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Methods and protocols for incremental exercise testing in tetraplegia, using arm-crank ergometry assisted by Functional Electrical Stimulation

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Abstract

Cervical spinal cord injury (SCI) leads to tetraplegia, with paralysis and loss of sensation in the upper and lower limbs. The associated sedentary lifestyle results in an increased risk of cardiovascular disease. To address this, we require the design of exercise modalities aimed specifically at tetraplegia and methods to assess their efficacy.

This paper describes methods for arm-crank ergometry (ACE) assisted by Functional Electrical Stimulation (FES) applied to the biceps and triceps. The instrumented ergometer enables work-rate control during exercise, implemented here for incremental exercise testing during FES-ACE. Detailed protocols for the tests are given.

Experimental data collected during exercise tests with tetraplegic volunteers are provided to illustrate the feasibility of the proposed approach to testing and data analysis. Incremental tests enabled calculation of peak power output and peak oxygen uptake.

We propose that the high-precision exercise testing protocols described here are appropriate to assess the efficacy of the novel exercise modality, FES-ACE, in tetraplegia.

Keywords: spinal cord injury; cardiopulmonary fitness; rehabilitation; exercise testing; functional electrical stimulation; tetraplegia

1 Introduction

In tetraplegia, which results from cervical spinal cord injury (SCI), there is paralysis and loss of sensation in the arms, trunk and legs, and disruption to autonomic nervous system function. This leads to functional limitations which, as a result of extensive research, are gradually being addressed through rehabilitation and assistive technology. Many of these rehabilitation tools are based on the technique of Functional Electrical Stimulation (FES) [1]. In addition to functional systems, there is a growing need for technology and interventions to address the secondary consequences of SCI. Some of these issues relate to the much reduced activity that follows from extensive paralysis. Long-term health problems include an increased risk of cardiovascular disease in tetraplegia [2] associated with greatly reduced cardiopulmonary fitness. The way in which exercise may be used to address this needs to be explored.

In tetraplegia, there are two main obstacles to tackling low cardiopulmonary fitness through exercise prescription. Firstly, the options for exercise in the tetraplegic population are limited. Secondly, with the extent of autonomic dysfunction resulting from a cervical SCI [3], a number of autonomic responses normally involved in cardiopulmonary function during exercise are compromised [4].

We propose that general physical activity and exercise participation need to be increased in this group to address the issue of reduced fitness, but in order to achieve this we need: (i) new tailor-made exercise modalities that are appropriate to people with extensive physical disability (as is the case in tetraplegia), and (ii) clinical exercise testing protocols to determine the causes and extent of exercise limitation in the individual with tetraplegia, and to determine the most appropriate means of tackling these.

Clinical cardiopulmonary exercise testing (CPET) is a popular tool for the evaluation of exercise intolerance and the effect of treatment and rehabilitation in individuals with a wide variety of conditions [5, 6]. Clinicians and therapists already use CPET to obtain diagnostic information for a number of patient groups, including people with a range of cardiorespiratory diseases [6], such as Chronic Obstructive Pulmonary Disease, Interstitial Lung Disease, Pulmonary Vascular Disease, Cystic Fibrosis, and Exercise Induced Bronchospasm. A number of key diagnostic features of the data collected during incremental exercise tests for people with cardiopulmonary limitations would not be identifiable from resting cardiopulmonary data or other clinical investigations made at rest [7].

Similarly to the use of clinical exercise testing in these patient groups, we propose that a systematic and accurate method is required for the determination of cardiopulmonary variables through exercise testing protocols adapted for tetraplegics. The main uses for the data collected during these tests would be: (i) to enable determination of the extent and causes of exercise limitation in individuals with high SCI, on a case-by-case basis, (ii) to enable clinically relevant evaluations and comparisons of exercise modalities and training programmes in this population.

Some of the variability in exercise responses within this population can be attributed to the completeness of the injury, and the degree of sparing of the pathways of the autonomic nervous system. A clinically complete SCI (Grade A on the American Spinal Injury Association (ASIA) scale) is diagnosed where there is no motor or sensory function preserved in the lowest sacral segments (S4-S5) [8]. There are three grades (B, C or D) of incomplete injury on the ASIA scale, depending on the extent of sensory and/or motor function that is preserved. In incomplete SCI, any amount of sparing to the pathways of the nervous system may have occurred. Furthermore, there may be some sparing of sympathetic nervous system (SNS) pathways even in clinically complete SCI. This is because only motor and sensory scores are included in the routine clinical classification of SCI at present. Ellaway and colleagues [9] have been working towards incorporating a clinical test for SNS dysfunction in the evaluation of SCI patients. There is large variability in the extent of autonomic dysfunction, in addition to the variability in the amount of upper limb musculature remaining under voluntary control in tetraplegia. Therefore, it is inappropriate to look at average responses in the tetraplegic group. Instead, it seems more suitable to use tests that identify the physiological limitations on a case-by-case basis, and to analyse the results of the test in relation to the individual.

This paper provides a description of methods and protocols for exercise testing, designed for this group. These methods would allow for the investigation of exercise capacity or limitation, and the monitoring of certain cardiopulmonary benefits of exercise intervention by performing regular repeat exercise tests over the duration of a training programme [10]. The exercise modality with which these methods and protocols are tested here is arm-crank ergometry (ACE) assisted by Functional Electrical Stimulation (FES) of the biceps and triceps muscles of both arms. FES-ACE is appropriate in tetraplegia as the electrical stimulation recruits weak or paralysed muscles that are key for an effective arm-cranking motion. Protocols are described for incremental exercise tests, and the outcome measures and their validity are discussed with reference to the target population. Examples of cardiopulmonary data from tests with tetraplegic patients are provided to illustrate how the results can be used to identify exercise capacity and limitations in tetraplegia, and to determine the feasibility of precision exercise testing in a population with variable and often complex multifactorial exercise limitation.

2 Methods

2.1 Subjects

Inclusion criteria were: (i) traumatic cervical SCI at C4–C6 (ii) no history of recurring autonomic dysreflexia, (iii) neurological stability, (iv) psychological stability, (v) no extensive denervation of the biceps or triceps muscles, and (vi) no excessive spasticity.

We present data from two subjects, Subject A was male, with motor-complete, sensory-incomplete (grade B on the ASIA Scale of Impairment) SCI at the C6 level, 18 years post-injury and 38 years old at the start of participation, and Subject B was female, with motor- and sensory- complete (grade A on the ASIA Scale of Impairment) C6 SCI, 8 months post-injury and 52 years old.

The study was approved by the South Glasgow University Hospitals Research Ethics Committee, and written informed consent was obtained from the subjects prior to participation.

2.2 Methods for FES-assisted Arm Crank Ergometry

During FES-assisted arm crank ergometry (FES-ACE) sessions, the subject is sitting in his/her own wheelchair. The height of the ergometer is such that the centre of the cranks is horizontally aligned with the subject's shoulders. The subject is positioned with the elbows in slight flexion when the crank is at the furthest distance from the body, and the wrists are stabilised in the armrests using straps and bandages.

The overall setup is shown diagrammatically in Figure 1 and consists of the ACE device, the pattern generator (implemented in the PC) and the neuromuscular stimulator.

