FOCUS: BIOMEDICAL ENGINEERING

Neuromuscular Electrical Stimulation for Skeletal Muscle Function

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Lack of neural innervation due to neurological damage renders muscle unable to produce force. Use of electrical stimulation is a medium in which investigators have tried to find a way to restore movement and the ability to perform activities of daily living. Different methods of applying electrical current to modify neuromuscular activity are electrical stimulation (ES†), neuromuscular electrical stimulation (NMES), transcutaneous electrical nerve stimulation (TENS), and functional electrical stimulation (FES). This review covers the aspects of electrical stimulation used for rehabilitation and functional purposes. Discussed are the various parameters of electrical stimulation, including frequency, pulse width/duration, duty cycle, intensity/amplitude, ramp time, pulse pattern, program duration, program frequency, and muscle group activated, and how they affect fatigue in the stimulated muscle.

INTRODUCTION

Damage to the human nervous system during an event such as stroke or spinal cord injury (SCI) produces a rapid denervation of muscle resulting in weakness or paralysis. This lack of neural innervation renders muscle unable to produce the voluntary forces needed to create joint movement that will allow functional performance of daily tasks [1]. Numerous scientific investigations have focused on devices, strategies, and regimens that may potentially restore body movement critically needed for daily function and quality of life.

Using electrical stimulation to produce human movement is not a novel procedure.

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†Abbreviations: CFT, constant frequency trains; DFT, doublet frequency trains; ES, electrical stimulation; FES, functional electrical stimulation; NMES, neuromuscular electrical stimulation; SCI, spinal cord injury; TENS, transcutaneous electrical nerve stimulation; VFT, variable frequency trains.

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In 1790, Luigi Galvani first observed motion after applying electrical wires to leg muscles severed from the body of frogs, and in 1831, Michael Faraday showed that electrical currents could stimulate nerves to create active movement [2]. One of the earliest clinical experiments that used electrical stimulation for muscle function stimulated the peroneal nerve in the leg in an effort to correct foot drop in persons with stroke-related hemiplegia during ambulation [3].

Whether used alone to improve motor impairment or embedded within complex systems to create functional multi-joint movement, the potential that electrical stimulation holds for rehabilitation recovery is immeasurable. Electrical stimulation is currently used in many forms to facilitate changes in muscle action and performance. In clinical settings, electrical stimulation can be used for improving muscle strength, increasing range of motion, reducing edema, decreasing atrophy, healing tissue, and decreasing pain. Neuromuscular electrical stimulation (NMES), used interchangeably with electrical stimulation (ES), is typically provided at higher frequencies (20-50 Hz) expressly to produce muscle tetany and contraction that can be used for "functional" purposes and can be found in literature as early as 1964 [4]. TENS is an alternate form of electrical stimulation that historically used high frequencies for pain relief [5] but is now also administered at very low frequencies (sensory level TENS, 2-10 Hz) [6]. TENS propagates along smaller afferent sensory fibers specifically to override pain impulses. When very low frequencies are used, TENS specifically targets sensory nerve fibers and does not activate motor fibers; therefore, no discernible muscle contraction is produced.

The acronym FES (functional electrical stimulation) is probably the most commonly used in the literature; however, a distinction should be made that this method of electrical stimulation usually refers to the process of *pairing the stimulation simultaneously or intermittently with a functional task* as initially described by Moe and Post [7]. For example, Thrasher et al. [8] designed a program of FES for the upper extremity of persons with stroke that consisted of initial stimulation of the anterior and posterior deltoid, followed by triceps brachii stimulation. This resulted in flexion of the shoulder and elbow extension to produce a forward reaching motion for function. The second phase of the study stimulated wrist extensors and finger flexors to contract the fingers around an object in order to facilitate a grasping task. The stroke group that received FES in addition to conventional therapy significantly improved in function when compared to those receiving only conventional therapy. FES has also been used extensively to reproduce the activation pattern of lower extremity muscles to produce human gait [9] and to create the sequence of lower extremity muscle activation needed during a cycling task [10-12] in persons unable to actively perform these movements. Several studies demonstrate the benefit of pairing ES with tasks that demand the use of intact cognitive and motor skills of the patient as compared to using ES simply as a passively delivered modality [13-16]. The term sometimes used to describe stimulation that cycles on and off repetitively without patient involvement is known as "cyclic" electrical stimulation [17,18].

