Peak and kinetic cardiorespiratory responses during arm and leg exercise in patients with spinal cord injury

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Study design: A paired comparison of the peak and submaximal responses of oxygen uptake and heart rate in patients with spinal cord injury (SCI) performing voluntary arm cycle exercise and functional electrical stimulation (FES) leg cycling exercise.

Objectives: To test if the blunted heart rate response and slower rate of adjustment of oxygen uptake seen in patients with SCI performing FES leg cycle exercise are also characteristic of arm exercise in these patients.

Methods: Eight paraplegics performed incremental and constant work rate (CWR) exercise with the legs and arms. Mean response times (MRT) for $\dot{V}O_2$ during exercise (on) and in recovery (off) were calculated from the breath-by-breath $\dot{V}O_2$ profile.

Results: Peak heart rate was higher during incremental arm exercise, and uncorrelated with that observed during incremental FES leg cycling. For the same increase in $\dot{V}O_2$, constant work rate arm exercise was associated with faster (and normal) $\dot{V}O_2$ kinetics, greater increase in heart rate, and lower end-exercise blood lactate, compared to FES leg cycling.

Conclusions: The consistently higher peak heart rate and $\dot{V}O_2$, and faster $\dot{V}O_2$ kinetics, for voluntary arm compared to FES leg cycle exercise suggest no intrinsic dysfunction of heart rate control in these paraplegics. Rather, these data suggest that during FES leg cycling the changes seen are due to some characteristic specific to the injury, such as reduced muscle mass and/or deconditioning of the remaining muscle.

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Introduction

The kinetics of $\dot{V}O_2$ during and following functional electrical stimulation (FES) leg cycle exercise in patients with spinal cord injury (SCI) have been shown to be extremely long,¹ and are associated with a reduction in peak $\dot{V}O_2$. However, unlike other conditions which result in such decrements of aerobic function (eg, sedentarity,² deconditioning via bedrest,³ cardiovascular disease(s),⁴ acute hypoxic^{5,6} or anemic⁷ hypoxia), the peak heart rate was also reduced in the patients with SCI – correlating significantly with the reduced peak $\dot{V}O_2$.¹ As the maximum work rate was not symptom-limited in these subjects, this cannot account for the low maximum heart rate such as is

often the case in subjects with severe chronic obstructive lung disease.⁸ Consequently, it was not possible from these studies to rule out impaired neural control of heart rate as being contributory to the slowed $\dot{V}O_2$ kinetics.

We hypothesized, therefore, that if the consequences of SCI on cardiovascular control and exercise tolerance were confined to the lower limbs (ie, below the lesion), then peak and kinetic responses of $\dot{V}O_2$, and the associated peak and submaximal heart rate responses, during voluntary arm exercise would be similar to those reported for able-bodied subjects performing similar exercise, that is, they would be independent of those that characterize FES leg cycling. The kinetics of $\dot{V}O_2$ for arm exercise have not, to our knowledge, been established for paraplegic subjects. The purpose of the present study, therefore, was to

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compare peak and kinetic responses of $\dot{V}O_2$, and the associated heart rate responses, during arm exercise with those of similar FES leg cycle ergometry in patients with SCI who exhibited a wide spectrum of peak heart rates during FES leg exercise.

Methods

Subjects

Eight male volunteers with SCI were enrolled in the project after giving written informed consent. The project was approved by the Research and Development Committee at the VA West Los Angeles Health Care Center. Each subject was medically screened prior to testing. This included: physical examination; sensory/motor neurological assessment; X-rays of the chest, spine and lower limbs; blood chemistry and urinalysis; and a resting and stress test ECG during arm crank ergometer testing. All subjects were ASIA/IMSOP Class A.⁹ The age of the subjects averaged ($\pm$ SD) 34.3 ± 6.7 years, height was 176.2 ± 3.6 cm, weight was 73.1 ± 11.8 kg, and level of injury ranged from T4 to T12-L1.

Functional electrical stimulation leg cycle exercise

Leg exercise was performed on a REGYS1 FES leg cycle ergometer coupled to a computer system (Therapeutic Alliances, Inc., Fairborn, OH, USA), as previously described.¹ Exercise was performed by sequential stimulation of the quadriceps, hamstrings and gluteal muscle groups via carbon-filled silastic surface electrodes which were placed over the motor points for each muscle. The current was varied under computer control over the range of 10–132 mA to provide the minimum level necessary to maintain a pedalling frequency of 50 r.p.m. Limitations of system design did not permit recording of the actual current used during a study.

