Archives of Physical Medicine and Rehabilitation
journal homepage: www.archives-pmr.org
Archives of Physical Medicine and Rehabilitation 2014;95:1750-8

ORIGINAL ARTICLE

Whole Body Oxygen Uptake and Evoked Torque During Subtetanic Isometric Electrical Stimulation of the Quadriceps Muscles in a Single 30-Minute Session

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Abstract

Objective: To evaluate the time course of fatigue in torque output and oxygen uptake during isometric subtetanic neuromuscular electrical stimulation (NMES) to facilitate the design of NMES-based rehabilitation protocols that can accumulate a defined aerobic exercise volume within a given time period.

Design: Single-arm intervention study with within-subject comparisons.

Setting: University research laboratory.

Participants: Volunteer sample of healthy men (N=11; mean age, 34.2±11.5y; range, 19–53y; body mass, 79.1±11.7kg; range, 58–100kg).

Intervention: A single 30-minute session of continuous bilateral isometric quadriceps NMES at 4Hz evoking a mean twitch amplitude of 12% of the maximum voluntary contraction.

Main Outcome Measures: Whole body oxygen consumption rate ($\dot{V}O_2$), and evoked torque were measured simultaneously throughout.

Results: Mean increment in $\dot{V}O_2$ was 596±238mL/min, and average exercise intensity during the session was 3±.47 metabolic equivalents. The $\dot{V}O_2$ and torque declined slowly at a rate of −.54%±.31% and −.47%±.57% per minute, respectively.

Conclusions: Despite having a higher incremental $\dot{V}O_2$, the observed fatigue rate was considerably less than that previously reported during intermittent isometric tetanic stimulation, suggesting that subtetanic isometric NMES is more sustainable for exercise interventions aimed at accumulating a therapeutic aerobic exercise volume.

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There is increasing interest in the use of isometric neuromuscular electrical stimulation (NMES) as part of cardiopulmonary rehabilitation for patients with limited capacity for movement or volitional exercise.[1] Recent intervention studies with NMES have reported improved aerobic capacity in patients with heart failure,[2] chronic obstructive pulmonary disease,[3] and spinal cord injury.[4,5] Because of rapid fatigue during NMES-induced muscle activity,[6-8] it can be difficult to sustain therapeutically significant exercise intensities for long enough to accumulate a meaningful exercise volume. In healthy neurologically intact subjects, exercise intensities in the range of 3 to 5.9 metabolic equivalents (METs), accumulating to 10 METs·h·wk^{-1}, are associated with reduced cardiovascular disease and reduced premature mortality.[9] Patients with abnormally low functional capacity may benefit from lower exercise loads.[10] The relation between incremental volume of oxygen uptake per minute ($\dot{V}O_2$) and pulse frequency in the range of 1 to 12Hz during bilateral quadriceps stimulation has recently been investigated; however, the duration of stimulation at each frequency was limited to 4 minutes,[11] which precluded any conclusion about fatigue. Continuous low-frequency (4–5Hz) NMES, designed to elicit a train of unfused twitches of the quadriceps, hamstring, and gluteal muscles, has recently been demonstrated to achieve exercise intensities of 4.6 METs in healthy subjects[12] and may provide a less fatiguing alternative to conventional tetanic stimulation for evoking sustained aerobic exercise in sedentary or patient populations. This exercise intensity corresponded to a mean oxygen uptake of 19.1mL·min^{-1}·kg^{-1}, which is equivalent to light to moderate

Disclosures: Minogue is an employee of Biomedical Research Ltd, who produces the stimulator used in the study; however, the reported results could be obtained with any stimulator capable of producing the pulse train specified. The other authors have nothing to disclose.

0003-9993/14/$36 - see front matter © 2014 by the American Congress of Rehabilitation Medicine
http://dx.doi.org/10.1016/j.apmr.2014.04.004

exercise.[13] However, the decline in oxygen uptake during sustained evoked activity at these frequencies has not yet been quantified. Intervention studies with this form of NMES have reported increased aerobic capacity in patients with spinal cord injury and chronic heart failure.[5,14]

The metabolic cost of contraction has been proposed as a primary factor in fatigue.[15] Consistent with this, exercise patterns, whether volitional or electrically stimulated, giving the greatest metabolic changes have been shown to result in the greatest fatigue.[16-18] Substantial attention has been paid in the past to the rapid decline in muscle force output, which occurs in response to repeated electrical stimulation.[15,19,20] So rapid is the reduction in force output that most studies consider only a few minutes of stimulated muscle activity. As a typical example, a reduction in force output of 40% was observed within 2 minutes using repeated 0.3-second bursts of 20-Hz stimulation that evoked contractions at 20% of the maximum voluntary contraction (MVC) in the quadriceps muscles.[21] The rate of fatigue has been shown to increase with stimulus pulse frequency but not with pulse duration or pulse amplitude, a finding attributed to the higher metabolic cost per active muscle area at higher stimulation frequencies.[8,15] The rate of fatigue during intermittent stimulation also depends on the duty cycle of the contraction relaxation sequence.[22] The peak force response to NMES has been shown to be a more important factor in predicting fatigue than the force time integral,[15] which has been attributed to the higher metabolic cost of force development than force maintenance.[15,23]

