over a greater active muscle mass. Therefore, with appropriate cardiopulmonary adjustments, SCI quadriplegics should be able to continue this hybrid exercise at a relatively high VO₂ without undue muscle fatigue or physiologic complications. The individually selected PO levels in the present study enabled each subject to accomplish the 10 minutes of continuous hybrid exercise during testing. We speculate that hybrid exercise could have been continued for at least another 10–20 minutes. Therefore, this form of hybrid exercise appears appropriate for promoting safe exercise of sufficient intensity and duration to promote central cardiovascular training benefits in SCI quadriplegics. More fit SCI quadriplegics and SCI paraplegics with better voluntary ACE capability who can accomplish hybrid exercise at higher combined absolute PO levels will have a better opportunity to induce central cardiovascular training adaptations than would less fit SCI quadriplegics. Extremely deconditioned SCI quadriplegics who have more to gain from hybrid exercise training should also incur central cardiovascular training effects. Of course, any central training adaptations would soon be lost once hybrid exercise (or other exercise) training has been terminated. Additional research documenting the central and peripheral training adaptations to hybrid exercise training is well warranted.

CONCLUSION
This study clearly demonstrated that the aerobic metabolic demand and cardiac-volume load generated during concurrent subpeak ACE and FES-LCE were significantly higher than elicited during subpeak ACE or FES-LCE performed independently. The absolute increments in hybrid VO₂ and CO above resting levels indicated that the central circulation was able to sufficiently meet the combined oxygen demands of the active arm and leg muscles at the PO levels used. The data demonstrate that the absolute subpeak exercise intensities employed in the present study were appropriate for
enhancing physiologic responses to levels suitable for aerobic training during hybrid exercise. Due to the more advantageous hemodynamics and increased aerobic metabolic rate, concurrent subpeak FES-LCE and ACE may provide for markedly greater central cardiovascular benefits in SCI quadriplegics than training with either subpeak ACE or FES-LCE alone.

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APPENDIX: Abbreviations

- a-\( \bar{\nu} \) \( \text{O}_2 \) diff = arteriovenous oxygen difference
- ACE = arm crank exercise
- BP = blood pressure
- C = cervical
- CO = cardiac output
- ECG = electrocardiogram
- FES-LCE = functional electrical stimulation leg cycle exercise
- HR = heart rate
- Hz = hertz
- mA = milliamperes
- MAP = mean arterial pressure
- msec = milliseconds
- min = minutes
- PO = power output
- rpm = revolutions per minute
- SCI = spinal cord injured
- SE = standard error
- sec = seconds
- SV = stroke volume
- T = thoracic
- TPR = total peripheral resistance
- \( \dot{V}_E \) = pulmonary ventilation
- \( \dot{V}_{CO_2} \) = carbon dioxide output
- \( \dot{V}_O_2 \) = oxygen uptake
- W = watts
- WERG = wheelchair ergometry