A significant limitation of any non-physiologically induced muscle activation is the overall decreased efficiency of contraction and propensity for development of neuromuscular fatigue. With NMES, the primary causes are suggested to be an alteration of the normal recruitment order and the unnatural simultaneous activation of motor units (see following section "Limitations of Electrical Stimulation"). Therefore, strategies must be designed as part of electrical stimulation regimens to offset the high degree of fatigue associated with ES.

The delivery of electrical stimulation can be customized to reduce fatigue and optimize force output by adjusting the associated stimulation parameters. A full understanding of the settings that govern the stimulation is vital for the safety of the patient and the success of the intervention. Consideration should be given to the fre-

quency, pulse width/duration, duty cycle, intensity/amplitude, ramp time, pulse pattern, program duration, program frequency, and muscle group activated.

PARAMETERS OF ELECTRICAL STIMULATION

Frequency

Frequency refers to the pulses produced per second during stimulation and is stated in units of Hertz (Hz, e.g., 40 Hz = 40 pulses per second). The frequencies of electrical stimulation used can vary widely depending on the goals of the task or intervention, but most clinical regimens use 20-50Hz patterns for optimal results [19,20]. In order to avoid fatigue or discomfort, constant low frequency stimulation is typically used, which produces a smooth contraction at low force levels [21]. In a study comparing several different frequencies and stimulation patterns, frequencies under 16Hz were not sufficient to elicit a strong enough contraction to allow the quadriceps to extend to a target of 40º [22]. Interestingly, lower frequencies of stimulation have been shown to impart a long-lasting depression of force output known as "low-frequency fatigue," first described by Edwards, Hill, Jones, and Merton (1977). These researchers observed that fatigued muscle stimulated with lower frequencies (10-30Hz) had the potential to produce lower forces, a condition that lasted for 24 hours or longer; the same effect was not seen when the muscle was stimulated with higher frequencies. Later work by Bigland-Ritchie, Jones, and Woods (1979) showed that higher frequencies of stimulation (50 Hz and 80 Hz) administered to hand muscles resulted in a rapid decline in force after approximately 20s. More recently, stimulation frequency rates closely aligned with physiological rates of motor unit discharge were studied in the hand that showed a consistent frequency of 30 Hz preserved force better than a decreasing frequency pattern (30 Hz decreasing to 15 Hz) [23]. Mang et al. [24] showed that high frequencies of peripheral stimulation can have central con-

tributions as well; activation of motor neurons in the spinal pool was highest when the tibialis anterior muscle was stimulated with 100Hz as compared to stimulation at 10 and 50 Hz. Higher frequencies are generally reported to be more comfortable because the force response is smoothed and has a tingling effect, whereas lower frequencies elicit a tapping effect where individual pulses can be distinguished [6].

RAMPING OF STIMULATION FREQUENCY

Frequently, a gradation of stimulation up to the desired frequency and intensity is used for patient comfort. Ramp time refers to the period of time from when the stimulation is turned on until the actual onset of the desired frequency [25]. Ramp time is used in clinical applications when a patient may have increased tone that creates resistance against the stimulated movement. For instance, a person with flexor hypertonicity at the elbow would benefit from a gradual ramping up of stimulation frequency to allow more time to activate elbow extensors moving in opposition to tightened flexors to successfully complete the movement [26]. Ramp times of 1 to 3 seconds are common in rehabilitation regimens with longer ramp times sometimes used for hypertonic or spastic musculature or for the patient with an increased sensitivity to stimulation [25]. Ramp times also can be modulated in multiple-muscle applications such as standing and walking to produce smooth gradations of tetany between individual muscles and more closely replicate natural movement [27].

PULSE WIDTH/DURATION

Electrical stimulation devices deliver pulses in waveform patterns that are often represented by geometric shapes such as square, peaked, or sine wave. These shapes characterize electrical current that rises above a zero baseline for the extent of the stimulation paradigm (uniphasic; e.g., direct current) or current that alternates above and

below the baseline (biphasic or alternating current) [28]. Biphasic and uniphasic waveforms were noted to produce greater torque than polyphasic waveforms when administered to the quadriceps muscles of young healthy individuals [29].

