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ScienceDirect
Biomedical Signal Processing and Control 2 (2007) 311–322
Biomedical Signal Processing and Control
www.elsevier.com/locate/bspc

Control approach for high sensitivity cardiopulmonary exercise testing during stimulated cycle ergometry in spinal cord injured subjects

C. Ferrario [a], K.J. Hunt [a,b,*], S. Grant [c], A.N. McLean [b], M.H. Fraser [b], D.B. Allan [b]

[a] Centre for Rehabilitation Engineering, Department of Mechanical Engineering, University of Glasgow, Glasgow G12 8QQ, UK
[b] Queen Elizabeth National Spinal Injuries Unit, Southern General Hospital, 1345 Govan Road, Glasgow G51 4TF, UK
[c] Faculty of Biomedical and Life Sciences, University of Glasgow, Glasgow G12 8QQ, UK

Received 7 February 2007; received in revised form 14 June 2007; accepted 14 June 2007
Available online 6 August 2007

Abstract

Aim: People with complete lower-limb paralysis resulting from spinal cord injury (SCI) can perform cycle ergometry by means of functional electrical stimulation. Here, we propose and evaluate new exercise testing methods for estimation of cardiopulmonary performance parameters during this form of exercise.
Methods: We utilised a customised ergometer incorporating feedback control of stimulated exercise workrate and cycling cadence. This allowed the imposition of arbitrary workrate profiles with high precision with the potential for improved sensitivity in exercise testing. New incremental exercise test (IET) and step exercise test (SET) protocols for determination of peak and steady-state performance parameters were assessed.
Results: The IET protocol allowed reliable determination of the ventilatory threshold, peak workrate and oxygen uptake-workrate relationship, but gave unrepresentative peak oxygen uptake values and highly variable measures of oxygen uptake kinetics. The SET protocol gave reliable estimation of steady-state oxygen uptake and metabolic efficiency of constant load exercise, but high variability in the estimation of oxygen uptake kinetics.
Conclusion: The feedback-controlled testbed and the new IET and SET protocols have the potential for estimation of cardiopulmonary performance parameters with improved sensitivity during stimulated cycle ergometry in subjects with SCI.

Keywords: Feedback control; Exercise physiology; Spinal cord injury

1. Introduction

People with spinal cord injury (SCI) often have restricted exercise options and therefore are more subject to cardiopulmonary and muscular deconditioning than able bodied (AB) people. Paralysis causes rapid muscle atrophy in the affected limbs, blood pooling and consequent reduced resting blood flow. Many studies have shown that peak oxygen uptake ($\dot{V}_{O_{2peak}}$), heart rate and power output are much lower in the SCI population than in AB people [1–3]. In paraplegic people with a motor-complete lesion, the muscle mass available for voluntary exercise is reduced. This means that it is difficult to challenge the cardiopulmonary system, as the number and the size of the muscles involved in the exercise are small. It has been shown that even in AB people, arm exercise is less effective than leg exercise in improving cardiopulmonary fitness [4].

Barstow et al. [5] reported that oxygen uptake kinetics in SCI subjects are slower than in AB subjects. They also reported a three-fold increase above resting metabolic rate in SCI subjects during unloaded cycling, compared to a doubling in AB. They suggested that the slower pulmonary gas exchange and ventilation kinetics in SCI subjects could be due to their reduced aerobic power. Raymond et al. [3] compared functional electrical stimulation (FES) cycling in paraplegics with voluntary cycling in AB subjects. The outcome was that when the SCI and AB groups cycled at a similar steady-state oxygen uptake, the power outputs were 9.2 and 42.8 W, respectively, that is 4.5 times lower for SCI subjects. Barstow et al. [6] compared voluntary arm exercise and FES leg cycling in SCI subjects. They found that $\dot{V}_{O_{2peak}}$ was similar for both exercise

* Corresponding author at: Centre for Rehabilitation Engineering, Department of Mechanical Engineering, University of Glasgow, Glasgow G12 8QQ, UK.
E-mail address: k.hunt@mech.gla.ac.uk (K.J. Hunt).

1746-8094/$ – see front matter
doi:10.1016/j.bspc.2007.06.001

modalities, but the peak heart rate and power output were significantly lower for the leg exercise. In constant load tests during arm exercise the heart rate was higher and the gas exchange kinetics quicker than during leg exercise. They concluded that gas exchange responses during arm cranking were in the normal range for paraplegics doing voluntary exercise. Thus, the reduced cardiac response and exercise tolerance that occur during FES cycling are specific to FES-exercise only. Glaser et al. [1] found that at the same power output SCI subjects presented significantly higher $\dot{V}_{O_2}$ than AB subjects, while the maximum power output that they could sustain was lower. They explained this as the result of the unusual recruitment pattern of the muscles and their deteriorated condition. Therefore, they suggested that there is much scope for improving SCI people's cardiorespiratory system by means of FES exercise, because of the relatively high metabolic rate it elicits.

