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Case report

Could Low-Frequency Electromyostimulation Training be an Effective Alternative to Endurance Training? An Overview in One Adult

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Abstract
This preliminary study aimed to investigate the effects of a six-week low-frequency electromyostimulation training (10Hz) on the cardiovascular, respiratory and muscular systems. To that purpose, aerobic capacity, knee extensor muscles strength and architecture, muscle sympathetic nervous activity, blood pressure and heart rate have been evaluated in one healthy male subject (33 year-old, 1.73 m, 73 kg). Results showed improvement of aerobic capacity (+4.5% and +11.5% for maximal oxygen uptake and ventilatory threshold) and muscle strength (+11% and +16% for voluntary and evoked force). Moreover, for the first time, this study demonstrated low-frequency training effects on muscle architecture (+3%, +12% and -11% for muscle thickness, pennation angle and fascicle length) and cardiovascular parameters (-22%, -18% and -21% for resting muscle sympathetic nervous activity, heart rate and mean blood pressure). Interestingly, these results suggest that this method may have beneficial effects on all systems of the body. The investigation of training effects on muscle architecture and cardiovascular parameters should therefore be pursued since highly deconditioned subjects are likely to fully benefit from these adaptations.

Key words: Electrical stimulation, aerobic capacity, muscle architecture, muscle sympathetic nervous activity.

Introduction

In the last decades, electromyostimulation (EMS) has been widely used in rehabilitation medicine (Deley et al. 2005; Snyder-Mackler et al., 1995) and in sports (Babault et al., 2007; Lattier et al., 2004; Maffiuletti et al., 2002) to counteract the effects of pathology/hypoactivity and to increase strength. High and low frequencies of stimulation (>40 Hz vs. <15 Hz), respectively inducing tetanic and non-tetanic contractions, can be used for training. In sports, several studies showed that, when used alone or in association with other strengthening techniques or with technical workout, high-frequency EMS results in significant improvements in muscle strength, anaerobic power production (jump height and sprint time) and in specific movements (Babault et al., 2007; Maffiuletti et al., 2002). Moreover, several studies have suggested that EMS can have significant central effects and even that multiple sessions of high-frequency EMS result in significant increases in voluntary activation (Maffiuletti et al., 2002). Low-frequencies are mostly used as a recovery intervention (Babault et al., 2011; Lattier et al., 2004) and their effects for training have been less studied (Deley et al., 2005; Nuhr et al., 2003). Indeed, some beneficial effects on aerobic and functional capacities have been demonstrated in patients but little is known regarding the neuromuscular and cardiovascular adaptations. Investigating the possible adaptations to low-frequency EMS at the different levels of exercise performance would not only determine the primary mechanisms for improvement but also guide future therapeutic use of low-frequency EMS.

The aim of this preliminary report was therefore to investigate the effects of a six-week low-frequency EMS training program at the different levels of exercise performance: respiratory, neuromuscular and cardiovascular. Since low-frequencies have been suggested to mimic endurance-type training (Atherton et al., 2005), we can expect improvements of the subject's aerobic capacity, resistance to fatigue and cardiovascular control (muscle sympathetic nervous activity, MSNA; resting blood pressure and bradycardia). Also, results obtained in patients (Deley et al., 2005; 2008) suggested that this low-frequency EMS training might have significant effects on muscle strength attributable to neural and/or muscular adaptations.

Methods

Subjects

A 33 year-old man (height 1.73 m, body mass 73 kg), free from previous knee injury, participated in this study. The subject was recreationally active and had never engaged in systematic strength training or had experience with EMS. The investigation conformed to the principles outlined in the Declaration of Helsinki and the subject gave his written informed consent after being clearly advised about the protocol, which was approved by the Institutional Ethics Committee.

Design of the study

The subject underwent a 6-week EMS training on knee extensor muscles of both legs. Exercise capacity, neuromuscular properties, muscle architecture and sympathetic activity were evaluated at least four days before the first training session and four days after the last training session. The subject was familiarized with all measurements before entering the study.

