Electrical Muscle Stimulation and Its Use for Sports Training Programs: A review

Chapter · January 2016

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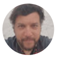

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Dumlupinar Üniversitesi

Recent Advances in Health Sciences

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ISBN 978-954-07-4136-9

ST. KLIMENT OHRIDSKI UNIVERSITY PRESS
SOFIA • 2016

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St. Kliment Ohridski University Press

ISBN 978-954-07-4136-9

Cover Design: Murat Poyraz

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Chapter 64

Electrical Muscle Stimulation and Its Use for Sports Training Programs: A review

Fatih KAYA*, Mustafa Said ERZEYBEK**

INTRODUCTION

Currently, there are several sport training methods that are used to increase the sportive performance. However, since the target is to obtain the effects promptly, there is a need for new and innovative methods. One of these methods is the artificial electrical muscle stimulations (EMS) which is used as the protective strength training (Pichon *et al*., 1995; Maffiuletti *et al*., 2000; Maffiuletti *et al*., 2002; Brocherie *et al*., 2005; Babault *et al*., 2007). The general purpose of the electrical stimulations is to develop the basic muscle properties that are related with the training (intramuscular blood flow, maximum strength, endurance) with the help of repetitive contractions (Pichon *et al*., 1995; Maffiuletti *et al*., 2000).

At the beginning of the several unprompted sports activities, the central nervous system (CNS) generally activates the smallest alpha motoneurons firstly. When exercising continues and more energy is needed to be generated for the muscles, larger alpha motoneurons are increasingly activated (Porcari *et al*., 2002). It has been reported that the electrical muscle stimulations activate the fast twitch (FT) fibers that are generally more difficult to activate and of which the stimulation depends on the largest alpha neurons by reversing the motor unit recruitment order (Sinacore *et al*., 1990); that it enables more motor unit to take part in the training (Gregory and Bickel, 2005); that the indirect electrical stimulation activates almost all fibers in the given muscle group (Egginton and Hudlicka, 2000) and thus, this selective increase of the FT fibers may improve the overall strength of a muscle or a group of muscles through the electrical stimulation (Anderson, 2009). Electrical muscle stimulation may be an easy way to 'train' fast twitch motor units without great overall muscular effort (Komi, 2003).

Currently, strengthening the muscle through the electrical stimulation is a routin procedure in the rehabilitation clinics and the studies regarding the EMS use on the healthy skeletal muscle as a training method have been increased in the last decade.

The studies about the effects of the electrical muscle stimulations on the muscle performance have revealed the the high frequence impulses are efficient in terms of the strengthening (Alon and Smith, 2005; Filipovic *et al*., 2011; Hortobágyi 1996; Komi 2003; Matsunaga *et al*., 1999; Mohr *et al*., 1985) and the low frequence impulses are efficient in terms of the endurance (Thériault et al., 1996; Callaghan 2002; Hamada et al., 2004, Atherton *et al*., 2005). Also, the low frequence impulses are used for muscular recovery after the fatigue (Raymond *et al*., 2007; Maffiuletti *et al*., 2011; Babault 2011).

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The extensive variation of the stimulation parameters as well as the duration of the entire program and of each session affect the success of the training programs.

In this research, the efficiency of EMS used in the sports training programs have been studied and discussed and suggestions have been provided for the future researches.

1. ELECTRICAL MUSCLE STIMULATION

The use of EMS in sports has been started in 1960's with Kots' practices and it has been claimed that a new stimulation form (Russian form) strenghtens the muscles up to 40% for elite athletes (Ward and Shkuratova, 2002), and thus the use of EMS in sports became popular. In 1970's, these studies were shared with the Western sports institutions. However, since the mechanisms involved in the EMS were not properly understood, the results were conflicting. The recent medical physiological researches have revealed precisely the adaptations of the muscle cell, blood vessels (Perez *et al*., 2002; Harris, 2005) and nervous system (Hortobágyi, 1996; Boerio *et al*., 2005; Gondin *et al*., 2006; Jubeau *et al*., 2006) caused the electrical stimulation.

1.1. Electrical Muscle Stimulation Mechanism

The muscular contraction resulting from the EMS is different from the voluntary muscular contraction started by the CNS. The motor neuron excitation (action potential) started by the nervous system or by an electrical stimulus are always exactly the same (all or none principle) and each excitation causes the same basic mechanical muscular response. Thus, regardless if it is started by the nervous system or EMS, the action is similar. In this regard, the voluntary muscular action is started by the nervous system: brain → spinal cord → motor nerve → muscle (Johnston, 2004). EMS causes an artificial muscular activation by eliminating this process (Trimble and Enoka, 1991).

Whereas the brain is capable to stimulate most of the muscular fibers, an EMS device can stimulate the muscular fibers up to 100%. Furthermore, unlike the human brain, an EMS device can provide high quality impulses to make the muscles work without causing cardiovascular and psychological fatigue. Compared to the voluntary training alone, this enables better and safer muscle performance results. The electrical stimulus is transferred from the EMS device to the muscles via nerve fibers or motoneurons. The role of the impulse is to provide a muscular response (twitch) upon conversion of the nerve stimulus into a mechanical activity. If the electrical impulse continues, the muscle excitation/stimulation occurs and muscular twitch is repeated. If the muscles are stimulated with the frequent impulses, the muscular fibers reach the contraction point. Thus, the muscles respond with a constant contraction (tetanization) and it depends on the summation of the basic responses. When the frequency of the stimulation impulses are increased, each individual twitch becomes less significant; until the contraction point, the appearance of the muscular contraction becomes smooth (Johnston, 2004; Starkey, 2013).

The electrical impulse triggering the motor neuron excitation, the impulse frequency (number of impulses per second-Hertz), contraction duration (duration of the continous muscular contraction), rest duration (duration of the rest between the contractions), number of repetitions (repeating contraction-rest cycle) and the intensity (miliampere, mA) are the parameters that define the quantity and quality of the muscular activity (Johnston, 2004; Starkey, 2013).

The number of the muscular fibers that will be recruited in the muscular activity depends on the intensity of the electrical stimulus. If the stimulation comprises the intense impulse levels, more muscular fibers would be recruited to the activty. On the contrary, the lower density would cause a few number of fibers to take part in the activity (Starkey, 2013).

