Exercise Responses during FES Cycling in Individuals with Spinal Cord Injury

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ABSTRACT

**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 (SCI) during maximal and submaximal exercise. **Methods:** Nine male subjects with long-standing neurological lesions from C7-T12 were recruited. All subjects performed arm crank ergometry (ACE), FES-leg cycle exercise (FES-LCE), combined ACE+FES-LCE 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), stroke volumes (SV) and arteriovenous oxygen extractions (Ca-Cv)O$_2$ were measured at 40%, 60% and 80% of modesspecific VO$_2$peak. **Results:** Arm exercise alone and arm+leg exercise resulted in significantly higher VO$_2$peak and HRpeak compared to FES-LCE (p<0.05). Submaximal VO$_2$ 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 VO$_2$, and HYBRID evoked 99-148% higher VO$_2$ compared to FES-LCE. Steady-state FES-LCE also produced significantly lower Q, HR, and (Ca-Cv)O$_2$. 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 to 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 SCI population. **Key words:** hybrid exercise; cardiorespiratory responses, maximal and submaximal tests; oxygen uptake
INTRODUCTION:

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 not only because of reduced muscle mass and impaired motor function, but also due to 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 due to paralysis after SCI. Upper body exercise, such as arm crank ergometry (ACE) and wheelchair propulsion are commonly prescribed for this population, but due to 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 to similar workloads during leg exercise (4). Previous studies have demonstrated lower stroke volumes and reduced cardiac outputs in SCI individuals performing upper body exercise (17). This has been attributed to: (i) ‘circulatory hypokinesis’, whereby leg venous return is reduced due to an impaired muscle pump in the paralysed 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 paralysed 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 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 haemodynamic responses by promoting higher stroke volumes and cardiac outputs (4, 5, 30). However, FES leg exercise alone has often resulted in significantly lower submaximal oxygen uptakes compared to ACE (1, 30).”

FES-LCE has been combined with ACE to augment submaximum oxygen uptake, as the larger muscle mass utilised 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 arm crank ergometer mounted over a 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 which 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 four weeks 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 rates 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 (ie. cardiac output and stroke volume)
METHODS:

Subjects

Nine male subjects (aged 40.6 ± 1.1 y, stature 1.73 ± 0.01 m, body mass 73.1 ± 1.0 kg, time since injury 6.6 ± 0.4 years) with traumatic spinal cord injury 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 prior to 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 aged between 18 and 65 years old. All subjects underwent a full medical screening which included a physical and neurological examination, a 12-lead resting ECG, measurement of resting blood pressure and lower limb radiographs prior to the study. All subjects were healthy, neurologically stable and had previous experience with FES cycling exercises for at least 8 weeks prior to the study. Previous experience with arm crank exercise was not a pre-requisite for the study.”

Protocol

The subjects were assessed on four different exercise modalities presented in a set order: (i) an arm crank ergometer (ACE), (ii) a FES-leg cycle ergometer (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 a FES system to recruit the leg musculature. The arm crank ergometer 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-fibre leg supports. HYBRID was then mounted on a stationary cycle resistance trainer (Tacx i-Magic, Tacx BV, Wassenaar, The Netherlands) which calculated external power output during combined arm and leg effort.”

Prior to 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 fibre recruitment was similar between trials. Subject preparation and the experimental set-up 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 pre-set by a computer programme (7). The maximum stimulation amplitude was limited to 140 mA.”

The research design involved 8 sessions of testing over 7 days which were performed on separate days. Testing were conducted in two stages (as described below) with all assessments separated by at least 48 hours.”
In the first stage, all participants underwent an incremental power output test to maximal effort in all four different exercise modes. Peak oxygen uptake (VO$_2$peak) was derived to ascertain the highest physical work capacity for each individual in all four different exercise modes, as described below.