The arm-crank ergometer provides measurements of the crank angle, the angular velocity and the motor torque. The crank angle and the angular velocity are used in the pattern generator to decide when each muscle group is to be stimulated. In addition, a work-rate controller can be included. Four stimulation channels are used: left and right biceps and left and right triceps. Stimulation is applied using standard surface electrodes (Pals, Axelgaard).

The components of this setup are described in more detail below.

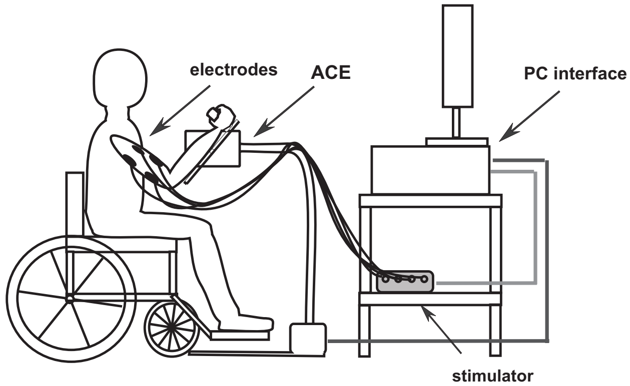


Figure 1: Schematic set-up for FES-assisted arm-cranking with tetraplegic subjects.

2.2.1 Arm-crank ergometer

In this study, a motor-assisted ACE device is used which allows for (i) passive arm-cranking where the arms are moved by the motor of the ergometer, and (ii) active arm-cranking where the motor acts as a load for the movement generated by the user. Measurements of motor torque m_o, angular velocity (cadence) ω and crank position θ are provided through a serial communications link (RS232) to the computer.

The inner control structure of the ACE device is shown in Figure 2. The difference between the motor torque, m_o, and the external moment, m_{ext}, (which is typically generated by the user) leads to a change in cadence,

$$\omega(t) = \frac{1}{I} \int (m_o(t) - m_{ext}(t))\, dt\,. \tag{1}$$

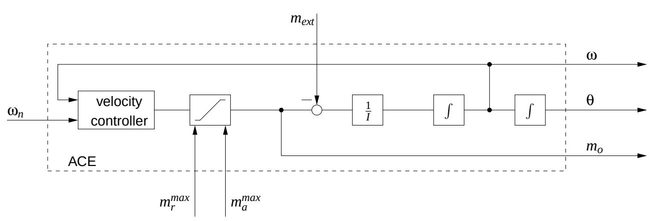


Figure 2: Inner control structure of the ACE.

The ACE velocity controller aims to adjust the motor torque, m_o, in such a way that a nominal crank speed, ω_n, is maintained. Two saturation parameters, maximal resistive moment, m_r^{max}, and the maximal active moment, m_a^{max}, affect the motor torque as follows: (i) if the external moment acts as a load then the torque generated by the ACE to drive the cranks is limited by m_a^{max} while (ii) for an external moment which drives the cranks actively, the maximal resistance generated by the motor is limited to m_r^{max}.

As a result of this, two related operation modes can be distinguished (neglecting the dynamics of the velocity controller): (i) if $\omega < \omega_n$, then $m_o = m_a^{max}$, and (ii) if $\omega > \omega_n$, then $m_o = m_r^{max}$.

The TheraVital ACE (Medica Medizintechnik, Germany) used in this study allows the three input parameters ω_n, m_r^{max} and m_a^{max} to be set via a control terminal. Additionally, these parameters can be adjusted on-line via a bi-directional communications link which allows the workrate control described below to be implemented fully automatically.

2.2.2 Pattern Generator and Stimulator

A pattern generator determines when each muscle group is to be stimulated, depending on the position of the cranks and the crank velocity. The algorithm used is similar to the one developed for FES-assisted leg cycling [11, 12]: for each muscle group, a nominal angular stimulation range is defined by a pair of start and stop angles, $\theta_i^{\text{on/off}}$, where i indicates the four muscle groups. The nominal stimulation ranges for all four muscle groups are shown in Figure 3.

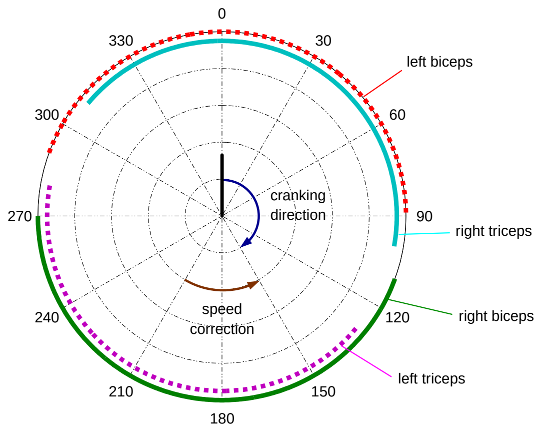


Figure 3: Nominal stimulation ranges. The angle is shown as the position of the right crank arm.

The detailed structure of the pattern generator is depicted in Figure 4. While cranking at an angular velocity ω the nominal stimulation ranges as defined by the static on/off angles, $\theta_i^{\text{on/off}}$, need to be adjusted to compensate for the muscle latency, t_d. This results in a set of dynamically varying on/off angles $\tilde{\theta}_i^{\text{on/off}}(\omega)$,

$$\tilde{\theta}_i^{\text{on/off}}(\omega) = \theta_i^{\text{on/off}} - t_d\,\omega\ . \tag{2}$$

The latency results from (i) the time t_d^{on} it takes for the muscle to generate a moment after stimulation is applied, and (ii) the time t_d^{off} which it takes for the muscle to relax after the stimulation is switched off. The latencies generally vary depending on the muscle and the load, and t_d^{on} can generally be different from t_d^{off} [13, 14]. Experimental measurements from our labs (unpublished observations) using a load cell to measure the torque response to stimulation under isometric conditions indicate that $t_d^{\text{on}} \approx t_d^{\text{off}} \approx 100 \ldots 150$ms for biceps and triceps. From our experiments, the muscle latency is described by a single factor $t_d = 130$ms that includes any delays between the controller and the electrodes. For a typical exercise cadence of 50rpm this results in an adjustment of the stimulation sequence by 0.68rad (39^o).

Whether a stimulation channel should be switched on or off is determined by comparing the dynamic angles $\tilde{\theta}_i^{\text{on/off}}(\omega)$ to the measured crank angle $\theta(t)$.

The level of stimulation pulsewidth, $p(t)$, is adjusted by a throttle signal which is implemented as a potentiometer connected via a data acquisition (DAQ) card. The pulsewidths can be individually scaled for each muscle group by a corresponding weighting factor. A rate limiter ensures that the stimulation is gradually switched on for each channel. This results in a smoother movement and was found to be less likely to trigger spasms than using a steep switching flank, in particular for slow crank speeds. The stimulation current is maintained at a constant level of typically 30mA, and the stimulation frequency is 20Hz. The pattern generator drives the neuromuscular stimulator (Stanmore Stimulator [15]) via an isolated RS232 link.

