31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Neuro-Muscular Electrical Stimulation Training Enhances Maximal Aerobic Capacity in Healthy Physically Active Adults.

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Abstract — **Previous research has shown that a novel form of neuro-muscular electrical stimulation (NMES) can be used to bring about aerobic training effects in sedentary adults and in patients with heart failure. However, it is not clear whether this form of NMES could induce a significantly strong cardiovascular exercise effect in a more active group where a greater stimulus is required for training. In this study we investigated the aerobic training effects of repeated exposure to low frequency NMES in a group of physically active healthy adults. Results demonstrated a clinically and statistically significant training response following 18 trainings sessions, suggesting that this form of NMES has a role to play in cardiovascular exercise training in a physically active healthy population.**

I. INTRODUCTION

Neuro-muscular electrical stimulation (NMES) has been used in health and sport for many years as a means of augmenting voluntary exercise programmes to re-educate and strengthen muscle skeletal muscle [1]. However, in recent years there has been a growing awareness of the potential for using NMES as a training modality in management of diseases associated with inactivity and reduced cardiovascular exercise capacity. Researchers have demonstrated that repeated exposure to NMES can bring about improvements in measures of exercise capacity and functional status in patients with chronic obstructive pulmonary disease and heart failure [2]. The NMES applications in these studies have typically incorporated stimulation parameters that elicit tetanic isometric contractions of the large lower limb muscle groups with a duty cycle of 5-7s on and off.

We have developed a new approach to cardiovascular training using NMES that involves using low frequency stimulation to elicit a pattern of rhythmical contractions of the large leg muscle groups at sub-tetanic frequencies. Initial investigations demonstrated that the physiological effect of acute exposure to this form of NMES is similar to the physiological response to regular cardiovascular exercise such as jogging or cycling [3]. Furthermore, there is evidence of a repeatable dose-response relationship with increases in stimulation intensity resulting in increases in physiological cost as evidenced by heart rate, respiratory rate and oxygen consumption [4].

Subsequent training studies revealed that repeated exposure to this form of low frequency NMES over a period of 6-weeks resulted in significant improvements in maximal aerobic capacity, 6 minute walk distance and quadriceps strength in separate studies on sedentary adults [5] and patients with chronic heart failure [6]. These results indicate that this form of NMES induced cardiovascular exercise has significant potential as an alternative exercise modality in patient cohorts in whom traditional forms of exercise may be difficult and for whom a relatively low training stimulus is required. Its potential as an alternative exercise modality in a physically active population in whom greater training stimulus is needed to bring about improvements in physical fitness is less certain. We have recently demonstrated that acute exposure to this form of NMES results in a cardiovascular exercise response that is consistent with the low end of the therapeutic training intensity spectrum (50-80% of VO2max) for a physically active population as recommended by the American College of Sports Medicine [7]. The purpose of the present investigation was to determine whether repeated exposure to this form of low frequency NMES would provide sufficient training stimulus to effect an improvement in maximal aerobic capacity in a young, physically active population.

II. METHOD

Subjects.

Nineteen healthy adult subjects (14m, 5f) volunteered to participate in this study. The institutional Ethics Committee approved the study and written informed consent was obtained in all cases. The subjects had a mean age of 32.6 ± 10.6 years and an average mass and body mass index (BMI) of 79.6 ± 16.1 kg and 25.1 ± 4.2 kg/m^2 respectively. All subjects were recruited within the University, were free from illness or injury, and were physically active in recreational activities at the time of participation in the study.

Manuscript received April 23rd 2009. This work was supported by Enterprise Ireland under the Academic-Industry Innovation Partnership scheme.

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Potential Conflict of Interest Disclosure - C Minogue is an employee of the manufacturer of the stimulation device used in this study.

Study Design.

