Novel treatment (new drug/intervention; established drug/procedure in new situation)

Pushing out the limits of electrical stimulation. A case study in the aggressive use of an alternative to voluntary exercise

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Summary

Recent advances in neuromuscular electrical stimulation (NMES) suggest that sophisticated techniques can exercise and train people aerobically. However, the limits of this exercise modality would be of interest to sportspeople, trainers and rehabilitation experts. Additionally, there are physical and other barriers which prevent many from undertaking aggressive voluntary exercise. Maximum voluntary and peak NMES efforts were assessed for 1) maximal heart rate and oxygen consumption, 2) excess postexercise oxygen consumption (EPOC), 3) lactate and 4) time-to-fatigue while exercising at 65% of predicted maximal heart rate (maximum voluntary versus peak NMES efforts). Heart rates: 195 bpm and 194 bpm; Oxygen consumption: 52 ml/kg/min and 39 ml/kg/min. EPOC: 110.5 kcal and 96.5 kcal; Lactate: 15.0 mmol/l and 15.3 mmol/l; Time-to-fatigue: 4 h and over 6 h. Sophisticated NMES compares well to voluntary exercise with potential applications for sportspeople and some who cannot exercise due to disease or injury.

BACKGROUND

Neuromuscular electrical stimulation (NMES) sends small electrical impulses across the body eliciting controlled muscle contractions. It is commonly used in rehabilitation¹ and prevention of disuse atrophy.² Traditional NMES techniques can only induce an aerobic effect of 1–2 metabolic equivalents (METs)³ – insufficient to be useful in the aerobic training of healthy individuals. Recent advances have allowed us to aerobically train the comparatively fit,⁴ those with cardiac failure⁵ and the sedentary.⁶ This case study seeks to demonstrate the full potential of these new techniques by benchmarking the acute effects against maximal voluntary efforts.

While physical activity is considered of central importance to health⁷ there are many who engage in insufficient exercise, for example, over 60% of adults in Western Europe may be considered sedentary.⁸ If effective, a ‘passive’ or non-voluntary exercise modality that could be done at home may appeal to some. A system that could aggressively exercise the legs without loading or moving the hip or knee joints would have potential in sportspeople who are injured or those with a physical barrier to exercise, for example, over ten million US citizens are co-morbid with diabetes and arthritis.⁹ Additionally, a new exercise modality that could genuinely challenge the body in a new way may lead to adaptations not easily or typically acquired through traditional training techniques.

Using an experienced NMES practitioner this paper reports, for the first time, the present exercise limits of sophisticated NMES and shows that compared to maximal voluntary efforts, NMES can:

- ▶ achieve maximum heart rate
- ▶ achieve over 75% maximum aerobic capacity exercising the leg muscles only
- ▶ generate comparable lactate levels and excess post exercise oxygen consumption

- ▶ allow one to exercise for longer at 65% heart rate max. A description of the NMES pulses and technique used is given.

INVESTIGATIONS

Methods and results

A series of four experiments was conducted. Each compared maximal voluntary efforts with peak NMES efforts. The physiological response to the exercise was measured. The exercises were chosen to elicit maximal heart rate, oxygen consumption (VO₂), lactate and aerobic fatigue.

The subject tested gave informed consent. He was 40 years old; of reasonable fitness (VO₂ max 52 ml/kg/min); 72 kg of which 60.2 kg was lean mass and 9.0 kg adipose (on dual energy x-ray absorption (DXA) scan). He played recreational soccer once a week and commuted by bicycle for 10 min twice daily. Additionally, his research required him to test and evaluate novel NMES parameters.

There follows a description of the basic NMES technique used, followed by an overview of the experiments, then a brief description of individual experiments and their results.

An explanation of the novel NMES technique as used for aerobic exercise

The original NMES parameters were inspired by shivering. In shivering, there is an uncoupling of energy consumption and work done, that is, one ‘burns calories’ without doing any external work. This was mimicked and then improved upon.

