Exercise Responses during Functional Electrical Stimulation Cycling in Individuals with Spinal Cord Injury

NAZIRAH HASNAN1,2, NALAN EKTAS1, ALDRE IZABEL P. TANHOFFER1, RICARDO TANHOFFER1, CHE FORNUSEK1, JAMES W. MIDDLETON1, RUBY HUSAIN3, and GLEN M. DAVIS1

1Clinical Exercise and Rehabilitation Unit, Faculty of Health Sciences, University of Sydney, Sydney, AUSTRALIA; 2Faculty of Medicine, Department of Rehabilitation Medicine, University of Malaya, Kuala Lumpur, MALAYSIA; 3Faculty of Medicine, Department of Physiology, University of Malaya, Kuala Lumpur, MALAYSIA; and 4Rehabilitation Studies Unit, Faculty of Medicine, University of Sydney, Sydney, AUSTRALIA

ABSTRACT

HASNAN, N., N. EKTAS, A. I. P. TANHOFFER, R. TANHOFFER, C. FORNUSEK, J. W. MIDDLETON, R. HUSAIN, and G. M. DAVIS. Exercise Responses during Functional Electrical Stimulation Cycling in Individuals with Spinal Cord Injury. Med. Sci. Sports Exerc., Vol. 45, No. 6, pp. 1131–1138, 2013. Purpose: This study compared acute exercise responses during arm cranking, functional electrical stimulation (FES)–assisted leg cycling, and combined arm and leg (“hybrid”) cycling in individuals with spinal cord injury during maximal and submaximal exercise. Methods: Nine male subjects with long-standing neurological lesions from C7 to T12 were recruited. All subjects performed arm crank ergometry (ACE), FES leg cycle exercise (FES-LCE), arm + leg FES exercise (FES-LCE + ACE), and cycling on a hybrid FES tricycle (HYBRID). They were assessed for their peak exercise responses in all four modalities. Subsequently, their submaximal heart rates (HR), cardiac outputs (Q), and arteriovenous oxygen extractions (Ca-Cv)O2 were measured at 40%, 60%, and 80% of mode-specific VO2peak. Results: Arm exercise alone and arm + leg exercise resulted in significantly higher VO2peak and HRpeak compared with FES-LCE (P < 0.05). Submaximal VO2 during FES-LCE was significantly lower than all other modalities across the range of exercise intensities (P < 0.05). ACE elicited 70%–94% higher steady-state VO2, and HYBRID evoked 99%–148% higher VO2 compared with FES-LCE. Steady-state FES-LCE also produced significantly lower Q, HR, and (Ca-Cv)O2. ACE evoked 31%–36% higher Q and 19%–47% greater HR than did FES-LCE. HYBRID elicited 31%–49% greater Q and 23%–56% higher HR than FES-LCE. Conclusions: Combined arm and leg exercise can develop a higher oxygen uptake and greater cardiovascular demand compared with ACE or FES-LCE alone. These findings suggested that combined arm + leg FES training at submaximal exercise intensities may lead to greater gains of aerobic fitness than would arm exercise alone. These data also proffered that FES leg cycling exercise by itself may be insufficient to promote aerobic fitness in the spinal cord injury population. Key Words: HYBRID EXERCISE, CARDIORESPIRATORY RESPONSES, MAXIMAL AND SUBMAXIMAL TESTS, OXYGEN UPTAKE