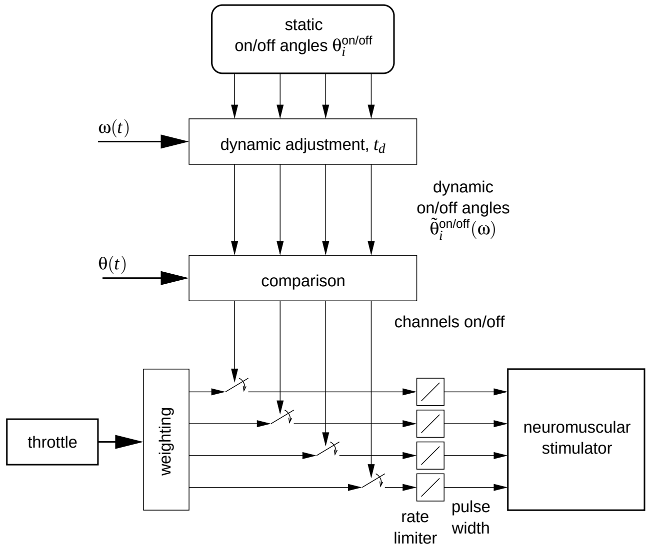


Figure 4: Pattern Generator for four stimulation channels. See text for details.

2.2.3 Work-rate Control

The work-rate W can be defined as the product of external torque and cadence,

$$W(t) = m_{ext}(t) \times \omega(t) \ . \tag{3}$$

Provided that the cadence is approximately constant, it follows from equation (1) that $m_0 - m_{ext} \approx 0$. This implies that the work-rate can be estimated using the measured output torque from the ergometer,

$$W(t) \approx m_o(t) \times \omega(t) \quad \text{if}\, \omega(t) \approx \text{const}\,. \tag{4}$$

In order to control the work-rate both cadence and torque need to be regulated. For a specific exercise test, the desired work-rate, W_{ref}, is typically given at a nominal cadence, ω_{ref}. The corresponding desired output torque can be calculated as $m_{\text{ref}} = W_{\text{ref}}/\omega_{\text{ref}}$.

A control strategy was implemented which maintains the desired output torque by adjusting the resistive torque parameter of the ACE device accordingly while the subject is asked to maintain a constant reference cadence ω_{ref} through visual feedback of the measured crank speed. A schematic representation is given in Figure 5.

Work-rate control during FES-ACE exercise enables incremental exercise testing in tetraplegia, as described in detail in the section "Methods for exercise testing".

2.2.4 Signal processing & analysis

The raw measurement data for torque, m_o and cadence, ω, available from the ACE contain significant noise components and can vary over a wide range during one revolution of the cranks. The work-rate control described above does not aim to regulate the work-rate within one crank cycle. In order to reduce noise entering the feedback loop through visual feedback to the user and through the pattern generator, the torque and cadence were filtered using a moving average filter with a horizon of one crank revolution, ie.

$$m_o(t) = \frac{1}{t - t_{2\pi}} \int_{t_{2\pi}}^{t} m_o^{raw}(\tau) d\tau \tag{5}$$

$$\omega(t) = \frac{1}{t - t_{2\pi}} \int_{t_{2\pi}}^{t} \omega^{raw}(\tau) d\tau \tag{6}$$

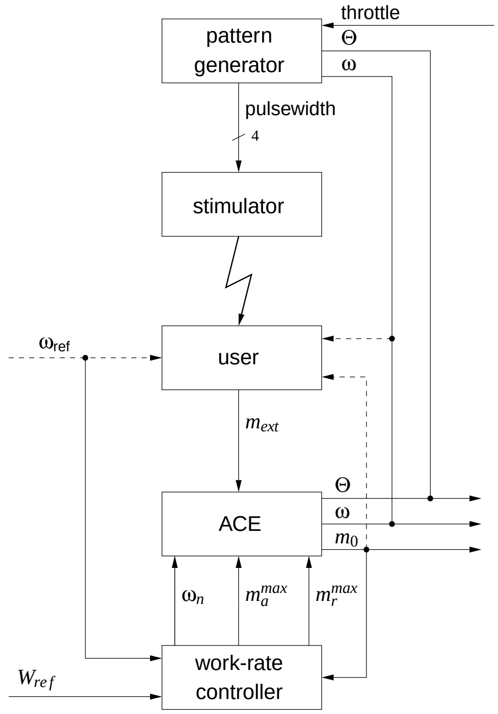


Figure 5: Work-rate control setup.

where m_o^{raw} and ω^{raw} are the unfiltered measurements of torque and cadence, respectively, t is the current time instance and $t_{2\pi}$ is the time at which the crank position is one revolution preceding the current position $\theta(t)$, ie.

$$\theta(t_{2\pi}) = \theta(t) - 2\pi \tag{7}$$

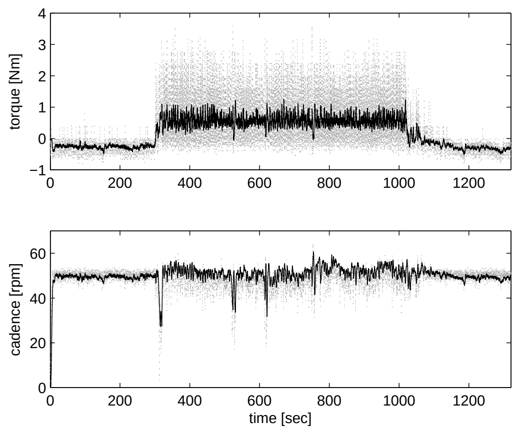
This signal processing approach is illustrated in Figure 6(a) with sample data recorded with a subject with C6 tetraplegia (Subject B), where the raw torque and cadence data are shown together with their filtered versions. At the end of the FES-ACE session, it is possible to select time windows within the total session for further analysis.

To analyse the contribution of different muscle groups within one crank revolution, the variation of the torque within one turn of the crank is evaluated by averaging the torque profile over a number of revolutions and displaying it as a function of crank position θ. This is illustrated in Figure 6(b) with experimental data from the same subject as above. It can be clearly seen that the torque varies over a wide range throughout a single crank cycle, with two distinctive periods where the torque contribution reaches peak values.

