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Neuromuscular Electrical Stimulation

An Overview and its Application in the Treatment of Sports Injuries

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Contents

320	Summary
321	1. Electrical Currents and Stimulators Used in NMES
322	2. Important Parameters of NMES and Their Effect on Muscle Stimulation
323	2.1 Waveform/Current Type
323	2.2 Current Amplitude
324	2.3 Pulse Duration
324	2.4 Stimulus Frequency
324	2.5 Duty Cycle
325	2.6 Amplitude Ramp Modulation
325	3. Electrode Size and Placement in NMES
326	4. Uses of NMES
326	4.1 Muscle Strengthening in Healthy Subjects
328	4.2 Muscle Strengthening to Prevent Disuse Atrophy
329	4.3 Recommended NMES Protocols for Muscle Strengthening
330	4.4 Selective Muscle Strengthening and 'Muscle Re-Education'
331	4.5 Recommended NMES Protocols for Selective Strengthening
332	4.6 Control of Oedema
333	4.7 Recommended Protocols for Oedema Reduction
335	5. Conclusions

Summary

In sports medicine, neuromuscular electrical stimulation (NMES) has been used for muscle strengthening, maintenance of muscle mass and strength during prolonged periods of immobilisation, selective muscle retraining, and the control of oedema. A wide variety of stimulators, including the burst-modulated alternating current ('Russian stimulator'), twin-spiked monophasic pulsed current and biphasic pulsed current stimulators, have been used to produce these effects.

Several investigators have reported increased isometric muscle strength in both NMES-stimulated and exercise-trained healthy, young adults when compared to unexercised controls, and also no significant differences between the NMES and voluntary exercise groups. It appears that when NMES and voluntary exercise are combined there is no significant difference in muscle strength after training when compared to either NMES or voluntary exercise alone. There is also evidence that NMES can improve functional performance in a variety of strength tasks. Two mechanisms have been suggested to explain the training effects seen with NMES. The first mechanism proposes that augmentation of muscle strength with NMES occurs in a similar manner to augmentation of muscle strength with voluntary exercise. This mechanism would require NMES strength-

ening protocols to follow standard strengthening protocols which call for a low number of repetitions with high external loads and a high intensity of muscle contraction. The second mechanism proposes that the muscle strengthening seen following NMES training results from a reversal of voluntary recruitment order with a selective augmentation of type II muscle fibres. Because type II fibres have a higher specific force than type I fibres, selective augmentation of type II muscle fibres will increase the overall strength of the muscle.

The use of neuromuscular electrical stimulation to prevent muscle atrophy associated with prolonged knee immobilisation following ligament reconstruction surgery or injury has been extensively studied. NMES has been shown to be effective in preventing the decreases in muscle strength, muscle mass and the oxidative capacity of thigh muscles following knee immobilisation. In all but one of the studies, NMES was shown to be superior in preventing the atrophic changes of knee immobilisation when compared to no exercise, isometric exercise of the quadriceps femoris muscle group, isometric co-contraction of both the hamstrings and quadriceps femoris muscle groups, and combined NMES-isometric exercise. It has also been reported that NMES applied to the thigh musculature during knee immobilisation improves the performance on functional tasks.

There is some evidence to suggest that NMES is effective in selective strengthening of individual muscles within muscle groups or parts of muscles. Evidence for selective strengthening of the abdominal muscles, back muscles, triceps brachii and the vastus medialis obliquus has been presented. It is unclear whether this selective strengthening is due to local changes in the muscle or muscle area stimulated or to a change in the relative magnitude of recruitment of the different muscles within a muscle group or of the different portions of a muscle.

NMES has been suggested to be a useful adjunctive treatment in oedema. Several investigators have shown some effect of monophasic pulsed stimulation in the treatment of acute oedema when applied to produce muscle pumping. One investigator has demonstrated an effect of monophasic pulsed stimulation on acute oedema but only when applied at amplitude levels below those needed to produce muscle contraction.

Neuromuscular electrical stimulation (NMES) is the application of electrical stimulation to produce skeletal muscular contractions as a result of the percutaneous stimulation of peripheral nerves. In sports medicine, NMES has been used for muscle strengthening, maintenance of muscle mass and strength during prolonged periods of immobilisation, selective muscle retraining and the control of oedema. To produce these effects a wide variety of stimulator types have been used.

The objectives of this article are to:

1. Review the types of electrical currents and stimulators used in NMES;
2. Identify the important parameters of NMES and how the modification of those parameters affects the stimulation of muscle;
3. Describe the application of NMES to specific conditions seen in sports medicine.

1. Electrical Currents and Stimulators Used in NMES

The Clinical Electrophysiology Section of the American Physical Therapy Association established a unified terminology for clinical electrical currents (Kloth & Cummings 1991). This review uses that terminology.

There are 3 types of therapeutic currents: (a) direct current; (b) alternating current; and (c) pulsed current.

Direct current is used only in wound healing and iontophoresis and not in NMES.

In present therapeutic use, alternating current is delivered at a high frequency (2500 to 4100Hz) and then either interference modulated or burst modulated.

Interference-modulated current is the so-called

interferential stimulation. There are 2 slightly different high frequency carrier currents (at approximately 4000Hz) which are passed through 2 different circuits. One of the 2 currents is held at 4000Hz and the other can be held constant or varied over a range of 4001 to 4100Hz. The currents from these 2 circuits are superimposed either in the stimulator or in the body. This superimposition of 2 currents at different frequencies generates an interference pattern. This interference pattern produces an amplitude modulation with a distinct series of nodes of high intensity when the peaks of the two alternating currents temporally coincide (in-phase) and antinodes of zero intensity when the peak of 1 current temporally coincides with the trough of the second current (180° out-of-phase). The high intensity nodes are referred to as beats, and these beats are felt as individual stimuli. The beat frequency can be altered by changing the frequency of the variable high frequency carrier currents. Interference-modulated current is used primarily for pain relief and only occasionally in NMES.