This was a prospective case control study in which we followed each subject for a period of 10 weeks with 3 measurement points in each case. Measures of maximal aerobic capacity were taken at baseline, following a 4 week period in which subjects adhered to their habitual activity patterns (control phase), and following 6 weeks of habitual activity supplemented with 18 1-hour sessions of low frequency NMES training (training phase).

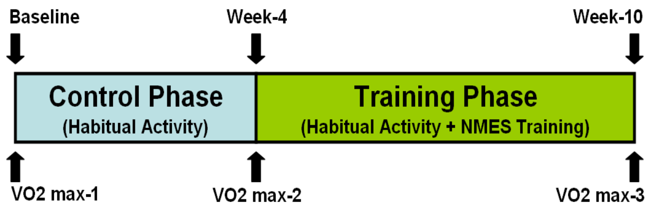

Figure 1. Study Design

Aerobic Testing Procedures.

Maximal aerobic exercise capacity was evaluated using an incremental cycle ergometer test protocol with simultaneous cardiopulmonary gas exchange analysis. Subjects wore a facemask and a gas analysis system (Quark b^2, Italy) was used to measure the expired oxygen and carbon dioxide concentration and volume. $V'O_2$ was calculated from these measurements. Subjects were required to pedal at incremental workloads until a leveling of $V'O_2$ response despite increasing exercise intensity occurred. $V'O_2$ max was calculated from the average $V'O_2$ measurement during the last 30 seconds of the cycle test at each test session. Heart rate (HR) was also recorded throughout the test and the workload (Watts) at the end of each test was noted. The maximal aerobic test was carried out by the same investigator at baseline, and following the control and training phases of the study.

Stimulation Protocol.

A specially designed hand held muscle stimulator (NT2010, BioMedical Research Ltd, Galway, Ireland) was used to produce rapid rhythmical contractions in the large lower extremity muscle groups in this investigation. The stimulator current waveform was designed to produce rhythmical contractions in the lower extremity muscle groups. These contractions were achieved by means of delivering a burst of 4 mixed frequency pulses at a beat frequency of 5Hz. The maximum peak output pulse current used in the present study was 200 mA. Impulses were delivered through an array of 4 adhesive electrodes on each leg (area per leg = 800 cm^2), with a different combination of electrodes from the array being involved in delivery of each of the 4 pulses in a burst. The current pathways, electrode combinations per pulse and pulse train characteristics are outlined in Figure 2. The electrode arrays were applied to the body via a neoprene 'wrap' garment that was secured to the thigh with Velcro straps. This array of electrodes produced rhythmical contractions in the quadriceps, hamstrings, and calf muscles. This rhythmical pattern of muscle contraction was associated with an increase in oxygen tissue in the tissues and resulted in a physiological response consistent with cardiovascular exercise in the absence of limb loading or the need to perform external work.

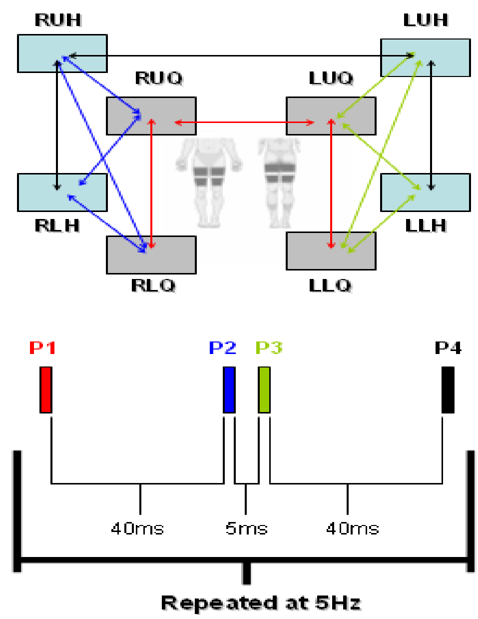

Figure 2. Location of Stimulating Electrodes, pulse pathways (color coded), and pulse intervals. RUQ – right upper quadriceps, RUH – right upper hamstring, RLQ – right lower quadriceps etc)

Training Protocol.