Technical details

The pulses are delivered through an array of eight large hydrogel electrodes, 17×10.3 cm, applied to the skin

Figure 1 Wrap and electrode positioning. A wrap, prewired and with mounted electrodes was applied to the thighs. The model's left leg has no wrap to illustrate electrode positioning.

using two neoprene wrap garments, one applied to each thigh (figure 1). The electrodes are prewired and mounted for convenient, rapid and correct application. The basic aerobic NMES pulse pattern is a composite of four complex pulses shared between the electrode arrays (figure 2). Repeating the pulse pattern at 5 Hz induces a strong non-fused, non-tetanic contraction of the large muscle groups in the legs (quadriceps, hamstrings, gluteal and calf muscles).

Pulses 1, 2 and 3 are 760 microseconds long; pulse 4 is 857 microseconds. All pulses are biphasic, symmetrical with an interphase delay of 100 microseconds. In turn each pulse is divided into separate segments, called timeslots. There were between three and five timeslots per pulse. For each of the timeslots a subset of the electrode array has been designated as source or sink of the current. Furthermore each timeslot is allocated a percentage of the maximum current available – set by the user-controlled intensity button. For instance, for user comfort, the timeslots targeting vastus medialis are set at 60% of those targeting the proximal quadriceps. Using this system the current densities 'seen' throughout the thigh can be optimised. The variability of this system enables the targeting of the gluteal and calf muscles, even though there are no electrodes over these muscles, for example, the motoneurons supplying the calf muscle are stimulated as they traverse the upper leg. Bio-Medical Research Ltd. (Galway, Ireland) provided the programmable stimulator capable of delivering these pulses.

The above parameters are our default aerobic pattern. In the experiment, to maximise lactate production the frequency and the staggering of pulses was optimised for lactate production not oxygen consumption.

Overview of experiments

Four separate experiments were undertaken. Each compared a maximal voluntary effort to a peak NMES effort. Each comparison examined a different aspect of maximal exercise. The NMES effort is described as 'peak' as maximal unit intensity was never reached and the physiological response continued to increase.

Except where indicated, under similar conditions and with the exact same set-up, the effects of voluntary and NMES exercise were measured for comparison. There was no exercise session the day preceding the experiments, no alcohol ingestion and no carbohydrate preloading. There was a similar diet (in time, quantity and type) the day preceding and the day of the experiment. The exercise to fatigue sessions were separated by a week; the others by at least 2 days.

For indirect calorimetry, a Quark b2 (Cosmed srl, Italy) metabolic gas analyser was used. It was prewarmed and calibrated as per manufacturer's guidelines. Heart rate was measured with a precordial strap monitor (Polar Electro, Finland). The lactate levels quoted are capillary samples measured with a Lactate Pro (Arkray Factory, Inc., Japan). An Excalibur bicycle and Lode software (Lode B.V., Holland) was used for the cycling. All of the NMES

Figure 2 Simplified representation of the pulse pattern. Each pulse is coded and their various pathways indicated. RUQ, right upper quadriceps; RUH, right upper hamstrings; RLQ, right lower quadriceps; RLH, right lower hamstrings; RLQ, left upper quadriceps.

were undertaken using a programmable NeuroTech 2010 Research Stimulator, (Bio-Medical Research Ltd, Ireland).

1 Heart rate and voluntary VO_2 max versus heart rate and VO_2 peak with NMES

Voluntary VO_2 max was assessed using an incremental cycling ergometre test protocol¹; subjective maximum was achieved, maximum heart rate was 195 beats per min (bpm) exceeding the age-predicted rate of 180 bpm (220 bpm minus age) with a respiratory exchange ratio (RER) value greater than one. The mean of the last 30 sec of the test was taken as the VO_2 max value. VO_2 peak with NMES was also measured with an incremental protocol. Every three min the NMES intensity was increased in 20 milliamps (mA) steps until 180 mA was reached, (figure 3). The mean of the last 30 sec at this intensity was taken to be the peak.