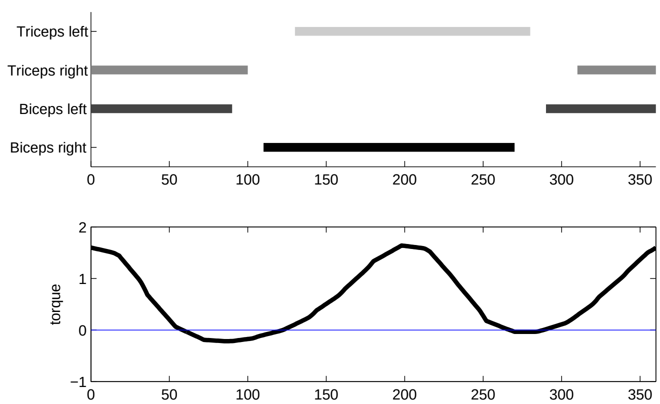
2.3 Methods for exercise testing

2.3.1 Apparatus

For the breath-by-breath cardiopulmonary measurements during exercise, a portable system (MetaMax3B, Cortex Medical, Germany) is used. With the subject breathing through a low dead-space mask (Hans-Rudolf), inspired and expired O_2 and CO_2 concentrations, and inspired and expired volume and flow are monitored continuously by discrete gas analysers and a turbine, respectively. This enables determination of oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$) and end-tidal tensions of oxygen (end-tidal PO_2) and carbon dioxide (end-tidal PCO_2). Via an RS232 link, we record pulse rate and oxygen saturation using a pulse



(a) Raw and filtered FES-ACE data



(b) Variation of torque within a cycle

Figure 6: Data from a constant load FES-ACE exercise session with a C6 tetraplegic subject (Subject B) to illustrate aspects of data filtering and averaging.

oximeter (3800, Datex-Ohmeda, Finland) with an earlobe sensor. Prior to each test, the breath-by-breath cardiopulmonary measuring system's volume transducer is calibrated using a 3-litre syringe, and the O_2 and CO_2 gas analysers are calibrated using two references gases of known concentrations.

Ratings of perceived exertion (RPE) and ratings of perceived breathlessness (RPB) are used during testing. RPE is on a 15-point Borg scale (from 6-20) [16] and RPB on a 12-point scale (from 0-10). For this, the investigator points to the chart and moves down each scale until the subject signals the appropriate level with one clear blink of the eyes.

Each subject is familiarised with the physiological measurement equipment and protocols over a minimum of two sessions prior to baseline testing. Familiarisation is especially important in this group of patients as they have limited possibilities for indicating discomfort or distress during the exercise tests. Testing sessions are performed in an adequately ventilated room, with minimal background distractions. To allow communication during testing between the subject and the investigator, a system of eye-blinking is practised. In response to clear questions from the investigator, the subject replies with one single blink of the eyes for a "yes" and two blinks of the eyes for a "no" answer.

2.3.2 Protocol for incremental exercise testing

The subject is asked to refrain from eating, smoking, and drinking alcohol or coffee for at least two hours prior to the test. He/she is required to empty their urine bag before starting the test. Ideally, the subject should not have performed any exercise training for 24 hours prior to the test.

Prior to incremental exercise testing, the investigator determines the step-size of the increments, and programmes the sequence of work rate changes in the Matlab/Simulink FES-ACE exercise testing software. For the incremental portion of the test, the work rate is set to be stepped up every minute. Based on the results of familiarisation tests (or training work rates used with the subject in the week preceding the formal tests), the investigator chooses a step size for the test that is predicted to limit the incremental phase of the test to between 8 and 12 minutes [17]. The time line of the incremental tests is illustrated in a schematic diagram in Figure 7.

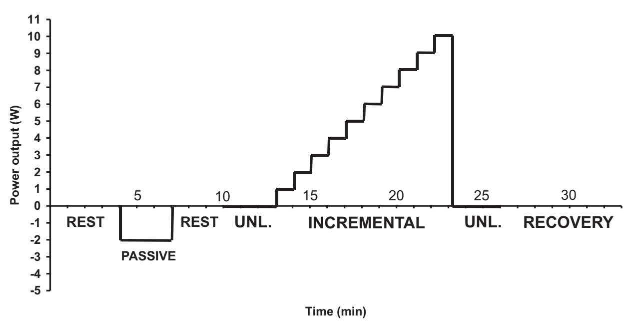


Figure 7: Schematic diagram to show the phases of the incremental exercise tests; 'UNL.' refers to 'unloaded exercise'.

Electrodes are attached and each muscle is tested for response to stimulation and to determine stimulation intensities to be used during the FES-ACE exercise test. The subject is set-up at the arm-crank ergometer, as shown in Figure 8. When the subject has settled down, the mask is placed over the nose and mouth and tightened to ensure a tight seal.

Monitoring of cardiopulmonary data begins with the recording of resting data. This is

Figure 8: General set-up for incremental FES-assisted arm-cranking test with tetraplegic subjects.

initiated when consecutive breaths over a period of three minutes show no greater than 5% variation in oxygen uptake ($\dot{V}O_2$), the respiratory exchange ratio (RER) is between 0.7 and 0.9, and the end-tidal PCO_2 shows no signs of hyperventilation. At least two minutes of recorded resting data are collected.

To loosen the muscles and to reduce the likelihood of triggering spasms in the exercising muscles when the stimulation is switched on, the passive mode of the arm-crank ergometer is used for a “warm-up”. Three minutes of passive arm-cranking are programmed, during which time only the motor maintains the desired cadence.

A second resting phase follows. During this time, recording of cardiopulmonary data continues for at least three minutes, or until values stabilise.

With no load applied, the subject is then instructed to begin moving the cranks round or the electrical stimulation is gradually increased, depending on the remaining voluntary control of upper limb muscles by the individual, until the target 50 rpm cadence is achieved and maintained. Visual feedback of actual and target cadence are continuously provided to the subject using real-time graphical display on the PC screen. Unloaded arm-cranking is maintained for three minutes.

After this, the resistance is automatically stepped up every minute to increase the work rate in pre-programmed equal steps. The size of the steps in work rate varies between tests and subjects, from 1W to 4W. The incremental phase generally lasts between 8 and 12 minutes. In order to maintain the cadence at increasing work rates, the stimulation intensity is increased manually by the investigator when necessary.

During the last 30 seconds at each work rate, RPE and RPB are recorded.

When the desired cadence of 50 rpm can no longer be maintained (dropping consistently to below 35), the load is reduced back down to zero-load. Unloaded arm-cranking during this active recovery phase lasts for 2 to 4 minutes.

Stimulation is switched off. The arms are then brought to rest and passive recovery begins.

Recording of cardiopulmonary data stops when values return to pre-exercise resting levels.

2.3.3 Analysis of cardiopulmonary data

Breath-by-breath data are edited and analysed using commercially available statistical software (Origin 7.5, OriginLab, Massachussets, U.S.). The raw cardiopulmonary data are systematically edited: outliers are removed if they are outwith +/- 2 SD of the fitted regression line. Roughly 95% of datapoints would be expected to lie within +/- 2 SD. We propose that the low signal-to-noise ratio in the cardiopulmonary data collected from this tetraplegic subject justifies the choice of +/- 2 SD as the cut-off point for excluding aberrant breaths.[1]

The editing is applied to the following variables: breathing frequency, tidal volume, times of inspiration and expiration, end-tidal PO_2 and PCO_2, and fractions of expired oxygen and carbon dioxide. The edited data are then 4-breath or 8-breath averaged (according to the length of the test) for clearer graphical representation, and to identify patterns of gas exchange.

2.3.4 Outcome measures

The combined cardiopulmonary and ACE datasets are used to determine the following:

- **Peak power output** (in W) — calculated as the mean power output over 60 s at the highest completed work rate.
- **Peak oxygen uptake** (in $\mathrm{l.min^{-1}}$) — the breath-by-breath data are edited to remove outliers, and time-aligned with the power output data. The peak oxygen uptake is calculated as the mean oxygen uptake (after editing) over the last 30 s at the highest completed work rate.
- **Oxygen uptake-work rate relationship** — a linear regression is fitted to the $\dot{V}O_2$-WR relationship for each incremental test, and the slope of the regression is calculated.
- **Graphical representation** — 10-panel arrays of the edited and 4-breath or 8-breath averaged data are produced for each incremental test. These are based on Wasserman et al.'s 9-panel array [5], but with an additional panel to incorporate the RPE and RPB data.