Exercise tests

Each subject performed incremental and constant work rate tests on both the Regis FES system and a Monark arm ergometer. The constant work rate tests were maintained for at least 10 min. The work rate for the FES leg cycling was unloaded cycling. The constant work rate for the arm test was chosen from the arm incremental test to provide a steady state $\dot{V}O_2$ equivalent to that of the constant work rate leg test. The constant work rate FES leg cycling protocol began with 2 min assisted cycling. During this period the pedals were turned at 40–45 rpm by a technician while FES was applied to the subject's muscles. This was followed by 10 min of unassisted, unloaded FES cycling. Recovery from the FES exercise began with assisted pedalling for the first 2 min, followed by several minutes of rest. The assisted pedalling during the first 2 min of recovery was included in order to

minimize effects of blood pooling. The arm exercise protocol consisted of 2 min of rest, 10 min of exercise, and 10 min of rest recovery.

Measurements

Pulmonary gas exchange ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, and other variables) was measured breath-by-breath throughout each testing protocol using a Medical Graphics CPX metabolic cart (Medical Graphics Corporation, Minneapolis, MN, USA). The gas analyzers and pneumotachograph were calibrated before each exercise test. In addition, the system was validated at regular intervals using a metabolic simulator (MGC).¹⁰ Heart rate was continuously monitored via a 6-lead ECG and stored in the breath-by-breath gas exchange file.

Data analysis

The breath-by-breath $\dot{V}O_2$ data from the constant work rate tests were aligned to the start and end of exercise, and interpolated once per second to create evenly spaced data points. The responses of $\dot{V}O_2$ for each

Table 1 Peak exercise responses for leg and arm exercise

	Legs	Arms
$\dot{V}O_2$, $l \text{ min}^{-1}$	1.27 ± 0.27	1.44 ± 0.35
Heart rate, $b \text{ min}^{-1}$	127.1 ± 27.9	$166.8^a \pm 16.4$
O_2 pulse, $ml \text{ b}^{-1} \text{ min}^{-1}$	10.1 ± 1.4	$8.6^b \pm 2.0$
Work rate, Watts	12.2 ± 5.6	$58.1^b \pm 12.5$

^a $P=0.015$ compared to legs; ^b $P<0.01$ compared to legs

Figure 1 Peak heart rate during FES leg cycling exercise compared to peak heart rate during voluntary arm cranking exercise in same subjects with SCI. Dashed line is identity

subject both during exercise and in recovery were then fit to an exponential model,

$$\dot{V}O_2(t) = REF + A_1 (1 - e^{-(t - TD)/\tau}) \quad (1)$$

where REF represents either the average over the 2 min of assisted exercise prior to the transition to work, or the last minute of exercise prior to the start of recovery, A_1 is the increase (exercise) or decrease (recovery) from baseline, TD is a time delay from the start of exercise or recovery to the beginning of the exponential process, and τ is the time constant. The kinetics were described as the mean response time (MRT_{on} for exercise, MRT_{off} for recovery), which is equal to the sum of $\tau + TD$. The 2 min of assisted cycling at the beginning of recovery did not have a discernible effect on the gas exchange responses or heart rate in recovery.

Figure 2 Peak heart rate (upper panel) and peak $\dot{V}O_2$ (lower panel) plotted against level of SCI lesion. Open symbols, voluntary arm cranking exercise; solid symbols, FES leg cycle exercise. Neither peak heart rate nor peak $\dot{V}O_2$ for either mode of exercise was significantly related to level of lesion

Statistics

Paired t -tests were used to compare the peak and constant work rate exercise values for arms *versus* legs. Significance was declared for $P < 0.05$. Relationships between variables were examined using linear correlational analysis. Data are presented as mean $\pm$ standard deviation.

Results

Peak exercise responses

While the peak $\dot{V}O_2$ for the arm exercise was similar to that achieved during the FES leg exercise, the peak heart rate and work rate were significantly higher, and the peak O_2 pulse was lower (Table 1).

As previously found in a similar cohort,¹¹ peak heart rate during FES-LCE showed a wide range among the subjects (78–168 bpm). Further, the peak heart rate was significantly correlated with the peak $\dot{V}O_2$ ($r = 0.80$, $P < 0.01$). However, as seen in Figure 1, peak heart rate during arm exercise was consistently higher and somewhat less variable among the subjects, than during FES-LCE. There was no significant relationship between these maximum values. Furthermore, the peak $\dot{V}O_2$ during arm exercise was not a function of the corresponding peak heart rate ($r = 0.12$, $P > 0.05$), unlike the case for FES-LCE. Consequently, the blunted heart rate response and associated reduction of exercise tolerance for FES-LCE did not translate into comparable blunted peak responses to incremental arm exercise. Finally, neither peak heart rate nor peak $\dot{V}O_2$ for either arm or leg exercise were significantly correlated with level of lesion of the spinal cord injury below T_4 (Figure 2).

