<table>
<thead>
<tr>
<th>Title</th>
<th>The effects of a neuromuscular electrical stimulation training intervention on physiological measures in a spinal cord injured male: a case study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors(s)</td>
<td>McCormack, Kirsti; Carty, Amanda; Coghlan, Garrett; Crowe, Louis; Caulfield, Brian</td>
</tr>
<tr>
<td>Publication date</td>
<td>2010-04</td>
</tr>
<tr>
<td>Publication information</td>
<td>Physiotherapy Ireland, 31 (2): 30-35</td>
</tr>
<tr>
<td>Publisher</td>
<td>Irish Society of Chartered Physiotherapists</td>
</tr>
<tr>
<td>Item record/more information</td>
<td><a href="http://hdl.handle.net/10197/2425">http://hdl.handle.net/10197/2425</a></td>
</tr>
</tbody>
</table>
The effects of a neuromuscular electrical stimulation training intervention on physiological measures in a spinal cord injured male: a case study

Mc Cormack K,1 Carty A,1,2 Coughlan GF,1 Crowe LM,1 Caulfield BM1

ABSTRACT

Background: People with spinal cord injury (SCI) are exposed to the development of comorbidities secondary to a decreased ability to exercise and pathological complications. Aerobic exercise has been advocated as a means of preventing the development of these illnesses. Previous research has indicated that functional electrical stimulation (FES) provides an appropriate aerobic stimulus in an SCI population to provide cardiovascular fitness gains. However, FES devices are time consuming for both clients and medical staff in a rehabilitation and home setting with devices often expensive. Our research group have developed a novel neuromuscular electrical stimulation (NMES) system which may provide an alternative to FES and elicit a similar response.

Methods: A 40 year old male with a T6 incomplete SCI, undertook 6 weeks of NMES training for one hour, five days per week. Pre and post intervention measures include a treadmill VO2 peak test, a DXA scan and subjective feedback regarding the NMES device and training stimulus.

Results: Improvements in VO2 peak, heart rate and exercise tolerance were observed with minor decreases in total body fat mass. The participant reported that the NMES was an acceptable form of cardiovascular training.

Conclusion: Our pilot case study has indicated that our NMES system is capable of eliciting an aerobic training effect in people with SCI, which could potentially improve their cardiovascular fitness. Further study with a greater number of participants is warranted in this population using a similar training program.

Keywords: Spinal Cord Injury, Neuromuscular Electrical Stimulation, Aerobic Capacity

Correspondence to: Dr Garrett Coughlan Email: garrett.coughlan@ucd.ie

INTRODUCTION

The spinal cord serves as a bidirectional channel between the brain and its motor, sensory and autonomic targets, allowing the brain to communicate effectively with the rest of the body resulting in healthy, normal human functioning.1,2 A spinal cord injury (SCI) occurs following an insult which disrupts the spinal cord’s conveyance of impulses and can be caused by either a crushing, compressing or stretching insult to the cord within the vertebral canal. 84% of SCI are as result of trauma,3 including motor vehicle accidents (36–48%), violence (5–29%), falls (17–21%), and recreational activities (7–16%).4 Whilst 16% of SCI are owing to non-traumatic causes,3 e.g. tumours, infections, toxins, congenital and developmental disorders, and results in temporary or permanent loss of motor, sensory and autonomic control.3 The gravity of resultant dysfunction will depend on the extent of injury to a particular level of the cord as each level is responsible for a unique bodily function.