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

2) Maximal FES-LCE: The FES-LCE was set up to enable the subjects to perform passive cycling at 0W (no electrical stimulation) at 50 rev min$^{-1}$ for 3 min. Resistance was increased via a pre-set programme in the computer system. The cycling cadence was pre-set at 50 rev min$^{-1}$ throughout the test. The cycle power output was increased by 1-3 W every 2 min. The FES system microprocessor automatically increased electrical stimulation to match the power output demand (“Feedback” mode; 7). The subject was considered to have reached leg-specific VO$_2$peak when the power output 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 and colleagues (11). The graded hybrid test
consisted of a warming up phase at 0W for 3 min followed by increase in workload of 10W every minute. Subjects were instructed to perform voluntary arm cranking and FES-leg cycling simultaneously and to maintain pedalling 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 140mA) at equivalent heart rates of resting HR, 33%, 66% and 100% of heart rate reserve. The goal of this protocol was to exhaust the arm and leg muscles simultaneously. The endpoint of the test was determined when cadence fell below 35 rev min\(^{-1}\) or when power output 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 VO\(_{2}\)peak, determined from each of the previous maximal effort tests.

1) Submaximal ACE: Subjects were instructed to arm crank at 50 rev min\(^{-1}\) at 0W for 3 minutes, followed by power output increases of 10W minute\(^{-1}\) until reaching a target power output corresponding to 40% ACE VO\(_{2}\)peak. After a short recovery wherein the heart rate and VO\(_2\) were observed to have returned to near pre-exercise levels, subjects then continued arm cranking until reaching target power output corresponding to 60% VO\(_{2}\)peak. Finally, after another recovery, they continued arm cranking up to 80% VO\(_{2}\)peak. 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 0W (without FES) at 50 rev min\(^{-1}\) for 3 min, followed by power output increments of 1-3 W min\(^{-1}\) every minute until reaching target power output corresponding to 40%, 60% and 80% of FES-LCE specific VO\(_{2}\)peak. After each exercise bout a short recovery was
provided, followed by incremental power output to the next intensity. Increases of leg power output were achieved by deploying incrementally higher FES current amplitudes. At each fraction of mode-specific VO\textsubscript{2peak}, 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 power outputs until reaching a target power output corresponding to 40% VO\textsubscript{2peak} of ACE+FES-LCE. The subjects then continued ACE and FES-LCE until reaching target power outputs corresponding to 60% VO\textsubscript{2peak} and 80% VO\textsubscript{2peak} 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 power output corresponding to 40% HYBRID VO\textsubscript{2peak}. They then continued arm cranking and leg cycling until reaching target power outputs corresponding to 60% VO\textsubscript{2peak} and 80% VO\textsubscript{2peak} in steady-state similar to the ACE+FES-LCE protocol.”

**Physiological measurements and techniques**

**Heart rate and oxygen uptake**

Heart rate and cardiorespiratory parameters were measured continuously breath-by-breath by 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, USA) was calibrated before each test. Heart rate (HR), and oxygen uptake (VO\textsubscript{2}), carbon dioxide production (VCO\textsubscript{2}), expired ventilation (V\textsubscript{E}) and respiratory exchange ratio (RER) were smoothed with a three breath rolling average. Subsequently, all measures were averaged over 15-s periods during the third to fourth minute
of rest and during the last minute of maximal exercise to derive the resting VO$_2$, and VO$_{2\text{peak}}$ during maximal effort.”

**Cardiac output and stroke volume**

Indices of cardiovascular performance during submaximal-state exercise at 40%, 60% and 80% of mode-specific VO$_{2\text{peak}}$ comprised of left ventricular stroke volume (SV) and cardiac output (Q). These were determined noninvasively via carbon dioxide (CO$_2$) rebreathing as described by Collier (2). The subjects breathed from an anaesthetic bag filled with a mixture of approximately 10% carbon dioxide in oxygen. The volume in the bag was fixed at 1.5 times the mean tidal volume of the preceding respirations. The CO$_2$ rebreathing equilibrium method and calculations of heart rate and stroke volume were performed using the software integrated into the gas analysis system (Medical Graphics CPX metabolic cart). Arteriovenous oxygen difference (Ca-Cv)O$_2$ was calculated via the Fick principle from Q and VO$_2$.”