During the training phase all subjects were required to complete a total of 18 separate NMES sessions of 1-hour duration each. All sessions were performed in the University. The subjects were not directly supervised throughout each session but a record of their attendance was kept by the main investigator throughout the study period. Further to this, each subject kept a log of their training in which they recorded subjective feedback and the stimulation intensities reached during each session. During each session subjects performed a gradual warm-up and cool down during the first and last 10 minutes with a 40 minute period at their training intensity. Subjects were instructed to select a stimulation intensity that resulted in a subjective increase in rate of perceived exertion (RPE) to the 'somewhat hard' level [8]. RPE was used to govern exercise intensity due to previous work that demonstrated that V'O2 response and RPE were linearly related with low frequency NMES induced exercise in a manner similar to the relationship observed during voluntary exercise [7].

Data Analysis.

V'O_2 max and maximal exercise test workload values were identified for each subject for each time point – baseline, week 4 and week 10. The difference between V'O_2 max at week 4 and baseline was calculated for each subject and represented the Control Response. The difference between V'O_2 max at week 10 and week 4 was calculated for each subject to derive the NMES Training Response.

To test for statistical significance, separate repeated measures ANOVA F-tests were carried out to determine whether differences existed between group mean V'O_2 max or maximal exercise test workload at each measurement interval during the study. This was followed up with post hoc paired 2-sided t-tests performed to test for differences between baseline and week 4, week 4 and week 10 and baseline and week 10 respectively. Finally, paired, 2-sided t-tests were carried out to test for differences between group average control and NMES training responses. All statistical analysis was performed using SPSS software (V12.0).

III. RESULTS.

All subjects completed the test procedures without any difficulty and all completed the 18 training sessions as prescribed. ANOVA F-test analyses revealed highly significant differences in both V'O_2 max and maximal exercise test workloads across the 3 test conditions ($P<0.0001$). Post hoc analysis indicated that there were no significant differences between group mean V'O_2 max levels or maximal exercise test workloads at baseline and at 4 week follow up ($P>0.05$). However, there were highly significant differences between both V'O_2 max levels and maximal exercise test workloads at 10 week follow up compared to both baseline and 4 week follow up ($P<0.005$). We also observed significant differences between the group mean Control and NMES Training responses for V'O_2 max ($P<0.05$) (Figure 3). Group mean (±SD) V'O_2 max was 42.3±6.6 ml/kg/min at baseline. This remained largely unchanged at 4 weeks at 42.9±6.8ml/kg/min yet increased to 45.8±6.4ml/kg/min at 10 week follow up (Figure 4). Group mean (±SD) maximal exercise test workloads were 253.7±48.6 and 253.7±49.2Watts at baseline and 4 week follow-up respectively. This increased to 265.4±57.7Watts at 10 week follow-up (Figure 5).

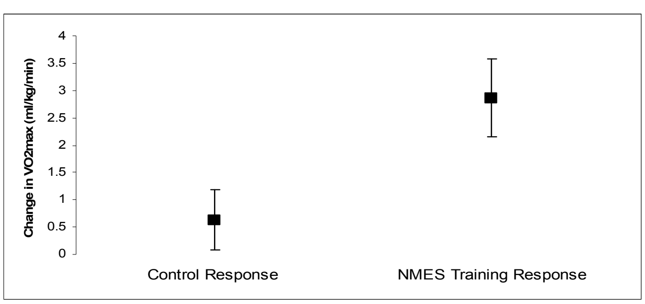

Figure 3. Average (±SE) Control and NMES V'O_2 max training responses.

