ORIGINAL ARTICLE

Effects of electrical stimulation on Vo_2 kinetics and delta efficiency in healthy young men

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Br J Sports Med 2003;37:140–143

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Accepted 12 June 2002

Objective: To determine the effects of electrical stimulation (ES) on oxygen uptake (Vo_2) kinetics and delta efficiency (DE) during gradual exercise. The hypothesis was that ES would attenuate the Vo_2 -workload relation and improve DE.

Methods: Fifteen healthy, untrained men (mean (SD) age 22 (5) years) were selected. Ten were electrostimulated on both quadriceps muscles with a frequency of 45–60 Hz, with 12 seconds of stimulation followed by eight seconds recovery for a total of 30 minutes a day, three days a week for six weeks. The remaining five subjects were assigned to a control group. A standardised exercise test on a cycle ergometer (ramp protocol, workload increases of 20 W/min) was performed by each subject before and after the experimental period. The slope of the Vo_2 -power output (W) relation ($\Delta\text{Vo}_2/\Delta\text{W}$) and DE were calculated in each subject at moderate to high intensities (above the ventilatory threshold—that is, from 50–60% to 100% $\text{Vo}_{2\text{max}}$).

Results: The mean (SEM) values for $\Delta\text{Vo}_2/\Delta\text{W}$ and DE had significantly decreased and increased respectively after the six week ES programme ($p < 0.05$; 9.8 (0.2) v 8.6 (0.5) ml $\text{O}_2/\text{W}/\text{min}$ respectively and 27.7 (0.9) v 31.5 (1.4)% respectively).

Conclusions: ES could be used as a supplementary tool to improve two of the main determinants of endurance capacity, namely Vo_2 kinetics and work efficiency.

Electrical stimulation (ES) can be used as a supplementary tool to improve physical conditioning, especially in clinical settings.¹ In humans, transcutaneous chronic (several hours a day) ES sessions can increase muscle oxidative capacity, capillarisation of fast twitch fibres, or induce some fibre type transitions among type II fibre subtypes.^{2–4} However, most studies showing significant effects of ES in human skeletal muscles have used protocols that are unrealistic and difficult to apply in clinical and sport training situations—that is, sessions that are too long (several hours a day)^{4–7} and/or using frequency currents that can produce discomfort (50–100 Hz, with pulse duration about 100 μs).^{1,8,9}

Some studies^{10–12} have evaluated the effects of protocols with short (30 minutes), low frequency ES sessions on the functional capacity of healthy humans. One of these studies showed a significant increase in the maximal oxygen uptake ($\text{Vo}_{2\text{max}}$) of cardiac transplant patients after an eight week ES programme on the quadriceps muscle.¹¹ However, this improvement was largely attributable to the very poor physical condition of the subjects before the ES protocol—that is, muscle atrophy resulting from previous detraining and immunosuppressive therapy. In a recent study from our laboratory, a group of healthy, untrained male subjects underwent a six week ES programme (three 30 minute sessions a week) on both quadriceps muscles with a frequency of 45–60 Hz.¹² The ES protocol induced a very significant decrease in the percentage of pure type IIX fibres ($\Delta 88\%$) and, to a much lower degree, of type I fibres ($\Delta 15\%$), whereas the percentage of type IIA fibres increased ($\Delta 63\%$). These considerable changes at the muscle tissue level were not accompanied by an improvement in conventional estimators of endurance performance, such as $\text{Vo}_{2\text{max}}$, measured during an incremental cycle ergometer test. This finding can be explained by the fact that central factors (maximal cardiac output) place a limit on peak muscle blood flow and O_2 delivery to working muscles during incremental exercise tests involving large muscle mass—for example, cycle ergometry¹³—whereas ES only acts at the peripheral level.

