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The effects of a neuromuscular electrical stimulation training intervention on physiological measures in a spinal cord injured male: a case study

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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

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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. B4% 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 paralysis, sympathetic autonomic impairment and decreased venous return.5 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 9 Exercise attenuates the development of these comorbidities amongst those with SCI, highlighting the importance of making it routine for those affected.10 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
electrical stimulation (FES), has been used since the 1960’s as
an exercise tool for the paralysed muscles of individuals with
SC1.14 This exercise modality harnesses the original technique
of NMES and applies it in a functional manner to evoke a
muscle contraction producing an otherwise unattainable
dynamic movement. Examples include FES assisted cycling,
rowing, standing and stepping and studies in these areas,
although largely of low quality due to a lack of randomised
controlled trials, demonstrate that FES induced exercise is
capable of eliciting and maintaining CV fitness in this
population with 10-70% increases in VO2 peak being
reported.15-18 Despite these favourable trends, the improper
facilitation of correct muscle contractions during FES – leg
cycle ergometry (FES-LEC) has been reported to be a possible
reason for these metabolic increases.16-18 Therefore the true
efficacy of this intervention to improve fitness is inconclusive.

Added to this, FES induced exercise is hindered by the need
for expensive equipment which is cumbersome and assistance
of trained staff to operate them, therefore limiting its
application for home use for those with SCI.19 Whilst the
arrival of FES technology is encouraging for those with SCI,
the obstacles to training highlighted in the literature clearly
demonstrate that it is still far from the optimal type of training
for clients and clinicians.

In response to the evident limitations of FES based exercise,
we have developed a new method of using NMES technology
which could potentially exercise opportunities for this
population in need of such fitness innovation. This novel
system develops previous FES induced exercise as it causes an
exercise response within users without loading the limbs or
joints or requiring external work.20 It evokes rapid, rhythmical
NMES induced muscle contractions that mimics shivering,
causing a subsequent demand for oxygen in the large lower
limb muscles.20 This physiological response is similar to that
achieved during physical exercise.21 In an earlier study which
explored the effects submaximal stimulation has on healthy
adults, the system triggered significant increases in VO2, heart
rate (HR) and minute ventilation which were comparable to
levels expected during light to moderate voluntary exercise.22
Furthermore, physical fitness improved in sedentary adults
after 6 weeks of training with this system as recorded by
significant increases in VO2 peak, 6-minute walk test and
quadriiceps strength.20 Additionally, this type of stimulation has
shown improvements in the same fitness parameters in people
with stable chronic heart failure (CHF).23 This research
highlights the possibility that people with SCI, who also have
reduced CV fitness similar to that of sedentary adults and those
with CHF, could potentially benefit from NMES. Furthermore,
with the knowledge that improving CV fitness is necessary to
prevent the development of comorbidities and that new
exercise ingenuity is required to incorporate the lower limb
musculature and increase CV stress, further investigation into
the effects of this system is warranted. Therefore the objective
of this investigation was to evaluate if our novel NMES system
could improve the CV fitness in an SCI population.

METHODS
Design of study
This study was a pilot case study and was approved by the
local university ethics committee.

Participant
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
take part 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 mask 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%). The prior to each image the DXA
machine was calibrated. Body Composition (BC) variables
including total body fat percentage (TBF%), 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.25,26

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.
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. 22 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
learnt 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>
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<th>Pre</th>
<th>Post</th>
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<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 (kmh⁻¹)</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>
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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

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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>
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**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 VO₂ is an index of exercise capacity and its increase illustrates the participant’s exercise tolerance following the NMES training intervention improved.

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 VO₂. Reasons for the improvements in VO₂ 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.

Furthermore, researchers suggest that the paralysed muscles which are externally contracted will exert more oxygen, thus enhancing VO₂ peak. Additional peripheral mechanisms have been discussed such as those by Krauss and colleagues whereby increased VO₂ peak post FES-LCE was proposed to be due to increased muscle metabolism. 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 1 fibres and capillarisation. Krauss et al also discuss central adaptations following bouts of NMES training as being responsible for improvements in VO₂ peak due to the resultant increased oxygen consumption for a given HR which was observed after a period of FES-LCE training. 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. Conversely, this NMES system, which achieved a 65% improvement in VO₂ 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

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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 BMD 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 18 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.

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.

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