Constant work rate exercise

The responses of $\dot{V}O_2$, heart rate, and blood lactate during the exercise are presented in Table 2, along with the mean response times for the exercise (MRT_{on}) and recovery (MRT_{off}) kinetics of $\dot{V}O_2$. The $\dot{V}O_2$ and heart rate response profiles for arm and leg exercise for a representative subject are shown in Figure 3. As intended, the mean steady-state $\dot{V}O_2$ for the arm exercise was similar to that for the FES leg cycling. This also represented similar per cent peak $\dot{V}O_2$ for each mode of exercise. However, arm exercise was associated with higher heart rates, and lower blood lactate and MRTs compared to FES leg exercise. Interestingly, the higher heart rate for the arm CWR exercise represented a similar percentage of the peak heart rate for arm exercise as the lower heart rate did for the FES leg CWR exercise. Consequently, both $\dot{V}O_2$ and heart rate for the constant-work rate tests were scaled to the same relative per cent of the corresponding peak responses. Finally, peak heart rate for FES-LCE did not significantly correlate with the $\dot{V}O_2$ MRT_{on} or MRT_{off} for either leg or arm exercise ($P > 0.05$).

Table 2 Responses to constant work rate exercise

	$\dot{V}O_2$ (l min ⁻¹)	$\dot{V}O_2$ (% peak)	HR (b min ⁻¹)	HR (% peak)	Lac (mmol l ⁻¹)	MRT _{on} (s)	MRT _{off} (s)
Arms	0.92 ± 0.23	68 ± 22	133 ± 26	81 ± 18	2.9 ± 1.0	67.5 ± 22.8	51.7 ± 10.4
Legs	0.93 ± 0.19	75 ± 15	103 ^b ± 17	85 ± 22	6.3 ^a ± 1.5	147.5 ^b ± 52.7	100.1 ^a ± 22.0

% peak = percentage of peak value during incremental exercise; HR = heart rate; MRT = mean response time for $\dot{V}O_2$ response: on, during exercise; off, during recovery. ^a $P < 0.05$ compared to arms; ^b $P < 0.01$ compared to arms

Figure 3 $\dot{V}O_2$ and heart rate (HR) during constant work rate exercise for voluntary arm exercise (left panels) and for FES leg cycling (right panels) for one subject. Numbers represent mean response times (MRT) for $\dot{V}O_2$ during exercise and recovery. Note blunted rise in heart rate for FES leg exercise, and the corresponding slowed $\dot{V}O_2$ response

Discussion

Our findings demonstrate that peak heart rate and $\dot{V}O_2$, and the mean response time for the $\dot{V}O_2$ kinetics are normal during voluntary arm exercise in paraplegic subjects, even those who exhibit a marked reduction in peak heart rate during FES leg cycle exercise.

Peak heart rate is often markedly reduced during FES-LCE in paraplegics.^{11–14} Peak $\dot{V}O_2$ is also reduced^{13–15} and has been shown to be well correlated with the heart rate achieved.¹¹ We hypothesized that if the low maximum heart rate was a result of a fundamental alteration in regulation of heart rate in patients with SCI, then we would also expect to see a reduction in peak heart rate during arm

exercise similar to that seen with FES leg cycling. This was not the case, however. Heart rate was consistently higher during voluntary arm exercise than during FES leg cycling. Furthermore, there was less intersubject variability, and no significant correlation with peak $\dot{V}O_2$ (as was the case for FES leg exercise), and no significant correlation between peak heart rate for leg cycling and for arm exercise. That is, a low heart rate response during FES leg cycling was not predictive of low heart rate during voluntary arm exercise, or any other cardiorespiratory response which we examined.

The mean peak heart rate achieved by our patients with SCI during arm exercise is similar to that reported for other paraplegic groups^{16–18} as well as able-bodied subjects.^{19–21} It thus appears that the

reduced heart rate response seen in some subjects with SCI while performing FES leg cycling is not due to an inherent dysfunction in control of heart rate. Rather, it is likely due to something specific to FES-induced exercise of muscle mass below the level of injury. Whether the attenuated heart rate response with FES leg cycling is due to reduced muscle mass and/or premature fatiguing of the existing deconditioned leg musculature, or in fact causes the early fatigue due to inadequate cardiovascular support of O_2 delivery, is presently unclear.