**Lactate**

Blood lactates were obtained from finger prick capillary samples before and within 2 minutes after maximal and submaximal tests for the determination of lactate responses (16). Samples were taken at rest and after cessation of exercise. Lactate measurements were made via a portable lactate analyser (Accutrend, Roche Diagnostics, Basel, Switzerland).”

**Power output**

Power outputs (PO) during submaximal and maximal tests were recorded from the power output obtained during the last minute of exercise during all four tests modalities. The recorded ACE PO was based on the set workload on the arm ergometer. The PO obtained
during the FES-LCE was recorded from a computer programme which was linked to the leg cycle ergometer (7) and the total PO from the ACE+LCE were derived from the sum of PO of the ACE and FES-LCE. The PO from HYBRID (commercially-available Berkelbike tricycle) was recorded from the software that ran the commercial cycle trainer (Tacx i-Magic) and was a summation of both the arm and leg power outputs. ACE, FES-LCE and HYBRID were calibrated according to manufacturer’s instructions before the study was commenced.”

Data analysis:

Differences of outcome measures obtained during maximal and submaximal exercise amongst the four exercise modalities (i.e. ACE, FES-LCE, ACE+FES-LCE and HYBRID) were contrasted by one-way analysis of variance. For all variables, where there was a significant main effect for exercise modality, a posteriori analyses were performed using Tukey B tests (two-tailed). All statistical analyses were performed using the SPSS 18 statistical package. Data are presented as mean ± standard error (SE), and 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, heart rate, lactate concentration and power output between the four modalities. Tukey B post-hoc analyses further revealed that absolute (ml·min⁻¹) and relative peak oxygen uptakes (ml·kg·min⁻¹), expired ventilation, heart rate and power output were significantly lower during FES-LCE compared to the other exercise modes (Figure 1). Power outputs were significantly higher during ACE+FES-LCE compared to ACE only and HYBRID, and lactate
concentrations significantly higher during ACE+FES-LCE and HYBRID compared to ACE and FES-LCE (Table 1)."

Submaximal tests:

The resting and submaximal cardiorespiratory data during ACE, FES-LCE, ACE+FES-LCE and HYBRID across all exercise intensities are presented in Table 2 and Figure 2. All nine subjects completed the submaximal tests at exercise intensities of 40%, 60% and 80% mode-specific VO$_2$peak, except for one individual wherein equipment failure prevented measurement at 80% HYBRID VO$_2$peak. Power output for exercise intensities was determined from the mode-specific VO$_2$ peak, ie. 40%, 60% and 80% of each modality’s highest VO$_2$ during maximal effort.”

At 40% VO$_2$peak, oxygen uptake, heart rate, cardiac output and arterio-venous O$_2$ differences were significantly lower during FES-LCE than for all the other exercise modalities. ACE elicited 70% greater VO$_2$ than FES-LCE; ACE+FES-LCE and HYBRID elicited 99% and 122% greater VO$_2$ than FES-LCE, respectively. ACE evoked a 42% higher HR than FES-LCE; ACE+FES-LCE and HYBRID elicited 33% and 55% higher HR, respectively, compared to FES-LCE. Q was higher by 31% during ACE and ACE+FES-LCE and 46% greater during HYBRID compared to legs-only exercise. Comparing arm and leg exercise to arms alone, ACE+FES-LCE elicited 17% higher VO$_2$ and HYBRID exercise elicited 30% greater VO$_2$.”

At 60% VO$_2$peak, oxygen uptake, heart rate, cardiac output and arterio-venous O$_2$ 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 VO$_2$ than FES-LCE; ACE+FES-LCE and HYBRID elicited 122% and 148% higher VO$_2$ 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 VO$_2$ and HYBRID exercise elicited 36% greater VO$_2$."

