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Physiological considerations on Neuromuscular Electrical Stimulation (NMES) in muscular strength training

Consideraţii fiziologice asupra utilizării electrostimulării neuro-musculare (ESNM) ca metodă de creştere a forţei musculare

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Abstract

Neuromuscular Electrical Stimulation (NMES) is a form of electrical stimulation that uses the application of electric current through electrodes, leading to the depolarization of the motoneuron, thus eliciting a muscular contraction (stimulation over the motor threshold). Although its beneficial effects on strength training are widely recognized, some controversial aspects concerning the underlying physiological mechanisms of this strength gain still persist. This paper reviews the main aspects of motor unit recruitment in NMES versus Voluntary Muscular Contraction (VMC) and of the involvement of the Central Nervous System - through spinal and supraspinal mechanisms - in the muscle strength gain during NMES.

Key words: electrical stimulation, muscle, strength, nervous system.

Rezumat

Electrostimularea neuromusculară (ESNM) reprezintă o formă de electrostimulare care constă în aplicarea unui curent electric prin intermediul unor electrozi, ceea ce determină depolarizarea motoneuronului şi la producerea contracţiei musculare (stimulare peste pragul motor). Deşi efectele sale benefice asupra creşterii forţei musculare sunt general recunoscute, persistă încă anumite controverse asupra mecanismelor fiziologice, care stau la baza acestui câştig de forţă. Lucrarea de faţă trece în revistă principalele aspecte ale recrutării unităţilor motorii în cursul ESNM versus contracţia musculară voluntară (CMV) şi ale implicării sistemului nervos central - prin intermediul mecanismelor spinale şi supraspinale - în producerea forţei în cursul ESNM.

Cuvinte cheie: stimulare electrică, muşchi, forţă musculară, sistem nervos.

Introduction

Neuromuscular electrical stimulation (NMES) is a form of electrical stimulation that consists of the application of electric current through electrodes, leading to motor neuron depolarization, thus eliciting a muscle contraction (stimulation is performed above the motor threshold). It has to be differentiated from other forms of electrical stimulation.

- *Functional Electrical Stimulation (FES)*

This method uses electrical stimulation for activating the paralyzed muscles in a sequential mode, thus assisting the performance of the ADLs (Activities of Daily Living). It is also called ”neuroprosthesis” or ”electric orthosis”. The level of complexity of FES can range from a dual-channel stimulation (e.g. to enhance foot dorsiflexion during gait) (Kim et al., 2004) to a multichannel FES (e.g. to activate several muscle groups to restore stance and gait in paraplegic patients) (Karimi, 2013).

Electrical impulses can be delivered through surface electrodes (transcutaneous electrodes - placed on the area of the muscle body or on motor points) or through fully implanted electrodes (”cuffs” of peripheral nerves or nerve roots) powered and controlled by radio-frequency from an external unit (Iliescu et al., 2010).

- *Transcutaneous Electrical Nervous Stimulation (TENS)*

It is a non-invasive analgesic technique that is used for the symptomatic treatment of acute and non-malignant chronic pain (low back pain, arthritic pain including ostheoarthritis and rheumatoid arthritis, myofascial, neuropathic, postoperative, orofacial pain, etc.) (Barlas & Lundeber, 2005). It is also used as a palliative method in metastatic bone disease and neoplasms (Berkovitch & Waller, 2005; Stannard, 2002). The analgesic effect of TENS can be explained by the “gate control theory”

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proposed by Melzack & Wall (1965).

- *Threshold Electrical Stimulation (TES)*

This method was initially developed as a pediatric protocol for neuromuscular stimulation; it produces a stimulation at the sensory threshold (low intensities of 2-10 mA), for long periods of time (e.g. overnight for 8-12 hours, 6 nights a week). Although the promoters of this method assert its role in the reeducation of the paralyzed muscle, the results are inconclusive (Pape, 1997; Dali et al. 2002).

Fields of application

If NMES was first conceived to treat muscle atrophy as a result of immobilization or denervation, for the initiation of the natural biological reinnervation process, this method has been taken into account as a training tool of the normally innervated, weak muscle for almost 30 years (Jackson & Seddon, 1945). For about 20 years it has been largely adopted.