It has been demonstrated that FES cycling is an effective way of reconditioning the body by means of exercise of the paralyzed limbs. Improvements in peripheral muscular fitness, central cardiovascular fitness, exercise tolerance, gas exchange kinetics and aerobic metabolism following FES exercise are documented [4,7–11]. Barstow et al. [7] investigated the changes in gas exchange kinetics that occurred in SCI subjects following training. They found that the kinetics for $\dot{V}_{O_2}$, carbon dioxide output ($\dot{V}_{CO_2}$) and minute ventilation ($\dot{V}_E$) became faster and the intersubject variability of kinetics decreased with training. Some studies have also found that sustainable power output, muscle strength and time endurance increased with training [4,8]. Therefore, the performance of daily activities improved, as they became physically less stressful. Moreover, the risk of cardiovascular disease is reduced after training [12].

An accepted means of measuring a subject's cardiopulmonary fitness is to monitor respiratory gas exchange during exercise. Incremental and constant load tests have been used to investigate changes in cardiopulmonary fitness and performance of SCI subjects following FES exercise [8,9,11,13].

Exercise tests have often been performed on commercially available FES-cycle ergometers (e.g. the ERGYS system, Therapeutic Technologies, Inc., Tampa, FL). Such ergometers typically have the limitation that the minimum increment in power output possible is 0.125 kp, equivalent to 6.1 W. Thus, incremental test protocols included steps of 6.1 W, starting from 0 W (unloaded cycling). Considering that the peak power output reached by SCI subjects is generally reported to be below 20 W [7,3,14,8], the maximum number of steps achievable in an incremental test is usually no more than three. It is generally agreed that in order to detect the key markers of cardiopulmonary status it is better to have a ramp or 1-min increments in power output, rather than a few large steps [15]. A duration of 10–12 min for the incremental part of the test is also suggested in order to achieve the highest peak $\dot{V}_{O_2}$ possible in AB subjects. Extended or reduced durations will result in slightly lower values [15]. In previous SCI studies the average duration of the incremental tests has been no less than 15 min [8,10] and in some cases it was as long as 20 min [9]. Moreover, rest bouts have sometimes been introduced between steps, thus breaking the continuity of the test [9,10].

Previously, constant load tests have typically been performed in an "unloaded" condition (0 W). However, this is considered unsatisfactory, because the power needed to move the legs is relatively high for SCI subjects. Barstow et al. quantified this power and found that it corresponded to approximately 12 W in their subjects [5]. For AB subjects the peak value for power output is much higher than for SCI subjects. Therefore, the gap between rest and 0 W would account for a small percentage of their total capacity, i.e. small enough to be neglected. In Barstow's study an SCI subject could reach a peak power output of about 14.5 W, thus the "unloaded" cycling was a significant percentage of the total workrate range of 26.5 W (from −12 to 14.5 W): 45%. It is likely that for untrained subjects, such as those at the beginning of the training, this level could be close to 100% or could in fact exceed their capability. Moreover, in subjects who *are* able to sustain at least 0 W, the next available level in previously used ergometers is 6.1 W, which represents a very large increment since 6.1 W is generally a large proportion of the total workrate range in these subjects. Therefore, it is important to be able to use smaller steps for the increments in power output and it would be highly advantageous to be able to set the constant load power output to an arbitrary level within the "negative workrate range", i.e. at an effective power of less than 0 W. We provide a method for achieving this. It is also possible that 0 W is a level above the ventilatory threshold (VT) as defined by Wasserman et al. [15], thus causing the $\dot{V}_{O_2}$ kinetics to be slower. This hypothesis could explain why in most of the previous studies the respiratory exchange ratio (RER, defined as $\dot{V}_{CO_2}/\dot{V}_{O_2}$) values were above 1 during the constant load tests [5,7,8,16]. 0 W could also be a level between the critical and the peak power for SCI individuals, the critical power being that power level above which reaching a metabolic steady-state is no longer possible [17]. This means that $\dot{V}_{O_2}$ keeps increasing until it reaches the maximum level of the subject.

In all the previous SCI studies, the target cadence was 50 rpm, but it was allowed to vary within the range of 35–50 rpm and to drop down to 35 rpm before the test was stopped [4,5,7–10]. The energy required to turn the legs of the subject, i.e. to overcome frictional losses, can be considered a constant loss only if the cadence does not change during exercise. However, if the cadence changes, this energy requirement is bound to change too. Given the low value of $\dot{V}_{O_2}$ during exercise, the energy required to overcome frictional losses is likely to be a considerable percentage of the overall metabolic expenditure. Therefore, it is important to be able to keep the cadence constant during the tests.

In the present paper, we utilize a test apparatus, described previously in ref. [18], which allows accurate feedback control of cycling cadence and workrate. We propose novel protocols for incremental and constant-load exercise tests for determination of the key markers of cardiopulmonary status.

The proposed incremental exercise test (IET) allows determination of peak oxygen uptake, the time constant of the dynamic oxygen uptake response, the dynamic oxygen cost of the exercise and the peak exercise workrate. Moreover, the