The burst-modulated alternating current stimulator is commonly referred to as a 'Russian stimulator' because this type of NMES was introduced by the Soviet scientist Kots. Typically, this type of stimulator delivers a 2500Hz carrier current in 10 msec bursts interspersed with 10 msec periods with no current flowing, producing 50 bursts per second. Newer stimulators of this type have a wider range of carrier current and burst frequencies.

The theoretical foundation of both types of high frequency alternating current stimulators is that a high frequency stimulation lowers the capacitive impedance of skin (Kloth 1991), allowing more current to reach the motor nerves. However, others (Alon 1991) have reported that the capacitive impedance of skin is more related to the phase duration of the stimulation. This view suggests that the higher frequency (2500 to 4000Hz) alternating current stimulators are not any more effective in lowering skin impedance than pulsed currents with phase durations of 125 to 200 μ sec.

The third type of current is pulsed current, which is defined as 'the uni- or bidirectional flow of charge

which periodically ceases for a finite period of time' (Robinson 1989). The period of time during which the charge flows is called the pulse duration (or more commonly and incorrectly pulse width).

Pulsed current with a unidirectional flow of charge is termed monophasic pulsed current. The waveform of monophasic pulsed current most commonly used in stimulators is the twin-spiked waveform. Stimulators which use this twin-spiked monophasic pulsed current are commonly called 'high volt' stimulators because the driving voltage of this type of current must be very high (greater than 150V) to produce currents strong enough to reach the threshold of motor and sensory nerve fibres. Although charge accumulates in the tissues with all types of monophasic pulses, the twin-spiked waveform deposits charge in the tissue for such a brief period of time that no harmful effects of charge disposition is seen with these stimulators (Newton & Karselis 1983).

Pulsed current with a bidirectional flow of charge is termed biphasic pulsed current. In biphasic pulsed current, the flow of charge in each direction may be the same or differ in the time- and amplitude-dependent features (referred to as pulse waveform). If these features are the same in both pulse phases, the biphasic current pulse is labelled 'symmetric'; but if these features differ between the 2 phases, the biphasic current pulse is named 'asymmetric'. If the total amount of charge in 1 phase equals that of the other phase, the asymmetric biphasic pulsed current is termed 'balanced'. However, if the total charge in each phase is not equal, the asymmetric biphasic pulsed current is called unbalanced. Balanced, asymmetric biphasic pulsed current is the current form most commonly used in electrotherapeutics, and is commonly used in portable NMES stimulators. Symmetric biphasic pulsed current is commonly used in clinical model NMES units.

2. Important Parameters of NMES and Their Effect on Muscle Stimulation

The important parameters of NMES include waveform and current types, pulse or burst dura-

tion, pulse or burst frequency, duty cycle, stimulus current amplitude, and amplitude ramp modulation.

2.1 Waveform/Current Type

Several studies have investigated the effects of different electrical currents and waveforms in neuromuscular electrical stimulation.

Kramer and colleagues (1984), Walmsley and associates (1984) and Snyder-Mackler and colleagues (1989) compared several types of clinical stimulators to determine which was the most effective at generating force in the quadriceps femoris muscle group, measured as percentage of maximal voluntary isometric torque (MVIT). All 3 studies found that the burst-modulated alternating current asymmetric biphasic pulsed current stimulators were the most effective in producing muscle force. The least effective were the monophasic pulsed current and the interference-modulated alternating current stimulators. These results were confirmed by Grimby and Wigerstad-Lossing (1989) who were unable to show a significant difference between burst-modulated alternating current and asymmetric biphasic pulsed current in force generated and level of discomfort when applied to the quadriceps femoris muscle group. Wong (1986) reported slightly different results when she demonstrated no difference between a twin-spiked monophasic pulsed current and an asymmetric biphasic pulsed current in force production and perceived discomfort when applied to the quadriceps femoris. However, the twin-spiked monophasic pulsed current was significantly more comfortable and produced more force than asymmetric biphasic pulsed current when applied to the gastrocnemius-soleus. Wong suggested that this difference between proximal and distal stimulation sites was due to differences in the ability to discriminate sensory stimuli. Forces were not reported in terms of MVIT, so these results are difficult to compare to the previous studies.

Bowman and Baker (1985) demonstrated that symmetric biphasic pulsed current was preferred over asymmetric biphasic pulsed current regardless

of pulse duration or pulse shape when applied to the quadriceps femoris group.

Delitto and Rose (1986) investigated the comparative comfort of 3 waveforms, sinusoidal, square-wave and sawtooth (triangular) produced by a burst-modulated alternating current stimulator when percutaneously stimulating the quadriceps femoris muscles. They found that there was no particular waveform preferred by most subjects, but that each subject definitely preferred one of the 3 waveforms over the others.

Thus it would appear that the burst-modulated alternating current stimulators can produce the most force, particularly when applied to large, proximal muscle groups. It would be best to use a stimulator with a selection of waveforms, because although no single waveform suits all subjects, each subject has a distinct preference in waveform. When lower forces are generated there appears to be less of a difference in the perception of discomfort between the different current types. It appears that at low stimulus intensities, particularly to more distal musculature, the twin-spiked monophasic pulsed current might be the most comfortable.

2.2 Current Amplitude

Stimulus current amplitude, measured in mA, can be a limiting factor on how much force NMES can produce. Force of muscle contraction and amount of current applied are linearly related (Ferguson et al. 1989; Underwood et al. 1990). Therefore, a stronger force of contraction requires a greater stimulation amplitude.

The resistance of current flow through skin results from both ohmic skin resistance and capacitive impedance of skin. Capacitive impedance varies from person to person but cannot be modified to lower skin resistance except perhaps by the use of high frequency stimulation (Alon 1991). Ohmic resistance of the skin can be lowered by washing away skin oils, shaving the area to be stimulated or abrading the skin. Lowering skin resistance can lower the driving voltage needed for current to penetrate the skin.