One of the leading causes of death in the chronic spinal cord–injured population is cardiovascular disease (8,9,25). Reduced physical function and chronic immobilization underlie a sedentary lifestyle, and the concomitant lower energy expenditure is a contributing factor to the high morbidity and mortality after spinal cord injury (SCI) (25). These low physical activity levels are due to not only reduced muscle mass and impaired motor function but also lack of accessibility and opportunities to undertake exercise (25,33). There is very good evidence that exercise is effective in improving physical fitness and general health in the SCI population (19,26,35). However, leg exercise is usually restricted because of paralysis after SCI. Upper body exercise, such as arm crank ergometer (ACE) and wheelchair propulsion, are commonly prescribed for this population, but because of the relatively small muscle mass in their upper limbs, such exercise is not as beneficial as lower limb exercise (10). Upper body exercise elicits greater cardiorespiratory stresses when compared with similar workloads during leg exercise (4). Previous studies have demonstrated lower SV and reduced cardiac outputs in SCI individuals performing upper body exercise (17). This has been attributed to (i) “circulatory hypokinesis,” whereby the leg venous return is reduced because of an impaired muscle pump in the paralyzed limbs resulting in reduced cardiac outputs for a given oxygen uptake, and (ii) impaired autonomic cardiovascular control below the level of spinal lesion (3,10,18).

In the past three decades, functional electrical stimulation (FES) has increasingly been used to elicit rhythmic muscle contractions and purposeful movements of the paralyzed
lower limbs of SCI individuals. FES leg exercise can be performed either as static muscle contractions, dynamic knee extension, or rhythmic cycling exercise (12,28). Previous studies have also demonstrated that the activation of the skeletal muscle pump in the lower limbs augments venous return, improves ventricular filling, and increases oxygen uptake (22,23). FES leg exercise has been shown to promote central and peripheral hemodynamic responses by promoting higher SV and cardiac outputs (4,5,30). However, FES leg exercise alone has often resulted in significantly lower submaximal oxygen uptakes compared with ACE (1,30).

FES leg cycle exercise (FES-LCE) has been combined with ACE to augment submaximum oxygen uptake, as the larger muscle mass used during the combined arm and leg exercise has demonstrated greater cardiorespiratory demands and enhanced venous return (4,30). Concurrent voluntary ACE and FES-LCE, termed “hybrid exercise,” can be deployed in the form of an adapted stationary ACE mounted over an FES leg cycling system, FES rowing ergometers, or roadworthy integrated hybrid FES bikes (11,30,34). With hybrid exercise, increased muscle mass is activated, with augmented sympathetic outflow, reduced venous pooling in the legs, higher cardiac outputs, and elevated oxygen uptakes, providing better whole-body exercise benefits (12,24,34). In recent years, integrated hybrid bikes that can be used indoors or outdoors have become commercially available. Exercise training using these hybrid FES cycles has resulted in improvement of physical fitness after only 4 wk of training (11).

This study compared the acute cardiorespiratory exercise responses during ACE, FES-LCE, and two modes of arm + FES leg cycling in SCI subjects. We hypothesized that submaximal steady-state oxygen uptakes and heart rate (HR) during both types of hybrid FES exercise would be higher than those elicited during ACE or FES-LCE alone. This study also investigated whether indices of cardiac performance (i.e., cardiac output and SV) during both types of hybrid FES cycling would be greater than that elicited during arm cranking exercise or FES leg cycling alone.

**METHODS**

**Subjects**

Nine male subjects (age = 40.6 ± 1.1 yr, stature = 1.73 ± 0.01 m, body mass = 73.1 ± 1.0 kg, time since injury = 6.6 ± 0.4 yr; mean ± SE) with traumatic SCI ASIA A, B, and C from C6 to T12 (International Standards for Neurological Classification of Spinal Cord Injury [32]) volunteered to participate in this study (Ref No. 09-2009/12147). The Human Research Ethics Committee of the University of Sydney approved this study, and written informed consent was obtained from all subjects before their participation. The subjects were recruited through convenience sampling methodology. They were participants regularly attending a gymnasium catering to persons with disability at the Faculty of Health Sciences, University of Sydney. At the time of subject recruitment, there were no female participants attending the gymnasium. Eligible subjects were those between ages 18 and 65 yr old. All subjects underwent a full medical screening, which included a physical and neurological examination, a 12-lead resting ECG, and a measurement of resting blood pressure and lower limb radiographs before the study. All subjects were healthy, neurologically stable, and had previous experience with FES cycling exercises for at least 8 wk before the study. Previous experience with arm crank exercise was not a prerequisite for the study.