Despite its long time utilization, NMES has received increasing attention in the last years, due to its capability to serve as (Maffiuletti et al., 2010):

1. a strength training tool (healthy subjects and athletes), since its chronic utilization may induce neuromuscular adaptations similar/complementary to those induced by voluntary strength training;
2. a rehabilitation/preventive instrument in completely/partially immobilized patients, since its chronic use may preserve muscle mass and function during periods of inactivity;
3. a testing tool for the assessment of muscular and neural function based on the possibility to induce standardized muscular contractions whose electrical (electromyography-EMG) and mechanical (torque) properties could be easily measured;
4. a post-exercise recovery tool for athletes, since its acute application may increase blood flow, thus accelerating metabolite washout (Babault et al., 2011).

NMES as a rehabilitation tool or as a muscle strength training method is used in many medical fields: *orthopedic medicine*: anterior cruciate ligament reconstruction (Taradaj et al., 2013), fractures (Galkowski et al., 2009), knee osteoarthritis (Elboim-Gabyzon & Rozen, 2013), rheumatoid arthritis (Piva & Goodnite, 2007), total knee arthroplasty (Petterson & Snyder-Mackler, 2006), total hip arthroplasty (Suetta & Aagaard, 2004), patellofemoral syndrome (Callaghan & Oldham, 2001); *neurology*: promoting voluntary control (Lin & Yan, 2011), reducing muscle spasticity (Bakhtiary & Fatemy, 2008), improving muscle strength (wrist extensors, knee extensors, foot dorsiflexors) (Rosewilliam et al., 2012), reducing shoulder subluxation after stroke (Ada & Foongchomcheay, 2002); *general medicine:* patients with hemophilia (Querol & Gallach, 2006), cancer (Crevenna et al., 2006), critically ill patients (Gerovasili et al., 2009); *geriatric medicine:* (Amiridis et al., 2005); *space medicine:* astronauts (Carpenter et al., 2010), simulated microgravity (Duvoisin et al., 1989); *sports medicine*: healthy athletes, sport injuries (individual or team sports) (Maffiuletti et al., 2006); *cardiovascular and pulmonary medicine* (improvement of exercise capacity, peripheral muscle strength training in patients with heart failure and chronic obstructive pulmonary disease) (Dumitru et al., 2013; Smart et al., 2012; Sbruzzi et al., 2010).

Physiological principles in NMES

Although NMES's capability to improve (healthy and dysfunctional) muscle performance is nowadays widely accepted and adequately demonstrated, some controversial aspects concerning the underlying physiological mechanisms of strength gain in NMES versus voluntary contraction still persist.

a) Motor unit recruitment

Neurophysiological studies have demonstrated the existence of two types of motor units - large (*"fast"*) and small (*"slow"*), having different characteristics in terms of excitability, contractility and resistance to fatigue.

The motor unit - the smallest neuromuscular functional unit, was described in 1925 by Liddel and Sherrington. It represents a neuromuscular complex comprising the motor neuron body, its dendrites and axon, together with all the muscle fibers that it stimulates (Sbenghe, 2002).

The differences between the two types of motor units are described in Table I.

Table I

Motor unit types and their characteristics.

Large (*"fast"*) motor units	Small (*"slow"*) motor units
- Large diameter axons	- Small diameter axons
- Fast-twitch fibers	- Slow-twitch fibers
- Low resistance to fatigue	- High resistance to fatigue
- Low excitability threshold	- High excitability threshold

Due to their lower excitability threshold, the fast *(large)* motor units are more easily depolarized than are the slow *(small)* ones, thus fast motor units would be preferentially activated by the NMES current.

It was thought for a long time that NMES initially activates the large motor units (i.e. with the lowest threshold of depolarization); then, at increasing current intensities, the small motor units are also activated, which represents a reversal of Henneman's principle (known as the *"size"* principle).

Henneman's principle (the "size" principle) states that during a voluntary muscle contraction, the recruitment order of motor units moves from small, slow-twitch motor units to large, fast-twitch ones. (Figure 1) (Henneman et al., 1965).