Currents with shorter pulse or phase durations

require a greater current amplitude to produce a particular muscular force. Because of the short pulse duration, twin-spiked monophasic pulsed current requires the highest current amplitudes. Biphasic pulsed currents (either symmetric or asymmetric) require an intermediate level of current amplitude. Burst-modulated alternating current requires the least current amplitude.

Portable, battery-operated NMES units are more limited in the current output that they can deliver to the patient than 'house current' clinical models.

Current amplitudes are measured in a variety of ways, and there is no industry standard for which methods are used on stimulator displays. In addition, there can be an inconsistency between the true current output and what is displayed on the stimulator.

2.3 Pulse Duration

Because of the strength-duration relationship of electrical stimulation to motor and pain nerve fibres, pulses wider than 60 μ sec increase the likelihood of recruiting pain fibres (Howson 1978). However, pulses with longer durations (300 to 400 μ sec) produce a more powerful contraction (Bowman & Baker 1985).

Biphasic pulsed stimulators may have either fixed or variable pulse durations. Burst-modulated 2500Hz alternating current has a cycle duration of 400 μ sec. Twin-spiked monophasic pulsed currents have pulse durations of 90 μ sec or less and interference-modulated alternating current stimulators have cycle durations of 250 μ sec (Alon 1991), which may explain, at least in part, why these forms of stimulation are less effective in producing muscle contractions.

2.4 Stimulus Frequency

Although a frequency of greater than 20 stimulations per second is required to produce a smooth tetanic contraction, maximum force is produced only at higher frequencies of 60 to 100 stimuli per second (Binder-Macleod & Guerin 1990). Jones and colleagues (1979) have demonstrated that electrical

stimulation of skeletal muscle at frequencies as low as 20 pulses per second can greatly reduce muscle fatigue. However, at such low frequencies of stimulation the muscle only develops 65% of the force that it could develop at higher frequencies. So, it would appear that the clinician has the choice between a high force, highly fatiguing contraction or a lower force, less fatiguing contraction. However, Binder-Macleod and Guerin (1990), using intermittent stimulation, and Jones and colleagues (1979), using continuous stimulation, have demonstrated that if the frequency of the electrical stimulation of muscle is gradually reduced during the stimulation period a high force can be maintained throughout the stimulation period.

Most pulsed current and interference modulated alternating current stimulators have a wide range of stimulation frequencies available. Although many burst-modulated alternating current stimulators have a fixed burst frequency of 50 bursts per second, the newer units of this type offer a range of burst frequencies. However, no commercially available clinical stimulator can be automatically programmed to reduce the stimulation frequency as has been suggested by Binder-Macleod and Guerin (1990) and Jones and colleagues (1979).

2.5 Duty Cycle

In addition to stimulation frequency, an important stimulation characteristic on controlling premature muscle fatigue is duty cycle. Duty cycle is defined as ratio of 'on-time' to 'total cycle time' expressed as a percentage (Kloth & Cummings 1991). 'On-time' is the time during which a series (train) of pulses or bursts is delivered in clinical electrical stimulation. 'Off-time' is defined as the period between sequential on-times. 'Total cycle time' is the combination of a single on-time duration and off-time duration. For example an 'on-time' of 10 seconds and an 'off-time' of 30 seconds equals an on-off ratio of 1 : 3 and a duty cycle of 25%.

The effect of NMES duty cycle on muscle fatigue has been demonstrated by Snyder-Mackler and colleagues (1988a) and Packman-Braun (1988).

In both studies, there was a progressive decrease in muscle fatigue with a progressive reduction in 'on-time'.

Biphasic pulsed stimulators offer controls which allow for a wide range of duty cycles. It is very rare for a twin-spiked monophasic pulsed stimulator to offer duty cycle controls, but using reciprocal stimulation controls a 50% duty cycle can be obtained. Interference-modulated alternating current stimulators do not offer duty cycle controls. Although many burst-modulated alternating current stimulators have only the 2 duty cycles introduced by Kots (on-off ratios of 12 : 8 for 'strengthening' and 15 : 50 for 'rehabilitation'), the newer units of this type offer a range of duty cycles.

2.6 Amplitude Ramp Modulation

Amplitude ramp modulation is defined as the gradual, sequential increase or decrease in the peak amplitude of a series of pulses (Kloth & Cummings 1991). A gradual increase in the peak amplitude at the beginning of a series of pulses is designed to gradually increase the number of recruited motor units and gradually increase the force of contraction, and a gradual decrease in peak amplitude at the end produces a smooth, gradual decline in muscle force. This is done primarily for client comfort (Delitto & Robinson 1989).

Most stimulators have controls for regulating ramp durations. In electrical stimulation protocols ramps vary from 2 to 4 seconds at the beginning of a stimulation series and 1 to 2 seconds at the end. There is no research to suggest what optimal ramps may be, therefore ramps should be adjusted for individual client comfort.

3. *Electrode Size and Placement in NMES*

In the application of NMES, electrode placement is critical for best results (Ferguson et al. 1989). NMES is best done using a bipolar electrode arrangement with both electrodes on the muscle or muscle group to be stimulated with one of the electrodes on the motor point. The motor point is the

point on the surface of the skin over the muscle belly at which the smallest amount of current is required to produce muscle contraction (Delitto & Robinson 1989). Although the approximate position of these points for each muscle can be found in a number of motor point manuals and charts, it is necessary to find the point for each stimulated muscle on each client for effective NMES.

Motor point identification can be done with either probe or pad electrodes. This is done by placing a pad electrode on the distal belly of the muscle while the probe or pad electrode is moved over the proximal aspect of the muscle at low current levels to see what point produces the best contraction. Once that point is found the process can be repeated with the distal electrode to get the optimal contraction. Large muscle groups may require four electrodes from a single channel or 2 pairs of electrodes from 2 channels.

Electrode size must be matched to the muscle or muscle group that is being stimulated (Alon 1991; Delitto & Robinson 1989). If the electrodes are too small, the current density will be very high which could make the NMES very uncomfortable. Alon (1985) showed that larger electrodes are more effective in producing stronger muscular contractions with less pain than smaller electrodes. However, if the electrodes are too large current will spread to other muscles including antagonistic muscles (Delitto & Robinson 1989).