To the best of our knowledge, no previous research has assessed the effects of ES on other determinants of endurance

capacity that are largely related to muscle characteristics (for example, fibre type distribution), such as Vo_2 kinetics at high submaximal workloads¹⁴ or delta efficiency (DE).^{15,16} Although these two variables are not commonly studied during “routine” functional evaluation in humans, one of the major adaptations induced by endurance training is an improvement in DE^{15–17} and a change in Vo_2 kinetics¹³—that is, attenuation of the slope of the Vo_2 -work rate relation at high intensities during either constant load^{18–20} or more conventional gradual exercise tests.²¹ It was therefore the purpose of this study to assess the effects of an applicable ES programme on the Vo_2 kinetics and DE of healthy humans at the high workloads of an incremental (ramp protocol) test. Vo_2 kinetics and DE were studied before and after ES in the subjects from our previous study.¹² Based on the fact that (a) the ES programme induced a highly significant decrease in IIX fibres and (b) these fibres are the least efficient ones—that is, they consume more O_2 for the same workload than the other subtypes^{14,22,23}—we hypothesised that ES would attenuate the Vo_2 -workload relation and improve DE.

MATERIALS AND METHODS

Subjects

We used data from subjects who were recruited for a recently published study.¹² Written consent was obtained before their participation. All were fully informed of possible risks or discomfort associated with the experimental protocol. Fifteen sedentary, healthy, young men (mean (SD) age 22 (5) years) were selected. Their good health had been confirmed by physical examination. The study conformed to the code of ethics of the World Medical Association (Declaration of Helsinki), and the ethics committee of the Universidad Complutense de Madrid approved it.

Abbreviations: ES, electrical stimulation; Vo_2 , oxygen uptake; DE, delta efficiency; VT, ventilatory threshold

Figure 1 Example of attenuation of $\Delta\text{Vo}_2/\Delta\text{W}$ above the ventilatory threshold (VT) in one subject after the six week electrical stimulation (ES) programme. $\Delta\text{Vo}_2/\Delta\text{W}$ is the slope of the relation between oxygen uptake (Vo_2) and power output. Data points correspond to each 15 second interval. In this example, $\Delta\text{Vo}_2/\Delta\text{W}$ decreased from 10.828 $\text{ml O}_2/\text{W}/\text{min}$ to 8.882 $\text{ml O}_2/\text{W}/\text{min}$ after ES.

Protocol

The participants were randomly divided into two groups: control and electrostimulated (ES) subjects. The five subjects forming the control group (mean (SD) age 22 (3) years; height 176.2 (8.6) cm; body mass 74.0 (9.4) kg) did not undergo muscle ES but were subjected to the same tests as those in the ES group. The latter ($n = 10$; age 22 (5) years; height 175.0 (5.5) cm; body mass 71.2 (6.7) kg) underwent ES of both quadriceps muscles over a six week period as described below. All participants continued with their sedentary lifestyle during the six week period of the study. Before and after this period, all subjects performed an exercise test on a cycle ergometer.

ES programme

The quadriceps muscles of both legs of subjects assigned to the ES group were subjected to 30 minutes per session and day of transcutaneous ES, three days a week for six weeks. ES was elicited using bipolar electrodes²⁴ and a portable battery powered neuromuscular electrical stimulator (Stiwel Medical Technologies, Villeneuve, Switzerland). The cathode was positioned proximally—that is, 5 cm below the major trochanter of the femur—and the anode was placed over the motor point of the vastus lateralis muscle—that is, the region 5 cm laterally above the upper edge of the patella.⁴

The stimulation frequency during each session was 45–60 Hz with an impulse of 300 μs and a duty cycle of 12 seconds on/eight seconds off. This frequency was selected because it has been applied in numerous human studies and because low frequencies are used by most physiotherapists. The pulse amplitude was selected by each subject according to their maximum tolerance level. The average stimulation intensity during the six week period increased from about 25 mA (1st week) to about 75 mA (6th week). During each session, subjects lay on a bed in a supine position with legs semiflexed (knee joint at 150–160°).