Result

Heart rate: 195 bpm and 194 bpm for voluntary and NMES respectively. Oxygen consumption: voluntary VO_2 max was 52 ml/kg/min; NMES VO_2 peak was 39 ml/kg/min (figure 3).

2 Comparison of 2 min burst of exercise on lactate levels and excess post exercise oxygen consumption

The subject sat still for ten min and baseline oxygen consumption and heart rate were measured. NMES exercise was built up over one min to limit of tolerability and maintained at that level for one min. Comparison was made with a supra-maximal cycle test on a Lode bicycle, resistance increasing to 225 Watts (W) over a min and then maintained at this resistance as the subject exercised at his maximal capacity for a further min. Recovery was passive in the sitting position and the capillary lactate levels measured 5 and 20 min post exercise. For calculation purposes, the baseline energy expenditure of both was 1.4 kcal/min.

Result

Five min postexercise, lactate levels were 11.9 mmol/l for NMES and 12.1 mmol/l for voluntary exercise, (figure 4), with the NMES being slower to clear at 20 min.

The total calories consumed in 30 min (2 min exercise and the following 28 min passive recovery) were 110.5 kcal for the voluntary exercise and 96.5 kcal for NMES. At the end of the half an hour, energy consumption had

Figure 3 Incremental NMES exercise response. Heart rate and oxygen consumption versus time/NMES intensity (x-axis). The NMES intensity increased every 3 min until 180 mA were reached.

apparently returned to baseline (sitting) levels for both exercise ~ 1.4 kcal per min. This gives an excess calorie consumption of 68 kcal and 54 kcal, respectively. The NMES had a higher mean heart rate during recovery, 98 bpm versus 90 bpm (table 1).

3 Comparison of maximum lactate produced by exercise in this subject.

The highest lactate levels recorded after using NMES were achieved using repeated 2 min bursts of stimulation, 1 min ramping up to tolerability limit and 1 min at constant intensity. There were four bursts separated by 5 to 10 min of passive recovery. The highest lactate the subject recorded with voluntary exercise was 5 min post three supra-maximal thirty-sec 'wingate' cycling bouts (resistance was set at 7.5% body weight); separated by 5 min of easy cycling (80 revolutions per min at a resistance of 80 W). The peak power generated was 770 W. This voluntary effort was followed by emesis.

Result

NMES exercise recorded a lactate level high of 15.3 mmol/l compared to 15.0 mmol/l for voluntary exercise.

4 Comparison of exercise to fatigue at ~65% of maximum heart rate.

A comparison of cycling and NMES exercise at equivalent levels in terms of percentage of maximal heart rate was

Table 1 Total calories, EPOC and heart rate following 2 min bursts of voluntary and NMES exercise

	Total calories, kcal (time 0–30 min)	Excess kcal (above resting 0–30 min)	Mean post exercise heart rate, bpm (time 2–32 min)
Voluntary exercise (2 min)	110.5	68	90
NMES (2 min)	96.5	54	98

done. The two exercise sessions were separated by a week with no scheduled exercise on the 2 days preceding the sessions, a similar diet on the preceding day and fasting on the day of exercise. (Inadvertently) NMES exercise started 2 h later than the voluntary exercise. Coffee intake was the same in quantity and timing for both exercise sessions. Tap water and hypotonic saline solution was also drunk during the sessions. Exercise was continuously monitored. The metabolic gas analyser was recalibrated at hourly intervals.

The exercise was interrupted by hourly 5 min breaks to recalibrate, allow for bodily functions, etc.; after 2 and 4 h, DXA scans were performed requiring a 15 min break. The voluntary exercise was on a stationary bicycle with a variable resistance. Pedalling was at a rate of 70 revolutions per min and the resistance adjusted to maintain the target heart rate of ~125–130 bpm.

Figure 4 Lactate levels before exercise and 5 min and 20 min following 2 min of supra-maximal exercise (voluntary and NMES).

Figure 5 Cycling at 65% max heart rate, top graph. Lower graph NMES at 65% max heart rate for the first 5 of 6 h. Heart rate, right-hand scale and top line on each graph; oxygen consumption, left-hand scale, lower line on each graph.