EMS training

The bilateral low-frequency training program consisted of 45-min sessions, five days per week for six weeks. Knee extensors of both legs were stimulated using a portable battery-powered stimulator (Compex-2, Medicompex SA,

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Ecublens, Switzerland). Two self-adhesive positive electrodes (each measuring 25 cm^2, 5 × 5 cm), which have the property of depolarizing the membrane, were placed on the thigh as close as possible of motor points of *vastus medialis* (VM) and *vastus lateralis* (VL) muscles, near the proximal insertion of each muscle. Rectangular negative electrodes, each measuring 50 cm^2 (10 × 5 cm, Medicompex SA, Ecublens, Switzerland), were placed over the femoral triangle of each thigh (1-3 cm below the inguinal ligament). During stimulation, the subject was in the supine position and the lower limbs were positioned without hip or knee flexions. Rectangular wave pulsed currents of 10 Hz lasting 250 µs were used and the stimulus was alternately on for 9 s and off for 2 s. The duration of each training session was 40 min, following a 5-min warm-up (submaximal contractions at 3 Hz). After warm-up, stimulation intensity for each muscle was increased according to the patient's tolerance, to always be at the maximal tolerated level. The validity of these stimulation characteristics for the improvement of knee extensor muscles strength and exercise capacity have been confirmed by previous low-frequency EMS training studies (Deley et al. 2005, Dobsak et al. 2006). During the study period, the subject was asked not to perform any physical activity, except the EMS program, in order to exclude confounding parameters.

Measurements and data analysis

Before and after training, the subject came four times to the laboratory for testing sessions: (i) cardiopulmonary exercise test, (ii) neuromuscular tests on knee extensor muscles, (iii) quadriceps muscle architecture, and (iv) cardiovascular measurements (Figure 1).

Cardiopulmonary exercise test

The cardiopulmonary exercise test was performed on an electromagnetically braked cycle ergometer (Lode, Groningen, Nederlands). The exercise protocol began with 3 min resting followed by 3 min of warm-up pedalling at 50 watts (W), and then power was increased by 25 watts every minute. The exercise test was terminated when the subject was unable to maintain the imposed pedalling rhythm of 80 revolutions per min, limited generally by dyspnea and/or muscular fatigue. Six minutes of passive recovery followed the incremental exercise test. Heart rate was monitored throughout the test and recovery (Polar Electro Oy, Kempele, Finland). Gas exchanges were measured breath-by-breath using a portable system (K4b2, Cosmed, Rome, Italy). Before each test, the system was calibrated with a 2-liter Rudolph syringe and a standard gas of known concentration.

Maximal oxygen uptake (VO_2), power and heart rate (HR) were defined as the mean values during the last 30 s of exercise. The ventilatory threshold (VT) was determined visually using the Beaver et al.'s method (Beaver et al., 1986).

Neuromuscular tests on knee extensor muscles

During this session, the subject was seated in comfortable upright position on an isokinetic dynamometer (BIODEX system 2, Biodex Corporation, Shirley, NY) with a 95° hip angle. Velcro straps were applied tightly across the thorax. The leg was fixed to the dynamometer lever-arm and the axis of rotation of the dynamometer was aligned to the lateral femoral condyle, indicating the anatomical joint axis of the knee. Mechanical traces were digitized online and stored for analyses (Biopac sytems, Inc., MP System hardware and Acknowledge software).

The session began with a standardized warm-up composed of 10 to 15 progressive dynamic leg extensions performed at 120 °·s^{-1}. Then, the subject performed 30 maximal knee extensions (60 °·s^{-1} angular velocity, 100° range of motion) preceded and immediately followed by (i) maximal voluntary contractions (MVC) of the right quadriceps with activation level assessment (see below) and (ii) electrically evoked contractions at rest.

MVC: Two 5-s MVC (separated by 15 s) were performed and the best was retained for further analysis (75° knee flexion, 0° corresponding to full extension).

Evoked contractions: Quadriceps contractile properties were studied using femoral nerve stimulations. Electrical impulses were delivered through a pair of surface electrodes. The anode (self-adhesive stimulation electrode, 10 cm × 5 cm) of the electrical stimulator (Digitimer DS7, Hertfordshire, England) was pasted halfway between the superior aspect of the greater trochanter and the inferior border of the iliac crest. The cathode (10 mm diameter ball probe) was pressed in the femoral triangle and moved to the position allowing the biggest contraction. Optimal stimulation intensity was determined in isometric condition using series of three square-wave stimuli (1-ms duration, 400 V maximum voltage and intensity ranging from 60 to 200 mA stimulations), each separated by 5 s, with progressively increasing intensity until twitch torque failed to increase.