The time span of a single pulse is known as the pulse width or pulse duration. In biphasic (a positive phase combined with a negative) pulses, the pulse duration considers both phases [30]. Typically, dynamic quadriceps extensions similar to those used in FES cycling tests exhibit pulse widths between 300μs-600μs [31-34]. Some investigators have suggested that low frequency stimulation with short pulse durations (500μs-1000μs) will exhibit a lower fatigue index [35]. However, even shorter pulse widths (10μs-50μs) have been shown to affect the recruitment of muscle fibers and can generate a larger maximum torque in a smaller number of fibers before causing a contraction in another muscle fascicle [36]. This is important as a greater recruitment ratio within muscle fascicles can possibly increase performance time; therefore, pulse width can be increased to potentially recruit more fibers in the surrounding area as fatigue ensues. Recent work comparing 50, 200, 500, and 1000μs pulse widths when 20 Hz stimulation was delivered to the soleus muscle found that the wider pulse widths produced stronger contractions of plantarflexion and additionally augmented overall contractile properties [37]. In addition, longer pulse durations will typically penetrate more deeply into subcutaneous tissues, so these widths should be used when trying to impact secondary tissue layers [26].

Duty Cycle

Early work in persons with SCI demonstrated that when periods of force development were interrupted with silent periods, muscle tissue was able to recover more quickly and produce greater torque as compared to when constant stimulation patterns were used [38]. Cycling pulses on and off (intermittent stimulation) is a common practice to preserve force development and simultaneously increase comfort for the

patient. Duty cycle describes the actual on and off time of an NMES program and is usually stated in ratio form, such as 1:2 (10 seconds on, 20 seconds off) or percentages such as 70 percent, indicating time on percentage when compared to total on and off time combined [25]. Common clinical applications use a 1:3 duty cycle as standard, but this ratio can be modified to accommodate the needs of the patient as well as the goals of the treatment [26].

Amplitude/Intensity

Another parameter that will contribute to fatigue is the strength of the current being administered or the intensity/amplitude (usually reported in milliamperes, mA) with which the stimulation is delivered. The higher the intensity, the stronger the depolarizing effect in the structures underlying the electrodes [39]. Higher intensities can foster increases in strength; strength gains are consistently found following training with electrical stimulation programs [15,40-42]. Recent work examining the optimal parameters for stimulation has suggested that lower intensities can induce more central nervous system input than higher intensities. Higher amplitudes of NMES activate a large number of muscle fibers that create forceful peripheral-mediated contractions, but antidromic transmission can occur (neural transmission toward the cell body rather than normal orthodromic transmission away from the cell body). Antidromic transmission blocks both motor and sensory impulses emanating from the spinal motor pool, resulting in less overall CNS activation [43]. The impact of stimulation amplitude on fatigue remains unclear. Downey et al. [44] found that when both frequency and amplitude were varied during a stimulation regimen of knee extension in healthy adults, more contractions were performed as compared to when a constant frequency and amplitude program was used. In contrast, when NMES was delivered to the knee extensors of seven healthy participants and the influence of frequency, pulse width, and amplitude on fatigue was studied, investigators found that fatigue decreased only when *fre-*

quency was decreased; lowering the other parameters had no appreciable effect on reducing fatigue [45]. Stimulation frequency rates closely aligned with physiological rates of motor unit discharge were studied in the hand that showed a consistent frequency of 30 Hz preserved force better than a decreasing frequency pattern (30 Hz decreasing to 15 Hz) [23]. Intensity will also factor into patient comfort with higher intensities being typically less tolerated; however, frequency and intensity inevitably will determine the quality of muscle contraction produced [25].

STIMULATION PULSE PATTERNS

Several investigations have examined the effects of various stimulation patterns on force output and neuromuscular fatigue. Common stimulation patterns studied are constant frequency trains (CFTs), variable frequency trains (VFTs), and doublet frequency trains (DFTs) [32-34,46-49]. CFTs are stimulation trains in which the frequency remains constant throughout the entire train. In contrast, VFTs are usually trains that begin with an initial doublet, (two closely spaced pulses, typically 5-10 μs apart) followed by pulses at a chosen frequency. The idea of VFT comes from studies where it was found that muscles have a "catchlike property," a unique mechanical response to stimulation that allows muscle to hold a higher force level than normal (van Lunteren, JAP 2000). This response enhances muscle tension prior to contraction when a brief, high frequency burst is followed by a train of subtetanic pulses [47,50,51]. The phenomenon does *not* appear to be a result of greater muscle fiber recruitment but an inherent property of the individual muscle cells [50,52].