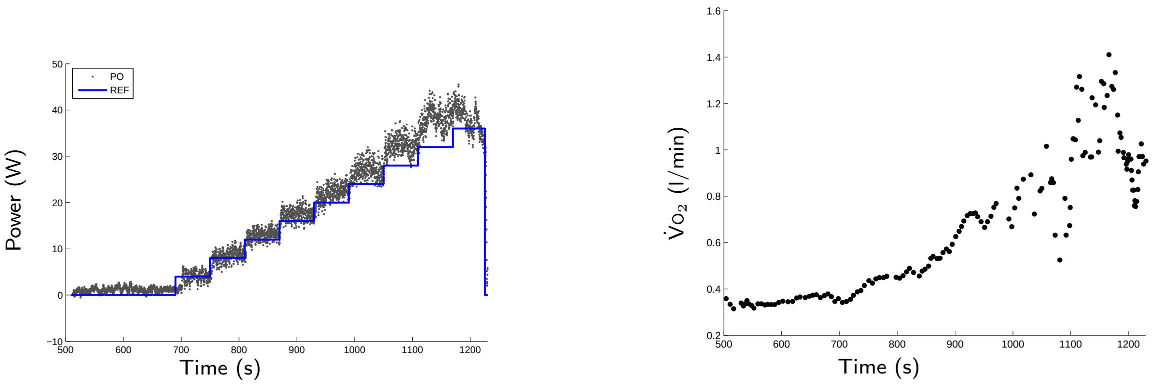
3 Results

Data presented here were taken from an incremental exercise test with two subjects with tetraplegia to illustrate features of the data collection and analysis. The purpose is to put forward a full specification of the FES-ACE incremental exercise testing protocol, and to demonstrate feasibility of the proposed protocol in this population.

3.1 Peak values

The profile of changing power output over time during an incremental FES-ACE exercise test is shown for Subject A in Figure 9 (a). The peak power output was calculated at 38 W. The corresponding oxygen uptake response after editing and 8-breath averaging is plotted in Figure 9 (b) for the same time sequence. The estimated peak oxygen uptake from this test was 1.1 $\mathrm{l.min^{-1}}$. Similarly, the power output and oxygen uptake profiles are shown for Subject B in Figure 10, with a peak power output calculated at 6 W (Figure 10 (a)) and peak oxygen uptake at 0.5 $\mathrm{l.min^{-1}}$ (Figure 10 (b)).

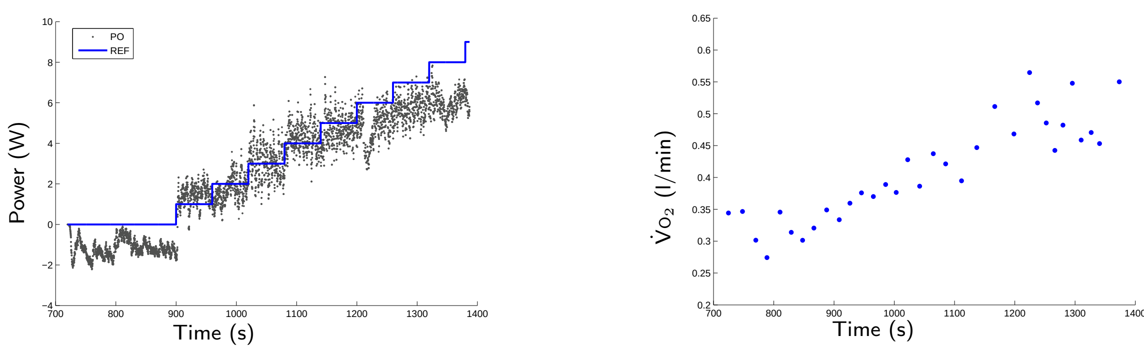
[1] In a study by Lamarra et al. [18], the authors delete breaths with values exceeding +/- 3 SD from the mean, but suggest that the noise variance varies significantly between subjects, and consequently so do the statistics of the noise.



(a) Power output profile

(b) Oxygen uptake profile

Figure 9: Work-rate control and corresponding oxygen uptake response during an incremental FES-ACE exercise test with Subject A. (PO: actual power output; REF: reference work rate)



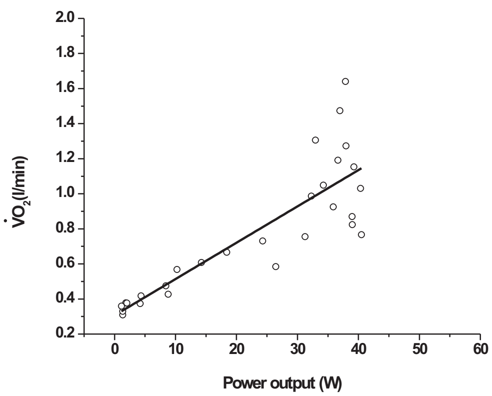
(a) Power output profile

(b) Oxygen uptake profile

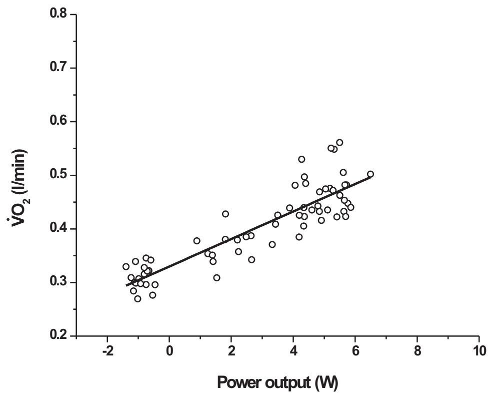
Figure 10: Work-rate control and corresponding oxygen uptake response during an incremental FES-ACE exercise test with Subject B. (PO: actual power output; REF: reference work rate)

3.2 $\dot{V}O_2$-work rate relationship

The $\dot{V}O_2$-WR relationship is shown in Figure 11. A linear regression was fitted to the relationship, giving a slope of 0.02 $l.min^{-1}.W^{-1}$ (with a Pearson correlation coefficient, R^2, of 0.72) for Subject A (Figure 11a) and 0.02 $l.min^{-1}.W^{-1}$(with a Pearson correlation coefficient, R^2, of 0.70) for Subject B (Figure 11b).



(a) Subject A



(b) Subject B

Figure 11: Linear regression of the $\dot{V}O_2$ -WR relationship for the incremental test.

3.3 Graphical representation

The edited and 8-breath averaged cardiopulmonary data were combined with the FES-ACE data to produce 10-panel graphical arrays summarising the subjects' exercise responses, and are given in the Appendix (Figures 12 & 13).