These impulses are transferred from the EMS device to the skin through electrodes. The electrodes transmit the electrical current to the skin and motor nerve. When the electrodes are fixed on the skin and the current in the unit is turned on, the stimulation is transmitted to the muscle and thus, indirectly to the motor nerve. The appropriate electrode size and location (Forrester and Petrofsky, 2004) as well as the quality of the current are considered and the electrical current flows between the electrodes through the tissues (Johnston, 2004).

1.2. Electrical Muscle Stimulation Theory

The muscular performance increasing ability of the EMS protocols with regard to both healthy and dysfunctional muscles is widely accepted and reported as a routin together with the clinical applications (Dudley *et al*., 1999; Belanger *et al*., 2000; Stevenson and Dudley, 2001; Lewek *et al*., 2001). However, although several researchers have reported increases in the muscular performance with EMS, there are differences in the literature with regard to the specific EMS responses compared to the voluntary contractions. The positive effects of the EMS training have been based on various mechanisms; especially the one about the voluntary muscle activation is related with the recruitment order (Kubiak, Whitman, and Johnston 1987).

Henneman's size principle (1965) defines the voluntary motor unit recruitment as the gradual recruitment of the large, typically fast motor units after recruitment of the small and typically slow motor units. There are certain facts that demonstrate the variability of the size principle (Denier *et al*., 1985; Nardone *et al*., 1989) and it has been reported that the electrical muscle stimulus is one of the factors that reverse the motor unit recruitment order (Anderson 2009, Feiereisen *et al*., 1997; Porcari *et al*., 2002; Komi, 2003; Starkey, 2013).

The first of the theories claims that the EMS produces intense muscle contractions which are similar to those contractions occuring during the strength training and thus, the muscular response emanates in a similar way to the adaptations in a regular training. Another theory, the strongest claim is that the EMS reverses the voluntary motor unit recruitment order (Gregory and Bickel, 2005). Despite a statement reporting that rather than the reverse physiological voluntary recruitment order, the muscle fiber recruitment during the EMS is of the non-selective, spatially fixed and temporarily synchronised model (Gregory and Bickel, 2005; Maffiuletti *et al*., 2011), the EMS results support that the size principles is reversed. Compared to the voluntary contractions (6%), the reverse recruitment rate during the electrical stimulation is 28-35 % arasındadır (Feiereisen *et al*., 1997) and the claim that the fast motor units are ahead of the slow motor units is based on the two prevailing views: (1) the electrical resistence of the large axon motor units against the external current is much lower and they transmit their action potentials faster than the small axon motor units; (2) the data showing the increase in fatigue with EMS, compared to the voluntary contractions (Gregory and Bickel, 2005).

The fact that EMS (75Hz) produces more cardiorespiratory demands compared to the voluntary contractions of the same intensity and causes more muscular fatigue in a single session, has been accepted as an indicator of the variability regarding the motor unit recruitment model (Theurel *et al*., 2007). Another important indicator is the glycogen discharge in the FT muscle fibers, right after the electrical stimulation (Sinacore *et al*., 1990). It has been shown that the glucose carrying activity is higher in FT's compared to the slow twitch (ST) fibers, when EMS is applied (Roy *et al*., 1997). Contrary to the motor unit recruitment order encountered during the low intensity voluntary exercising where the ST fibers are first used (Gollnick *et al*., 1974), the fact that large and fatigable glycolytic fiber FT motor units are first activated during EMS (Sinacore *et al*., 1990) supports the "reverse-size principle" regarding the motor unit recruitment with EMS. The reverse motor unit recruitment order obtained with EMS has been tested also with H-reflex (H-reflexes show the total motor unit activity) and motor responses (M-response) and it has been shown that the motor unit population activated with electrical stimulus as well as the motor unit recruitment order have changed (Trimble and Enoka, 1991).

Due to this selective recruitment, an increase of up to 44% in the muscular strength has been observed (Brocherie *et al*., 2005; Anderson 2009). Theoretically, electrical stimulus application during a voluntary muscle movement can activate more motor units compared to the voluntary contraction alone; and it has been reported that this can led to an increase in the contraction strength and the training programs where electrical stimulus is used are much more efficient and provide more volume and muscle strength compared to the separate use of the electrical stimulus and voluntary contraction programs (Paillard *et al*., 2005).

1.3. Changes Related with EMS

In this section, the effects of EMS on the muscle, changes in the myofibril mechanism and energy metabolism, neurophysiologic, tissular and biochemical, blood flow and capillary changes have studied in consideration of the literature.

1.3.1. Changes in Myofibril Mechanism and Energy Metabolism

For the high level contractions, the basic muscular adaptations are the increases in actin and myosin (contractile proteins). Both voluntary activation and electrical stimulation may cause an increase in the contractile protein quantity of the muscle (Robinson and Snyder-Mackler, 2007).

Animal testing provides useful information about the effects of EMS at the cellular level. The studies covering chronic low frequency impulses showed that the basic function elements of the muscles fibers such as (Ca^{2+}) regulating system, myofibril system, energy metabolism and microvascular system are also affected by EMS (Callaghan, 2002).

In the contraction produced by the chronic low frequency EMS, the alteration of the Ca^{2+} dynamics and then a change from fast to slow characteristic have been observed. These are ultra structural changes in the cross-sectional area (CSA) and the significant decreases have been observed in its weight, although the width of the band Z (this is the reason why it reminds of the ST fibers) and the number of the fibers are preserved (Pette, 2001). Also, it seems that the chronic stimulation causes the complete reorganization of the myofibrillary proteins during the conversion of the sarcomere from fast to slow (Callaghan, 2002). Furthermore, it leds to continous increase of the intracellular calcium and activates the calcium regulating enzymes such as calcineurin and calmodulin-inked protein kinase (CaMK) (Wu *et al*., 2000).