At 80% VO$_2$peak, oxygen uptake, heart rate 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 VO$_2$ than FES-LCE; ACE+FES-LCE and HYBRID evoked 135% and 132% higher VO$_2$ 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 VO$_2$ and the HYBRID exercise elicited 19% higher VO$_2$. 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 stroke volume amongst any exercise modality from 40% - 80% of mode-specific VO$_2$peak. However we observed at 40% exercise intensity during FES-LCE, that there was 8.3% increase in SV compared to ACE, and at 80% VO$_2$peak a 13.3% increase in SV compared to ACE.”

**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 (2 separate pieces of equipment used concurrently) and a commercially-available arm and leg hybrid FES tricycle. Based on 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 VO₂peak in all four exercises."

Cardiorespiratory responses during maximal exercise

The results from this study demonstrated lower oxygen uptakes and heart rates during FES-LCE compared to 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 1980's 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 stroke volumes 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, heart rate, cardiac output and stroke volume 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 to 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 and colleagues (34), in confirming a significantly lower VO$_2$ peak attained during FES cycling, compared to 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 heart rate, since 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 heart rate responses between ACE and ACE+FES-LCE or HYBRID. These findings contrasted with those of Hooker et al. (14) who observed exercise heart rates during ACE+FES-LCE to be significantly higher than ACE alone. These differences may be explained by a different subject population, since Hooker investigated responses in tetraplegic subjects whereby an increase in heart rate during exercise was driven by predominantly parasympathetic withdrawal (14). This is in comparison to the current study, where participants were either paraplegics with spinal lesions below T4, or they possessed “incomplete” spinal lesions (ASIA B or C). Raymond and colleagues (31) have proposed that FES-LCE lacks a “central command” component of leg exercise and also lacks complete skeletal muscle afferent feedback due to the spinal cord lesion. Thus, the underlying mechanisms for sympathetically-induced exercise cardioacceleration driving such exercise would be blunted or lacking, resulting in the low peak heart rates observed herein.”

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

Cardiorespiratory responses during submaximal exercise

It is useful to investigate submaximal cardiorespiratory exercise responses since 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 power output was predetermined based on the results from maximal exercise assessments (i.e. the corresponding mode-specific workload at 40%, 60% and 80% of \( P_{\text{O}_{\text{peak}}} \)). Interestingly, we observed that the \( \text{VO}_2 \) achieved at the different submaximal intensities performed at the predetermined power outputs were higher than the predicted \( \text{VO}_2 \) 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 minutes of exercise prior to steady state, as compared to the gradual increment over 8 – 12 minutes 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 \( \text{VO}_2 \) during FES-LCE was significantly lower than all other exercise modalities from 40% to 80% \( \text{VO}_{2\text{peak}} \). Further analysis revealed there were also significant differences in the oxygen uptake between both types of arm and leg exercise compared to arm cranking alone at the highest exercise intensity (i.e. 80% \( \text{VO}_2\text{peak} \)). During steady-state exercise within the 40% to 80% \( \text{VO}_2\text{peak} \) range, ACE elicited up to 90%, the ACE+FES-LCE up to 135% and the hybrid bike up to
150% higher VO₂ than FES-LCE. The ACE+FES-LCE elicited up to 20% and the hybrid bike up to 40% higher VO₂ 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 stroke volume compared to ACE, ACE+FES-LCE or HYBRID by 3% to 13%. This finding however did not achieve statistical significance, although it was obvious by visual inspection of the data (Figure 2). Davis and colleagues (4) and Raymond et al. (30) demonstrated significant increases of stroke volume when FES leg exercise was superimposed on ACE. Raymond and co-worker attributed this to an augmented venous return, rather than increased sympathetic neural drive augmenting cardiac contractility, as there was no simultaneous increase of heart rate during FES-leg cycling (30).”

