Upper-limb Exercise in Tetraplegia using Functional Electrical Stimulation

Introduction

Cervical spinal cord injury can result in dysfunction in both the lower and upper limbs (tetraplegia), and may be accompanied by a range of secondary complications. The degree of upper-limb dysfunction depends upon the level and completeness of the lesion; in this paper we consider tetraplegics with a neurological level in the range C4-C6.

A person with a C5- or C6-level injury will generally retain control of the shoulder and elbow flexor muscles (biceps), but will have no control of the hand, wrist or elbow extensors (triceps). With a complete C4 injury voluntary control of the entire arm is lost. Thus, we propose that functional electrical stimulation (FES) of the biceps and triceps muscles may enhance the efficacy of cyclical upper-limb exercise. Alternatives for partial restoration of function include tendon transfer surgery or mechanical orthoses[1].

Previous FES research for C4-C6 tetraplegics has focused on systems for hand function[2,3] and improved working area (i.e. overhead reach)[4,5,6,7], but the provision of upper-limb exercise modalities using FES assistance has been neglected. This is important because the lack of effective exercise can lead rapidly to severe cardiopulmonary deconditioning in this population.

Methods

With functional electrical stimulation, low levels of pulsed electrical current are applied to motor nerves. If the depolarisation threshold is exceeded, action potentials will be propagated and the associated muscle fibres will contract. Here, we use adhesive electrodes attached to the skin surface in the area of the target muscle (see figure 1).

For FES to function properly, it is necessary that the target muscles retain central innervation. Damage to the cell bodies, nerve roots or peripheral nerves may occur around the site of the spinal trauma, and this can lead to denervation of the associated muscle fibres. Thus, a test of target muscle innervation should be included in the assessment of candidates.

The overall setup is shown in figure 2 and consist of a motor-driven arm-crank ergometer (ACE), a pattern generator and a neuromuscular stimulator[8]. The arm-crank ergometer (TheraVital, Medica Medizintechnik, Germany) has an electric motor which can actively move the cranks if the moment applied by the user is not sufficient to drive the cranks, or it can resist the cranking movement, acting as a load. The levels of active support and resistance can be adjusted. The device provides measurements of the crank angle and of the angular velocity which are used in the pattern generator to decide when each muscle group is to be stimulated. The pattern generator uses the angular velocity to adjust the nominal stimulation pattern (which is based on the measured crank angle) to compensate for the delay between stimulation and muscle contraction. The stimulation intensity is set by a "throttle" which is implemented as a potentiometer. The pattern generator drives the neuromuscular stimulator (Stanmore Stimulator, UK) which delivers electrical pulses to the four stimulation channels: left and right biceps, and left and right triceps. The moment generated at the cranks is measured and, together with the angular velocity, used to calculate the power output.

Figure 1: Location of electrode pairs over the biceps (top left) and triceps (above) muscles.

Figure 2: FES-assisted arm cranking ergometer.

Exercise Response Results

Four people with a C4-C6 level SCI are involved in our experimental evaluation of the proposed systems for FES-assisted upper limb exercise[9]. Muscle strength data are recorded throughout each subject's participation. Changes in cardiopulmonary fitness are monitored by measuring oxygen uptake during rigorously-specified exercise tests, which are performed at test points throughout the FES-assisted ACE exercise programme. Spirometry measurements are also made to assess pulmonary function. Together, these measurements allow us to evaluate possible functional and health benefits of this form of exercise in tetraplegia.

As an illustration, data for one subject are presented here. This person is 38 years old, with a C6 (incomplete) SCI. The injury occurred 17 years ago. The FES-ACE training programme consists of a one-month muscle strengthening and familiarisation period, followed by a progressive three-month FES-assisted ACE exercise training programme.

Figure 3 shows the set-up used for exercise testing, using a portable breath-by-breath gas exchange measurement system (MetaMax 3B, Cortex, Germany). A baseline test prior to the start of the FES-ACE training programme revealed that this subject could attain a maximum power output of around 7 W initially. The maximum oxygen uptake recorded in this baseline test was around 0.8 l/min, which is typical for a tetraplegic. The data from tests carried out after just two months of FES-

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ACE exercise are shown in figure 4, when the maximum power output reached was around 30 W and the maximum oxygen uptake was 1.3 l/min. Generally, the greater an individual's maximal oxygen uptake, the greater his (or her) cardiopulmonary fitness. Thus, the steady increase in both maximum oxygen uptake and maximum power output following a progressive FES-assisted arm-cranking exercise regime illustrates its potential benefits to the tetraplegic population.

Figure 3: Incremental exercise test set-up.

Clinical and Therapeutic Implications

Societies with modern health care systems now have a cohort of tetraplegic patients living into their sixties and beyond. These patients are unable to voluntarily recruit enough large muscle groups to maintain cardiovascular fitness and are at high risk of cardiovascular disease. FES-assisted arm cranking devices offer an option for regular exercise, which is otherwise unavailable for people with limited or no upper limb movement. We have shown increases in oxygen uptake and power output following an FES programme and it seems likely that this is a genuine cardiovascular training effect as seen in non-spinal-injured subjects.

We have noted other less obvious but important benefits including improvement in upper arm muscle bulk, which improves self-image. Subjects have also commented on their feelings of exercise fatigue after an FES session. Non-spinal-injured people recognise post-exercise tiredness as a part of everyday life. Tetraplegic subjects may not have experienced "normal" fatigue for many years and the return of this sensation can be rewarding and stimulating. The exercise and movement itself is also rewarding for patients who may have little or no voluntary power below the neck.

We anticipate other medical benefits of FES exercise including maintenance of existing shoulder power and upper limb joint range of movement. These will help daily activities such as transfers, weight shifts, and manual wheelchair propulsion where that is feasible.

Health care commissioners will not fund such treatment unless we can show direct clinical benefits. The improvements in cardiovascular fitness are encouraging and provide a basis for larger trials. The set-up costs are small when compared to overall tetraplegic care costs and we believe there may be a case for long term prescription of FES exercise for tetraplegic people who can commit to the daily regime which is probably necessary to achieve and maintain the improvement in fitness.

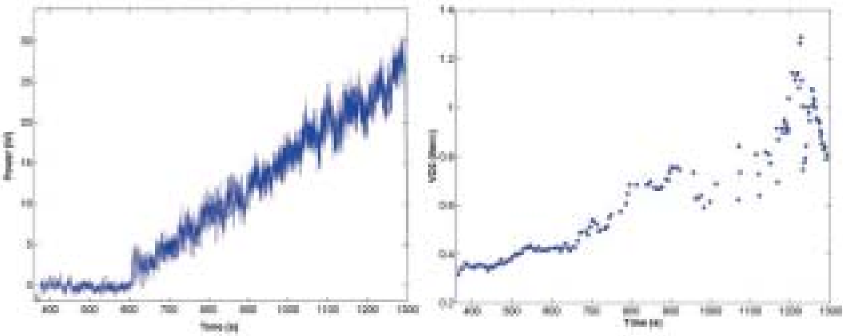

Figure 4: Incremental test data. Increasing power output (left) and oxygen uptake response (right) data for one subject, after two months of exercise intervention, are shown here.

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