Stimulations were then applied using two electrical impulses separated by 10 ms (here called doublet). The peak doublet amplitude was measured from the mechanical traces associated with doublets (Peak doublet, Pd) and MVC. More specifically, stimulations were delivered at

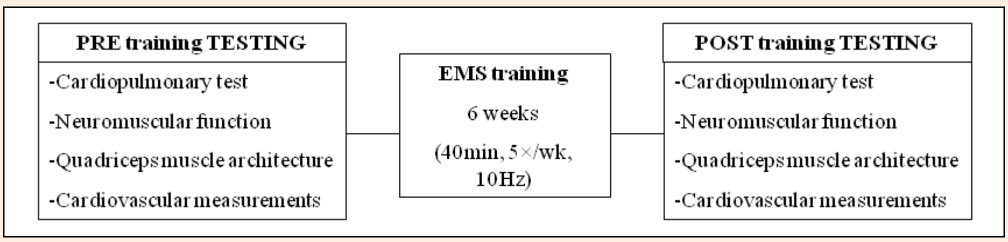

Figure 1. Schematic view of the study design. EMS: electromyostimulation.

rest before each MVC to assess contractile properties and during the MVC plateau (superimposed doublet) as well as 1 s after the MVC (control doublet) to determine activation level, according to the twitch interpolation technique.

Activation level was calculated using the following formula: activation level = (1-superimposed doublet/control doublet) ×100.

The torque developed for each of the 30 maximal contractions was measured in order to quantify the total work performed. Lastly, MVC and Pd measured after the 30 contractions were considered as indicators of the subject resistance to fatigue.

Quadriceps muscle architecture

B-mode ultrasonography (Esaote Biomedica, AU5, Florence, Italy) with a 50-mm, 7.5-MHz linear-array probe was used to examine vastus lateralis architecture in vivo in relaxed muscles. Axial-plane images were obtained at 50% of the length of the thigh and centre of the muscle width (Gondin et al., 2005). The probe was aligned perpendicularly to the dermal surface of vastus lateralis muscle and oriented along the median plane of the muscle. The probe was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. Great care was taken to consistently apply minimal pressure during scanning to avoid compression of the underlying structures. The probe was firmly attached in place at the measurement site with a custom-made apparatus. Measurements were performed after the subject had been in the supine position for at least 20 min to allow fluid shift to occur (Berg et al., 1993). Scans were performed by the same investigator, recorded onto SVHS videotape and acquired using frame-capture software. During each testing session, a total of four single scans were performed for further analysis.

Thickness, pennation angle and fascicle length were determined using digitizing software (ImageJ version 1.43, National Institutes of health, USA). Muscle thickness was the distance between superficial and deep aponeuroses. Pennation angle was defined as the angle between fascicular path and the deep aponeurosis of vastus lateralis muscle. Vastus lateralis fascicles generally extended off the ultrasound scan window. Fascicle length was therefore estimated by linear extrapolation of both fascicular path and aponeurosis. For each ultrasound session, the mean of 16 fascicle angles was obtained (Figure 2).

Cardiovascular measurements

Cardiovascular measurements were recorded between 8:00 am and 12:00 am after subjects had fasted overnight and with subject in the supine position. Testing was performed in the following order: resting supine measurements, handgrip to exhaustion. All data were digitized continuously at 500 Hz to computer and analyzed subsequently with signal processing software (Windaq, Dataq instruments, Akron, OH, USA).

Heart rate was obtained from a 3 lead electrocardiogram. Arterial pressures were measured on the right arm at 1-min intervals via an automated arm cuff sphygmomanometer (Dinamap Model, Critikon, Tampa, FL) and on a beat-by-beat basis via digital photoplethysmography (Finapres®; Ohmeda, Louisville, CO, USA).

Muscle sympathetic nerve activity was obtained via microneurography, as described previously (Tamisier et al. 2007). Briefly, multiunit, postganglionic muscle sympathetic nerve activity was recorded from the peroneal nerve posterior to the fibular head. Recordings were made with a tungsten microelectrode (0.2 mm diameter insulated shaft, tapered to an uninsulated tip of ~1-5 µm) inserted near the fibular head (~2-3 cm from the recording electrode). The nerve was located by using the microelectrode first as a stimulating electrode to initiate muscle twitches, and then as a recording electrode to identify a fascicle which contained muscle sympathetic activity. Muscle sympathetic activity was distinguished from other sources of nerve activity by the following criteria: (1) presence of spontaneous pulse synchronous bursts, (2) increased activity during Vasalva straining, (3) muscle afferent activity with muscle stretch; and (4) no change of activity during light stroking of the skin or startling the subjects with loud noises, indicating lack of skin nerve activity. Sympathetic activity was recorded in the leg ipsilateral to the arm performing handgrip exercise.