**Protocol**

The subjects were assessed on four different exercise modalities presented in the following order: (i) an ACE, (ii) an FES-LCE, (iii) a combined ACE and FES-LCE system (ACE + FES-LCE), and (iv) a commercially available arm and leg tricycle (HYBRID; BerkelBike BV, ‘s-Hertogenbosch, the Netherlands), which incorporated an FES system to recruit the leg musculature. The ACE was mounted over the leg cycle ergometer for ACE and ACE + FES-LCE assessments. For all tests, the crank axle of the ACE was positioned at shoulder height with the subject in the seated posture. For FES-LCE and ACE + FES-LCE, the subjects transferred themselves onto the leg cycle ergometer chair, and their feet were strapped and held in position by ankle-calf supports to minimize leg movements during cycling. Subjects transferred onto the HYBRID had their feet and legs strapped and held in position by customized carbon fiber leg supports. HYBRID was then mounted on a stationary cycle resistance trainer (Tacc i-Magic; Tacc BV, Wassenaar, the Netherlands), which calculated external PO during combined arm and leg effort.

Before the tests involving electrical stimulation, gel-backed self-adhesive surface electrodes were placed over the bellies of the quadriceps, hamstrings, and glutei muscle groups. Electrode placement was kept consistent by measurements to key anatomical landmarks to ensure muscle fiber recruitment was similar between trials. The subject preparation and the experimental setup were all performed by the primary investigator. During the FES cycling, electrical stimulation was delivered via biphasic rectangular pulses at a frequency of 35 Hz and pulse width of 300 μs. The muscle stimulation “firing” angles were fixed and the timing of stimulation was preset by a computer program (7). The maximum stimulation amplitude was limited to 140 mA.

The research design involved eight sessions of testing for 7 d, which were performed on separate days. Testing was conducted in two stages (as described in the following paragraphs), with all assessments separated by at least 48 h.

In the first stage, all participants underwent an incremental PO test to maximal effort in all four different exercise modes. Peak oxygen uptake (VO2peak) was derived to
ascertain the highest physical work capacity for each individual in all four different exercise modes, described as follows.

1. Maximal ACE: Subjects were instructed to arm crank at 50 rev·min⁻¹ at 0 W for 3 min (warm-up). Resistance was subsequently increased by 5–10 W every minute until volitional fatigue. The criteria for termination of the test were as follows: subject requested to stop, subject unable to maintain cadence at 50 rev·min⁻¹ for at least 15 s, or an obvious plateau of oxygen uptake from 1 min to the next (30).

2. Maximal FES-LCE: The FES-LCE was set-up to enable the subjects to perform passive cycling at 0 W (no electrical stimulation) at 50 rev·min⁻¹ for 3 min. Resistance was increased via a preset program in the computer system. The cycling cadence was preset at 50 rev·min⁻¹ throughout the test. The cycle PO was increased by 1–3 W every 2 min. The FES system microprocessor automatically increased electrical stimulation to match the PO demand (“Feedback” mode [7]). The subject was considered to have reached leg-specific VO₂peak when the PO produced by the electrically stimulated muscles could not further increase despite reaching maximum stimulation amplitude of 140 mA.

3. Maximal ACE + FES-LCE: Subjects underwent a combined maximal ACE and maximal FES-LCE test protocol as previously described. The combined test was terminated when the subject stopped arm cranking at volitional fatigue.

4. Maximal HYBRID: The test protocol was performed following the arm and leg loading protocol of Hesteerbeek et al. (11). The graded hybrid test consisted of a warming up phase at 0 W for 3 min followed by increase in workload of 10 W every minute. Subjects were instructed to perform voluntary arm cranking and FES leg cycling simultaneously and to maintain pedaling cadence at 50 rev·min⁻¹. The electrical stimulation was increased manually in four increments (minimum contraction, 33%, 66%, and 100% of maximum amplitude of 140 mA) at equivalent resting HR, 33%, 66%, and 100% of HR reserve. The goal of this protocol was to exhaust the arm and leg muscles simultaneously. The end point of the test was determined when cadence fell below 35 rev·min⁻¹ or when PO dropped below 70% of the imposed power (11).