Although an in-depth analysis of the full dataset for each subject is beyond the scope of this paper, the key features to take from the graphical representations include:

- *Heart rate profile* — This is shown in plot (b). The data from both subjects show the expected linearity of the HR-PO relationship with increasing work rate, over the range of work rates performed. However, in both cases, the peak HR is much lower than would be expected in healthy neurologically-intact individuals performing voluntary exercise — as a guide, "220-*Subject's age*" is typically used as a quick estimate of peak HR for lower limb exercise. Here, Subject A's (38 years old) peak HR was around 100 bpm (Figure 12(b)), and Subject B's (52 years old) was around 90 bpm (Figure 13(b)) — much below their potential peaks of 182 bpm and 168 bpm, respectively.

- *Ventilatory profile* — This is shown in plot (a). There is no indication of severe ventilatory limitation in either subject, as ventilation increases in accordance with the ventilatory requirements of the increasing exercise work rates.

- *Gas exchange threshold* — This is determined predominantly from plot (e), with confirmation from plots (f), (h) and (i). The gas exchange threshold (GET) should represent the lactate threshold (LT) and is determined using the V-slope method [19]. It is identified as the oxygen uptake at the point of inflexion in the $\dot{V}CO_2$–$\dot{V}O_2$ relationship (right-axis on plot (e)) over the incremental phase of the test. To increase the confidence that the threshold represents metabolic acidosis, the information obtained from the V-slope method is correlated with characteristic changes in the ventilatory equivalents for oxygen and carbon dioxide (plot (f)), in the respiratory exchange ratio (plot (h)), and in the end-tidal CO_2 and O_2 tensions (plot (i)). For Subject A, the data suggest that during this test the GET occurs at approximately 1.0 $l.min^{-1}$, at a power output of between 35 and 38W. For Subject B, the GET is estimated at around 0.45 $l.min^{-1}$, at a power output of 4W.

- *Ratings of perceived breathlessness and exertion* — These can be found in plot (j), and provide us with an indication of the subject's own perception regarding the extent to which their breathing is altered and how hard they think they are working during the incremental phase of the exercise. Subject A perceived that he had almost reached his limit of exercise tolerance by the end of the test, but did not perceive his breathlessness to be near-maximal. In contrast, Subject B felt that she was neither excessively breathless nor exerting herself to any great extent by the end of the test.

4 Discussion

In this paper, we describe systems and protocols for FES-ACE exercise testing, designed for individuals with C4–C6 SCI. The devices used include the ACE device, a pattern generator and the neuromuscular stimulator, to stimulate the biceps and triceps at the appropriate parts of the arm-cranking cycle. Accurate work-rate control during FES-ACE, requiring regulation of both cadence and torque, was implemented during incremental exercise testing for the assessment of the individual's cardiopulmonary fitness. We propose that the information obtained from incremental FES-ACE exercise testing protocols described here provide a clear representation of the tetraplegic individual's capability and potential for upper-limb exercise. The proposed protocols allowed us to produce a number of key outcome measures, as illustrated with data from two subjects with C6 SCI performing the exercise test. In addition to the main cardiopulmonary outcome measures, peak power output (or work rate) was determined during FES-ACE exercise, to provide an indication of the individual's upper-limb strength.

Here, the main cardiopulmonary outcome measure was peak $\dot{V}O_2$. This surrogate for $\dot{V}O_{2max}$ is now accepted for patient groups with severe exercise limitation [5, 6], as is the case in tetraplegia. Furthermore, the term peak $\dot{V}O_2$ is more suitable than $\dot{V}O_{2max}$ when referring to arm-exercise in any group as the exercise only involves a small exercising muscle mass, in contrast to leg-cycling or treadmill running. At rest, a person consumes around 0.25 $l.min^{-1}$ of oxygen. If this person leads a sedentary lifestyle, oxygen consumption can increase to around 2.5 to 3.0 $l.min^{-1}$ in an incremental treadmill or leg-cycle ergometry exercise test (and around 50-75% of this value in an arm-cranking exercise test). For an athlete, values of up to 5.5 $l.min^{-1}$ can be reached. Maximum or peak oxygen uptake is considered to be a good indicator of cardiopulmonary fitness, as it reflects the maximal functional ability of the circulation. When this is clearly lower than predicted, other indicative values need to be looked at to explore the exercise limitation further. From the data presented here, both subjects had low peak $\dot{V}O_2$ values when compared to the general population, of 1.1 $l.min^{-1}$ in Subject A and 0.5 $l.min^{-1}$ in Subject B , but these are in the typical range for tetraplegia [20]. One component of the exercise limitation is likely to be an inability to increase heart rate sufficiently through sympathetic drive to meet the demands of increasing exercise work rates. In tetraplegia (and paraplegia at T6 and above), there may be extensive disruption to the sympathetic innervation to the heart depending on the completeness of the injury. This limitation to exercise manifests itself as a "blunted heart rate response" [21, 20] as the inadequate input to the cardiac plexus would prevent the normal sympathetic acceleration of heart rate during exercise [22]. The heart rate data showing this exercise limitation in the two tetraplegic subjects are plotted in the 10-panel graphical representation (plot (b)).

In order to summarise the gas exchange responses in this 10-panel array of graphs, the raw cardiopulmonary data from the incremental FES-ACE exercise tests were edited and averaged. In healthy subjects, gas exchange responses are remarkably uniform between individuals and so the 10-pannel arrays representing the tetraplegic subjects' exercise responses can be compared to the plots for "normal" responses to exercise, and any discrepancies can be followed up to identify the source(s) of exercise limitation in each individual. A series of flowcharts, such as those produced by Wasserman et al. [5] can be used to facilitate the interpretation of the data obtained through exercise testing. Wasserman et al. also provide examples of the equivalent plots of the gas exchange data to illustrate the typical symptoms of coronary artery disease, peripheral arterial disease, dilated cardiomyopathy, pulmonary vascular disease, obesity, chronic obstructive pulmonary disease, sarcoidosis, and interstitial pulmonary fibrosis.

In clinical exercise testing, the results of the incremental exercise test can therefore be used to identify the extent and cause(s) of exercise limitation. In addition, it can inform the decision regarding which work rates should be implemented in the individual's training programme. In healthy individuals, exercise work rates can be set to elicit a desired percentage of maximum heart rate. However, this is of limited value in tetraplegia, as this group has been shown to have a blunted heart rate response. An alternative is to base the training work rates on a percentage of peak oxygen uptake (or a percentage of peak power output), which may be the most appropriate exercise prescription method for this group. Finally, work rates for training can be set within the moderate intensity domain, by choosing a range of work rates below the lactate threshold (LT). The LT concept would need to be shown to be reliable in this group, and for this mode of exercise, if this method of exercise prescription were to become applicable in tetraplegia. The LT concept is questionable for FES-exercise, as the pattern of recruitment of motor neurones (and, subsequently, muscle fibres) during FES-induced muscle contraction differs from that in normal voluntary control of muscle contraction. We therefore recommend that exercise training in tetraplegia should be set according to a percentage of the individual's peak $\dot{V}O_2$.