Low frequency EMS during 48 hours may cause significant decrease in the maximum Ca^{2+} use capacity in the sarsarcoplasmic reticulum and the initial rate. Longer stimulation causes more significant changes and accompanied with the decrease in the Ca^{2+} activity to reach ATPaza (Pette, 2001). Also, with chronic low frequency EMS, a significant increase in the aerobic-oxidative capacity of the FT muscles and a five times increase in the capillary density may be observed (Brown *et al*., 1989).

There are important evidences demonstrating that when the exercising protocols are applied with low intensity, the glycolytic anaerobic metabolism is more significant in EMS compared to the voluntary exercising due to the formation of the hydrogen ions and phosphocreatine catabolism (Hultman and Spriet, 1986; Vanderthommen *et al*., 2003). Additionally, it has been shown that the glucose carrying activity is higher in FT fibers compared to ST fibers when EMS is applied (Roy *et al*., 1997). EMS may be a better approach to increase the glucose carrying activity to the skeletal muscle without intensive voluntary exercising. Also, the functional and enzymatic adaptations in the skeletal muscle response against the chronic low frequency EMS have been observed in the human subjects (Chilibeck *et al*., 1999; Mohr *et al*., 2001; Nuhr *et al*., 2003).

1.3.2. Neurogenic Changes

Although EMS is accepted in general as a technique used to activate the muscles without activating the nervous system, the mutual transmission of the action potentials through the stimulated axones (Maffiuletti *et al*., 2006), the dose-response relation between the activation of the selected brain sections by quadriceps stimulation (Smith et al., 2003), the cross effects of the training at the same time (Hortobágyi *et al*., 1999; Maffiuletti *et al*., 2006) showed clearly that EMS activates the neural system. All these results demonstrate that the electrical stimulation does not completely bypass the peripheral system.

However, in the recent statements about the neurophysiologic effects of EMS, it has been reported that when the normal muscles are trained through electrical stimulation, the initial rate of strength gain is fast without any change in the muscle volume, and this is an indicator showing that the adaptive mechanisms are neural. Another possible mechanism is the increasing spinal motor neuron pool activation. It has been reported that the motoneurons regulate the strength gain through the simulation of the afferent neurons and it is associated with a long term potantialization together with a snaps sensitivity due to the stimulation of the afferent nerve fibers, and thus the strength gains can be preserved for a couple of weeks even if the training is stopped and this has a long term potantialization (Hortobágyi, 1996; Gondin *et al*., 2006; Jubeau *et al*., 2006). These useful effects of the electrical muscle stimulation is accompanied by the increasing blood flow in the intramuscular and peripheral soft-wall vessels and thus, the pumping activity of the muscles increases (Hortobágyi, 1996).

Various EMS studies claiming that the strength gains are associated with the neural factors rather than the changes at the muscular level covers a period of 4 weeks or less (Singer, 1986; Maffiuletti, Pensini, and Martin 2002; Malatesta *et al*., 2003). For example Maffiuletti, Pensini and Martin (2002) after an EMS training of 4 weeks, the significant increase in the maximum voluntary contraction (MVC) has been associated with the increase in the muscle activation and in the EMG (electromyography) activity, (Gondin *et al*. (2005) and upon a research where the effects of the 4 and 8 weeks EMS trainings on the neural and muscular adaptations of the knee extensor muscles, it has been reported that after a 8 weeks EMS training, quadriceps MVC tork increase is associated with both muscular and neural adaptations. The first 4 weeks period being the start of the strength increase, the second 4 weeks period has led to more strength gain. Similarly, after a 5 weeks EMS training of the plantar flexor muscle, the increase in the voluntary tork has been associated with the spinal level adaptations and an increased voluntary function in the supraspinal centers (Gondin *et al*., 2006a).

Upon the neuromuscular electrical stimulation training of fiwe weeks and then the following detraining period of five weeks, it has been observed that the neural adaptations affected by the training continue after the detraining and thus this shows that the neural changes are preserved for long term and do not affect the H-reflex elements (Gondin *et al*., 2006b).

Maffiuletti *et al*. (2003), have shown in their study that the EMS training of the plantar flexor muscles (4 weeks-16 isometric EMS sessions - 75Hz) does not affect the alpha motor excitability and presynaptic inhibition as is the case with the H-reflex. Additionally, in a research where the H-reflex and M-response in the electrical stimulation are studied (Trimble and Enoka, 1991) it has been demonstrated that EMS directly activates the large afferent axones and provide cutaneous feedback that changes the motor unit population activated during the H-reflex.

In a study where the central and peripheral fatigue caused by a typical EMS session (75Hz) is examined, it has been reported that the significant decrease in the maximum voluntary contraction strength after the EMS is associated with the significant decrease in the center activation and both central and peripheral factors contribute to the fatigue, and the neuromuscular propogation weakness has been demonstrated for the muscles having higher FT fiber percentage (Boerio *et al*., 2005).

1.3.3. Tissular and Biochemical Changes

The use of muscular biopsy has provided important evidences about the cellular changes caused by EMS in human muscles and especially in the quadriceps muscle. As reported by Callaghan (2002) in the first studies (1980s), the muscle fiber area and the fiber type composition of the healthy quadriceps were not changed by 200Hz EMS; whereas in other studies, 50 Hz modulated 2500 Hz "Russian" EMS protocol caused a significant decrease in the FT fiber area, but no change has been observed in terms of the fiber type distribution. However, the post-stimulation decrease in the fiber area in the healthy subjects is the contrary to that observed in the patients with knee injury after the stimulation and this has been explained by the variations in the mechanisms covered by the strength training. Furthermore, Callaghan (2002) has indicated that the neural factors or enzymatic changes in the healthy subjects can be much more significant compared to the fiber type changes and in certain studies no significant change has been observed in the enzyme activity involved in the contraction process, whereas in certain studies, after the knee and quadriceps immobilization of 5 weeks, the decrease in the succinate dehydrogenase activity (an indicator of the mitochondrial oxidative activity) observed in the patients has been significantly slowed down after EMS. On the other hand, after the chronic low frequency EMS (8Hz, 8 hours daily) applied to the quadriceps for 8 weeks, a significant increase in the aerobic enzyme activity has been observed and no change has been seen in terms of the anaerobic indicators.