Isometric handgrip was performed at a constant submaximal level of voluntary force (40% of maximum) that has previously been shown to produce peak levels of MSNA in older subjects (Ng et al., 1994). Each contraction was sustained until exhaustion, defined as an inability to maintain force within 10% of target plus the attainment of a peak level of perceived effort (Taylor et al., 1991). Contractions were performed to exhaustion because peak MSNA and cardiovascular responses have been shown to occur in individual subjects at this standardized performance and perceptual end point (Seals, 1993).

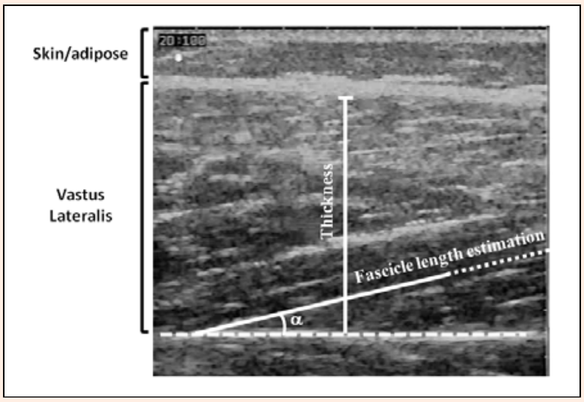

Figure 2. Sagittal plane ultrasound image of the *vastus lateralis* muscle. Muscle thickness was the distance between superficial and deep aponeuroses. Dashed line: deep aponeurosis; dotted line: partial extrapolation of a single fascicle; α: pennation angle.

We analyzed sympathetic activity to obtain a clean representation of nerve activity in the form of a spike train. This analysis involves explicit steps ordered to take advantage of the different statistical properties of artifacts, background noise, and the actual nerve signal in the recorded raw signal, as described previously (Tan et al., 2009). Briefly, we first remove line noise and movement artifacts from the recording and then use the statistical properties of background noise to identify actual spikes. This results in a sympathetic nerve tracing that has minimal noise and can be quantified as spikes (i.e, nerve firings) per unit time (i.e, per beat).

Effect sizes (η^2) were determined, with values of 0.2, 0.5 and above 0.8 considered to represent small, medium and large differences, respectively. Significant difference was accepted when $p < 0.05$.

Results

Reliability of neuromuscular function and muscle architecture parameters was good, with coefficients of variation ranging from 0.09 to 19.00%

Cardiopulmonary exercise test

After training, maximal VO_2 increased by 4.5% (49.3 *vs.* 51.5 mL·min^{-1}·kg^{-1}) and maximal power from 16.7% (300 to 350 Watts). VO_2 at ventilatory threshold increased by 11.5% (40.1 *vs.* 44.7 mL·min^{-1}·kg^{-1}).

Neuromuscular function

Muscular adaptations: Table 1 shows all neuromuscular parameters before and after EMS training. After training, MVC and Pd amplitude respectively increased by 11% and 16% (η^2 = 82.4 and 18.8 respectively).

Neural adaptations: After training, voluntary activation level was only slightly increased by 7%.

Resistance to fatigue: After training, the sum of the torque developed during the 30 maximal contractions was 26% higher (4305.5 *vs*. 5434.7 N·m). Resistance to fatigue was improved after training as shown by the lower decreases in MVC and Pd amplitude measured immediately after the 30-contraction fatiguing protocol (-33.5% after training *vs.* -43.5% before training for MVC and -39% *vs.* -48% for Pd).

Quadriceps muscle architecture

Muscle thickness was only slightly increased after training (24.4 ± 0.2 mm *vs.* 25.2 ± 0.6, +3%; η^2 = 1.73), whereas fascicles pennation angles meanly increased by 12% (12.8 ± 3.0 ° *vs.* 14.3 ± 2.6 °; η^2=0.54). Fascicles length was decreased by 11% (from 118.0 ± 22.7 mm to 105.3 ± 18.5 mm; η^2= 0.61).