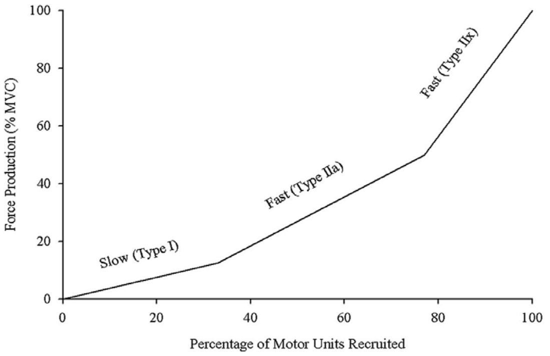

Fig. 1 – Graphic representation of the recruitment order during voluntary contraction of skeletal muscle (by Henneman et al., 1965).

For a long time, the rule of the reversal of the "size" principle of Henneman in NMES versus voluntary muscle contraction was generally accepted. Two neurophysiological findings are commonly cited to support this fact:

- the axons of large motor units have a lower resistance to the electric current and conduct the action potential more rapidly than the axons of small motor units;
- data demonstrating an early onset and rapid increase in muscle fatigue (a characteristic of large motor units) during NMES compared with voluntary contraction.

Two aspects should be pointed out regarding motor unit recruitment during NMES:

- the ”preferential recruitment” of motor units with NMES is only valid during direct motor nerve stimulation (in vivo/in situ); in clinical practice, we generally use surface electrodes; in this case, the muscle response to NMES is different (Gregory & Scott Bickel, 2005).
- although the preliminary studies which confirm the reversal of Henneman’s principle in NMES are well-designed, they are based on research on lower mammals. Therefore, their results cannot be directly extrapolated to human subjects.

The participation of motor units in the NMES-induced contraction is different from that underlying voluntary muscle activation.

The first logical difference refers to *temporal recruitment,* which is asynchronous during voluntary contraction (in untrained subjects) and synchronous (demanded by the electrical stimulator) during NMES (Adams & Harris, 1993).

With regard to *spatial recruitment* (*in vivo*, using surface electrodes), it has been demonstrated that the variable distribution of the motor axonal branches in a non-uniform electric field (in which the current density decreases with depth) is more important than their excitability threshold (in other words, than the size of motor units) in NMES muscle response.

For that reason, in NMES, motor unit recruitment is *non-selective, random*, with no precise order related to the type or size of the motor units. In other terms, in NMES, spatial recruitment is *disorderly*, implying the activation of some large (*”fast”)* motor units, in addition to small (*”slow”)* ones, even at relatively low force levels (Jubeau et al., 2008; Gregory & Scott Bickel, 2005).

At constant intensities, NMES induces a continuous contractile activity in the same population of superficial muscle fibers, namely those with the axonal branches in proximity to the stimulating electrode. Therefore, spatial recruitment is *fixed*, which means that the same motor units are repeatedly activated by the same amount of electric current; the recruitment decreases proportionally to the increasing distance from the electrode.

With increasing intensities, new muscle fibers located at a greater distance from the electrode (*”deep”*fibers) are activated, while superficial ones maintain their contractile activity (Theurel et al., 2007; Zory et al., 2005).

The characteristics of motor unit recruitment in voluntary contraction and NMES are presented in Table II.

The characteristics of motor unit recruitment in NMES bring not only disadvantages imposed by the early onset of muscle fatigue, but also several clinical benefits, with practical applicability.

The advantages of NMES use

Irrespective of their type (”slow” or ”fast”), muscle fibers can be selectively activated at relatively low current intensities. This NMES feature can be used in:

- elderly individuals (presenting a selective atrophy of type II muscle fibers)
- patients with Chronic Obstructive Pulmonary Disease (COPD) or Chronic Heart Failure (CHF) (also with selective atrophy of type II muscle fibers) (Gosker et al., 2002; Kanda et al., 2001)
- orthopedic patients – who cannot perform voluntary contractions at high intensity levels (these high levels imply the activation of type II muscle fibers) (Stevens et al., 2004).