It is important to note that the different results obtained from the different studies are related with the different EMS parameters. For example, in a study regarding the healthy human vastus lateralis phenotype after EMS (Perez *et al*., 2002), it has been seen that while short periods (45-60Hz for 6 weeks, 3 days a week, 30 minutes each day, 300 μs) reduces completely the percentages of other fiber type, it increases the FT-a fiber percentage.

The chronic muscle weakness is related with the decrease in the muscle protein synthesis and the results obtained from the atrophic muscle studies show that EMS causes changes in the muscle physiology at the cellular level and it protects the protein synthesis in the atrophic muscles especially after the immobilization (Callaghan, 2002).

1.3.4. Changes in the Muscle Blood Flow and Capillary Structure

Various studies showed that exercising with EMS can increase the blood flow in the stimulated muscles in parallel with the voluntary exercising (Currier *et al*., 1986; Walker *et al*., 1988, Levine *et al*., 1990). What is interesting is that Vanderthommen at al. (1997) have reported that compared to the voluntary exercising with the same work load, the blood flow is higher during EMS. Since in all of these studies (Currier et al., 1986; Walker *et al*., 1988; Levine *et al*., 1990; Vanderthommen *et al*., 1997) the disturbing tetanic stimulation frequencies (35-100Hz) have been used, it is likely that a vasoconstriction that resists to the expected increase in the blood flow occurs (Walker *et al*., 1988).

Kim *et al*. (1995) has reported that pulmonary O_2 use being same for both exercising forms, the ventilator coefficient is higher in EMS compared to the voluntary exercising; that the leg blood flow and O_2 use are similar for both exercising forms and the heart rate and average blood pressure are partially higher in EMS. Other results obtained show that the lactate and ammonia flows in the leg are higher in EMS and they increase with the increasing exercising intensity; that the muscles' glucose use is similar for both exercising forms; that the femoral venous potassium (K^+) concentration increases with the exercising intensity and higher in EMS.

In animals, the histochemical characteristics of the fast muscle fibers become similar to those of the slow muscle fibers after low frequency EMS and the fast muscles gain higher capillary density and more fatigue resistence (Callaghan, 2002). When these muscles are stimulated with low frequency (10 Hz continous) for 2-4 days (8 hours/day), it has been shown that the fast glycolytic transforms into fast oxidative fibers and that after 4 days of stimulation, this transformation is much higher and that the number of the capillaries is higher in the stimulated muscles (Hudlicka, 1982). It has been reported that an EMS training for 21 days regarding the human triceps surae muscles (50 Hz and 2500 Hz alternate current) develops the capillary source (Perez *et al*., 2002).

2. EMS IN MUSCLE STRENGHTENING

The basic problem about the muscle stimulation literature is the way how EMS changes the muscular performance in the EMS or in the EMS and voluntary exercising combination as compared with the voluntary exercising.

The strength response of the skeletal muscle against the stimulation depends on the intensity and frequency of the stimulation. A single shock on a muscle results in a single twitch in 200 milliseconds. If the stimulation frequency is increased 10 to 20 impulses per second, the muscle contraction is fragmental or twitch like. Unlike this, when a muscle is stimulated with high frequency, the contraction becomes smooth and the strength production peaks (tetanus). However, the muscle get tired fast (Hortobágyi, 1996; Starkey, 2013).

Under the natural conditions, while the motoneurons are activated unsynchronised, the artificial EMS signals are synchronised. In the natural stimulation, the motor units produce the muscular strength hierarchically (size principle). A second natural strength regulation form is the increase in the stimulation ratios of the motor units at the high contraction levels (Hortobágyi, 1996). However, in the electrical stimulation, the larger motor units are recruited first due to their low resistence. Therefore, in the artificial EMS aiming higher strength production, higher stimulation frequencies must be used. However, the muscle would get tired inevitably (Hortobágyi, 1996). The high frequency stimulation (> 70Hz) causes deficiency in the nerve-muscle intersection and the muscle get tired fastly. It has been reported that the appropriate frequency is of the similar rate to the normal motor unit discharge frequency (20-50 Hz) produced during the voluntary activity and the very low frequencies do not guarantee the muscle contraction (Petrofsky, 2004).

Bickel *et al*. (2003) has shown that the acute EMS is sufficient to stimulate the responses at the molecular level. This kind of changes show that the hypertrophy process has started in the muscles. Therefore, after multiple EMS sessions, the changes at the muscular level can be expected. However, the effect of an EMS training program on the muscle hypertrophy is still ambigous in the literature depending on the training duration (Singer, 1986; Stevenson and Dudley, 2001; Gondin *et al*., 2005) and selected EMS parameters (Stevenson and Dudley, 2001). For example, in a study (Stevenson and Dudley, 2001) an impressive increase is observed in the quadriceps muscle volume after an EMS training of 8-9 weeks, whereas in the studies covering 4 weeks EMS programs, no such changes have been reported (Singer, 1986). Therefore, it has been assumed that an EMS program lasting more than 4 weeks can provide muscle hypertrophy (Obajuluwa, 1991).

In all recent whole body EMS studies, it has been reported that the obtained strength gains are quite low (Filipovic, 2011).

2.1. EMS or Isometric Exercising

The study results have revealed that the isometric strength can be increased up to 50% with the electrical stimulation of the knee extensor muscles (Hortobágyi, 1996). However, the studies conducted on the healthy skeletal muscles show that the strength development is not as high as in the atrophic muscles.

In the publications comparing the isometric exercising and EMS (Laughman *et al*., 1983, Mohr *et al*., 1985; Robinson and Snyder-Mackler, 2007), despite the significant differences in the methodological approaches, no difference has been observed in terms of the strength/tork gains between the quadriceps isometric exercising and EMS for the healthy subjects. Only Mohr *et al*. (1985) have found a significant development with regard to the quadriceps muscle with the isometric exercising (14.7%). In the study that shows the voluntary isometric training is more efficient than EMS in terms of the strength increase of the elbow flexor muscles (Holcomb, 2006) the significant ineffectiveness of the EMS is associated with the exercising intensity.