Alignment of the electrodes also appear to be important. Brooks and associates (1990) compared electrodes positioned perpendicular (transverse placement) and parallel (longitudinal placement) to the direction of the muscle fibres. Longitudinal placement of the electrodes resulted in a 64% increase in the maximal tolerable torque produced by NMES when compared to a transverse placement.

Most commonly, twin-spiked monophasic pulsed current is delivered by using a monopolar electrode arrangement. The active, cathodal pad electrodes are placed on the target tissue and the large anodal dispersant electrode is placed on some remote site, usually the upper or lower back. This is done because most clinicians mistakenly believe

that the large dispersant pad which comes with these stimulators must always be used. However a single, small pad electrode can be combined with a small electrode attached to the dispersant lead can be placed in a bipolar arrangement on the muscle to be stimulated. Some of the newer twin-spiked monophasic pulsed current stimulators no longer come with the dispersant electrode, and both anode and cathode are in the pad output from the stimulator.

4. Uses of NMES

4.1 Muscle Strengthening in Healthy Subjects

The purpose of this section is to briefly review the effects of NMES on muscle strength. For a more complete review, the reader should consult Currier (1991).

Several investigators have compared NMES, done under isometric conditions, and voluntary isometric exercise to nonexercise control groups on the strength of the quadriceps femoris muscle group in healthy subjects (Currier et al. 1979; Currier & Mann 1983; Halbach & Straus 1980; Kramer & Semple 1983; Kubiak et al. 1987; Laughman et al. 1983; McMiken et al. 1983; Mohr et al. 1985). All, except Mohr and colleagues (1985), reported increased isometric quadriceps strength in both NMES and exercise groups when compared to the unexercised controls, and there were no significant differences between the NMES and voluntary exercise groups. Mohr and colleagues (1985), using a twin-spiked monophasic pulsed stimulator were unable to demonstrate any increase in quadriceps strength. Currier and Mann (1983) reported that when NMES and voluntary exercise were combined there was no significant difference in quadriceps strength after training when compared to either NMES or voluntary exercise alone. Although these studies have demonstrated that NMES and voluntary exercise produce similar training effects, it must be stressed that the voluntary exercise groups worked at much higher workloads during training (78 to 119% of initial maximum voluntary isometric contraction) than did the NMES groups (33 to 68% MVIT).

In all of these studies on the quadriceps femoris group, isometric exercise and NMES proved to be equally effective in muscle strengthening. In a study on the abdominal muscles, Alon and associates (1987) reported that a combined NMES/exercise group achieved significantly higher gains in abdominal strength and endurance than NMES alone, exercise and nonexercise control groups, and both the combined NMES/exercise and NMES alone groups achieved significantly higher gains in abdominal strength and endurance than either the exercise or nonexercise control groups. Alon and colleagues (1987) attributed the effectiveness of the electrical stimulation to the observation that abdominal musculature even in normal healthy adults is likely to be atrophic, and electrical stimulation is particularly effective in strengthening atrophic muscles.

NMES has also been shown to be as effective as exercise in back musculature (Kahanovitz et al. 1987). In this study, there was no significant difference between the exercise and biphasic NMES groups in the improvement in isokinetic muscle strength, but both groups were significantly stronger than either the nonexercise control and monophasic NMES groups. Both the monophasic and biphasic NMES groups had significantly higher endurance than either the exercise or control groups. This suggests that monophasic electrical stimulation is relatively poor in muscle strengthening, but all forms of electrical stimulation may increase the endurance of stimulated muscle.

There is also evidence that NMES can improve functional performance. Wolf and collaborators (1986) showed that NMES applied bilaterally to the quadriceps femoris muscles and exercise both produced improved performance on force measurements from a computerised squat machine, 25-yard (23m) dash time and vertical jump.

In a single subject study by Delitto and colleagues (1989), an Olympic level weightlifter received NMES as part of a normal training regimen. The subject showed clear increases during the NMES periods in the amount of weight lifted in the squat (9 to 16% increase), clean and jerk (6% increase) and the snatch (4 to 10% increase). How-

ever, this is not a definitive study of the training effects of NMES on elite athletes because: (a) the tremendous psychological component in the performance of weightlifters was not addressed in this study; (b) most of the performance increases seen with NMES were acute effects of the electrical stimulation because they occurred after only 1 week of NMES (performance measures were made only weekly); and (c) there were also decreases in performance following the cessation of NMES.

Multiple muscle group NMES as used in muscle toning clinics has proven totally ineffective in muscle strengthening (Lake 1988; Lake & Gillespie 1988). The NMES was applied through 8 pairs of electrodes bilaterally to the hamstrings, quadriceps femoris, abdominals and gluteus maximus for 30 minutes/session and 3 sessions/week for 7 weeks. The investigators measured hamstring and quadriceps strength, thigh and waist girth and body fat before and after NMES and in a control unexercised, unstimulated group. Neither group showed any significant changes in any measure during the 7-week period.

In addition to the type of stimulator and current type, a major limiting factor in muscle strengthening using electrical stimulation is the discomfort associated with muscle stimulation (Currier 1991). This discomfort comes from the application of the NMES (Halbach & Straus 1980) and not from postexercise muscle soreness (Currier & Mann 1984). Several approaches have been used to minimise the pain associated with the application of NMES. Subjects can accommodate to the discomfort with repeated exposure to electrical stimulation (Halbach & Straus 1980; Owens & Malone 1983). Soo and colleagues (1988) demonstrated that stimulation at levels which produce only a 50% maximum voluntary isometric contraction of a muscle can produce significant muscle strengthening, and lower stimulation intensities are more comfortable than higher intensities. Miller and Webers (1990) showed that a 2-minute ice massage prior to the application of NMES increases the maximally tolerated force of contraction. In a similar attempt to reduce cutaneous pain associated with NMES, Underwood and colleagues (1990) re-

ported that subjects were able to tolerate a higher intensity of stimulation and were able to generate more force when the NMES was preceded by transcutaneous electrical nerve stimulation (TENS) as electroanalgesia.