In the current study, the heart rate responses during steady-state were significantly lower during FES-LCE across all exercise intensities compared to the other modes of exercise. In addition, there was no significant difference of steady-state heart rate between ACE and the combined arm and leg exercise modes. Only two previous studies that investigated heart rate response during arms exercise, FES leg exercise and hybrid exercise have suggested a lack of difference in steady state heart rates between ACE and hybrid exercise (4, 29). Interestingly, in one of these, Raymond and colleagues (29) noted significantly lower HR responses during combined arm and leg exercise compared to 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 heart rates (up to 33%) compared to ACE or FES-LCE. In that early study, the authors investigated tetraplegic subjects and attributed their findings to a diminished vagal tone in the absence 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% to 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 to able-bodied subjects. This has been due to a greater increase in heart rate in the paraplegic individuals, which was largely responsible for their increase in cardiac output while the stroke volume was not significantly altered (13, 20, 27). Arm exercise alone may not be capable of stressing the cardiovascular system for a sustained period of time to enable a beneficial training effect to occur. Active lower limb exercises in spinal cord injured paralyzed limbs via electrical stimulation enable improvement of central and peripheral circulation by 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 heart rate responses compared to arm exercise alone. Davis and co-workers (4) suggested that elevated central haemodynamic 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 heart rate 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, the different subject profile 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, stroke volume (Figure 2) and arteriovenous oxygen extractions during arm, FES-leg or arm plus leg exercise in a SCI cohort (Table 2). Taken together, these variables clearly showed that lower submaximal exercise power outputs 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%-80% of mode-specific VO$_2$peak, lower heart rates resulted in reduced cardiac outputs, and this played a role in lower submaximal oxygen consumptions. Even a slightly greater stroke volume during FES-LCE could not compensate for a ‘lower heart rate on cardiac output’ effect. However in addition, lower whole body arteriovenous oxygen extractions also contributed to lower VO$_2$ 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 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.”

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The authors wish to express our sincere appreciation to Mr. Raymond Patton for his technical assistance during the course of this study. We also would like to thank the research subjects who volunteered for this study. No external funding was received for this work. There is no conflict of interest present. The results of the present study do not constitute endorsement by ACSM.”
References:


FIGURE CAPTIONS

**Figure 1.** Peak oxygen uptake (ml•min\(^{-1}\)) and peak heart rate (b•min\(^{-1}\)) during maximal tests across all test modalities: ACE, FES-LCE, ACE+FES-LCE and HYBRID. * denotes p<0.05 compared to ACE, ACE+FES-LCE and HYBRID

**Figure 2.** Cardiovascular responses during ACE, FES-LCE, ACE+FES-LCE and HYBRID submaximal exercise at different intensities (rest, 40%, 60%, 80% modesspecific VO\(_{2\text{peak}}\)). Data are presented as mean ± SE for HR (b•min\(^{-1}\)), SV (ml•b\(^{-1}\)) and Q (l•min\(^{-1}\)). * denotes p<0.05 compared to ACE, ACE+FES-LCE and HYBRID
Figure 1
Figure 2

- Cardiac Output
- Heart Rate
- Stroke Volume

Comparison across different conditions: Rest, 40% VO₂peak, 60% VO₂peak, 80% VO₂peak.
Table 1. Peak exercise responses during arm versus leg exercise

<table>
<thead>
<tr>
<th></th>
<th>ACE</th>
<th>FES-LCE</th>
<th>ACE+FES-LCE</th>
<th>HYBRID</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO (W)</td>
<td>74.4 ± 7.5</td>
<td>26.4 ± 3.3*</td>
<td>100.7 ± 8.3†</td>
<td>75.6 ± 5.0</td>
</tr>
<tr>
<td>Oxygen uptake (ml/kg⁻¹.min⁻¹)</td>
<td>18.4 ± 1.7</td>
<td>9.6 ± 0.9*</td>
<td>20.8 ± 1.7</td>
<td>21.5 ± 1.6</td>
</tr>
<tr>
<td>VE (L.min⁻¹)</td>
<td>49.4 ± 2.9</td>
<td>26.7 ± 2.2*</td>
<td>63.7 ± 4.6</td>
<td>64.8 ± 6.6</td>
</tr>
<tr>
<td>RER</td>
<td>1.36 ± 0.05</td>
<td>1.38 ± 0.06</td>
<td>1.47 ± 0.06</td>
<td>1.35 ± 0.04</td>
</tr>
<tr>
<td>Lactate (mmol.L⁻¹)</td>
<td>6.3 ± 0.5</td>
<td>5.2 ± 0.5</td>
<td>9.9 ± 0.9‡</td>
<td>9.2 ± 0.6‡</td>
</tr>
</tbody>
</table>