2.2. EMS or Isokinetic Exercising

In the studies directly comparing the EMS and isokinetic exercising for the healthy quadriceps muscles (Halbach and Straus, 1980; Nobbs and Rhodes, 1986), it has been reported that a descriptive development in the quadriceps muscle strength (42% for the exercise group, 22% for the stimulation group) can be provided. What is interesting is that Nobbs and Rhodes (1986) have reported that there is no significant difference for 100°/second and 180°/second angular speeds and the strength gain is recorded at the speeds less or equal to 30°/second and 0°/second training speeds.

As reported by Lloyd *et al*. (1986), a significant strength development in the EMS and isokinetic exercising groups is observed for each angular speeds and knee joint angles. Although there is no difference between the groups, the highest strength increase has been observed in the isokinetic group, whereas the development in the EMS group has been revealed in the isometric and slow isokinetic contractions.

Similarly Halbach and Straus (1980) has found that although all of the groups have shown significant strength increase, isokinetic training have provided more strength gain compared to EMS. In this study, the isokinetic training has been applied with different speeds and tested for a single speed (120°/second).

2.3. Combination of EMS and Isometric / Isokinetic Exercising

In some studies where the voluntary exercising has been combined with EMS, the objective was to define the EMS effects. All of these studies have revealed clearly that combining exercising and EMS simultaneously is much more efficient than exercising alone (Convery *et al*., 1994; Burkett *et al*., 1998). Additionally, this has been concluded regardless whether isometric or isokinetic exercising were used. Therefore, although it has been reported that the combination of these two forms do not provide any gain in the healthy quadriceps muscles (Lloyd *et al*., 1986) the recent studies have proved the opposite. For example, Callaghan (2002) has reported that an isometric constraction in the 45° knee flexion with or without EMS, an isotonic concentric activity from 90° to complete knee extension and a squat jump comparison; 100 Hz EMS during 0.8 seconds has improved the isometric tork for a ratio of 23% and the isotonic tork for a ratio of 4%; however squat jumps with multiple joint activities have not caused any difference.

Dervisevic, Bilban and Valencic (2002) have reported that the isokinetic training combined with the low frequency EMS is a much more efficient method to develop the strength of the quadriceps, compared to the low frequency training and to the isokinetic training alone.

3. MUSCLE ENDURANCE AND EMS

The limited number of the studies examining the effects of the EMS training on the muscular training shows that there is a need for studies on human. Robinson and Snyder-Mackler (2007) have indicated that EMS training does not have a significant effect on the abdominal muscle in terms of the muscular endurance. Hartsell’s (1986) study showed an increase in the quadriceps endurance upon stimulation program; however these small increases have not been more significant than those obtained by exercising alone.

According to Robinson and Snyder-Mackler (2007), the basic problem for defining the effects of EMS on the muscular fatigue is the fact that the studied EMS training programs are based on the voluntary training programs and there is no clinical study showing that the voluntary endurance training principles (low intensity contractions, high numbers of repetition) were used in the EMS training to improve the muscular endurance.

However, with reference to the study conducted by Thériault *et al*. (1994), Callaghan (2002) has reported that when much lower frequencies such as 8 Hz are used on the animal models, together with an increase in the aerobic oxidative enzyme indicators of 25%, an improvement in the quadriceps endurance and a significant increase in the total quantity of the knee extension training have been observed. Callaghan (2002) who has indicated that the improvements in the endurance capacity are provided with the non uniform stimulation forms, has reported in 1995 with reference to the studies of Oldham *et al*. that the non uniform neuromuscular stimulation model used for the quadriceps of the old patient with osteoarthritis is better than uniform EMS. Also, the study by Lopez-Guajardo *et al*. (2001) has shown that low frequency (10Hz) stimulation (6 weeks, 30 minutes each day) applied to the tibialis anterior muscle of the rabbits has provided a significant increase in the endurance capacity of the muscle.

Perez *et al*. (2003) have reported that in human, the chronic electrical stimulation sessions (a couple of hours each day) via the skin may increase the oxidative capacity and capillarization of the FT fibers of the muscle and may cause some fiber transitions among the FT subfibers. However, Perez *et al*. (2003) have emphasized that in several studies showing the significant effects of EMS on the human skeletal muscles, the protocols that have been applied are unrealistic and difficult to apply under sports training conditions and in clinics and that the sessions are too long (a couple of hours per day) and the used frequency currents (a duration of approximately 100 ms pulse, 50-100Hz) are disturbing.

The experimental results obtained from the studies involving low frequency EMS on healthy people's muscles show that the oxidation potential of the stimulated muscles increases. For example, in the study that shows that low frequency electrical stimulation (8Hz) for 6 weeks improves the fatigue resistence of the knee extensor muscle significantly, the citrate syntasis activity, the capillary number per FT-a and FT-b fibers and the percentage of the FT-a muscle fibers in the vastus lateralis muscle have been significantly increased (Thériault *et al*., 1996).

4. STIMULATION PARAMETERS

Nowadays, the stimulation current is transmitted by fixing the electrodes of different structure and materials on the skin covering the motor nerve (motor point). Even if the stimulation is applied on the exact motor point, the strength production of a muscle varies according to the stimulus parameters. Other factors to be considered are the stimulus waveform manipulation (rectangular, sinusoidal, triangle, symmetrical, asymmetrical, etc.) as well as its duration, intensity and frequence (Hortobágyi, 1996).

One of the issues that prevents to reach a consensus about the EMS is the extensive variations in the stimulation parameters. However, it has been reported that the success of a training program depends on the allowable stimulation intensity, frequency, and the durations of the entire program and each session (Hortobágyi, 1996). The most important parameter is the frequency and generally is grouped as low, medium and high frequency (Callaghan, 2002). The conducted studies have revealed that the most appropriate program for the EMS training is three times a week, two times a day for 30 minutes and with an intensity of 0.4-30 mA (Boonyarom *et al*., 2009).

In addition to this, while examining the efficiency of EMS with regard to various knee joint angles, several researchers use the standardized 60° knee flexion position (Laughman *et al*., 1983; Selkowitz, 1985; Mohr *et al*., 1985; Soo *et al*., 1988). Other researchers emphasize various knee flexions changing between 15° and 90° (Obajuluwa, 1991). Also, the hip flexion is constant for both application and evaluation. When multiple angles are examined, it has been seen that strength improvement occur in the closest test angle (Maffiuletti *et al*., 2000). The variations in the results (1-49.7%) are arisen probably from the differences in the methodological approaches and stimulation parameters.