In the second stage of testing, cardiorespiratory responses were measured during submaximal steady-state exercise at 40%, 60%, and 80% of mode-specific VO₂peak, determined from each of the previous maximal effort tests.

1. Submaximal ACE: Subjects were instructed to arm crank at 50 rev·min⁻¹ at 0 W for 3 min, followed by PO increases of 10 W·min⁻¹ until reaching a target PO corresponding to 40% ACE VO₂peak. After a short recovery wherein the HR and VO₂ were observed to have returned to near preexercise levels, subjects then continued arm cranking until reaching target PO corresponding to 60% VO₂peak. Finally, after another recovery, they continued arm cranking up to 80% VO₂peak. Measurements were taken when the subjects demonstrated a physiological steady state at each exercise intensity (after 3–5 min).

2. Submaximal FES-LCE: Subjects performed passive leg cycling at 0 W (without FES) at 50 rev·min⁻¹ for 3 min, followed by PO increments of 1–3 W·min⁻¹ every minute until reaching target PO corresponding to 40%, 60%, and 80% of FES-LCE-specific VO₂peak. After each exercise bout, a short recovery was provided, followed by incremental PO to the next intensity. Increases of leg PO were achieved by deploying incrementally higher FES current amplitudes. At each fraction of mode-specific VO₂peak physiological measurements were taken in steady state (usually after 3–5 min).

3. Submaximal ACE + FES-LCE: Subjects performed a combined ACE and FES-LCE cycling, incrementing both arm and leg PO until reaching a target PO corresponding to 40% VO₂peak of ACE + FES-LCE. The subjects then continued ACE and FES-LCE until reaching target PO corresponding to 60% VO₂peak and 80% VO₂peak in steady state similar to the ACE and FES-LCE protocols.

4. Submaximal HYBRID: Subjects performed simultaneous arm cranking and leg cycling until reaching target PO corresponding to 40% HYBRID VO₂peak. They then continued arm cranking and leg cycling until reaching target PO corresponding to 60% VO₂peak and 80% VO₂peak in steady state similar to the ACE + FES-LCE protocol.

**Physiological Measurements and Techniques**

**HR and oxygen uptake.** HR and cardiorespiratory parameters were measured continuously breath-by-breath using open-circuit spirometry with a metabolic gas analysis system at rest and during the submaximal and maximal effort assessments. The metabolic gas analysis system (Medical Graphics CPX; Medical Graphics Corp., St. Paul, MN) was calibrated before each test. HR, oxygen uptake (VO₂), carbon dioxide production (VCO₂), expired ventilation (VE), and RER were smoothed with a three breath rolling average. Subsequently, all measures were averaged for the 15-s periods during the third to fourth minute of rest and during the last minute of maximal exercise to derive the resting VO₂ and VO₂peak during maximal effort.

**Cardiac output and SV.** Indices of cardiovascular performance during submaximal-state exercise at 40%, 60%, and 80% of mode-specific VO₂peak comprised of left ventricular SV and cardiac output (Q). These were determined noninvasively via carbon dioxide (CO₂) rebreathing, as
Data refer to PO, body mass–adjusted oxygen uptake, expired ventilation, RER, and lactate concentration during maximal exercise. Data are presented as mean ± SE. The level of statistical significance was set to the 95% confidence limit ($P < 0.05$).

### RESULTS

#### Maximal tests

All subjects completed all maximal effort exercise tests. During maximal effort, there were significant differences in peak absolute and relative oxygen uptakes, expired ventilation, HR, lactate concentration, and PO between the four modalities. The Tukey $B$ post hoc analyses further revealed that absolute (mL·min$^{-1}$) and relative peak oxygen uptakes (mL·kg$^{-1}$·min$^{-1}$), expired ventilation, HR, and PO were significantly lower during FES-LCE compared with the other exercise modes (Fig. 1). PO were significantly higher during ACE + FES-LCE compared with ACE only and HYBRID, and lactate concentrations were significantly higher during ACE + FES-LCE and HYBRID compared with ACE and FES-LCE (Table 1).