Kahanovitz and colleagues (1987) and Alon and associates (1987) have reported that NMES training increases endurance in back and abdominal muscles, respectively. However, Eriksson and co-workers (1981) and Duchateau and Hainaut (1988) have reported no increase in endurance in quadriceps femoris muscle following NMES training. The effect on endurance appears to be unresolved at the present time.

Delitto and Snyder-Mackler (1990) have proposed 2 mechanisms to explain the training effects seen with NMES. The first mechanism proposes that augmentation of muscle strength with NMES occurs in a similar manner to augmentation of muscle strength with voluntary exercise. This mechanism would require NMES strengthening protocols to follow standard strengthening protocols which call for a low number of repetitions with high external loads and a high intensity of muscle contraction. The second mechanism proposes that the muscle strengthening seen following NMES training results from a selective augmentation of type II muscle fibres. Recruitment of motor units in humans during volitional contractions proceeds from S type motor units (type I or SO muscle fibres) to FR type motor units (type II or FOG muscle fibres) as the force of the contraction increases (Anderson & Sjogaard 1976; Milner-Brown et al. 1973). This recruitment order changes with electrical stimulation (Garrett & Stephens 1981; Sincore et al. 1990). Sincore and colleagues (1990) demonstrated a specific glycogen depletion in type II muscle fibres (type FR and FF motor units) of the quadriceps femoris muscle electrically stimulated at submaximal levels. Garrett and Stephens (1981) showed that electrical stimulation of the skin lowers the threshold of high threshold motor units and raises the threshold of low threshold motor units. Together these studies suggest that NMES can recruit type II muscle fibres prior to recruiting type I muscle fibres. Because type II fibres have a higher

specific force than type I fibres (Burke 1981), selective augmentation of type II muscle fibres will increase the overall strength of the muscle. This view is supported by reports from several investigators (Currier & Mann 1983; Kubiak et al. 1987; Laughman et al. 1983) that equivalent strengthening occurred when the voluntary exercise groups trained at higher muscle contraction intensities than the NMES groups. Lai and coworkers (1988) reported increases in isokinetic and isometric strength after 15 sessions of NMES with training as low as 25% MVC and increases in muscle strength with volitional exercise require training at much higher % MVC levels (Atha 1981).

4.2 Muscle Strengthening to Prevent Disuse Atrophy

The use of NMES to prevent muscle atrophy associated with prolonged knee immobilisation following ligament reconstruction surgery or injury has been extensively studied. Muscle atrophy can be defined as a decrease in strength, muscle mass, oxidative capacity and indurance of the atrophied muscle. Studies investigating the effect of NMES on the prevention of muscle atrophy used these characteristics and a number of functional measures to assess the degree of atrophy of immobilised muscles.

Eriksson and Haggmark (1979) and Godfrey and colleagues (1979) compared NMES to the quadriceps femoris muscle group with isometric exercise. Eriksson and Haggmark (1979) showed that patients receiving NMES demonstrated significantly higher function scores based upon quadriceps muscle strength and thigh girth and higher levels of succinic dehydrogenase, and Godfrey and colleagues (1979) demonstrated patients in the NMES group had significantly higher isokinetic peak torque values at the slowest speed (3 rpm) and in an aggregate score developed from performance at all speeds.

Grove-Lainey and co-workers (1983), Sisk and associates (1987) and Wigerstad-Lossing and colleagues (1988) compared NMES with NMES combined with isometric exercise. Sisk and associates

(1987) noted no significant difference in MVIT between the combined NMES-isometric exercise and isometric exercise alone groups. However, Grove-Lainey and coworkers (1983) suggested that, during the first 2-week period following surgery, exercise alone was more beneficial in maintaining strength than NMES, but that NMES was superior during the last 4 weeks of training. Wigerstad-Lossing and colleagues (1988) reported that declines normally seen in MVIT, muscle cross-sectional area and oxidative enzymes were prevented by the combination of NMES and exercise, but not by exercise alone.

Gould and associates (1983) compared NMES with isometric exercise in patients with knees immobilised for 4 weeks following open joint meniscectomy. The % MVIT of the operated limb when compared to the unoperated limb was significantly greater in the NMES group than in the isometric exercise group. Additionally, they found several functional improvements including a significant reduction in the duration of postsurgical crutch use, a significant increase in range of motion after removal of the knee immobiliser, and a significant decrease in the use of pain medications.

Morrissey and colleagues (1985) compared NMES-treated patients to unexercised controls and reported that patients with NMES demonstrated a significantly smaller fall in thigh girth and MVIT than the control group at the end of the 6-week period of immobilisation. However, there were no differences in MVIT and thigh girth between the 2 groups 12 weeks after surgery (6 weeks after the end of the immobilisation period).

In a single subject case study, Nitz and Dobner (1987) studied the effects of NMES of the quadriceps femoris and hamstring muscle groups during a 3-week period of lower extremity cast immobilisation in an athlete who has sustained a grade II medial collateral and anterior cruciate ligament sprain. Following removal of the cast, the patient's injured leg had a greater girth than the uninjured leg, and single leg vertical leap with the injured leg was 78% that of the uninjured leg.

Delitto and associates (1988) and Snyder-Mackler (1990) compared the effect of NMES-induced

isometric co-contraction of the hamstrings and the quadriceps femoris muscle groups with voluntary isometric co-contraction of the hamstrings and the quadriceps femoris muscle groups. Delitto and associates (1988) reported that in the NMES group there was a significantly greater % MVIT of both hamstrings and quadriceps femoris muscle groups in the operated side when compared to the uninjured side than in the exercise group. Snyder-Mackler (1990) reported that patients receiving NMES demonstrated greater isokinetic strength and improved performance in different aspects of gait.