Approximately, 13.1 per one million Irish people are affected by SCI annually, and 50% of these injuries are due to motor vehicle accidents.5 Following injury, those affected experience significant changes in their physical, psychological and social capacity. This includes their ability to engage and profit from exercise due to muscle mass paralysis, sympathetic autonomic impairment and decreased venous return.6 Considerable physical deconditioning generally results from the effects of a SCI and contributes to secondary comorbidities such as cardiovascular (CV) disease, reduced bone mineral density (BMD), increases in body fat and decreases in lean body tissue.7,8 Exercise attenuates the development of these comorbidities amongst those with SCI, highlighting the importance of making it routine for those affected.9 Employing exercise as part of daily activity may be hampered by reduced accessibility owing to a loss or impairment of functional movement and lack of wheelchair friendly sports facilities.10 Quadriplegics and paraplegics are also generally restricted to upper extremity exercise which are less effective than lower extremity exercise in generating the CV stress required to experience gains in fitness, whilst also predisposing them to greater risk of developing upper limb over-use injuries. The exercise difficulties surrounding this pathology can decrease this population’s ability to perform daily activities, as well as increases their risk of developing medical complications is well supported by the literature.11–13 Collectively, these concerns have evoked clients, clinicians and researchers to call for exercise initiatives for the paralysed lower limbs.

One such treatment, neuromuscular electrical stimulation (NMES), has been employed to train the paralysed muscles of individuals with SCI whereby an electric current, managed by an external controller, is applied to the skin over muscle to evoke an action potential in the nerve fibre in order to stimulate a muscle contraction similar to that of a cortically induced contraction. This technology, known as functional...
A 40 year old male, (height: 1.80 metres [m], weight: 83.3 kilograms [kg], Body Mass Index (BMI): 24.7 kg/m², SCI level: T6 incomplete, 5 years post injury), volunteered to participate in the study. Following an introductory session with the NMES device he read a participant information leaflet and gave written informed consent.

Aerobic Capacity
Following a review of the literature a protocol was designed and piloted by the research team to measure the participants VO₂ and HR peak response during an incremental treadmill test. This test was conducted both pre and post the intervention period. Aerobic capacity was evaluated using cardiopulmonary gas exchange analysis. The participant wore a facemask attached to a gas analysis system (Quark b², Cosmed, Rome, Italy) to measure oxygen and carbon dioxide concentration and volume. HR was also recorded throughout the test using a chest strap embedded with electrodes (Polar, Tampere, Finland) and synchronized with the gas analysis system. The protocol initially involved the establishment of the participant’s baseline regular pushing speed whilst propelling on a treadmill (HP Cosmos Venus 200/100R, Germany). This baseline speed was ascertained by the participant as their normal everyday pushing speed were they outside. A 3 minute warm-up at this speed at a 2% gradient was then conducted. Following a short break to apply the facemask, the initial test stage was 0.5 km/h below the baseline regular pushing speed for a 1 minute duration. The speed was increased by 0.5 km/h for each additional 1 minute stage there after while gradient remained constant. Average HR and oxygen measurements were taken for the last 30 seconds of each stage. When VO₂ peak was reached i.e. when volitional exhaustion occurred, the treadmill test was immediately terminated by one of the investigators.

Bone mineral density and body composition
The Dual Energy X-ray Absorptiometry technique (DXA) (Lunar, DXA, GE Healthcare, USA) was used to evaluate BMD pre and post the intervention period using a DXA scanner. The DXA was used owing to its availability, reproducibility and good overall accuracy (5.8%). Prior to each image the DXA machine was calibrated. Body Composition (BC) variables including total body fat percentage (TBFP%), total body fat mass (TBFM) and total lean body tissue mass (TLBM) were also evaluated using this technique as DXA scanning has been reported to offer a reliable method of determining these components.

Subjective feedback
The participant filled out a modified version of the Perceived Discomfort in Running Scale (Tenenbaum et al, 1999) to help ascertain the extent of discomfort he experienced during NMES training. This scale lists 32 symptoms grouped into eight dimensions and it was originally designed to give to runners immediately after running a distance of between 2 km and 42 km to rate the level of perceived discomfort during running conditions. The 8 valid dimensions include:

- Proprioceptive symptoms (ten items, score range 10–50), leg symptoms (six items, range 6–30), respiratory difficulties (four...
Physiotherapy Ireland. 2010;31(2)