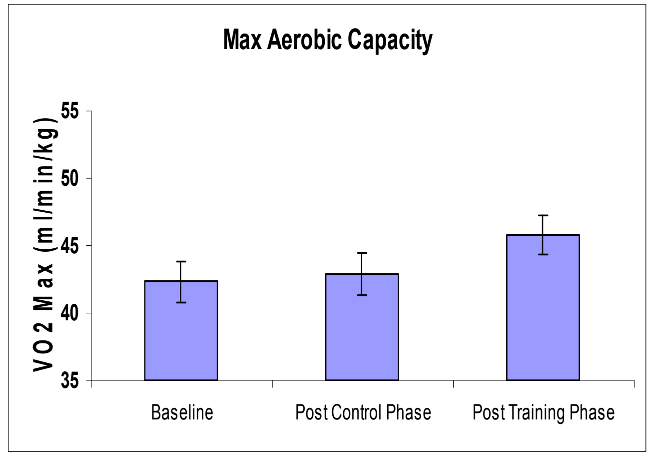

Figure 4. Average (±SE) maximal aerobic capacity (V'O_2 max) at baseline, and post control and training phases.

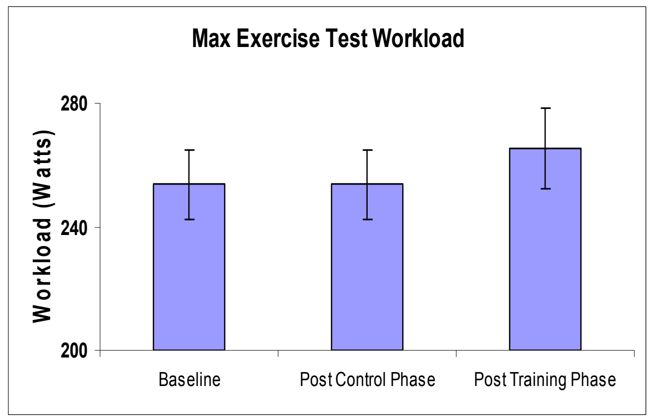

Figure 5. Average (±SE) maximal exercise test workload at baseline, and post control and training phases

IV. DISCUSSION.

The principal finding of this investigation was that a programme of repeated exposure to low frequency NMES targeting the large leg muscle groups resulted in significant improvements in aerobic fitness in a group of healthy physically active adult subjects.

Our subjects demonstrated a baseline level of aerobic fitness, having an average V'O_2 max of 43.7±6.5 ml/kg/min (MALE) and 38.3±5.3 ml/kg/min (FEMALE). This corresponds to a level of aerobic fitness that is considered 'good' with respect to the general population [9] and indicates a relatively high level of baseline fitness. To our knowledge, this is the first time that such a training effect is observed in a physically active population using NMES as an exercise training modality. The present results suggest that this form of NMES has considerable potential as an alternative means of promoting a training response in a physically active population.

We did not measure V'O_2 or heart rate during the training sessions. However, we have done this in previous work in which have demonstrated that this form of low frequency NMES was well tolerated by a healthy population and subjects could effectively exercise at moderate intensities, as measured using the Borg RPE subjective rating scale, HR and $V'O_2$ [7]. Based on this work, and the subjective feedback received from subjects, we can estimate that the subjects in the present study were training at a conditioning intensity of approximately 50% of their $V'O_2$ max. Our results demonstrate that this modest conditioning intensity produced an average aerobic capacity improvement of 7%. This is less than the level of improvement (approx 10%) that we have observed in other populations (sedentary adults and patients with heart failure) who underwent a similar training programme [5] [6]. The difference can be explained by the fact that individuals who have a higher level of baseline fitness usually experience a lower proportional response to a given training stimulus that those starting at a lower baseline [9]. Given the fact that the subjects in this investigation had a relatively high level of baseline fitness, the observed average increase of 7% is quite respectable. Furthermore, 17 of the 18 subjects demonstrated a positive training effect, however modest. The only subject who did not show an improvement demonstrated a very small decrease (<2%) in $V'O_2$ max. Of those who did improve, 10 demonstrated an improvement of over 5%.