Cycle ergometer tests

The exercise test consisted of a ramp protocol until exhaustion performed on an electronically braked cycle ergometer (Ergometrics 900; Ergo-line, Barcelona, Spain). Environmental conditions were similar for all the tests (21–24°C, 45–55% relative humidity), and the subjects were cooled with a fan throughout the bouts of exercise. After a two minute rest sitting on the cycle ergometer, the test started at 20 W and the workload was increased by 20 W/min (5 W/15 s). Pedalling

Figure 2 Example of increase in delta efficiency (DE) above the ventilatory threshold (VT) in one subject after the six week electrical stimulation (ES) programme. DE (%) is equal to the reciprocal of the slope (that is, $1/a$) of the linear regression $y = ax + b$, where y is energy expended per minute (kcal/min) and x is work accomplished per minute (kcal/min).¹⁵ Data points correspond to each 15 second interval. In this example, DE increased from 24.2% ($= 1/4.125$) before ES to 26.5% ($= 1/3.780$) after ES.

cadence was kept between 60 and 80 rev/min depending on the subject's preferences. A pedal frequency meter was used by the subject to maintain this cadence. Each exercise test was terminated when pedal cadence could not be maintained at 60 rev/min (at least). Verbal encouragement was given to the subjects to continue the test until they were exhausted.

Measurements during exercise tests

Gas exchange data were collected continuously using an automated breath by breath system (CPX; Medical Graphics, St Paul, Minnesota, USA). The ventilatory threshold (VT) was determined as the power output (W) corresponding to (a) the first breakpoint in CO_2 output (Vco_2) with respect to Vo_2 (the so-called V-slope method)²⁵ and (b) the first breakpoint in pulmonary ventilation with respect to Vo_2 but not to Vco_2 . Heart rate (in beats/min) was continuously monitored during the tests from modified 12 lead electrocardiogram tracings (EK56; Hellige, Freiburg, Germany).

Vo_2 kinetics

The slope ($\Delta\text{Vo}_2/\Delta\text{W}$) of the regression line of the Vo_2 -power output (W) relation was calculated in each subject across all workloads above the VT. Previous research has shown that Vo_2 kinetics above the VT in a ramp protocol such as the present one (a) could be used as an index of adaptation to endurance training,²¹ and (b) is related to muscle fibre distribution (percentage of type IIX fibres),¹⁴ on which ES had a significant effect, as mentioned above.

Delta efficiency

DE—that is, the ratio of the change in work accomplished/min to the change in energy expended/min—was calculated for each subject above the VT. DE was measured from linear regression ($y = ax + b$) of the relation between energy expended/min (y , in kcal/min), and work accomplished/min (x , in kcal/min).¹⁵ DE was equal to the reciprocal of the slope of the aforementioned relation—that is, $1/a$.

Data analysis

Once a gaussian distribution of results was established by the Kolmogorov-Smirnov test, an unpaired Student's t test was applied to examine the possible differences in $\Delta\text{Vo}_2/\Delta\text{W}$ and DE between control and electrostimulated groups before the onset of the experiment (week = 0). Given that no significant differences ($p > 0.05$) were observed in either variable between

Table 1 Effects of the six week electrical stimulation programme on VO_2 kinetics and delta efficiency

Variable	Week 0	Week 6	
	(All subjects, n = 15)	(Controls, n = 5)	(Stimulated, n = 10)
$\Delta\text{VO}_2/\Delta\text{W}$ (ml $\text{O}_2/\text{W}/\text{min}$)	9.8 (0.2)	9.1 (0.1)	8.6 (0.5)*
DE (%)	27.7 (0.9)	30.5 (0.4)	31.5 (1.4)*

Data are expressed as mean (SEM). $\Delta\text{VO}_2/\Delta\text{W}$ and DE were measured at all workloads above the ventilatory threshold (from 50–60% to 100% $\text{VO}_{2\text{MAX}}$).

* $p < 0.05$ v week 0.