Data refer to power output, body mass-adjusted oxygen uptake, expired ventilation, respiratory exchange ratio and lactate concentration during maximal exercise. * denotes p<0.05 compared to the other modes, † denotes p<0.05 compared to ACE, FES-LCE and HYBRID, ‡ denotes p<0.05 compared to ACE and FES-LCE. Data are Mean ± SE.
Table 2. Cardiovascular data during submaximal exercise

<table>
<thead>
<tr>
<th>Exercise intensity</th>
<th>40% VO$_2$peak</th>
<th>60% VO$_2$peak</th>
<th>80% VO$_2$peak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PO (W)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>20.1 ± 3.4</td>
<td>37.2 ± 4.9</td>
<td>56.7 ± 6.2</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>6.7 ± 0.4*</td>
<td>13.9 ± 1.5*</td>
<td>21.4 ± 2.3*</td>
</tr>
<tr>
<td>ACE+FES-LCE</td>
<td>28.2 ± 3.1</td>
<td>49.9 ± 4.9</td>
<td>74.1 ± 5.7‡</td>
</tr>
<tr>
<td>HYBRID</td>
<td>20.0 ± 2.9</td>
<td>37.8 ± 2.8</td>
<td>54.4 ± 3.8</td>
</tr>
<tr>
<td><strong>VO$_2$ (L min$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>702.1 ± 37.9</td>
<td>889.1 ± 54.9†</td>
<td>1165.6 ± 69.9†</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>411.3 ± 35.3*</td>
<td>488.4 ± 30.6*</td>
<td>600.0 ± 45.6*</td>
</tr>
<tr>
<td>ACE+FES-LCE</td>
<td>819.4 ± 30.8</td>
<td>1082.1 ± 22.7</td>
<td>1411.6 ± 47.1</td>
</tr>
<tr>
<td>HYBRID</td>
<td>912.6 ± 67.8</td>
<td>1210.8 ± 49.3</td>
<td>1392.0 ± 60.3</td>
</tr>
<tr>
<td><strong>(Ca-Cv)VO$_2$ (ml 100 min$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>7.4 ± 0.3</td>
<td>7.5 ± 0.3</td>
<td>9.0 ± 0.3</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>5.6 ± 0.4*</td>
<td>5.6 ± 0.4*</td>
<td>6.1 ± 0.3</td>
</tr>
<tr>
<td>ACE+FES-LCE</td>
<td>8.6 ± 0.4</td>
<td>8.9 ± 0.3</td>
<td>9.7 ± 0.3</td>
</tr>
<tr>
<td>HYBRID</td>
<td>8.4 ± 0.5</td>
<td>9.8 ± 0.3</td>
<td>9.4 ± 0.8</td>
</tr>
<tr>
<td><strong>Lactate (mmol L$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>2.8 ± 0.2</td>
<td>3.7 ± 0.3</td>
<td>5.7 ± 0.5</td>
</tr>
<tr>
<td>FES-LCE</td>
<td>3.4 ± 0.27</td>
<td>4.7 ± 0.4</td>
<td>5.7 ± 0.5</td>
</tr>
<tr>
<td>ACE+FES-LCE</td>
<td>3.5 ± 0.3</td>
<td>4.9 ± 0.6</td>
<td>7.4 ± 0.8§</td>
</tr>
<tr>
<td>HYBRID</td>
<td>4.4 ± 0.9</td>
<td>5.5 ± 0.9</td>
<td>8.3 ± 0.5§</td>
</tr>
</tbody>
</table>