Cardiovascular measurements

After training, resting heart rate was decreased by 18% (97 *vs.* 80 beats·min^{-1}). Systolic and diastolic pressures were also decreased by 24% (144 *vs.* 109 mmHg) and 19% (81 vs. 66 mmHg) after training.

Figure 3 presents the direct recording of sympathetic nerve activity (SNA) in baseline state and during isometric handgrip before and after training. After training, SNA is decreased in baseline state (-22%). As expected, the handgrip exercise induced a great increase in SNA. However, this increase was not lower after training (+227% before training and + 247% after).

Discussion

The main purpose of this preliminary study was to determine the respiratory, neuromuscular and cardiovascular adaptations to a six-week period of low-frequency EMS training in a young healthy subject. EMS training improved aerobic capacity as well as muscle strength, thickness and fascicles pennation angle and decreased resting sympathetic nervous activity and muscle fascicles length.

Improvements of aerobic capacity were characterized by slight increases in oxygen uptake both at maximal (VO_2max) and submaximal (VO_2 at ventilatory threshold) levels. Although the underlying adaptations for increased

Table 1 . Baseline (PRE) and post-training (POST) data measured during the neuromuscular tests.

	PRE	POST	% of change PRE/POST
MVC (N·m)	325.4	362.6	11%
Pd (N·m)	91.6	106.4	16%
% VA	93.2	99.4	7%
Sum of 30 contractions (N·m)	4305.5	5434.7	26%
MVC after 30 contractions (N·m)	184.0	241.3	31%
Pd after 30 contractions (N·m)	47.5	64.3	35%

MVC, maximal voluntary contraction; Pd, peak doublet amplitude; % VA, percentage of voluntary activation.

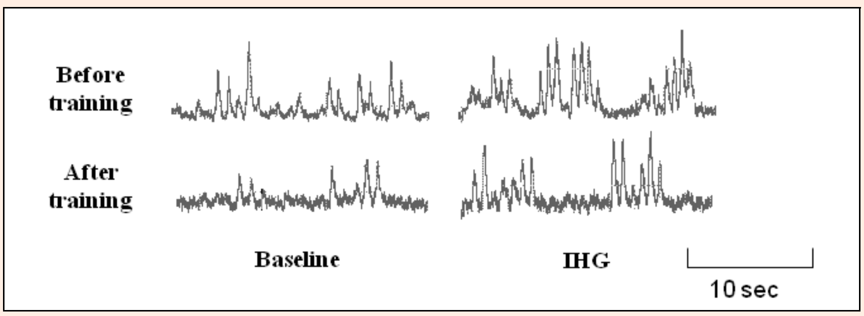

Figure 3. Recordings of sympathetic nerve activity (SNA) in baseline state and during isometric handgrip (IHG) before (top panel) and after EMS training (bottom panel).

aerobic capacity after low-frequency EMS program remain unclear, it has been suggested that mechanisms that mediate increases in oxygen uptake may relate to changes in mitochondrial content, blood supply, muscle mass and modifications in neural regulation (Dobsak et al. 2006; Nuhr et al., 2003). Therefore, there might be a link between these improvements of aerobic capacity and the neuromuscular adaptations observed after training.