#### Submaximal tests

The resting and submaximal cardio-respiratory data during ACE, FES-LCE, ACE + FES-LCE, and HYBRID across all exercise intensities are presented in

---

**TABLE 1.** Peak exercise responses during arm versus leg exercise.

<table>
<thead>
<tr>
<th>Exercise Modality</th>
<th>PO (W)</th>
<th>Oxygen uptake (mL·kg$^{-1}$·min$^{-1}$)</th>
<th>$V_{E}$ (L·min$^{-1}$)</th>
<th>RER</th>
<th>Lactate (mmol·L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>74.4 ± 7.5</td>
<td>18.4 ± 1.7</td>
<td>48.4 ± 2.9</td>
<td>1.36 ± 0.05</td>
<td>6.3 ± 0.5</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>26.4 ± 3.3$^*$</td>
<td>26.7 ± 2.2$^*$</td>
<td>1.38 ± 0.06</td>
<td>5.2 ± 0.5</td>
<td>9.9 ± 0.9$^{**}$</td>
</tr>
<tr>
<td>ACE + FES-LCE</td>
<td>100.7 ± 8.3$^{**}$</td>
<td>63.7 ± 4.6</td>
<td>1.47 ± 0.06</td>
<td>9.2 ± 0.6$^{***}$</td>
<td></td>
</tr>
<tr>
<td>HYBRID</td>
<td>75.6 ± 5.0</td>
<td>20.8 ± 1.7</td>
<td>64.8 ± 6.6</td>
<td>21.5 ± 1.6</td>
<td></td>
</tr>
</tbody>
</table>

Data refer to PO, body mass–adjusted oxygen uptake, expired ventilation, RER, and lactate concentration during maximal exercise. Data are presented as mean ± SE.

$^*$ $P < 0.05$ compared with the other modes.

$^{**}$ $P < 0.05$ compared with ACE, FES-LCE, and HYBRID.

$^{***}$ $P < 0.05$ compared with ACE and FES-LCE.
Table 2 and Figure 2. All nine subjects completed the submaximal tests at exercise intensities of 40%, 60%, and 80% mode-specific VO₂peak, except for one individual wherein equipment failure prevented measurement at 80% HYBRID VO₂peak. PO for exercise intensities was determined from the mode-specific VO₂peak, that is, 40%, 60%, and 80% of each modality’s highest VO₂ during maximal effort.

At 40% VO₂peak oxygen uptake, HR, cardiac output, and arteriovenous O₂ differences were significantly lower during FES-LCE than for all the other exercise modalities. ACE elicited 70% greater VO₂ than FES-LCE, and ACE + FES-LCE and HYBRID elicited 99% and 122% greater VO₂ than FES-LCE, respectively. ACE evoked a 42% higher HR than FES-LCE, and ACE + FES-LCE and HYBRID elicited 33% and 55% higher HR, respectively, compared with FES-LCE. Q was higher by 31% during ACE and ACE + FES-LCE and 46% greater during HYBRID compared with legs-only exercise. Comparing arm and leg exercise to arms alone, ACE + FES-LCE elicited 17% higher VO₂ and HYBRID exercise elicited 30% greater VO₂.

At 60% VO₂peak oxygen uptake, HR, cardiac output and arteriovenous O₂ differences were significantly lower during FES-LCE than for all the other exercise modalities. Oxygen uptake was also significantly higher during ACE + FES-LCE and HYBRID than ACE alone. ACE elicited 82% higher VO₂ than FES-LCE, and ACE + FES-LCE and HYBRID elicited 122% and 148% higher VO₂ than FES-LCE, respectively. ACE evoked a 19% higher HR than FES-LCE, and ACE + FES-LCE and HYBRID elicited 23% and 26% higher HR than legs-only exercise. Q was higher by 36% during ACE and greater by 40% during ACE + FES-LCE and HYBRID. Comparing arm and leg exercise to arms alone, ACE + FES-LCE elicited 22% higher VO₂ and HYBRID exercise elicited 36% greater VO₂.