In an isometric contraction of the thenar muscles of the hand, Bigland-Ritchie and colleagues showed that pulse trains that began with a doublet resulted in slower rates of force attenuation, suggesting a slower time to fatigue [53]. A similar study of isometric contraction of the thenar muscles of the hand examined variable patterns where a 20Hz CFT fatigue task was compared to two other fatigue tasks; a 20Hz CFT was administered for the first half of the fatigue task and then the frequency was increased gradually to 40Hz frequency or a 20Hz doublet train was added [54]. The findings of this study concluded that during submaximal stimulation, the doublet train was most effective in producing higher average forces and force-time integrals. These studies propose that using VFTs may be more beneficial in reducing fatigue in intrinsic hand muscles than CFTs alone.

Other studies have observed the lower limb comparing CFTs, DFTs, and VFTs. In particular, one study fatigued the quadriceps muscle using CFTs and VFTs with varying interpulse intervals [52]. The fatigued muscle was then stimulated with either a CFT of 14 or 18 Hz or a VFT (consisting of a train that used an initial doublet followed by a CFT). The results showed that VFT trains are more effective in producing higher peak forces, maintaining force output, and eliciting a more rapid rate of rise after being fatigued with a CFT as compared to using a VFT. Another investigation studied the effect of using CFTs, VFTs, and DFTs with the same interpulse interval (50 ms, 20 Hz frequency) to elicit dynamic leg extension. DFTs had the best overall performance in time to reach target [55]. These findings suggest that there may be several optimal stimulation patterns, but these will be dependent on the task, population studied, and the muscle group being investigated.

Electrode Placement

The success of the FES current to reach underlying tissue is highly related to electrode size and placement, as well as the conductivity of the skin-electrode interface [56]. In the past, a conductive gel was applied to the surface of electrodes to improve transmission of the current; typical stimulating electrodes used now are pre-gelled for convenience. Larger surface electrodes will activate more muscle tissue but will disperse the current over a wider surface area, decreasing current density. Smaller electrodes will concentrate current densities, allowing for focal concentration of current with less

chance of stimulation crossover into nearby muscles, but dense current increases the chance for discomfort or pain [57]. Placement of electrodes will also markedly influence the muscle response and should be carefully considered. Contention regarding optimal placement of electrodes is prevalent throughout the literature, with much of the debate centering on whether the muscle belly or the motor point is the preferential location. Rehabilitation therapists frequently place electrodes directly over the muscle belly [58] or in ineffective locations [59]. Manufacturers also provide suggested electrode placement charts or guides that are usually included with the device purchase, also a source for clinicians using NMES in practice. A recent investigation of NMES delivered to the tibialis anterior and the vastus lateralis of the lower extremity compared electrode placement using the motor point of the muscle (accurately located through stimulation) with placement using the recommended sites of several manufacturer's suggestions. This resulted in significant differences in muscle performance outcome; motor point placement not only produced higher torques, but blood flow and oxygen use was greater using the motor point positions [60].

STIMULATION INTENSITY

Stimulation can be delivered by means of constant voltage or constant current. The small portable units used in clinics and given to patients for home use are normally battery-operated and have modifiable current settings usually delivered through a constant voltage system of approximately 150V. These units use transcutaneous surface electrodes that adhere to the skin and can be easily removed. The contact area of the electrode is usually lined with the conductive gel described earlier that facilitates movement of the current from the electrode into the skin. Because the units use alternating current (AC) with a high degree of adjustability, muscle activation through these devices can be sometimes be variable and inconsistent; outcomes will depend on the quality of the skin-electrode interface and consistent placement of electrodes for repeatability [61].

DOSING OF STIMULATION

Dosing of FES programs can vary greatly and will ultimately depend on the muscle being stimulated, parameters used, and overall goal of the intervention. A review of the use of FES for motor recovery of the upper extremity in stroke examined several investigations and found an array of dosing protocols used [20]. Program duration ranged from 30 minutes one time per day to an hour at each session for three times per day. Overall period of treatment varied from 2 weeks to 3 months, with no justification by any author of why a particular dosing protocol was chosen. The researchers also found that increasing duration of treatment was not directly related to more successful outcomes; positive benefits were seen with short programs (2.5 hours/week), and limited benefits were seen with longer programs (21 hours/week). For rehabilitation of ambulation skills, FES-assisted walking programs usually consist of three to five hour-long sessions per week for at least 4 weeks [8].