4.1. Waveform

Different waveforms (i.e. the form of impulse) are used in EMS (Laufer *et al*., 2001) and the improvement is determined by the nature of the waveform (Kantor *et al*., 1994).

According to Callaghan'ın (2002), after the first trainings, during high frequency sinusoidal stimulation fatigue occurs and the strengthening effects decline. While Agrawal *et al*. (2008) did not find a significant strength improvement after the 2.5 kHz variable current stimulation, whereas in another study it has been reported that the improvement in the muscle strengthening was 47.7%. Similarly in the studies where 50 Hz stimulation is used without Carrier waveform, different results have been obtained. The muscle strengthening reached in these studies vary between 0% (Mohr *et al*., 1985) and 48.5% (Lai *et al*., 1988).

In a study where the efficiencies of the three waveforms were compared, it has been seen that the monophasic and biphasic orthogonal waveforms are more efficient than the polyphasic waveform in terms of tork production and that these two waveforms cause less fatigue (Laufer *et al*., 2001). In another study, it has been reported that the bipolar interferencial current (2500 Hz carrier frequency and 80 Hz amplitude modulation frequency) and low frequency current (symmetrical biphasic) can be used to improve the quadriceps muscular strength and the sensed discomforts are similar for these two waveforms (Bircan *et al*., 2002). However, it has been indicated that the optimum waveform is biphasic since it produces higher muscular strength and causes less pain (Petrofsky, 2004).

4.2. Pulse Duration

Although the pulse durations longer than 60 micro seconds (μs) probably activates the pain fibers, the durations over 200 – 300 μs produce a much stronger contraction (Lake, 1992) and a pulse duration of 200 to 400 μs specifically recruits motor nerves (Starkey, 2013). Also, an interval of 200 to 400 μs is applied in the human muscular trainings (Cheing *et al*., 2003); (Filipovic *et al*., 2012).

It has been reported that in general, a larger electrode pad structure allows better stimulation tolerence and a current interval of 250-300 μs results in minimum pain response (Petrofsky, 2004). Currently, the clinicians and researchers generally use the symmetrical biphasic waveform and a current interval of 300 μs (Alon and Smith, 2005).

Also, it has been reported that if the frequency and intensity are kept constant, the minimum frequency and maximum pulse duration would maximize the performance (Kesar and Binder-Macleod, 2006).

4.3. Duty Cycle

In general, this is related with the "on/off" ratio. The "on" phase is the period when the impulse is transmitted to the muscle. The "off" phase is the period between the consecutive "on" phases (Lake, 1992). This parameter is important in terms of resisting against the early muscle fatigue and providing a rest period between the contractions (Binder-Macleod and Snyder-Mackler, 1993).

Although the exact relationship between the fatigue and stimulated contraction duration and rest for most of the muscles (Robinson and Snyder-Mackler, 2007), Binder-Macleod and Snyder-Mackler (1993) have shown that the contraction intensity and frequency effect the fatigue directly. However, their effects are independent from each other. to reach the high strength levels while strengthening, the frequencies must be higher than the critical fusion frequency (tetani) (higher frequency, higher contraction causing more fatigue). The high contraction intensity provokes also the fatigue (Robinson and Snyder-Mackler, 2007).

A training cycle comprising of the shorther "on" and longer "off" durations are useful to protect the muscle against the fatigue and thus, to increase the muscle strength (Matsunaga *et al*., 1999). It has been observed that longer resting periods are required to minimize the muscle fatigue in higher frequencies, compared to the medium frequencies such as 30Hz (Callaghan, 2002). Furthermore, it has been indicated that in order to avoid the fatigue, the training cycle must be at least 1:5 and for a successful muscular strengthening a training cycle of 1:1 (4 seconds on, 4 seconds off; 15 seconds on, 15 seconds off) and 1:5 (10 seconds on, 50 seconds off) is suggested (Mohr *et al*., 1985).

4.4. Intensity and Length Stimulation

The current intensity (amplitude) is measured with various methods but defined often as miliampere (mA) (Callaghan, 2002). The strength of the contraction increases as the amplitude of the current increases and there is a linear relation between the higher contraction intensity and higher intramuscular changes (Starkey, 2013; Halbach and Straus, 1980).

The stimulation intensity can be of a value corresponding to a specified voluntary isometric contraction strength or mostly of a value corresponding to the tolerence of the subject (Paavo, 2003). It has been reported in many studies that depending on the subject tolerence, the current intensity increased gradually may vary between 30-90 mA and that this current intensity does not cause a serious discomfort for the subjects (Maffiuletti, Pesini, and Martin 2002).

Callaghan (2002) has reported that the maximum pain rate is experienced for the stimulus intensities corresponding to the 47.1, 70.3 and 42.8 % of the maximum voluntary isometric tork (MVIT). However, many studies covering the quadriceps stimulation application do not define higher stimulation levels (40-80% MVIT).

The basic difference regarding the studies where the effects of the EMS and exercising on the muscle strength are similar (Caggiano *et al*., 1994; Kubiak *et al*., 1987) is the contraction intensity reached with EMS or exercising. This supports once again that the higher activity and stimulation levels would provide more strength gains. However, the strength gains in some other studies show that the strength gains are not always related with the contraction intensity of a muscle. While the exercising group in the Laughman *et al*. (1983)'s has worked at average 78% maximum voluntary ısometric contraction (MVIC), the stimulation group has worked at average 33% MVIC. Nevertheless, similar results have been obtained from both groups.

In the clinical environment, the maximum comfortable intensity tends to be less than 30% of the MVIC (Starkey, 2013) and the initial level of a stimulation intensity that would provoke a reasonable contraction for affecting the intramuscular changes is 30% MVIT. Besides, the main restriction seems to be the current intensity that can be easily tolerated by the patient. This depends on the skin resistence and capacitive skin impedence (Lake, 1992). This is important because the patients using constant frequency stimulators with 35 Hz and higher (approximately 100Hz) would encounter problems while trying to produce strong contractions easily at higher intensities. Also, the cold application prior to treatment increaeses the maximum output tolerated by the patient, but does not translate increased torque production (Starkey, 2013).