The NMES exercise was undertaken on a reclining couch with the legs supported. After 2 h, a rolled towel was placed under the knees for added comfort. The stimulation intensity was titrated to maintain the target heart rate, ~125-130 bpm.

Result

For cycling, the time to fatigue was 4 h; with the NMES exercise the subject completed 6 h exercise and could have continued. The subject found the second and the fourth h of the cycling very difficult. The cycling was stopped at the end of the fourth h due to an inability to maintain the 70 rpm speed despite dropping the resistance to 65 W from a starting level of 120 W. The subject had

difficulty even walking afterwards confirming fatigue-to-exhaustion.

With the NMES, the subject felt remarkably fresh after 4 h so another 2 h were added on. During the last hour, the target heart rate was abandoned so that the subject could tire himself out and complete the session hoping to reach exhaustion. The average heart rate for the last half an hour was 139 bpm. Although being tired after 6 h, he could have continued the exercise (figure 5).

At equivalent heart rate averages the cycling consumed more energy, 22 ml/kg/min O_2 versus 18 ml/kg/min. The lactate levels after 30 min cycling were 3.9 mmol/l and only 1.4 mmol/l after 3 h. For NMES, it was 7.2 mmol/l after 25 min and still at 3.2 mmol/l after 4 h and 2.3 mmol/l at 6 h.

DISCUSSION

Standard NMES techniques achieve low aerobic effects, of the order of a couple of METS.³ It is clear that many of the physiological effects of high intensity exercise can now be mimicked with sophisticated NMES. Training effects with these NMES techniques had already been shown in the comparatively fit,⁴ those with cardiac failure⁵ and the sedentary.⁶ However, this is the first paper to highlight the full extent of the acute physiological effects in someone pursuing peak values with the techniques.

As the first viable alternative to vigorous voluntary exercise there may be widespread medical and sports science applications. As it is an exercise modality that challenges the body in a different way there is a possibility that this may lead to adaptations not easily or typically acquired through traditional training techniques. With these NMES techniques, lactate seems to accumulate at relatively low exercise intensities. The RER is observed to be much higher than equivalent voluntary exercise. Additionally, there are many things one can do with NMES that one cannot do voluntarily, for example, one cannot voluntarily mimic shivering for protracted periods. There may be advantages that are sport or condition specific, for example, in type 2 diabetes many of the advantages of exercise seem to be expressed at the level of the individual muscle fibre.¹⁰ As NMES is thought to preferentially recruit motorunits in a pattern that is dissimilar to voluntary exercise¹¹ this may confer changes on some, otherwise inactive, motor units. This may make it an especially effective supplement to voluntary exercise, or perhaps there may be a role when voluntary exercise is difficult, for example, an endurance athlete with hip pain may wish to maintain his fitness levels without moving the hip joint.

To date there have been no adverse incidences using this type of NMES which has been used to train over a hundred people. In addition to the regular precautions for vigorous exercise, for example, a cardiac stress-test where appropriate, there are additional contra-indications for NMES exercise, for example, those with a pacemaker, current or recent malignancy, impaired sensation, etc.¹²

The full scope and applications of the improvement in technology will only emerge with time.

CONCLUSION

Many of the physiological effects of high-intensity voluntary exercise can now be mimicked with sophisticated NMES. This has new therapeutic and training possibilities.

Learning points

- ▶ Exercise is a key determinant of health but many cannot or will not do sufficient voluntary exercise. An effective alternative, particularly for high-intensity exercise, is needed.
- ▶ At least in a moderately fit, middle-aged man many of the physiological measures of maximal voluntary exercise can be mimicked by new NMES techniques.
- ▶ Maximum heart rate, oxygen uptake, lactate levels as well as time-to-fatigue are now broadly comparable to voluntary exercise in this case

Competing interests Minor shareholding in the company (Bio-Medical Research Ltd.) that supplied some of the technology.

Patient consent Obtained.

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