LIMITATIONS OF ELECTRICAL STIMULATION

Although electrical stimulation has the capacity to produce movement in denervated, paralyzed, or spastic muscles, it is inherently less efficient than human movement. Most importantly, NMES induces excessive neuromuscular fatigue. Researchers have studied frequency [31,34,62], pulse width [35,36,63], modulation of pulses [64], amplitude [63], electrode placement [65], and the use of variable frequency pulse patterns [22,52-55,66,67] to determine if fatigue can be reduced through a modification of any of these parameters.

Causes for the excessive fatigue observed during NMES are multiple: First, NMES has the propensity to alter normal-motor unit recruitment order [68]. In normal

human movement, the smaller, fatigue-resistant motor units are activated first, which helps to delay the onset of fatigue; however, motor unit recruitment in electrically evoked contractions is suggested to be more random, thereby compromising the natural rate of fatigue resistance [69]. Although the reversal of Hennemann's size principle (where smaller motor units are recruited before larger motor units during voluntary contractions) [70] is a commonly reported shortcoming of NMES; some have postulated that, rather than an exact reversal of the process, activation may be less systematic or non-selective [71]. Jubeau et al. [72] reported that the when the quadriceps muscle belly in 16 healthy men was stimulated with NMES, motor units were recruited in a "nonselective/random order" regardless of fiber type. Additionally, recent work using NMES applied over the tibial nerve as compared to the triceps surae muscle belly observed that contractions were more forceful, activated spinal neurons for increased central nervous system input, and tended to follow the normal physiological motor recruitment size principle [73]. Other work by Thomas et al. [74] with spinal injured individuals indicated that a motor recruitment order similar to that which occurs in voluntary muscle contractions could be seen in the thenar muscles of the hand when using NMES.

Second, muscle fibers being stimulated are done so simultaneously, much unlike the normal, unsynchronized, highly-effective recruitment and derecruitment process of motor units seen during voluntary muscle contractions. In these contractions, the human motor system offsets fatigue by increasing the firing rate of active motor units and/or recruiting new motor units to replace others that have been derecruited due to fatigue [75]. This simultaneous activation observed during NMES can produce sudden, sometimes uncoordinated, inefficient movement patterns rather than the smooth gradation of force typically seen in human movement.

Third, surface-stimulating electrodes direct current precisely beneath the surface area of the electrode, and because the current will travel through various viscosities of subcutaneous tissue that create resistance, its strength will be diminished and the depth of penetration will be limited. Fuglevand et al. [76] noted that surface-stimulating electrodes typically reach superficial motor units 10-12 mm in close proximity to the electrode face and that only the larger motor units are detected from deeper tissues. Therefore, activation of deeper structures is usually not possible with standard surface stimulation; however, increasing pulse width or amplitude can improve penetration of current in an effort to reach muscles distant from the skin surface [26,77].

Another limitation of ES is related to its questionable long-term effectiveness following discontinuation. Few studies have follow-up data after treatment; however, some reports of received benefits waning following withdrawal of ES are present across different types of applications, such as spasticity reduction in children with cerebral palsy [78], functional hand use after-stroke [79,80], and shoulder subluxation [81]. Therefore, NMES may not be a long-term intervention for muscle re-education or restoration of movement. However, for SCI, some have suggested that only long-term use of ES helps to offset the muscle atrophy and complications of disuse [82].

VARIATIONS OF ELECTRICAL STIMULATION DELIVERY

Another type of transcutaneous stimulation is electromyography (EMG)-triggered electrical stimulation. This type of stimulation assists patients who are relearning specific muscle movements for function. Muscle activity is monitored by means of EMG recording electrodes such that when the EMG signal reaches a specific threshold (usually set by therapist), the stimulation will activate, thus assisting the patient to complete a movement. This intervention has been described as being even more reinforcing than cyclic stimulation due to the proprioceptive feedback and voluntary component involved [83]. Motor improve-

ments in hand function [84,85] and lower extremity motor skills for ambulation [86] following stroke have been observed. EMG-triggered electrical stimulation has also improved gait in patients with incomplete spinal injury [87].

Percutaneous stimulation uses electrodes that are inserted through the skin into the muscle of choice and are thought to be a superior choice to transcutaneous surface electrodes when specificity of stimulation is paramount. The leads of the electrodes exit the skin and connect to an external stimulator, bypassing sensory therefore minimizing discomfort. These hair-thin electrodes can usually target specific deeper muscle locations without the consequence of unintentionally activating surrounding tissues, as often happens in transcutaneous applications. The electrodes can be left in place on average for about 3 months, but skin irritation and breaking or dislodging of the electrode can occur [61]. Percutaneous FES implants have been shown to be effective for significantly reducing shoulder pain associated with post-stroke glenohumeral subluxation [88,89].