The short time scales of most studies of fatigue during isometric NMES[8,15,21] are insufficient to characterize the contribution of the aerobic energy production system. Few studies report energy rate and force output over prolonged periods that are representative of the duration of a typical aerobic exercise session. Hultman and Spriet[7] examined muscle biopsy samples during 45 minutes of intermittent (1.6s on/1.6s off) 20-Hz stimulation at a level initially producing 26% of the MVC. Output force decreased rapidly, reaching 25% of the initial value by 20 minutes, and the corresponding adenosine triphosphate rates reduced by more than half. However, whole body oxygen consumption was not measured. Hamada et al[24] observed an 18% decline in incremental whole body oxygen uptake after 20 minutes of intermittent 20-Hz stimulation; however, initial $\dot{V}O_2$ was less than twice resting levels, which may not be therapeutically significant.

The use of continuous subtetanic isometric stimulation appears to evoke higher $\dot{V}O_2$ responses than intermittent tetanic isometric stimulation,[25] and there is evidence that the elevated oxygen uptake is sustainable for longer.[12] However, in the studies to date using subtetanic stimulation, stimulus intensity was adjusted to compensate for fatigue; therefore, the reduction in $\dot{V}O_2$ during fatigue could not be determined directly.[12,26-28] Furthermore, these studies did not measure the evoked torque to assess the oxygen cost of isometric force production or the extent of force fatigue. An understanding of the fatigue response of the muscle during sustained electrically elicited contractions as necessary to design effective stimulation protocols, which can accumulate a defined aerobic exercise volume within a given time period.

The aim of this study was therefore to measure oxygen uptake and evoked torque during 30-minute sessions of bilateral continuous subtetanic isometric NMES of the quadriceps muscles to determine the rate of decrease of both variables over a time scale relevant to the delivery of an aerobic exercise dose. It was hypothesized that both force output and oxygen uptake would decline slowly, reflecting a less stressful metabolic profile compared with conventional intermittent tetanic NMES.

List of abbreviations:

MET	**metabolic equivalent**
MVC	**maximum voluntary contraction**
NMES	**neuromuscular electrical stimulation**
RER	**respiratory exchange ratio**
TTI	**torque time integral**
$\dot{V}E$	**expired volume per unit time**
$\dot{V}E/\dot{V}O_2$	**ventilatory equivalent for oxygen**
$\dot{V}O_2$	**oxygen consumption per unit time**

Methods

Participants

Eleven healthy men took part in the study (mean age, 34.2±11.5y; range, 19−53y; body mass, 79.1±11.7kg; range, 58−100kg). The exercise background of the group was mixed, ranging from moderately to highly active. All subjects had previous experience of electrical stimulation at high intensities. The study and experimental protocols were approved by the Human Research Ethics committee of University College, Dublin. All subjects gave written informed consent to participate in the study.

Experimental setup

Subjects were seated in a dynamometer (Cybex[a]) that was configured for measurement of isometric knee extensor torque of the right leg at 60° knee flexion (fig 1). The left leg was also restrained isometrically at the same angle. The torque signal from the dynamometer was continuously recorded using a data acquisition system (Biopac[b]) at a sampling rate of 200Hz. Two large (12×16cm) hydrogel stimulation electrodes (Axelgaard[c]) were applied to the quadriceps of each leg. One was positioned just proximal to the patella and covering the lower quadriceps, including the vastus medialis obliquus, and the other was positioned just distal and parallel to the inguinal fold. The electrodes were connected to a research stimulator (NT2010[d]), which was programmed to produce a constant current, symmetric biphasic, square wave pulse train in each leg at up to a 200-mA peak, with a phase duration of 600μs and an interphase interval of 100μs.

Energy usage during the stimulation session was estimated by indirect calorimetry. The subject was fitted with a face mask connected to a Quark[e] pulmonary gas analysis system, which was calibrated prior to each subject. In addition to the breathing rate (R_f) the following gas exchange responses were collected: $\dot{V}O_2$, expired volume per unit time ($\dot{V}E$), respiratory exchange ratio (RER), and ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$).

Experimental protocol

Subjects began by performing 3 maximum voluntary isometric knee extensions of the right leg. Each was approximately 5-seconds duration and separated by 60 seconds. The highest value was estimated to be their MVC. Using a continuous 4-Hz pulse sequence, the stimulus intensity was increased slowly until the subject indicated the highest level they could readily tolerate indefinitely. This level was noted and used for the subsequent session. The stimulation frequency of 4Hz was selected after