The training was well tolerated by subjects and we had full compliance with the programme as prescribed. Subjectively, subjects reported that the NMES was moderately uncomfortable yet did not feel that the level of discomfort experienced was disproportionate to the intensity of exercise. However, the majority of subjects also report that they would prefer to undertake voluntary means of physical activity such as jogging instead of using low frequency NMES as a long term training modality. This suggests that it may be most useful as an alternative means of training in situations where voluntary training is not advisable. As such, it could provide an alternative exercise modality during sports injury rehabilitation when patients need to perform cardiovascular exercise in a safe manner without loading the limbs or joints. It may also offer a viable means of introducing an element of variety to training efforts for those individuals who undertake large training volumes and are susceptible to issues relating to boredom, staleness, overtraining and overuse injury. Finally, we believe that this form of NMES may be of value in maintaining fitness levels in a microgravity environment as it offers a means of loading the cardiovascular system without the need to interact with external mechanical apparatus.

The low frequency NMES approach utilized in the present study offers a means of increasing oxygen demand with repetitive short duration isometric co-contractions of large leg muscle groups. Previous efforts to cause such an increase in oxygen demand using longer duration isometric exercise (with higher frequency currents) have produced responses consistent with a doubling of resting metabolic energy expenditure [10], an exercise intensity that would not be sufficient to elicit a training response in even a sedentary population.

The results of the present investigation are very encouraging. However, there is a requirement for more research to optimize the low frequency NMES approach to cardiovascular exercise training and to ascertain its range of physiological effects.

REFERENCES

[1] Lake D. Neuromuscular electrical stimulation. An overview and its application in the treatment of sports injuries Sports Med. 1992 May; 13(5):320-36.

[2] Sillen MJ, Speksnijder CM, Eterman RM, Janssen PP, Wagers SS, Wouters EF, Uszko-Lencer NH, Spruit MA. Effects of Neuromuscular Electrical Stimulation of Muscles of Ambulation in Patients With Chronic Heart Failure or COPD: A Systematic Review of the English-Language Literature. Chest. 2009 Apr 10. [Epub ahead of print]

[3] Caulfield B, Crowe L, Minogue C, Banerjee P, Clark A. The use of electrical muscle stimulation to elicit a cardiovascular exercise response without joint loading: A case study. Journal of Exercise Physiology 2004; 7: 84-88

[4] Banerjee P, Clark A, Witte K, Crowe L, Caulfield B., 2005. Electrical stimulation of unloaded muscles causes cardiovascular exercise by increasing oxygen demand. Eur J Cardiovasc Prev Rehabil. 2005 Oct;12 (5):503-8

[5] Banerjee P, Caulfield B, Crowe L, Clark A. 2004. Prolonged electrical muscle stimulation exercise improves strength and aerobic capacity in healthy sedentary adults. J Appl Physiol. 99:2307-11

[6] Banerjee P, Caulfield B, Crowe L, Clark A. Prolonged Electrical Muscle Stimulation Exercise Improves Strength, Peak VO2, and Exercise Capacity in Patients with Stable Chronic Heart Failure. Journal of Cardiac Failure 2009; 15(4): 319-26

[7] Crognale D, Grosset JF, Crowe L, Minogue C, DeVito G, Caulfield B. Electrical muscle stimulation can be used to elicit incremental cardiovascular exercise response and subjective effort without undue discomfort in adults. In, Proceedings of IFESS 2008. Freiburg, September 2008

[8] Borg G. Borg's Perceived Exertion and Pain Scales. Human Kinetics. 1998

[9] McArdle W, Katch F, Katch V. Essentials of Exercise Physiology. Lippincott, Williams & Wilkins, Philadelphia, 2007

[10] Minogue C, Caulfield B, Reilly R. What are the electrical stimulation design parameters for maximum VO2 aimed at cardio-pulmonary rehabilitation? Conf Proc IEEE Eng Med Biol Soc. 2007; 2007:2428-31

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