A
items, range 4–20), disorientation (two items, range 2–10),
dryness and heat (two items, range 2–10), task completion
thoughts (three items, range 3–15), mental toughness (two
items, range 2–10), and head/stomach symptoms (three
items, range 3–15). Participants rate how intensely they felt
each of the symptoms on a 5-point Likert-type scale ranging
from ‘1’ (not at all) to ‘5’ (extremely). The score of each of the
eight discomfort symptoms is determined by the summation of
all items within each dimension. The higher the score, the
more the symptom is felt during performance of the task. It is
recognised that NMES training is not directly comparable to
running, however, this questionnaire was chosen to measure
NMES training discomfort due to the absence of similar
questionnaires specific to this type of exercise. Furthermore,
Tenenbaum and colleagues discuss this questionnaire as being
suitable for measuring discomfort in a population performing
aerobic exercise and therefore it was felt that this tool would
be able to detect levels of discomfort in our version of aerobic
training with NMES. The questionnaire was modified slightly
by removing any reference to the activity of running. In place
of such references, the word, “task” was used instead. The
participant was also asked a number of open ended questions
regarding his overall training with the NMES unit to gain
further insight into his experience with this type of stimulation.

NMES training protocol
The participant undertook a familiarisation session where he
learned how to apply the system independently. He had no
previous experience with NMES or FES modalities. Four
adhesive electrodes each 175 cm², in size were applied
bilaterally to the proximal and distal quadriceps and
hamstrings. The electrodes were applied to the body using a
neoprene garment that was wrapped around the leg and
secured to the thigh with a velcro strap (Figure 1). A specially
designed hand held NMES stimulator (NT2010, BioMedical
Research Ltd, Galway, Ireland) delivered a series of four
complex pulses at an overall series frequency of 5 Hz was
used to deliver the stimulation. The participant trained at home
with the system for one hour five times a week for 6 weeks at
his maximum tolerable NMES intensity (120 milliamps [mA])
in his position of choice (long sitting). He received weekly
phone calls from the lead investigator to monitor his training
response and compliance.

RESULTS

Aerobic capacity, bone mineral density and body composition
The participant completed the 6 week training intervention
completing a total of 30 sessions. Pre and post test measures
revealed improvement in peak VO₂, HR and exercise
tolerance (Table 1). The test duration and speed in the post test
also increased. Furthermore, minor decreases in TBFM were
detected, as well as increases in LBM post intervention (Table 2).

Table 1. Differences in peak VO₂, HR, maximum propulsion
speed and duration of exercise pre and post intervention.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak VO₂ (ml/min/kg)</td>
<td>16.88</td>
<td>27.94</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>161</td>
<td>173</td>
</tr>
<tr>
<td>Max propulsion speed (km/h)</td>
<td>7.3</td>
<td>7.8</td>
</tr>
<tr>
<td>Duration of exercise (min:sec)</td>
<td>15:08</td>
<td>16:30</td>
</tr>
</tbody>
</table>

Table 2. Differences in BMD, BMI, total % BF, total BFM and
total LBM pre and post intervention.

<table>
<thead>
<tr>
<th></th>
<th>BMD</th>
<th>BMI</th>
<th>Total BF %</th>
<th>Total BFM (kg)</th>
<th>Total LBM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>1.20</td>
<td>24.7</td>
<td>28.6</td>
<td>23.96</td>
<td>56.83</td>
</tr>
<tr>
<td>Post</td>
<td>1.28</td>
<td>24.7</td>
<td>27.7</td>
<td>23.07</td>
<td>57.26</td>
</tr>
</tbody>
</table>

BMD = Bone Mineral Density, BMI = Body Mass Index, BF =
Body Fat, BFM = Body fat Mass, LBM = Lean Body Tissue Mass

Subjective feedback
Based upon the subjective feedback given by the participant,
he had a positive experience with this version of NMES
training. He reported that training with the unit 5 times a week
was achievable and that he preferred to do so just before
going to sleep at night as the training would normally leave