More recently, small stimulators can be surgically implanted for FES applications. This is a long-term alternative for stimulation protocols that require use for extensive periods. One of the earliest systems that became popular for spinal injured persons was the NeuroControl Freehand system (Neuro-Control, Cleveland, OH). This product consisted of an implanted stimulator, electrodes, and position sensor placed near the shoulder joint of the spinal injured individual. The system was attached to an external control unit for activation. The patient used intact shoulder muscles to trigger stimulation to paralyzed upper extremity muscles to produce a functional grasp and release of the dominant hand. In a multi-site randomized trial, 49 of 50 patients made improvements in grasp, pinch, and functional use of the hand, which was maintained 3 years following the implantation [90]. However, due to complicating logistical and marketing issues, the product is no longer available.

Implanted electrodes also have been used to activate spinal nerves to alleviate back pain or intractable pain associated with complex regional pain syndrome; however, while initial studies indicate effectiveness, extensive evidence for effectiveness is lacking [91].

Deep brain stimulation systems implanted directly into cortex are developing as a means to decrease symptoms of Parkinson's Disease [92] as well as to control seizures in persons with neurological pathology or epilepsy [93].

STIMULATION SYSTEMS CURRENTLY ON MARKET

By far, the most convenient way to apply ES is through the small portable units. These units have modifiable capabilities so therapists can set parameters and design custom ES programs that patients can use in the clinic or at home. Many come with pre-programmed regimens from which the therapist can choose that have fixed parameter settings, depending on the goal of treatment (strengthening, muscle re-education, pain relief, etc.). Most of these units can be locked so that patients can take them home without fear of altering the program or parameter settings, and the patient need only turn the unit on to activate the set program. Other options available on the units are tracking or compliance mechanisms that monitor activity in the unit. This allows the therapist to check how often and for what duration the unit was turned on, so that compliance with an ES program can be determined. Companies currently offering small portable units for patient use are numerous. Examples of these products are the Empi 300 PV (Empi, Inc.,www.empi.com), a multi-function portable device with TENS, NMES, and high-voltage stimulation capabilities [94]; the Chattanooga group (Chattanooga, Inc., www.chattgroup.com) offers portable and desktop clinical units with multiple ES options as well.

The Parastep I (Sigmedics,Inc., www.sigmedics.com) was one of the first FES ambulatory systems to be approved by the FDA and uses an array of stimulation across the back, gluteals, and lower extremities. The

Parastep also uses a walker apparatus with hand controls to regulate standing and sitting. Mushahwar et al. [95] summarized that Parastep I has modest success in restoring upright stance and gait as an activity of daily living and is better suited for users with complete SCI at the level of T4-T11.

The Advanced Reciprocating Gait Orthosis (ARGO) developed by Hugh Steeper Limited (London, UK) is another popular ambulatory device that uses a four-channel stimulator that activate hip and knee muscles combined with a double orthosis that moves the lower limbs through the gait cycle. Although these devices have advanced rehabilitation practices for ambulation, the systems can be complex to use and still require a high amount of stamina and energy expenditure of the patient. When Spadone et al. [96] compared these two systems, the Parastep required more energy output from the patient and was less efficient than the ARGO. Recently, Case Western Reserve University, Department of Veterans Affairs, developed an intramuscular implanted system that activates the hip, knee, and trunk muscles to facilitate ambulation. Seventeen subjects with high level cervical to mid thoracic spinal injuries saw improvement in time in standing and leg swing needed for gait [95].

FES also has become embedded into cycling systems for exercise purposes. Therapeutic Alliances (www.musclepower.com; Ergys 3) and Restorative Therapies (www.restorative-therapies.com; RT300) have been the leading developers of rehabilitative cycling systems. Their systems are comprised of ES for the lower and/or upper extremities that activate muscles in sequence to perform cycling movements. FES lower extremity cycling protocols have shown to reduce spasticity and improve posture [97] and increase strength and function in the lower limbs [10,98] of hemiplegic stroke patients. Johnston et al. [99] also found gains in the strength and function of an adult client with spastic cerebral palsy following a 12-week in-home FES cycling program. Restorative Therapies has recently released the RT600, a standing and stepping platform with ES functionality that facilitates these movementswith body weight support.