$\Delta\text{VO}_2/\Delta\text{W}$, Slope of the oxygen uptake (VO_2)-power output (W) relation; DE, delta efficiency.

the two groups of subjects at week 0, it was decided to consider these two groups as a single group (n = 15 subjects) to increase the statistical power of further analyses. Longitudinal changes (week 0 v week 6) in $\Delta\text{VO}_2/\Delta\text{W}$ and DE were analysed by one way analysis of variance. When significant differences were found ($p < 0.05$), a Fisher LSD test was used post hoc to determine which mean values were significantly different from remaining values.

The level of significance was set at 0.05 for all statistical analyses, and results are expressed as mean (SEM).

RESULTS

Figures 1 and 2 show an example of VO_2 kinetics and DE respectively in one subject before and after the ES programme. The average values of $\Delta\text{VO}_2/\Delta\text{W}$ and DE had significantly decreased and increased ($p < 0.05$) respectively after the six week ES programme (table 1).

DISCUSSION

This study represents the first attempt to determine the effects on VO_2 kinetics and DE of an ES programme of practical applicability—that is, short duration (30 minutes/session/day, three days/week for six weeks) and phasic, medium amount (45–60 Hz), intermittent (12 seconds on, 8 seconds off) stimulus pattern. The results indicate that the significant modifications induced by this ES programme on the histochemical and metabolic properties of human skeletal muscle fibres¹² are also reflected in an improvement in VO_2 kinetics and DE across the moderate to high workloads ($> \text{VT}$) of a ramp test. Although further research is needed, this finding suggests that ES could be used as a supplementary tool to improve one of the factors involved in human adaptation to endurance training—that is, work efficiency at high exercise intensities. Furthermore, in these experiments the physiological changes were obtained with a relatively low number of ES sessions (18 in total) that were of short duration (30 minutes a day). This, together with the minimal discomfort to the patient/athlete, is essential for successful application in clinical and sport medicine situations.

Ramp protocols using an electronically braked cycle ergometer are suitable for evaluation of human endurance performance both in sport²¹ and clinically.²⁶ For instance, in this type of test, the VO_2 response is linear above the VT (at least in cyclists who are not highly trained), and the VT shows an unequivocal and reproducible response.²⁷ In fact, ramp protocols similar to that used here have been used in research into VO_2 kinetics and its possible determinants.^{14 21 28} Exercise tests with workload increments of 10–30 W/min (20 W/min in this study) have proved invaluable for determination of work efficiency (from the VO_2 -work rate relation), and the short interval (one minute) at each work rate precludes the development of a “ VO_2 slow component”—that is, increase in VO_2 despite constant power output—within each work rate above the VT.²⁹ In this type of ramp test, $\Delta\text{VO}_2/\Delta\text{W}$ typically ranges between 9 and 11 ml $\text{O}_2/\text{W}/\text{min}$ across most workloads, at least in athletes who

are not highly trained²⁹ (average of about 9 ml $\text{O}_2/\text{W}/\text{min}$ for our three groups of subjects taken together), which gives a DE of 25–30%³⁰ (average of about 29% for our three groups of subjects taken together). This range of 25–30% fits closely with that calculated on the basis of intracellular chemical-mechanical coupling efficiencies³¹ and only appears to be significantly altered by training status—for example, DE can clearly surpass 30% in highly endurance trained, professional cyclists (based on calculations using data from a previous study²¹).