Figure 1. Setup of the NMES electrodes
Table 3: Results of the eight dimensions of the modified perceived discomfort in running scale.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Score</th>
<th>Total Possible Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proprioceptive symptoms</td>
<td>12</td>
<td>50</td>
</tr>
<tr>
<td>Leg symptoms</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>Respiratory difficulties</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Dissociation</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Dryness and heat</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Task completion</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Mental toughness</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Head and stomach symptoms</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>How demanding was the task?</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>How much suffering did you experience?</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Overall score</strong></td>
<td><strong>54</strong></td>
<td><strong>170</strong></td>
</tr>
</tbody>
</table>

him feeling extremely fatigued. The participant reported feeling an increase in HR and shortness of breath whilst training at his maximal tolerable intensity of 120 mA. Furthermore, the participant was impressed with the increase in lower limb circulation and temperature which occurred immediately post a bout of NMES training. Results of the modified perceived running discomfort questionnaire are outlined in Table 3.

**DISCUSSION**

The primary finding of this pilot case study demonstrates that a 6 week NMES training intervention can improve aerobic capacity in a SCI male. Secondary findings included alterations in BC. Subjective feedback from the participant indicated that this form of training is acceptable to people with SCI as an exercise tool.

**Aerobic capacity**

Peak VO\textsubscript{2} is an index of exercise capacity and its increase illustrates that the participant’s exercise tolerance following the NMES training intervention improved.\textsuperscript{28} This result is further supported by the increase in test time duration and propulsion speed which was observed in the post intervention peak VO\textsubscript{2} test. In agreement with other studies which have previously examined the effects of lower limb FES, improvements in aerobic capacity have ranged from 10% to 70% improvements in peak VO\textsubscript{2}.\textsuperscript{15-17} Reasons for the improvements in VO\textsubscript{2} peak are of a multiple nature. De Carvalho et al (2006) propose that the increased muscle contractions augment oxygen delivery rate to the musculature by increasing stroke volume, blood pressure and cardiac output.\textsuperscript{19}

Furthermore, researchers suggest that the paralysed muscles which are externally contracted will exert more oxygen, thus enhancing VO\textsubscript{2} peak.\textsuperscript{19,28} Additional peripheral mechanisms have been discussed such as those by Krauss and colleagues whereby increased VO\textsubscript{2} peak post FES-LCE was proposed to be due to increased muscle metabolism.\textsuperscript{29} Research by Martin and colleagues complements this theory whereby the group found that after 24 weeks of NMES, muscle oxidative capacity increased in alliance with an escalation in type I fibres and capillarisation.\textsuperscript{20} Krauss et al also discuss central adaptations following bouts of NMES training as being responsible for improvements in VO\textsubscript{2} peak due to the resultant increased oxygen consumption for a given HR which was observed after a period of FES-LCE training.\textsuperscript{29} The reason for this effect was placed on the increased venous return elicited by LCE which caused an increased cardiac output and blood flow to the exercising muscle.

Although physiological changes following the use of FES-LCE are encouraging, it is important to note that studies incorporating this exercise technique have many limitations including the requirement to engage the lower limbs in external work, the need to improve the biomechanics of the limbs whilst engaging in this type of exercise, its need for cumbersome and expensive equipment and the need for training in the system’s operation.\textsuperscript{19} Conversely, this NMES system, which achieved a 65% improvement in VO\textsubscript{2} peak in a participant similar to those in the previously discussed FES studies, overcomes these issues as it is a relatively smaller and cheaper unit to that of FES-LCE, thus aiding its ease in introducing it into a person’s home exercise regime. Furthermore, it does not require extensive training in its operation, can be easily applied by the individual and can be used in a position of comfort at any time of the day. Added to...
the improved aerobic fitness of our participant, these features highlight the potential value of this enhanced version of NMES training and allude to its potential use over current methods.

Further acute measurements on this participant using the same parameters as the intervention period revealed that when training at maximal current amplitude (200 mA), he achieved a VO2 peak of 12.88 ml/min/kg and a HR peak of 97 bpm and at his training current amplitude of 120 mA a VO2 peak of 10.32 ml/min/kg and a HR peak of 83 bpm was achieved. These values are akin to those experienced during arm cranking, basketball shooting and vigorous household chores, and indicate the capacity of the stimulator to induce training at high levels of aerobic intensity despite only stimulating the lower limb. Higher VO2 and HR values during the incremental treadmill test were due to the additional energy demand required with upper body movement to propel the wheelchair and greater levels of required venous return.