Neuromuscular electrical stimulation has been shown to be effective in preventing the decreases in muscle strength (Delitto et al. 1988; Eriksson & Haggmark 1979; Godfrey et al. 1979; Gould et al. 1983; Grove-Lainey et al. 1983; Morrissey et al. 1985; Snyder-Mackler 1990; Wigerstad-Lossing et al. 1988), muscle mass (Eriksson & Haggmark 1979; Morrissey et al. 1985; Nitz & Dobner 1987; Wigerstad-Lossing et al. 1988) and oxidative capacity (Eriksson & Haggmark 1979; Wigerstad-Lossing et al. 1988) of thigh muscles following knee immobilisation. A number of investigators (Gould et al. 1983; Nitz & Dobner 1987; Snyder-Mackler 1990) have reported an improvement in the performance of functional tasks following NMES applied to the thigh musculature during knee immobilisation.

In all but one (Sisk et al. 1987) of these studies, NMES was shown to be superior in preventing the atrophic changes of knee immobilisation when compared to no muscle exercise (Morrissey et al. 1985), isometric exercise of the quadriceps femoris muscle group (Eriksson & Haggmark 1979; Godfrey et al. 1979; Gould et al. 1983), isometric co-contraction of both hamstrings and quadriceps femoris muscle groups (Delitto et al. 1988; Snyder-Mackler 1990) and combined NMES-isometric exercise (Grove-Lainey et al. 1983; Wigerstad-Lossing et al. 1988).

4.3 Recommended NMES Protocols for Muscle Strengthening

Although there are a large number of specific protocols for muscle strengthening reported in the NMES literature, there are some general principles

which the clinician can use to select the appropriate stimulator and to set up their own stimulation protocol.

One of the most effective currents in producing muscle strengthening is the 2500Hz burst-modulated alternating current. This type of current can produce the greatest % maximum voluntary isometric contraction (Kramer et al. 1984; Snyder-Mackler et al. 1989; Walmsley et al. 1984) and has been used in the majority of recent strengthening studies. Better results might be obtained from one of the more recent models of the burst-modulated alternating current stimulators which has variable waveforms, because no single waveform is preferred by all subjects and individuals have different waveform preferences (Delitto & Rose 1986). The stimulator should have a variety of stimulation frequencies and duty cycle combinations to give the clinician the widest variety of stimulation options possible.

Another effective current in producing muscle strengthening is the symmetric or asymmetric biphasic pulsed current (Alon et al. 1987; Grimby & Wigerstad-Lossing 1989). Clinicians should avoid twin-spike monophasic pulsed currents, interference-modulated alternating currents and all portable stimulators for muscle strengthening. A number of studies (Kramer et al. 1984; Mohr et al. 1985; Snyder-Mackler et al. 1989; Walmsley et al. 1984) have shown these 2 current types to be ineffective in muscle strengthening, and in general, portable NMES units have been shown to be relatively ineffective in muscle strengthening (Sisk et al. 1987; Snyder-Mackler et al. 1988b;). This conclusion is not supported by the work of Grimby and Wigerstad-Lossing (1989), which showed no difference between a portable stimulator and a clinical model.

Stimulus amplitude should be at the maximum level tolerated by the client. Even though strengthening can occur with NMES training levels as low as 25 to 50% maximum voluntary isometric contraction (Laughman et al. 1983; Soo et al. 1988), strength gain is proportional to the NMES training level (Selkowitz 1985).

Stimulus frequency should begin at about 60 to 90 stimuli/second and should be gradually de-

creased during the stimulation session to reduce fatigue. This gradual decrease in stimulation frequency needs to be done manually, as there are no programmable stimulators presently on the market that can do this automatically. From the work of Jones and colleagues (1979) and Binder-Macleod and Guerin (1990), this reduction in frequency should be by 2 stimuli/second/train of pulses.

Burst-modulated alternating current stimulators usually have a fixed cycle duration of 400 μ sec, but many biphasic pulsed stimulators have a variable pulse duration. If the stimulator has a variable pulse duration, it should be set close to 300 to 400 μ sec (Bowman & Baker 1985).

The proper duty cycle to use is really dependent upon the fatigability of the muscle or muscle group being stimulated. Although Snyder-Mackler and associates (1988) and Packman-Braun (1988) have reported that 12.5, 14 and 17% duty cycles (1 : 7, 1 : 6 and 1 : 5 on : off ratios, respectively) were significantly less fatiguing than 25 and 33% duty cycles (1 : 3 and 1 : 2 on : off ratios, respectively), clinicians should not hesitate to use the more fatiguing duty cycles if they would like to use a more aggressive strengthening approach. Most strengthening programmes using the burst-modulated alternating current stimulator use either a duty cycle of 23% (15 seconds 'on' and 50 seconds 'off') or 60% (12 seconds 'on' and 8 seconds 'off') because most of the early models of this type of stimulator had only those 2 fixed duty cycles. Perhaps as a general rule, begin with a 20 to 25% duty cycle (1 : 4 to 1 : 3 on : off ratios), and then modify it to match the fatigue characteristics of each individual muscle or muscle group being stimulated. However, an even longer off period should be considered if very high current amplitudes and high stimulation frequencies are being used. In their strengthening study with an Olympic level weightlifter, Delitto and associates (1989) used a 6% duty cycle (10 seconds 'on' and 180 seconds 'off').

There is no research on the optimal amplitude ramp modulation. Most stimulators have preset ramps of 1 to 2 seconds or have variable ramps from 0.5 to 8 seconds. A moderate ramp of 2 to 3 seconds is probably sufficient for most cases of

muscle strengthening. If very high current amplitudes are used, a 5-second ramp up and a 5-second ramp down may be more appropriate.

There has been no published research specifically studying the best number of trains/stimulation session, number of sessions/week or total number of sessions in a strengthening programme. Most NMES strengthening programmes follow the same principles used in voluntary exercise strengthening programmes: 8 to 15 maximal contractions per session, 3 to 5 sessions/week, and 3 to 5 weeks of training. Until there is clear evidence to contradict these patterns, these protocols should be considered the general rule to follow.