At 80% VO₂peak, oxygen uptake, HR, and cardiac output were significantly lower during FES-LCE than for all the other exercise modalities. Oxygen uptake was also significantly higher during ACE + FES-LCE and HYBRID than ACE alone. ACE elicited 94% higher VO₂ than FES-LCE, and ACE + FES-LCE and HYBRID evoked 135% and 132% higher VO₂ than FES-LCE, respectively. ACE resulted in 47% higher HR than FES-LCE, and ACE + FES-LCE and HYBRID evoked 56% and 43% higher HR than legs-only exercise. Q was greater by 33% during ACE and 49% during ACE + FES-LCE and 47% during HYBRID exercise. Comparing arm and leg exercise to arms alone, ACE + FES-LCE elicited 21% higher VO₂, and the HYBRID exercise elicited 19% higher VO₂. ACE + FES-LCE elicited 16% higher Q, and the HYBRID exercise elicited 10% higher Q. ACE + FES-LCE evoked a 6% higher HR, but the HYBRID exercise did not evoke a higher HR response.

There were no significant differences in SV among any exercise modality from 40% to 80% of mode-specific VO₂peak. However, we observed an 8.3% increase in SV compared...
with ACE at 40% exercise intensity during FES-LCE and a 13.3% increase in SV compared with ACE at 80% VO$_{2peak}$.

**DISCUSSION**

This study compared the acute cardiorespiratory responses during maximal exercise in people with SCI performing four types of exercise involving arm and legs: ACE, FES-LCE, ACE + FES-LCE (two separate pieces of equipment used concurrently), and a commercially available arm and leg hybrid FES tricycle. On the basis of the peak exercise responses in the maximal exercise testing, we then compared the metabolic and cardiovascular responses during submaximal exercise at 40%, 60%, and 80% of mode-specific VO$_{2peak}$ in all four exercises.

**Cardiorespiratory responses during maximal exercise.** The results from this study demonstrated lower oxygen uptake and HR during FES-LCE compared with ACE or arm and leg exercise (ACE + FES-LCE and HYBRID). This finding agreed with previous studies that have shown lower peak oxygen uptakes during FES leg cycling than other type of exercise (24,30,34). A very early study conducted in the 1980s suggested that ACE alone might be less effective than lower limb exercise for health and fitness promotion in the SCI population due to the relatively small muscle mass in the upper limbs resulting in lower SV and cardiac outputs (10). The current investigation highlighted that leg exercise alone is not always superior to arm effort, even when the muscle mass of the legs exceeds that at the arms in SCI individual. Indeed, just because the paralyzed leg musculature can be artificially activated by FES is not evidence that the metabolism is markedly elevated sufficiently to promote enhanced cardiorespiratory fitness. The combination of ACE and FES-LCE, termed “FES hybrid” exercise, has shown significantly higher peak oxygen uptake, HR, cardiac output, and SV than arm-only or legs-only exercise (22,24,30). Findings from the current study revealed 14%–18% higher peak oxygen uptake during maximal hybrid exercise compared with arm exercise alone. This was likely due to the recruitment of a larger muscle mass with the addition of lower limb FES-evoked cycling to arm exercise. Our findings agreed with Verellen et al. (34) in confirming a significantly lower VO$_{2peak}$ attained during FES cycling, compared with ACE or FES hybrid exercises (arm + leg cycling and rowing), without much apparent difference between the latter two.

In this study, FES-LCE did not result in the attainment of “centrally limited” maximal HR because the highest HR observed was at the time when the electrically stimulated muscles had become fatigued. Consistent with previous studies (21,24,30), we did not observe any differences of peak HR responses between ACE and ACE + FES-LCE or HYBRID. These findings contrasted with those of Hooker et al. (14), who observed exercise HR during ACE + FES-LCE to be significantly higher than ACE alone. These differences may be explained by a different subject population because Hooker et al. investigated responses in tetraplegic subjects whereby an increase in HR during exercise was driven by predominantly parasympathetic withdrawal (14).