NMES has the capability to activate the “fast” muscle fibers (type II fibers) that are not typically recruited during the ADLs (Activities of Daily Living); these fibers can only be recruited during high-force voluntary contractions. The effect is an *improvement of muscle deconditioning syndrome.*

Disadvantages of NMES use

The main result of this specific motor unit recruitment pattern for NMES is the high metabolic cost of an electrically-evoked contraction (Vanderthommen et al., 2003); compared to a voluntary contraction at the same intensity (measured as percent of maximal voluntary contraction - % MVC), NMES-induced contractions generate an earlier occurrence and higher levels of muscle fatigue (Deley et al., 2006).

The spatially fixed recruitment in NMES entails that the same motor units are repeatedly activated by the same amount of electric current, therefore muscle fatigue occurs rapidly in such fiber type recruitment patterns (Gondin et al., 2011). On the contrary, during voluntary contractions, the recruitment patterns can be alternate, allowing a

Table II

Motor unit recruitment in voluntary contraction *versus* NMES.

Voluntary contraction	NMES
Temporal recruitment	
- asynchronous	- synchronous
Spatial recruitment	
- dispersed	- superficial (close to the electrode)
- rotation is possible	- spatially fixed
- almost complete	- incomplete (even at maximum)
Recruitment sequence	
- orderly, selective (”slow units” to ”fast” units)	- disorderly/non-selective/random (”slow” and ”fast” units)
Effects (consequences)	
- fatigue	- early onset of increased fatigue

recruitment of additional motor units, when fibers that were first activated become fatigued (during NMES, such recruitment pattern changes are not possible). Moreover, during voluntary contraction, muscle strength can also be maintained by increasing the firing rates of active motor units (the so-called ”*temporal summation*”) (Carpentier et al., 2001).

The differences between the two aforementioned contraction modalities (voluntary and NMES-induced) regarding the recruitment patterns of muscle fibers and the metabolic demand represent an argument for the *non-concomitant combination* of these two training techniques (Vanderthommen & Duchateau, 2007).

b) Nervous system adaptations during NMES

Although NMES has been usually considered a technique producing muscular contractions with an important contribution of the central nervous system, there are some elements that demonstrate a noticeable involvement of various neural structures in strength gain during NMES application.

In the last years, growing scientific evidence has confirmed these ”central effects” of NMES. We can even talk about a ”*multimodal bombardment*” of the central nervous system during NMES (Baker et al., 2000), which results in increased cortical activity and in spinal motoneuron recruitment, as well.

Spinal recruitment

The application of NMES generates, on the one hand, the depolarization of the motor axonal branches (the direct way = the peripheral way) and on the other hand, the depolarization of the sensitive axonal branches situated under the stimulation electrode.

In this way, NMES generates an afferent discharge (via sensory axons) to the spinal cord, which in turn induces the reflexive recruitment of spinal motoneurons (the reflexive pathway = the central pathway). This reflexive depolarization of the motoneurons along with their direct depolarization provides an additional strength gain in NMES muscle training (Collins et al., 2007).

The contribution of the ”central pathways” to the NMES-induced contraction has been confirmed by experiments that use an anesthetic block of the peripheral nerves, proximal to the stimulation site. In these experiments, the same amount of electric current and the same stimulation pattern produced significantly greater force (torque) *before* the anesthetic block (situation that involves the participation of the central nervous system) compared with muscle strength (torque) *after* the anesthetic block. In the latter situation, the afferent discharge to the spinal cord is blocked, therefore only the direct activation of motor axons could contribute to the muscle contraction (Lagerquist & Collins, 2010).

In order to enhance the reflexive spinal recruitment during NMES, the following stimulation parameters have been suggested:

- *low pulse amplitudes* of NMES (low current intensities) – the goal is to minimize the antidromic block, which is the collision between the action potential running antidromically along the motor axons and those generated after the reflexive recruitment of spinal motoneurons
- *pulse duration between 0.2-1 ms* (to maximize the activation of sensory/afferent axons that have a longer strength-duration time constant and a lower rheobase than motor axons)
- *stimulation train duration*
- below 2 seconds for stimulation *”over the nerve”*
- above 2 seconds for stimulation *”over the muscle”*
- high frequencies (50-100 Hz) to increase the rate at which the afferent/sensory volley is sent to the spinal cord and the supraspinal centers.