$\dot{V}O_2$ kinetics are thought to be determined largely by the aerobic capacity of the contracting muscles,^{2,22} which under many circumstances can be modified by the dynamic adjustment of O_2 delivery.^{23,24} Several studies have examined the kinetics of $\dot{V}O_2$ during arm and leg exercise in able-bodied subjects.^{19,20,25} These studies consistently found that $\dot{V}O_2$ kinetics were longer for arm than for leg exercise during moderate exercise, and slowed to a greater degree during heavy exercise (as blood lactate concentrations rose) compared to leg exercise.¹⁹ It was proposed that these differences in $\dot{V}O_2$ kinetics between leg and arm exercise in the same subjects were due to differences in level of conditioning of the limbs. In the present study, the opposite was apparent, with longer time constants for FES leg exercise compared to voluntary arm exercise. Here too, the most likely explanation for this patient group would be a difference in level of conditioning between the arms and legs, in concert with a blunted rise in heart rate for the FES leg cycling exercise.

Previous studies had implied¹⁸ or found²⁶ significant correlation between peak $\dot{V}O_2$ during arm cranking exercise and level of the SCI. In contrast, neither peak $\dot{V}O_2$ nor peak heart rate, for either arm or FES leg exercise, were significantly related to level of the SCI in the present study. However, in the present investigation, we only studied subjects with lesions of the thoracic region, whereas both of the previous studies included patients with cervical, thoracic and lumbar lesions. If one excludes the results of the quadriplegic patients (cervical lesions), the data of Burkett *et al*²⁶ then yields a nonsignificant correlation ($r=0.23$) between peak $\dot{V}O_2$ and level of injury. Thus, in paraplegic subjects, the level of the lesion does not appear to predict exercise tolerance or cardiorespiratory responses to incremental exercise (performed either voluntarily with the arms or FES-induced with the legs).

We utilized a simple monoexponential model including time delay to describe the kinetics of adjustment of $\dot{V}O_2$ during and in recovery from exercise in this study, as in previous studies of similar paraplegic subjects during FES leg cycle exercise.¹¹ This is in contrast to other work in able-bodied subjects in which we utilized a 3-exponential model.^{6,27} The reason for not applying a more complex exponential model to the current data lay in the frequently large breath-to-breath noise levels seen in

these patients, which in our judgement precluded confident assessment of specific components of the $\dot{V}O_2$ response. Ideally, we would have chosen to have each subject perform multiple transitions, and averaged them together as previously done⁶ so as to reduce the noise and enhance the underlying response. However, in the present study, even the lightest work rate on the leg FES ergometer (unloaded cycling, equal to approximately 15 W due to internal friction in the cycle) engendered blood lactates in the range of 4–8 mmol l⁻¹. This would have necessitated a rest period of at least 1–1.5 h before another exercise bout could be performed, so as to allow lactate levels to return towards the original pre-exercise baseline. Given the time necessary to prepare a paraplegic subject to perform one exercise bout, and the fact that the subjects were performing a variety of other tests as well over several days, we deemed it impractical to conduct multiple transition tests. There are two consequences to this decision. First, we sacrificed the ability to describe the $\dot{V}O_2$ kinetics in more detail than with summary statistics (ie, MRT). However, as previously reported,^{28,29} inordinately long overall kinetics as described here are associated with elevated blood lactate levels and emergence of a secondary, slow rise in $\dot{V}O_2$ which projects above the anticipated $\dot{V}O_2$ cost for the work rate performed. Thus, this current analysis approach yields conclusions regarding exercise intensity which are very similar to those derived in able-bodied subjects from more discriminative techniques. Second, the greater breath-to-breath noise ultimately translated into greater theoretical difficulty in finding statistically significant differences (type II error) between conditions (arms vs legs). In spite of this, however, the differences between leg and arm responses, were still significant. Thus, we believe that our conclusions regarding comparisons of the kinetic responses are sound.

Conclusions

Peak heart rate, and the associated peak $\dot{V}O_2$, were in the normal range for paraplegics performing voluntary arm exercise. $\dot{V}O_2$ kinetics for arm exercise were also normal, and consistently faster than those for FES-LCE. These findings suggest that the impaired cardiac response and concomitant peak and kinetic responses of $\dot{V}O_2$ with FES-LCE are specific to FES-induced exercise with the affected limbs, and do not indicate global impairment of cardiac function or exercise tolerance with unaffected muscles.

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