Although $\text{VO}_{2\text{MAX}}$ or lactate/ventilatory thresholds are commonly used as markers of endurance performance, endurance training also induces significant changes in VO_2 kinetics and work efficiency.¹³ The latter adaptation can be easily detected during constant load or more conventional ramp exercise tests such as the one used here. Indeed, endurance training attenuates the rate of VO_2 rise at the high workloads ($> \text{VT}$) of both constant load^{18–20} and gradual tests such as the one used here.²¹ Although the adaptations of central (cardiopulmonary) factors induced by endurance training may partly explain this improvement in VO_2 kinetics during exercise testing, intramuscular changes appear to be the most important factor.¹³ Indeed, motor unit recruitment patterns—for example, lower reliance on inefficient type IIX fibres after training³²—and percentage distribution of type IIX fibres¹⁴ are thought to be the main determinants of VO_2 kinetics above the VT. It follows that the adaptations in VO_2 kinetics observed here after the short term ES programme (a) mimic those produced by endurance training and (b) are largely attributable to the changes in muscle fibre subpopulations (see below) given that motor unit recruitment was not altered after ES (as shown in our previous study using electromyographic data¹²). As detailed elsewhere,¹² ES induced a very significant decrease in the percentage of pure type IIX fibres of our subjects ($\Delta 88\%$) and, to a much lower degree, of type I fibres ($\Delta 15\%$), while the percentage of type IIA fibres increased ($\Delta 63\%$). Furthermore, oxidative capacity and capillarisation of type II fibres improved with ES. The energetics of type II fibres, especially the IIX subtype (which showed the largest decrease here), can explain the findings of the study—that is, attenuation of the VO_2 rise and improvement in DE above the VT. From both in vitro (animal)²² and in vivo (human)^{14–23} studies, it appears that type IIX fibres are considerably less efficient than type I fibres for a given workload. However, it could be argued that, even if the number of inefficient type IIX fibres were decreased in our subjects after ES, the number of the most efficient fibres (type I) was also reduced and that of type IIA fibres increased.¹² This finding must be interpreted with caution. Firstly, it should be kept in mind that the capillarisation and oxidative capacity of type IIA fibres improved after ES, which in turn is expected to improve their efficiency. Secondly, although the pattern of fibre type observed with the present short term ES was $\text{IIX} \rightarrow \text{IIA} \leftarrow \text{I}$, it would probably be shifted towards a type $\text{IIA} \rightarrow \text{type I}$ transition—that is, $\text{IIX} \rightarrow \text{IIA} \rightarrow \text{I}$ —if the duration of the programme was prolonged for some

Take home message

A short term, feasible electrical stimulation protocol (18 sessions of 30 min each) can improve the work efficiency of sedentary, healthy men during a ramp exercise test. Further research is needed to extend the findings—for example, with trained athletes and/or longer electrical stimulation programmes.

more weeks.¹² This notion is also partially supported by previous studies showing a tendency towards a decreased percentage of type I fibres if ES is extended beyond six weeks.^{4 10}

DE is one of the main determinants of endurance performance—for example, in endurance cycling.^{15 16 17} This variable is calculated as the change in energy expended per minute relative only to the change in actual work accomplished per minute, which eliminates the possible influence of metabolic processes that do not contribute to actual work—for example, basal metabolic rate.^{15 31 33} Thus, the observed increase in DE over a wide range of work rates—that is, above VT or above 50–60% $\text{VO}_{2\text{MAX}}$ —supports the notion for a potential improvement in work efficiency after ES. These work rates were selected on the basis of the following: (a) most fibres (including both type I and II) of one of the main muscles involved in pedalling, the vastus lateralis muscle (to which ES was applied), are recruited over this range of work rates^{34 35}; (b) the most important phases of endurance training and competitions in general are held at these relative intensities.

In conclusion, the significant modifications that a short term (six weeks) ES programme induced in the local properties of the vastus lateralis muscle are accompanied by an improvement in VO_2 kinetics and DE across the moderate to high workloads (>VT) of a cycle ergometer ramp test. Furthermore, the physiological changes were obtained with a relatively low number of ES sessions (18 in total) of short duration (30 minutes a day). Although further research is needed—for example, with trained athletes—this finding suggests that ES may be used as a supplementary tool to improve one of the main factors involved in human adaptation to endurance training—that is, work efficiency.

ACKNOWLEDGEMENTS

We acknowledge Stiwel Medical Technologies for supplying material for the study.

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