Bone mineral density and body composition
Body composition measurements of increased LBM and concurrent decreased BF post NMES training are encouraging and suggest that our NMES system can have a positive effect on the body composition of people with SCI who are often subject to increases in BF and the development of muscle atrophy. Maintaining LBM is difficult for people with SCI and the loss of muscle function can have a detrimental effect on MBD as muscle contraction and loading are required to stimulate bone formation. Research has stated that paralysed muscle is still capable of adapting and this has been exhibited where NMES has improved torque output and fatigue resistance in paralysed muscle via overloading the muscle.

Similar to our study, reports based on MRI imaging have shown 12% increases in LBM and relative decreases in BF following one year of FES-LCE training. Furthermore, Pacy et al demonstrated large improvements in quadriceps muscle mass following resistance training. Although the changes in muscle composition are relatively small, it is noteworthy that in spite of not including resistance training, this NMES system still accomplished increases in muscle mass over a reasonably short duration of training. Our 6 week NMES training programme resulted in no changes in BMD and we propose that the short intervention period may be reason for this. Earlier research by Dudley-Javoroski and Shields which resulted in 31% increases in distal tibial trabecular BMD of trained limbs in people with SCI included participants training with NMES for 3 years. Similarly, nearly 30% of bone lost following SCI was recovered after 24 weeks of quadriceps stimulation. Bloomfield and colleagues detected an 18% increase in distal BMD following 3 months of FES-LCE in a subset of individuals with SCI who trained at a high power output of 1.8 watts. This research group’s total training group of participants with SCI however did exhibit a statistically significant improvement in their lumbar spine BMD following 9 months of training with a corresponding 78% increase in serum osteocalcin [a marker of bone formation]. To assess if comparable results can be achieved with our NMES system, it is suggested that future studies should include a longer intervention training period.

Subjective feedback
The total score from the modified version of the Perceived Discomfort in Running Scale equated to 54/170 indicating that the participant did not feel a significant level of discomfort with the NMES training. The participant reported that the training task was slightly demanding and that he felt an increased HR and a slight shortness of breath whilst using the NMES unit. He also reported feeling moderately fatigued after training. These reports are thought to be due to the effect of the exercise itself. In response to all the other symptoms, the participant did not experience them at all during episodes of training. This result encourages us that this NMES training device is one which people with SCI will be satisfied with in terms of comfort of training and that adverse effects of such training are minimal. During the open-ended questioning, our participant also reported that he would recommend this type of training to other people with SCI and that he found the training to be feasible and worthwhile.

CONCLUSION
This pilot case study has indicated that this type of NMES system is capable of eliciting an aerobic training effect in people with SCI which could potentially improve their overall CV fitness and strength. This could prove to be a beneficial method of offsetting a range of comorbidities of SCI such as CV disease and diabetes, whilst also advancing on existing NMES technology. The novelty of this NMES system is that it creates an exercise response without loading the limbs or joints or requiring external work, coupled with the ease of its application. It could provide people with SCI with a much needed exercise tool incorporating exercise of the lower limb musculature. This work is only a single case study, which limits the extent to which conclusions can be drawn, however it is suggested that the system used in this case study should be evaluated in a study with a larger number of participants to establish its efficacy in a broader SCI population.

ACKNOWLEDGEMENTS
This research is supported by Enterprise Ireland and BioMedical Research Ltd under an Enterprise Ireland Innovation Partnership Project. The authors would like to thank the participant for his involvement with this study.

REFERENCES:
7. Hjeltnes N, Janssen TW. Physical endurance capacity, functional status and medical complications in spinal cord subjects with

www.iscp.ie
18. Banerjee P, Caulfield B, Crouse L, Clark AL. Prolonged electrical muscle stimulation exercise improves strength, peak VO2, and