Because of these characteristics of the electrical stimulation impulses, this NMES pattern is known as “*wide-pulse high-frequency” neuromuscular electrical stimulation (NMES).*

The reflexive recruitment (through central pathway) of spinal motoneurons during NMES is more ”physiological”: more orderly, less synchronous and more spatially diffuse through the muscle.

It has been suggested that these stimulation characteristics could be used to diminish some limitations/disadvantages of NMES, especially those related to discomfort and random recruitment (Berquist et al., 2011).

As previously mentioned, the disorderly, superficial, spatially fixed and incomplete motor unit recruitment during NMES generates some limitations/disadvantages of this muscular training method. Nevertheless, there are some strategies that are able to enhance the spatial recruitment of motor units in the context of muscular strengthening (Maffiuletti, 2010).

I. The *stimulation current intensity* should be increased as often as possible (by the users themselves), after each muscular contraction; the reason is to stimulate more and more muscle fibers, situated in deeper muscle zones.

II. *The stimulation electrodes'* position has to be changed after a series of contractions (during and between NMES sessions), in order to alternate the superficial fibers preferentially stimulated by the electrical current.

III. The *length of the stimulated muscle* must be changed by alternating the joint angle, to vary the position of muscle fibers in relation to the electrode and to modify the presumable contribution of cutaneous and joint receptors to the evoked muscular contraction.

Supraspinal adaptations

Besides the depolarization of the motor neurons' axons situated beneath the stimulation electrode, NMES also stimulates the sensory neurons' axons, generating ascending action potentials to the sensory-motor cortex. The last years research, using functional magnetic resonance imaging (fMRI) (Blickenstorfer et al., 2009; Han et al., 2003), transcranial magnetic brain stimulation (TMS) (Everaert et al., 2010) or Near Infrared Spectroscopy (NIR spectroscopy) (Jang et al., 2014), provides strong evidence regarding the cortical adaptations involved in muscle strength gain by NMES.

Studies using fMRI have demonstrated an acute increase in the hemodynamic response in the sensorimotor cortex, also showing a dose-response relationship between the current intensity and cortical activity (Smith et al., 2003). This allows speculations that high current intensities would increase the supraspinal effects of NMES-induced muscle contractions.

There are strong lines of evidence demonstrating the neural adaptations induced by short-term NMES training programs on the healthy or affected muscle. These adaptations refer to:

- significant increases in maximal voluntary contraction (MVC) strength after only a few sessions of NMES (Brocherie et al., 2005), when there is no reason to imagine muscular hypertrophy induced by increased protein synthesis;
- strength gains without any noticeable changes in muscle enzyme activity, muscle fiber size, mitochondrial properties (Eriksson et al., 1981);
- increase in voluntary muscle activation as shown by surface electromyography (Gondin et al., 2006);
- the voluntary strength gain of the untrained, homologous muscle of the contralateral limb, after unilateral muscle training (”cross educational effect”), represents perhaps the strongest evidence for neural adaptations related to NMES (Hortobagyi et al., 1999; Bezerra et al., 2009; Farthing, 2009).

Based on these above-mentioned considerations, it has been assumed that NMES at high current doses would mostly induce *supraspinal* neural adaptations, while ”*wide-pulse high-frequency”* NMES would favor *spinal* adaptations. In the same way, high doses of NMES would hypothetically activate both (slow and fast) fiber types, whereas ”*wide-pulse high-frequency”* NMES mainly targets the slow muscle fiber population.

Conclusions

1. A good understanding of the physiological mechanisms by which NMES produces muscle strength gain would allow the optimization of NMES applications in clinical settings, research or sport training.
2. The different muscular and neural adaptations induced by NMES could be specifically ”*targeted”* during muscle strength training, according to the individual patient’s/ athlete’s needs.
3. Further studies are needed in order to confirm the hypothesis that NMES represents, beyond a familiar *muscular* training method, an efficient training technique, based on mechanisms that imply the *nervous system’s* involvement.

Conflicts of interests

There are no conflicts of interest.

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