For each incremental test, the combined gas exchange data and FES-ACE data also allowed us to plot oxygen uptake against WR. From this, a linear regression of the $\dot{V}O_2$-WR relationship was fitted to determine the efficiency of the exercise, in relation to the oxygen cost to the muscles of performing the work. This can be compared to the $\dot{V}O_2$-WR relationship determined for other types of cyclical exercise. For example, for cycle ergometry in able-bodied individuals, the slope of this relationship tends to be around 0.01 $\mathrm{l.min^{-1}.W^{-1}}$ [5]. The test data presented in this paper indicated that, for these two subjects, the slope was 0.02 $\mathrm{l.min^{-1}.W^{-1}}$. This suggests that the FES-ACE is half as efficient (in terms of oxygen cost) in these tetraplegic subjects, when compared to healthy able-bodied individuals performing leg-cycling exercise.

By applying the protocols described here for FES-ACE exercise and FES-ACE incremental exercise testing, we postulate that the information can be implemented to enable safe and beneficial exercise prescription in this patient group in the future. Based on the results of these incremental tests, tetraplegic subjects can be given individualised training programmes and offered repeat tests at regular intervals to monitor the effects of the exercise intervention. The aim of FES-ACE training would be to improve each of the stated outcome measures over time.

5 Conclusions

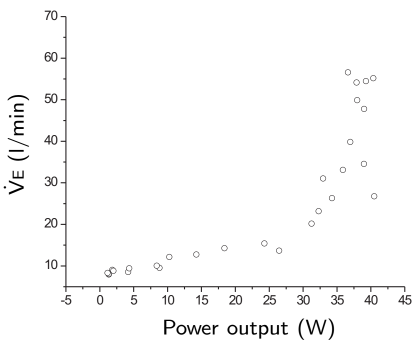
This paper describes methods for FES-ACE exercise and incremental exercise testing protocols during FES-ACE, for use in tetraplegia. Arm-cranking combined with electrical stimulation to the biceps and triceps muscles assists tetraplegics with limited or no voluntary control of those muscles. Accurate work-rate control and real-time recording of power output and stimulation intensity during FES-ACE enabled the design of protocols for incremental FES-ACE exercise tests to assess cardiopulmonary fitness in tetraplegic individuals.

Breath-by-breath cardiopulmonary data collected during exercise tests were combined with the FES-ACE data, to summarise exercise performance. Results from incremental exercise tests with two tetraplegic subjects illustrate aspects of the data collection and analysis, and provide examples of the key outcome measures from the proposed test.

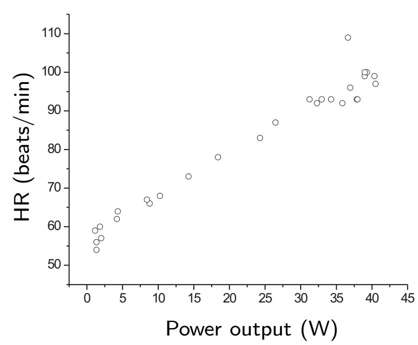
The main aim of developing these FES-ACE system and FES-ACE exercise testing protocols was to provide tools for (i) beneficial exercise in the upper limbs, and (ii) evaluation of upper-limb exercise capacity. These methods and protocols were designed and are appropriate for individuals with severely compromised muscular and cardiopulmonary function, as is the case in tetraplegia resulting from SCI.

Acknowledgements We should like to thank the subjects who took part in this pilot study. We also thank the UK Engineering and Physical Sciences Research Council (EPSRC Grant GR/R30730) and the European Commission (EU Grant MCFI 2000-02190) for funding the project.

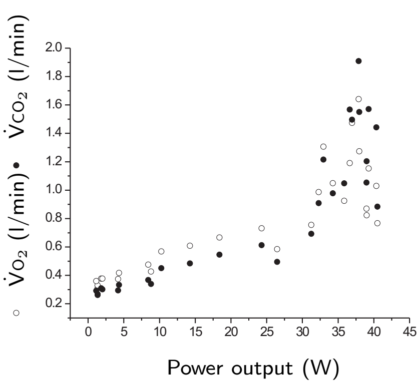
6 Appendix



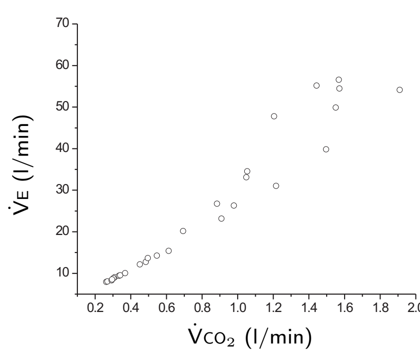
(a) Ventilation vs. power output



(b) Heart rate vs. power output

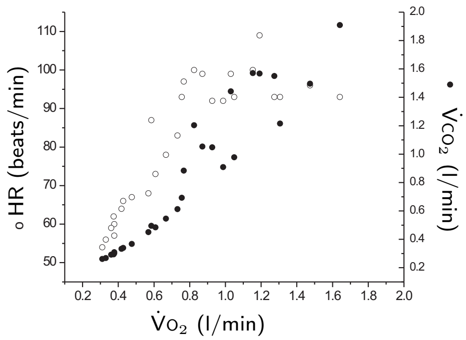


(c) Oxygen uptake and carbon dioxide output vs. power output

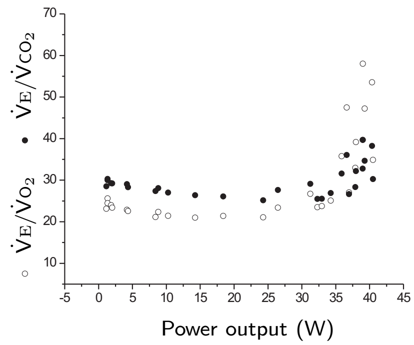


(d) Ventilation vs. carbon dioxide output

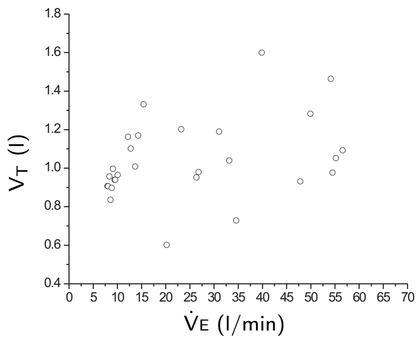
Figure 12: 10-panel array representing the cardiopulmonary data from an incremental test with a C6 (incomplete) tetraplegic subject, Subject A. The data have been edited and 8-breath averaged.