4.4.1. Length of Treatment

The examination of the application programs reveal that there are significant differences in terms of the daily stimulation quantity and the length of the experimental programs. While some of the studies are too short such as 5 days (Vinge *et al*., 1996) and some of them are long as 10 weeks (Obajuluwa, 1991) the common application period is 6 weeks (Draper and Ballard, 1991; Snyder-Mackler *et al*., 1991; Snyder-Mackler *et al*., 1995).

Due to the differences in the stimulation characteristics and training protocols, the number of the electrical stimulation sessions required for providing strength gain is quite variable. While some researchers have obtained the significant strength gain after a few period of time such as 10 sessions, others reached the significant increases in the strength after 12-25 training session (Mohr *et al*., 1985). However, when used 4 weeks and 3 times a week, it is possible to obtain significant effects (Parker *et al*., 2003). In summary, regardless of the EMS method used, the analysis revealed that a stimulation period in a range of 4–6 weeks (3.2 ± 0.9 sessions per week, 17.7 ± 10.9 minutes per session, 6.0 ± 2.4 seconds per contraction with 20.3 ± 9.0% duty cycle) shows positive effects for enhancing strength parameters, jumping and sprinting ability, and power. Therefore, the results of trials using whole-body EMS methods showed that a duration of 15 minutes (2 sessions per week over a 4-week stimulation period) can be assumed to be sufficient for stimulation to activate strength adaptations and thus increasing strength abilities (Filipovic *et al*., 2011).

4.5. Low Frequency Stimulation Versus High Frequency Stimulation

Low frequency stimulation (characteristically between 1-10 Hz) is used to improve the fatigue characteristic of a muscle. On the other hand, if the stimulation is used to provide the strength gain, it causes fatigue. A stimulation regime comprising consecutive high frequency periods together with the low frequency stimulation can be much more advantageous. (Callaghan, 2002).

It has been reported that the low frequency stimulation increases the fatigue resistence during the isometric rhythmic or continous contractions of the muscles and this reaches the peak after 4 weeks (Shenkman *et al*., 2007). Also, it does not produce significant change in the maximum voluntary strength or may cause a slight decrease (Nuhr *et al*., 2003).

The experimental results show that the low frequency electrical stimulation causes the oxidation potential of the stimulated muscles (Thériault *et al*., 1996). This is an important characteristic for keeping the activity level in the clinical applications. However, there is a significant decrease in the muscle mass (Salmons and Hendricksson, 1981), contraction speed and ability to produce strength (Jarvis, 1993). It has been accepted that 30 or 50 Hz frequency stimulation can produce higher tork value compared to the 10Hz stimulation (Lieber and Kelly, 1993). Although the high frequency stimulation improves the muscle strength theoretically, since it may cause muscle fatigue if no sufficient resting period is provided, the frequency of the electrical stimulation used for the fatigued muscles are low in general and the purpose is rather the recovery of these muscles (Raymond *et al*., 2007; Maffiuletti *et al*., 2011; Babault *et al*., 2011). Again the low frequency is preferred for the muscular endurance trainings. Likewise, it is known that the long term low frequency electrical stimulus makes the FT fibers gain ST fibers' characteristic. However, the evidences claiming the over stimulation causes muscular fatigue are conflicting and probably this is due to the use of different methodological approaches. For example, it has been reported that in human muscle 100 Hz uniform high frequency stimulation has a few effects on the endurance together with an increase in the contractile speed; and differently, the feline FT muscles become slower at 100 Hz stimulation (Callaghan, 2002). High frequences such as 30-50 Hz are above the natural stimulation frequency of the motor units and the regular stimulation frequencies of the motor units in daily life vary between 15Hz – 25 Hz (De Luca, 1997) and therefore, the muscle cannot cope with the extra energy demands (Callaghan, 2002). Nevertheless, it has been reported that the contraction intensity near to maximum has been reached with a stimulation of 50 Hz (Hultman, 1995). Likewise, the fast motor unit nerves in the skeletal muscle are discharged at high frequencies such as 40-60Hz (for those in the slow motor units it is 10Hz) (Bigard *et al*., 1991).

The frequence specific stimulation studies involving nerve free animal muscles have supported the idea of using low frequency for the slow muscles and high frequency for the fast muscles (Kit-Ian, 1991). It has been confirmed that the 100 Hz frequency used for the FT fibers slows down the atrophy in the FT fibers and restores the normal contraction speed and tension. With regard to the high frequency stimulation applied to the ST fibers, it has been reported that this can reduce the fatigue resistence and cause muscle transformation from slow to fast. On the other hand, it has been reported that applying low frequency stimulation to the fast fibers may provide some beneficial effects that improve and preserve the oxidative enzyme activities and improve the endurance (Kit-Ian, 1991).

In addition, it has been indicated that certain restrictions of the electromyostimulation such as random recruitment can be minimized by adding the contribution of the central pathways (reflexive recruitment of spinal motoneurons by the electrically evoked afferent volley) and that the pulse frequency should be as high as 100 Hz for this purpose (to increase the rate at which the sensory volley is sent to the spinal cord and supra-spinal centres) (Maffiuletti, *et al*., 2011).