Bioness, Inc. (Valencia, CA) currently offers a common peroneal nerve stimulator in a small discreet unit that attaches to the upper calf to assist with ambulation skills in persons with stroke, spinal injury, multiple sclerosis, brain injury or tumor, and cerebral palsy. The L300 also incorporates a heel component that senses the heel strike phase of gait and stimulates the tibialis anterior muscle to dorsiflex the ankle, a difficult movement for many persons after stroke. The Bioness L300 Plus adds a thigh component that facilitates knee extension and adds stability during walking as well. Other similar peroneal nerve stimulators commercially available are the WalkAide System (Innovative Neurotronics, Austin, TX) and the Odstock O2CHS (Odstock Medical, Avon, MA). These systems have demonstrated long-term improvement in walking skills for persons with stroke as well as persons with multiple sclerosis [61,100].

Bioness is one of the few companies that offer a commercially available upper-extremity neuroprosthesis, the Ness H200. Because of the intricate precision and coordination of the hands and fingers, creating functional movement through electronics is a difficult task. The H200 device is comprised of an electrical stimulation system embedded within thermoplastic exoskeleton shell worn on the forearm that facilitates hand opening and closing for function. Use of this device has demonstrated improvement in grasp and release of objects for daily function in persons with stroke [101] as well as tetraplegia [102]. Karlsruhe Institute of Technology (Berlin, Germany) is currently testing a wearable hand orthosis (Ortho-Jacket) that uses ES to facilitate both arm and hand function in tetraplegics [103]. Another novel hand system currently being investigated is the contralaterally controlled NMES glove [104]. This system uses two gloves, and the wearer performs movements with the intact hand at will that are subsequently replicated with ES embedded within the glove worn on the paralyzed hand. A recent study with 21 post-stroke patients show that the system has the potential to improve finger and hand movements for function

when used over a 6-week training period [105]. This device was also modified as a sock for use with stroke patients to improve ankle dorsiflexion as well [106-107].

REHABILITATION BENEFITS OF FES

As previously mentioned, FES is the process of combining electrical stimulation with a functional task such as walking, cycling, or grasping objects for a number of rehabilitative purposes and across differing diagnoses. FES has demonstrated the capacity for strengthening muscles [58,108], enhancing circulation and blood flow [109-111], reducing pain [112,113], healing tissue [114,115], retarding muscle atrophy [107,116], and reducing spasticity [117,118].

Although FES is applied peripherally, many have suggested that through modification of stimulation, central mechanisms can be activated as well. Although neuromuscular electrical stimulation creates muscle tetany through motor fiber activation, sensory fibers are also stimulated and evidence has shown that improvements in sensation and tactile awareness are common following implementation of a motor stimulation program [119]. Voluntary effort contractions can be performed by the client during the rest periods in the FES programs, alternating with the stimulated contractions; therefore, the regimen incorporates cognitive and motor learning skills as well. Several studies demonstrate the benefit of using neuromuscular electrical stimulation to facilitate improved arm and hand use [120-123], but when electrical stimulation is combined with adjuvant therapies such as voluntary movement or task based training, results are even more robust [20,124]. Finally, participants can be psychologically motivated by experiencing the sensation of active muscle movement through stimulation with the FES systems [125].

CONCLUSIONS AND OUTLOOK

Electrical stimulation is a modality used for the rehabilitation of persons with neuro-logical damage. It is effective for improving muscle strength, blood flow, decreasing atrophy, healing tissue, and decreasing pain. However, the biggest challenge of FES is fatigue of the working muscle. Although electrical stimulation has the capacity to produce movement in denervated, paralyzed, or spastic muscles, it is inherently less efficient than human movement. Most importantly, NMES induces excessive neuromuscular fatigue. Researchers have studied frequency, pulse width, modulation of pulses, amplitude, electrode placement, and the use of variable frequency pulse patterns to determine if fatigue can be reduced through a modification of any of these parameters. Several systems are available on the market, and new systems are continuously being developed. Additionally, it will be important to establish if NMES can provide long-lasting, functional changes in persons with profound motor limitations. In the future, we may find that a hybrid of FES and robotics may be the most efficient for providing continuous locomotion or performance of vital activities of daily living in individuals with paralysis.

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