The underlying mechanisms for sympathetically induced exercise cardioacceleration driving such exercise would be blunted or lacking, resulting in the low peak HR observed herein.

The RER values in the current study were all higher than 1.10, indicating maximal effort. However, despite achieving maximal mode-specific effort, the lactate concentration was significantly higher after hybrid exercise compared with ACE alone or FES-LCE. Clearly, the larger muscle mass engendered by arm plus leg exercise and possibly improved circulation at a maximal intensity, resulting in higher lactate production than by arms or legs alone.

**Cardiorespiratory responses during submaximal exercise.** It is useful to investigate submaximal cardiorespiratory exercise responses because these represent an intensity that can be sustained over prolonged periods of time, and which might represent real-world utility to the SCI individual undertaking fitness training using arms or legs.

During submaximal exercise, the PO was predetermined based on the results from maximal exercise assessments (i.e., the corresponding mode-specific workload at 40%, 60%, and 80% of PO$_{peak}$). Interestingly, we observed that the VO$_2$ achieved at the different submaximal intensities performed at the predetermined PO were higher than the predicted VO$_2$ for those intensities. This was attributed to the exercise protocol, whereby the incremental workload (for the given exercise intensity) was ramped up within the first 3 min of exercise before steady state, as compared with the gradual increment for 8–12 min during the maximal effort tests. The sudden increase in dynamic exercise had possibly resulted in the quick rise in oxygen uptake (6) as documented in this study.

In a similar way to maximal exercise, the submaximal VO$_2$ during FES-LCE was significantly lower than all other exercise modalities from 40% to 80% VO$_{2peak}$. Further analysis revealed that there were also significant differences in the oxygen uptake between both types of arm and leg exercise compared with arm cranking alone at the highest exercise intensity (i.e., 80% VO$_{2peak}$). During steady-state exercise within the 40%–80% VO$_{2peak}$ range, ACE elicited up to 90%, the ACE + FES-LCE up to 135%, and the hybrid bike up to 150% higher VO$_2$ than FES-LCE. The ACE + FES-LCE elicited up to 20% and the hybrid bike up to 40% higher VO$_2$ than ACE. These findings agreed with earlier studies that examined cardiorespiratory responses during FES hybrid exercise (1,24,34). The addition of arm exercise to FES-LCE clearly elicits a greater whole-body oxygen uptake,
supporting the view that hybrid exercise promotes better aerobic fitness potential.

This study also suggested that FES-LCE produced a larger submaximal SV compared with ACE, ACE + FES-LCE, or HYBRID by 3%–13%. This finding, however, did not achieve statistical significance, although it was obvious by visual inspection of the data (Fig. 2). Davis et al. (4) and Raymond et al. (30) demonstrated significant increases of SV when FES leg exercise was superimposed on ACE. Raymond et al. (30) attributed this to an augmented venous return rather than increased sympathetic neural drive augmenting cardiac contractility because there was no simultaneous increase of HR during FES leg cycling.

In the current study, the HR responses during steady state were significantly lower during FES-LCE across all exercise intensities compared with the other modes of exercise. In addition, there was no significant difference of steady-state HR between ACE and the combined arm and leg exercise modes. Only two previous studies that investigated HR response during arms exercise, FES leg exercise, and hybrid exercise have suggested a lack of difference in steady-state HR between ACE and hybrid exercise (4,29). Interestingly, in one of these, Raymond et al. (29) noted significantly lower HR responses during combined arm and leg exercise compared with arm cranking exercise alone, and they concluded that combined arm and leg exercise reduced cardiac stress for a given oxygen uptake. In contrast, Hooker et al. (14) observed that hybrid exercise elicited significantly higher HR (up to 33%) compared with ACE or FES-LCE. In that early study, the authors investigated tetraplegic subjects and attributed their findings to a diminished vagal tone in the presence of sympathetic-evoked cardioacceleration.