5. USE IN THE SPORTS TRAINING PROGRAMS

The effects of EMS on the strength gain have been tested in various training programs. For example, a stimulation period of 12 weeks has increased the muscular strength and power of the rugby players (Babault *et al*., 2007). However, it did not have any effect on technical rugby skills such as spurt and sprint. In another study, the combination of the EMS and plyometric training combination improved the maximum strength of the quadriceps femoris as well as the vertical jump and sprint (Herrero *et al*., 2006); however, EMS alone slowed down the sprint speed but did not exceed the gains obtained by the combination with the plyometric training. The current studies by Herrero *et al*. (2010a, 2010b) emphasize that in the endurance trainings, the superimposed electrical stimulation applied during the concentric phase of the movement is efficient on the strength improvement; however, it has been indicated that when the objective is to improve the anaerobic performance, the electrical stimulation must be used isometrically. In the study by Requena *et al*. (2005) it has been shown that the EMS combined with fast concentric (180^0/s) and eccentric training increases the maximum concentric movement. With regard to the ice hockey, while 3 weeks electrical stimulation has significantly increased the isokinetic strength of the knee extensors for the eccentric and concentric speeds, it has negatively affected the vertical jumping performance (Johnston 2004; Brocherie *et al*., 2005). In another study involving the volleyball players (Malatesta *et al*., 2003), the required level of effect in terms of the jumping performance has not been reached after 4 weeks of EMS training. On the contrary, it has been seen that a 4 weeks EMS program combined with the plyometrics is beneficial to improve the jumping skills among the volleyball players (Maffiuletti *et al*., 2002). In the study involving the basketball players, the EMS that has been applied as as part of the short term strength training (4 weeks) has improved the strength of the knee extensor and squat jumping ability (Maffiuletti *et al*., 2000). The study by Pichon *et al*. (1995) has shown that after an EMS program of 3 weeks, the swimming performance increases. An interesting result is that a 2 weeks complementary electrical stimulation program has positive effects on the paddling technique characterized by the power/time curve for the paddlers (Changsheng *et al*., 2002). However, it has been reported that most of the studies about this subject are weak methodologically (Dehail *et al*., 2008). With meta analysis, Bax et al. (2005) showed that the electrical stimulation is very efficient for strengthening the quadriceps femoris only compared to the control who does not exercise and that even if the stimulation is combined with the voluntary activity simultaneously, it is much more efficient. It has been reported that xcept those cases where it is combined with the eccentric training, the electrical stimulation is not significantly efficient in the classical training (Dehail *et al*., 2008). As summarized by Vanderthommen and Duchateau (2007), the strength gains due to the electrostimulation are not much higher than those obtained by the trainings covering the voluntary contractions. Because these gains are probably due to the intensity of the stimulation. Even if there is a standardized method, the use of the comfortable currents is very important. As a complementary element of the classical strengthening programs for the healthy individuals and athletes, especially when applied simultaneously with the voluntary contractions, EMS seems much more efficient. The basic advantages of EMS are: (1) increasing the work load of the muscle as a complementary element of the classical training and (2) causing a different contraction model than the model that occurs during the voluntary contraction (Paillard, Noe, and Edeline 2005; Vanderthommen and Duchateau, 2007). Consequently, even if the strength gains are transferrable to the sports activities, the negative results (Herrero *et al*., 2006) indicate that the skill training is always needed to improve the muscular coordination (Requena *et al*., 2005).

EMS has the potential to serve as a post-exercise recovery tool for athletes, since its acute application may increase muscle blood flow and therefore metabolite washout which could in turn accelerate recovery kinetics during and after exercise (Babault *et al*., 2011). However, since there are studies that show different effects of EMS on the recovery process (Barnett, 2006), the relation between EMS and recovery should be further examined.

Recently, the efficiency of the electrical stimulation as an exercise for preventing the muscle loss or increasing the muscle mass in gravity-free environment are studied.

In the studies based on the electrical stimulation of the antagonists together with the voluntary agonist muscle contractions (Ito *et al*., 2004; Iwasaki *et al*., 2006; Matsuse *et al*., 2006), it has been shown that the electrical stimulation can be used instead of the traditional weight training without need to the resistence equipment and stabilization. Ito *et al*. (2004) has reported that the hybrid training they have used during 4 weeks and 3 times a week is efficient to provide strength increase in the gravity-free environment (5000 Hz Carrier frequency and 20 Hz burst-wave stimulation frequency). Iwasaki *et al*. (2006) have reported that the hybrid training they have applied during 6 weeks, 3 times a week (voluntary knee extension and flexion simultaneously with the electrical stimulation) is comparable to the weight training among the healthy individuals in order to improve the knee extension strength and this method can be beneficial for the bedridden persons or space journeys. In the follow up study that gave similar results, it has been proved that the hybrid training (8 weeks / 3 times a week) provides significant strength increases and the strength gains continue longer compared to the isotonic weight training and electrical stimulation alone. It has been indicated that the increases in the muscular cross sections are comparable with the other two methods (*Matsuse et al*., 2006). It has been shown that in long term space journeys, as a precaution against the muscular strength and muscle mass loss, the low frequency electrical stimulation (15 Hz, 4.5 weeks, six times a week; each session lasts 6 hours) on the stretched muscles causes an insignificant decrease on the muscular strength and an increase in both types of muscular fiber cross section (Shenkman *et al*., 2007).

6. CONCLUSIONS

The animal studies have provided detailed evidences about the chronic low frequency stimulation effects at the vascular, cellular and metabolic levels. Currently, although it has been determined that the fast muscle fibers are transformed into slow fibers upon low frequency EMS, it is still difficult to prove the transformation from fast to slow in animal models.

With regard to human, it seems that there is a concensus about the benefit of the EMS regarding the functions measured by the walking analysis and some functional tests. Also, it has been accepted that the quadriceps atrophy measured with the cross sectional area can be reduced with EMS. However, with regard to the human studies, insufficient and conflicting results have been reported in terms of MVIC, MVIT, isokinetic strength, femur periphery by tape measurement, muscle protein and enzyme activity, fiber type composition, fiber type cross sectional area and fiber type ratio.

Also, the literature shows that when the muscle is weak after the immobilization, the EMS will provide a medium level strengthening, however when it is applied to the healthy or strong muscles, it will not provide the required improvement. When the literature is examined, the various reasons for these differences are seen.

Consequently; significant evidences demonstrating EMS's effects on the human muscles in terms of the cellular changes have been provided and it has the potential to serve as a sport tarining tool for developing physical performance.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

To better understand the effect of application on sport performance, future research might consider:

- Developing experimental models where the needs of the athlete and the specific components of the training are integrated.

- Developing complex training models including EMS in order to simultaneously improve the characteristics that are difficult to combine in a single training program due to the different demands (such as muscular strength and endurance).
- Developing new experimental models that realize the potential benefits of the EMS on recovery in order to tolerate the training loads and increase the training effects.
- Developing new models covering the whole body applications with different stimulation parameters.

Acknowledgements: No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

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