There is no evidence that in pure muscle strengthening NMES paired with volitional exercise is superior to NMES alone (Currier & Mann 1983). However, if there are aspects of 'muscle re-education' along with the strengthening programme, concurrent volitional effort with the NMES is required.

4.4 Selective Muscle Strengthening and 'Muscle Re-Education'

Several examples of selective muscle stimulation have been presented. Alon and associates (1988) produced selective strengthening of the abdominal muscles. Snyder-Mackler and colleagues (1988) have investigated strengthening of the triceps brachii. Kahanovitz and co-workers (1987) have demonstrated selective strengthening of the erector spinae muscles.

However, what is most desired in selective strengthening is the ability to change the relative magnitude of recruitment of certain muscles within a muscle group. This is commonly referred to as 'muscle re-education'. Although this is most commonly done with EMG biofeedback techniques, NMES has been used to promote 'muscle re-education' and to promote changes in the pattern of motor performance.

Fleury and Lagasse (1979) studied the effect of NMES and voluntary movement training on reaction time. In this study, 1 group received sequential pattern of NMES first to the anterior del-

toid and pectoralis major and then to the posterior deltoid and a second group practised the movement 100 times. While both groups showed decreased reaction times, the NMES group performed significantly better than the volitional practice group. Most of the improvement in total reaction time came from a decrease in the pre-motor time, the time between the presentation of the visual signal and the start of EMG activity in the muscles. This work suggested that NMES could be more effective in improving motor performance than volitional training.

The premise that this improvement in motor performance could be directed at specific muscles was further developed by LeDoux and Quinones (1981). In this study, normal subjects were trained to abduct the great toe. One group trained with volitional contractions of the abductor hallucis aided only by verbal cueing from the supervising therapists. The other group received NMES to the abductor hallucis during attempted voluntary abduction of the great toe. After 3 weeks of training the NMES group could produce a significantly greater volitional range of motion in abduction.

The combination of muscle strengthening and 'muscle re-education' has been applied to knee rehabilitation. Weakness of the vastus medialis obliquus has been associated with poor patellar tracking, chondromalacia patellae and other patellofemoral problems. Steadman (1979) has suggested that NMES can be a useful nonoperative measure for patellofemoral problems. Although protocols for vastus medialis obliquus 're-education' have been suggested by the manufacturers of NMES units, little research has been done which would suggest that this produces any long term correction of patellofemoral problems.

Jean Boucher, speaking at a 1986 Canadian research conference, reported on the effect of NMES on the pain associated with chondromalacia patellae. In this study, 4 patients and 5 normal, healthy subjects were pre- and post-tested on an isokinetic dynamometer isometrically and isokinetically. The integrated EMG signal from both the vastus medialis and vastus lateralis were recorded at maximal torque levels and the ratio (VM/VL) was com-

pared as an index of vastus medialis dysfunction. After the pretests on the patients, they received 8 weeks of NMES. NMES was applied to the vastus medialis obliquus and consisted of a biphasic pulsed current delivered at 70 pps and a 17% duty cycle (10 seconds 'on' and 50 seconds 'off'). There were 10 trains of stimuli/session, 3 sessions/weeks for 8 weeks. Following the electrical stimulation there was a dramatic improvement of the VM/VL. There was a 234% increase in the VM/VL ratio (0.62 to 2.07) in the chondromalacia patellae group and no change in the unexercised control group. Prior to the NMES training there was a significant difference between the VM/VL of the patient and control groups (0.62 vs 2.91), but after the NMES training there was no difference (2.07 vs 2.91). In addition, the patients reported the absence of pain during normal activities and during the testing procedures. This work further suggests the usefulness of NMES in functional improvement as a result of selective strengthening of the vastus medialis obliquus.

It is clear that NMES can produce a relative strengthening of individual muscles within muscle groups. However, it is not yet clear that the mechanism of this selective strengthening is truly muscle re-education. This selective muscle strengthening may be due only to local changes in muscle produced by the NMES and not to a change in the relative magnitude of recruitment of different portions of a muscle or muscle group.

4.5 Recommended NMES Protocols for Selective Strengthening

The protocols for 'muscle re-education' are not substantially different from those of strengthening except that there is no evidence that there is any advantage to high stimulus amplitudes. Low stimulus amplitudes for either a firm contraction or just 'cueing' may be all that is required.

Because high stimulation amplitudes are not needed, any stimulator used in NMES can be used for 'muscle re-education' protocols. In fact, portable NMES units may be the preferred unit for these

protocols because of their ease of use and ability to incorporate them into a home programme.

Stimulation frequencies can be at the lowest level that will produce a tetanic contraction, again because force production is not critical for successful motor re-learning. Additionally, at low frequencies the NMES can be continued for longer periods of time without the fear of premature fatigue.

The proper duty cycle to use in 'muscle re-education' is really dependent upon the fatigability of the muscle or muscle group being stimulated. The desire to have long periods of stimulation without fatigue would suggest a longer duty cycle such as 6 to 12.5% (1:16 to 1:7 on-off ratios).

There is no research on the optimal amplitude ramp modulation. Ramps of 1 to 2 seconds are probably sufficient for most cases of 'muscle re-education'.

There has been no published research specifically studying the best number of trains/stimulation session, number of sessions/week or total number of sessions in a 'muscle re-education' programme. Most 'muscle re-education' programmes using NMES follow the same principles used in voluntary exercise programmes of 100 to 200 repetitions of the activity. Until there is clear evidence to contradict these patterns, these protocols should be considered the general rule to follow.

Unlike muscle strengthening protocols, concurrent volitional effort with the NMES is required in 'muscle re-education' protocols.

4.6 Control of Oedema

NMES has been suggested to be valuable in the reduction of oedema following injury. Several different approaches and current types have been used.