Cardiac output (Q) during FES-LCE was significantly lower than all other exercise modalities, across the range of effort intensities. There was no significant difference, however, in the Q between ACE and ACE + FES-LCE at all exercise intensities. During steady-state exercise within the 40%–80% VO2peak range, ACE elicited up to 36% and ACE + FES-LCE and HYBRID up to 50% higher Q than FES-LCE. The ACE + FES-LCE and HYBRID elicited 10% higher Q than ACE.

Some studies have noted a lower cardiac output during maximal or submaximal arm exercise in paraplegic individuals compared with able-bodied subjects. This has been due to a greater increase in HR in the paraplegic individuals, which was largely responsible for their increase in cardiac output while the SV was not significantly altered (13,20,27). Arm exercise alone may not be capable of stressing the cardiovascular system for a sustained period to enable a beneficial training effect to occur. Active lower limb exercises in SCI paralyzed limbs via electrical stimulation enable improvement of central and peripheral circulation by the activation of venous muscle pumps in the lower limbs. However, electrical stimulation of the lower limbs alone does not result in substantial elevation of oxygen uptake or cardiac output (15,30). As demonstrated in this study, combined arm and leg exercises result in a higher cardiac output with no significant difference in HR responses compared with arm exercise alone. Davis et al. (4) suggested that elevated central hemodynamic responses during submaximal hybrid exercise may make blood more available to the working upper body musculature for improved exercise performance.

There is still sparse literature on the acute cardiovascular responses during hybrid FES cycling in individuals with traumatic SCI, and the findings of HR changes corresponding to increases in oxygen consumption and cardiac output have been conflicting. This perhaps can be attributed to the difference in exercise testing protocols, electrical stimulation procedures, and different subject profiles, whether high paraplegics or low paraplegics or tetraplegics, which can all influence the outcomes of cardiovascular and cardiorespiratory responses in the maximal and submaximal exercise testing.

The current study has provided insights into the cardiovascular and metabolic responses during different exercise modalities by measuring cardiac output, SV (Fig. 2) and arteriovenous oxygen extractions during arm, and FES leg or arm plus leg exercise in an SCI cohort (Table 2). Taken together, these variables clearly showed that lower submaximal exercise PO during FES leg cycling exercise could be seen as the end point in a chain of ablated underlying physiological variables. During steady-state FES-LCE from 40% to 80% of mode-specific VO2peak lower HR resulted in reduced cardiac outputs, and this played a role in lower submaximal oxygen consumptions. Even a slightly greater SV during FES-LCE could not compensate for a “lower HR on cardiac output” effect. However, in addition, lower whole-body arteriovenous oxygen extractions also contributed to lower VO2 during legs-only exercise. In contrast, when voluntary exercise using musculature above the spinal cord lesion was added (e.g., ACE + FES-LCE, HYBRID), these differences of physiological responses were eliminated. The real-world utility of these findings to the SCI individual undertaking fitness training using arms or legs is that legs-only training may not always provide sufficient intensity for promotion of whole-body aerobic fitness. Conversely, some component of upper body exercise may be needed to achieve sufficient intensity to increase aerobic fitness for cardiovascular health in this population.

CONCLUSION

This study demonstrated that the cardiorespiratory demands during submaximal ACE + FES-LCE were higher than that in FES-LCE in all exercise intensities. These findings suggest that hybrid-FES training within the submaximal exercise intensities may lead to greater gains in cardiovascular fitness than arm exercise training alone.

The authors wish to express their sincere appreciation to Mr. Raymond Patton for his technical assistance during the course of this study. They also thank the research subjects who volunteered for this study.
REFERENCES


No external funding was received for this work. No commercial company or manufacturer has any professional relationship with any of the authors involved in this work, and the results of this work will not confer any commercial benefit on any of the authors involved.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.