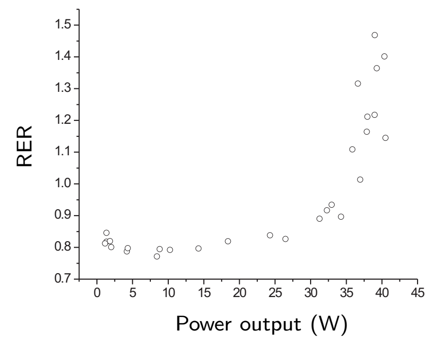
(e) Heart rate and carbon dioxide output vs. oxygen uptake



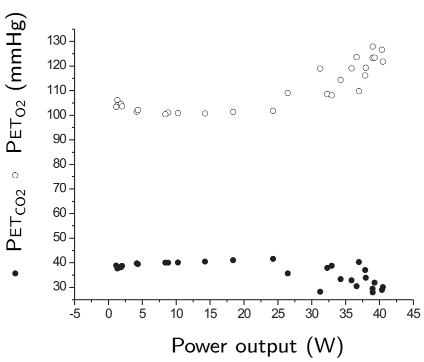
(f) Ventilatory equivalents vs. power output



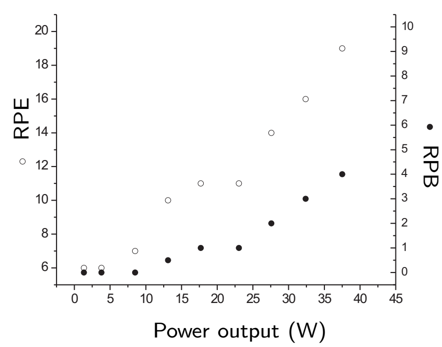
(g) Tidal volume vs. ventilation



(h) Respiratory exchange ratio vs. power output

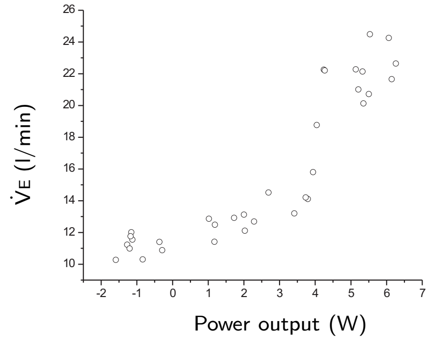


(i) End-tidal tensions vs. power output

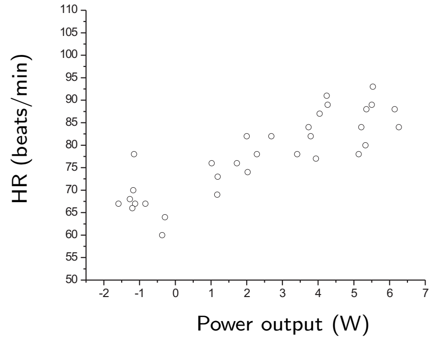


(j) Ratings of Perceived Exertion and Breathlessness vs. power output

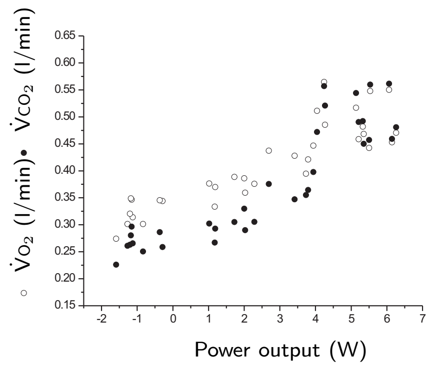
Figure 12: (Continued)



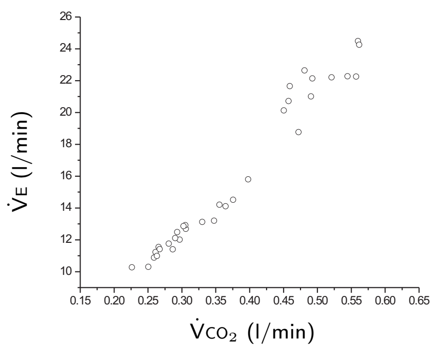
(a) Ventilation vs. power output



(b) Heart rate vs. power output

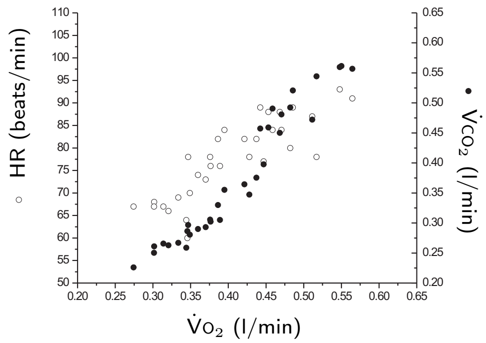


(c) Oxygen uptake and carbon dioxide output vs. power output

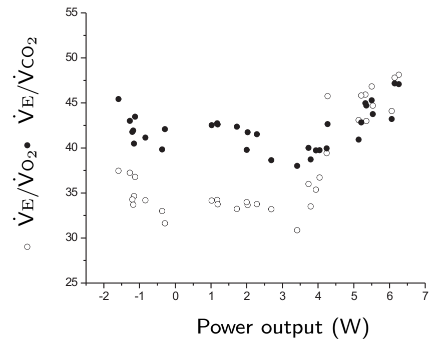


(d) Ventilation vs. carbon dioxide output

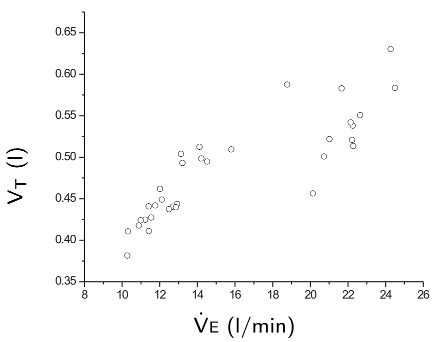
Figure 13: 10-panel array representing the cardiopulmonary data from an incremental test with a C6 (complete) tetraplegic subject, Subject B. The data have been edited and 8-breath averaged.



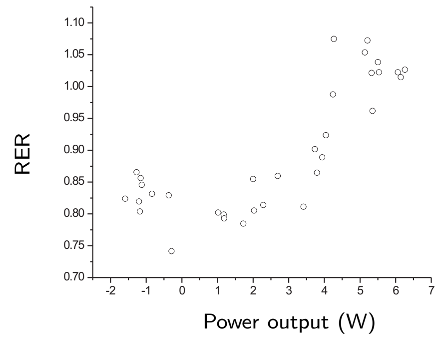
(e) Heart rate and carbon dioxide output vs. oxygen uptake



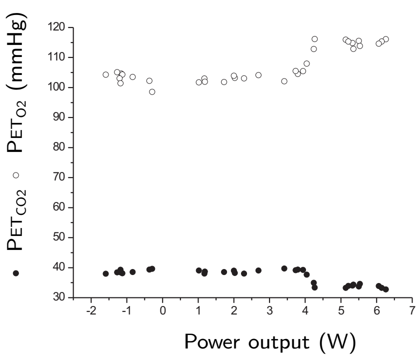
(f) Ventilatory equivalents vs. power output



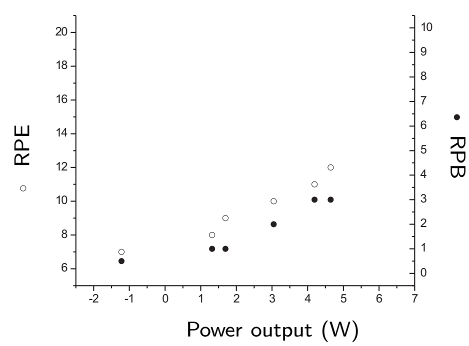
(g) Tidal volume vs. ventilation



(h) Respiratory exchange ratio vs. power output



(i) End-tidal tensions vs. power output



(j) Ratings of Perceived Exertion and Breathlessness vs. power output

Figure 13: (Continued)

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