Gould and colleagues (1983), using a 100 μ sec monophasic pulsed current, compared NMES with isometric exercise in patients immobilised for 4 weeks following open joint meniscectomy. They noticed a dramatic and statistically significant difference in knee oedema 4 weeks after surgery between the exercise and NMES groups as assessed by knee circumference measurements and clinical evaluation. In the NMES group, 7 patients had no

swelling and 3 patients had minimal swelling, while in the exercise group all of the patients showed visible or moderate swelling. Perhaps because of this difference in knee oedema, the NMES patients demonstrated a significantly greater knee range of motion and less postsurgical knee pain.

Lake (1989) has reported several, successful case examples of the use of NMES in the treatment of post-traumatic hand oedema. In these case examples, a twin-spiked monophasic pulsed current intensity was set at a level that produced substantial flexion of the wrist, thumb and fingers, and the patient was asked to flex the wrist and fingers along with the electrical stimulation to produce a 'pumping' action. Following the NMES treatment, there was a dramatic increase in the voluntarily produced range of motion of wrist and finger flexion and extension and a decrease in the circumferential measurements of the wrist and fingers. This work suggests that NMES may be a useful augmentation to voluntary contractions in reducing oedema.

Griffin and colleagues (1990) compared the efficacy of intermittent pneumatic compression and NMES in reducing chronic post-traumatic hand oedema. Patients were placed in one of 3 treatment groups: intermittent pneumatic compression, NMES and sham NMES. The twin-spike monophasic pulsed current intensity was set at a level that produced a slight contraction of the thumb and fingers. There was a significant reduction in hand oedema with both the intermittent pneumatic compression and the NMES after the single 30-minute treatment.

Thus it would appear that 'muscle pumping' effect of NMES may reduce traumatic oedema. NMES has been shown in animal studies to increase lymph flow out of the stimulated region (Bolter & Critz 1976). Changes in venous blood flow in the leg similar to voluntary contraction of the calf muscles are seen following NMES to the calf (Lindstrom et al. 1982). NMES has been shown to increase the microvascular perfusion in stimulated muscles (Clemente et al. 1991), and this may shift blood flow away from the site of injury and assist in reducing the oedema.

Monophasic pulsed current has also been shown

in animal studies to have another effect on oedema formation. When twin-spiked monophasic pulsed current was administered to the injury site immediately following injury, there is a significant reduction in post-traumatic oedema formation (Bet-tany et al. 1990). Stimulation is done at high frequency (120 pps) and at current levels below the level of stimulation required to produce muscle contraction. For this effect to occur the stimulation must be done within the first 24 hours following the trauma (Cosgrove et al. 1991; Mohr et al. 1987), the cathode must be on the oedematous area (Fish et al. 1991), and the stimulation must be done below the threshold for muscle contraction (Taylor et al. 1991b). Strictly speaking, this is not NMES and appears to be due to local tissue changes as the result of electrical stimulation. Recent work by Reed (1988) has shown that monophasic pulsed currents produce a decrease in capillary permeability to plasma proteins. This decreased capillary permeability is undoubtedly the principal underlying mechanism of oedema reduction.

In a clinical study, Michlovitz and colleagues (1988) reported that electrical stimulation combined with ice did not have a significantly greater effect on reducing the oedema associated with lateral ankle sprains than ice alone. This negative finding may have resulted from the different parameters used and the delay in application of the electrical stimulation.

4.7 Recommended NMES Protocols for Oedema Reduction

Although a great deal more research needs to be done in this area, it would appear that a protocol for the use of NMES for oedema reduction is beginning to emerge. Treatment for oedema should be divided into 2 phases with different protocols for each phase.

The first phase involves the use of monophasic pulsed stimulation with the cathode (negative electrode) directly on the oedematous site. This phase of treatment should begin immediately following the injury, and animal studies suggest that it should be at least 30 minutes in duration and be repeated

every 4 hours for the first 24 to 48 hours after injury (Taylor et al. 1991a). The stimulation should be applied at a high frequency (120 pps) and at a stimulation amplitude below motor threshold.

The second phase involves 'muscle pumping'. Although all of the clinical studies which have demonstrated oedema reduction following NMES used monophasic pulsed current, biphasic pulsed current, burst-modulated alternating current or interference-modulated alternating current should have a similar effect. 'Muscle pumping' can be approached in one of 2 ways: low frequency (less than 10 pps) 'twitch-like' contractions on continuously, or tetanic contractions (frequency greater than 25 to 30 pps) which rapidly cycle on and off (less than 5 second 'on-times'). The stimulation can be applied continuously to the motor point of the major muscle of a region or reciprocally to the motor points or major nerves of antagonistic muscle pairs. Stimulation amplitude needs to be above the threshold for muscle contraction. Muscle contractions should be only strong enough to produce a visible contraction or a slow movement through the range of motion which that muscle produces, because strong, prolonged muscle contraction may impede lymph flow and venous blood flow. Studies have shown significant reductions in oedema after single 15- to 30-minute treatments (Griffin et al. 1990; Lake 1989) and after more prolonged (16 hours/day, for 2 weeks) stimulation protocols (Gould et al. 1983). Although the proper dosage has not been established, daily or twice-daily treatments until the oedema is resolved should be sufficient.

5. Conclusions

NMES has been shown to be effective in the strengthening of normal muscle, the prevention of muscle atrophy associated with immobilisation, the selective strengthening of muscle and oedema reduction. With the exception of some specific applications such as the acute treatment of oedema, electrode placements and stimulation protocols are quite similar for the different treatment approaches. This similarity results from the fact that

all protocols are centered around the effective electrical stimulation of muscle.

The most versatile stimulators for NMES are the burst-modulated alternating current and biphasic pulsed current clinical models. However, other stimulators can be useful in specific applications of NMES, such as the use of twin-spiked monophasic pulsed stimulators in acute and chronic oedema reduction. The best stimulators for NMES are those that allow the clinician to vary as many of the stimulation parameters as possible, because this will allow the clinician to customise the stimulation to best suit the needs of the protocol and the client.

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