Indeed, our results reveal an 11% increase in voluntary strength and a 16% increased evoked torque. Such increases in strength have not always been found after EMS training, particularly when used alone in healthy subjects (e.g. Dehail et al. 2008; Porcari et al. 2002). However, in view of dose–response relationships previously observed for changes induced by electrostimulation in animal studies (Sutherland et al. 1998), it is not surprising that the stimulation protocol used in the present study (5-day a week during 45 minutes) elicited greater changes than short-term protocols usually used in EMS training (2 to 3 days per week, 20 to 30 min per day). Comparable improvements have been observed in a patient with chronic heart failure following a similar training program (5 weeks of training, 5-day a week during 60 minutes). According to Komi et al. (1978), improvements in strength production can be related to modifications within the muscle and/or in the nervous organization of muscle contractions. Several EMS studies have suggested that neural factors, rather than changes at the muscular level, largely account for the training-induced strength gains, particularly in the case of short-duration programs (Maffiuletti et al., 2002; Malatesta et al., 2003). However, our results showed that voluntary activation level, classically used to index training-induced neural adaptations, was barely modified. This strongly suggests that the increase in maximal knee extensors strength is attributable to improvements at peripheral level, *i.e*. muscular changes. Although the small neural adaptations obtained here are surprising, it is possible that different stimulation characteristics (*i.e.,* low *vs.* high frequency) result in different neuromuscular adaptations as previously suggested by Bax and coworkers (2005). Also, Bickel et al. (2003) showed that an acute bout of EMS was sufficient to stimulate molecular-level responses. Such changes indicated the initiation of hypertrophy processes in quadriceps muscles of both able-bodied and spinal cord–injured subjects. However, the effect of an EMS training program on muscle hypertrophy remains ambiguous in the literature, due mainly to the training duration adopted and EMS parameters selected (Gondin et al., 2005; Stevenson and Dudley 2001). For example, Gondin et al. (2005) observed increases in quadriceps muscle anatomical cross-sectional area and pennation angle after 8 weeks of high-frequency EMS training whereas these parameters were unchanged after 4 weeks. Regarding low-frequencies, to our knowledge, no study has ever investigated the effects of a training program on muscle architecture. However, low-frequency EMS is often compared to endurance training (Atherton et al., 2005) and endurance runners have been demonstrated to have shorter fascicles and greater pennation angles than sprinters (Abe et al., 2000). This is in line with the slight increase in muscle thickness, the 12% increase of fibres pennation angle and the 11% decrease in fascicle length observed in the present study. Although these results need to be confirmed, they are of great interest since it is known that the relative energy cost of force production is lower for shorter fascicles, and that a muscle with larger fascicle angulations could have a greater force-generating capacity (Fukunaga et al., 2001). Also, in a further study, it would be essential to measure the torque output during training sessions in order to relate the observed muscles' adaptations to the amount of produced torque.

Another remarkable result is the decreased baseline MSNA after EMS training. Although the effects of low-frequency EMS on MSNA are unknown, the influence of endurance training on this parameter has been extensively investigated (Somers et al., 1992; Sheldahl et al., 1994). Indeed, sympathetic nerve activity has long been regarded as an important regulator of blood flow and blood pressure. Among cardiovascular adaptations associated with exercise training are reductions in resting blood pressure (Tipton, 1991) and increases in blood flow to active skeletal muscle (Rowell, 1993). Reductions in sympathetic vasoconstrictor outflow following training may play an important role in these adaptations. However, inconsistent findings have been reported, with studies showing reduced, unchanged and increased resting MSNA (*e.g.,* Ray and Hume, 1998). Nevertheless, the decreased resting MSNA observed in the present study is in accordance with the decreased blood pressure and heart rate induced by low-frequency EMS training. Surprisingly, we did not found any modification of MSNA during handgrip exercise after training whereas longitudinal studies have consistently shown than MSNA responses to exercise are attenuated after training (*e.g.,* Ray and Hum,e 1998). However, several studies suggested that this adaptation is specific to trained muscles (Sheldahl et al. 1994, Somers et al., 1992). This might explain our results since the exercise performed during testing involved upper body muscles whereas EMS training only concerned muscles located under the electrodes (*i.e.,* knee extensors).

Conclusion

As a conclusion, the current preliminary study is the first to present an overview of the adaptations induced by a short-term low-frequency EMS training program. Our results confirmed the effectiveness of this training modality on aerobic capacity and muscle strength but most importantly, for the first time we demonstrated its beneficial effects (similar to those expected from endurance training) on muscle architecture (*i.e*., large pennation angle and short fascicles that would generate force with less metabolic cost) and cardiovascular parameters (resting MSNA, blood pressure and bradycardia). However, this study is a case report with no control, so the results should be interpreted with caution, and the authors are unable to draw any real conclusions for a larger sample. Nevertheless, it does suggest that the investigation of low-frequency EMS effects on muscle architecture and cardiovascular parameters should be pursued. In addition, it would be of great interest to assess these effects in patients with chronic heart failure likely to fully benefit from these adaptations.

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Key points

- These results confirmed that 5 weeks of low-frequency electrical stimulation have beneficial effects on aerobic capacity and muscle strength.
- This study demonstrated that low-frequency electrical stimulation applied for as short as 5 weeks have a great impact on muscle architecture and cardiovascular parameters and control.
- This type of training might therefore be interesting for rehabilitation of patients who are unable to perform endurance exercises.

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