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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 VO_2 peak test, a DXA scan and subjective feedback regarding the NMES device and training stimulus.
Results: Improvements in VO_2 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. 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.[7-9] 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 SCI.[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 VO_2 peak being reported.[15-18] Despite these favourable trends, the improper facilitation of correct muscle contractions during FES – leg cycle ergometry (FES-LCE) 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 evolve 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 VO_2, 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 VO_2 peak, 6-minute walk test and quadriceps 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/m^2, 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 VO_2 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 b^2, 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 kmh-1 below the baseline regular pushing speed for a 1 minute duration. The speed was increased by 0.5 kmh^{-1} 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 VO_2 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%).[24] 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.[27] 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 cm^2, 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.

Figure 1. Setup of the NMES electrodes

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 VO_2, 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 VO_2, HR, maximum propulsion speed and duration of exercise pre and post intervention.

	Pre	Post
Peak VO2 (ml/min/kg)	16.88	27.94
Peak HR (bpm)	161	173
Max propulsion speed (kmh-1)	7.3	7.8
Duration of exercise (min:sec)	15:08	16:30

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

	BMD	BMI	Total BF %	Total BFM (kg)	Total LBM (kg)
Pre	1.20	24.7	28.6	23.96	56.83
Post	1.28	24.7	27.7	23.07	57.26

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

A B

Table 3: Results of the eight dimensions of the modified perceived discomfort in running scale.

Dimensions	**Score**	**Total Possible Score**
Proprioceptive symptoms	12	50
Leg symptoms	11	30
Respiratory difficulties	8	20
Dissorientation	2	10
Dryness and heat	4	10
Task completion	6	15
Mental toughness	5	10
Head and stomach symptoms	3	15
How demanding was the task?	2	5
How much suffering did you experience?	1	5
Overall score	**54**	**170**

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_2 is an index of exercise capacity and its increase illustrates that the participant`s exercise tolerance following the NMES training intervention improved.[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_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_2.[15-17] Reasons for the improvements in VO_2 peak are of a multiple nature. De Carvahlo 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.[19] Furthermore, researchers suggest that the paralysed muscles which are externally contracted will extort more oxygen, thus enhancing VO_2 peak.[19, 28] Additional peripheral mechanisms have been discussed such as those by Krauss and colleagues whereby increased VO_2 peak post FES-LCE was proposed to be due to increased muscle metabolism.[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 1 fibres and capillarisation.[30] Krauss et al also discuss central adaptations following bouts of NMES training as being responsible for improvements in VO_2 peak due to the resultant increased oxygen consumption for a given HR which was observed after a period of FES- LCE training.[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.[19] Conversely, this NMES system, which achieved a 65% improvement in VO_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 $V0_2$ peak of 12.88 ml/min/kg and a HR peak of 97 bpm and at his training current amplitude of 120 mA a $V0_2$ 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,[31] and indicate the capacity of the stimulator to induce training at high levels of aerobic intensity despite only stimulating the lower limb. Higher $V0_2$ 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.[32, 33] 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.[13] 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.[13] 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.[35, 36] 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.[36] 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.[13] Similarly, nearly 30% of bone lost following SCI was recovered after 24 weeks of quadriceps stimulation.[38] 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.[8] 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).[8] 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.

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