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Neuromuscular Electrical Stimulation for Motor Restoration in Hemiplegia

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Synopsis

This article reviews the most common therapeutic and neuroprosthetic applications of neuromuscular electrical stimulation (NMES) for upper and lower extremity stroke rehabilitation. Fundamental NMES principles and purposes in stroke rehabilitation are explained. NMES modalities used for upper and lower limb rehabilitation are described and efficacy studies are summarized. The evidence for peripheral and central mechanisms of action is also summarized.

Keywords

stroke rehabilitation; upper limb hemiplegia; neuroplasticity; medical device; electrical stimulation therapy

Introduction

Motor impairment is common after stroke and directly impacts the stroke survivor's function and quality of life. Neuromuscular electrical stimulation (NMES) may reduce disability by improving recovery of volitional movement (therapeutic effect) or by assisting and replacing lost volitional movement (neuroprosthetic effect). This article describes

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NMES treatment modalities for upper and lower limb stroke rehabilitation and summarizes the research literature regarding the therapeutic and neuroprosthetic efficacy of those modalities. The scope of this article is limited to NMES interventions that produce limb movement by direct stimulation of the peripheral nerves or motor points of target muscles for the purpose of restoring motor function, and therefore does not cover somatosensory electrical stimulation,[1] electrical stimulation for post-stroke shoulder pain,[2] or brain stimulation modalities.[3]

NMES Fundamentals

NMES is the use of electrical current to produce contractions of paralyzed or paretic muscles. Lower motor neurons to target muscles must be intact for NMES to effectively produce muscle contractions; therefore, NMES is usually only applicable to patients whose paralysis or paresis is caused by upper motor neuron injury (e.g., stroke, spinal cord injury, etc.). NMES can be applied to paretic muscles with surface electrodes positioned on the skin over the motor points of target muscles, or with electrodes that are implanted near or on the muscle motor points or nerves that innervate target muscles. The electrical current generated by most NMES devices can be characterized as a waveform of pulses having a particular pulse frequency, width, and amplitude. The strength of evoked muscle contraction can be modulated by adjusting the pulse parameters. Typically, the stimulation frequency is set between 12 to 50 Hz, and the strength of muscle contraction is modulated by changing either the pulse amplitude (typically 0 to 100 mA) or pulse width (typically 0 to 300 μsec).

An NMES device fundamentally consists of electrodes that are connected to a stimulator, and a controller (Fig. 1). A pair of electrodes constitutes a stimulus channel. Surface (i.e., transcutaneous) electrodes, percutaneous intramuscular wire electrodes, and implanted epimysial, intramuscular, or nerve cuff electrodes may be used. The stimulator (i.e., pulse generator) may have a controller built into it or have a separate controller attached or wirelessly linked to it. The controller regulates the timing and intensity of stimulation delivered through one or multiple stimulus channels. Input to the stimulator’s controller may be via buttons, switches, and/or various types of external or implanted sensors or recording (e.g., electromyographic) electrodes.

Purposes of NMES for Upper and Lower Limb Rehabilitation after Stroke

Paresis is the inability or decreased ability to volitionally activate motor units and is one of the most common manifestations of stroke.[4] Clinically, paresis presents as muscle weakness and reduced speed of activation, and the inability to generate functionally useful movement of the involved limb. Lang and associates studied the relative strengths of the associations between specific upper limb impairments and function, and concluded that paresis was the strongest contributor to the loss of function.[5] In the upper limb, the combination of paresis, loss of fractionated movements, flexor hypertonia, and somatosensory abnormalities often manifests as difficulty extending the elbow and opening the hand in a functional manner, which severely limits the functional workspace. At six months post-stroke about 65% of patients still cannot incorporate the affected arm and hand into their daily activities.[6]

Therefore, NMES for upper limb stroke rehabilitation is usually applied to elbow, wrist, and/or hand extensor muscles.

In the lower limb, paresis, along with the inability to grade muscle contractions, poor motor coordination, poor endurance, spasticity, and impaired balance have significant consequences on ambulation.[7] At six months post-stroke approximately 30% of stroke survivors are unable to walk unassisted.[8] A major contributor to impaired ambulation is the inability to dorsiflex the ankle during the swing phase of gait. Diminished ankle dorsiflexion, knee flexion, or hip flexion can result in inability to clear the floor with the affected limb during the swing phase of gait, resulting in difficult and unsafe ambulation or nonambulation. Patients frequently use compensatory strategies such as circumduction, hip-hiking, or vaulting to clear the toes. An ankle-foot-orthosis (AFO) is the standard of care for footdrop, but because AFOs limit ankle mobility they may actually inhibit recovery of dorsiflexion. Therefore, NMES has been used to improve ankle dorsiflexion and a more normal gait pattern.

Various NMES modalities have been used for upper and lower limb motor relearning after stroke. Motor relearning is defined as the reacquisition of motor skills following central nervous system injury. NMES can be used as a motor relearning tool by enabling stroke survivors with significant paresis to participate in goal-oriented repetitive movement therapy. The NMES-mediated task must be repetitive, novel, volitionally controlled, and functionally relevant.[9–11] While the stroke survivor may use an NMES motor relearning system to assist execution of daily activities, its primary intent is training, such that improved functional use of the hemiparetic limb is maintained when the system is *not being used*. Improved upper limb function or ambulation that remains after an NMES device has been used is called a *therapeutic effect.*

For patients who are in the chronic phase of stroke and in whom motor relearning strategies have been exhausted, NMES may be used as a neuroprosthesis. The primary intent of a neuroprosthesis is to enable patients to execute functional tasks with the affected upper limb or walk *while using the device* as part of routine daily living. Improved function that is realized while using an NMES device is called a *neuroprosthetic effect*.

NMES Modalities for Upper Limb Rehabilitation

Cyclic NMES uses a one- or two-channel stimulator to activate the wrist and/or finger and thumb extensors in a repetitive (cyclic) fashion via surface electrodes placed on the forearm over the motor points of those muscles. Cyclic NMES devices typically have a menu of on/off cycle settings from which to choose. Once the device is set up and switched on, the stimulation automatically ramps on and off according to a selected duty cycle, with the patient not having to exert any simultaneous effort. The patient does not control the timing or intensity of cyclic stimulation (Table 1); therefore, this modality is not typically used to mediate functional task practice.

Cyclic NMES has been shown in several randomized controlled trials (RCTs) of *acute and subacute* hemiplegic patients to reduce upper limb motor impairment (e.g., increase in strength, upper limb Fugl-Meyer score, etc.) relative to controls.[12–16] Some studies reported an enduring effect over 2 to 6 months,[12,13,15,16] while others found that the effect was not sustained beyond the treatment period.[14] Some studies found that the positive effects on impairment did not translate to significant improvements in basic self-care tasks or upper limb function (i.e., functional independent measure (FIM) score, action research arm test (ARAT)) relative to controls,[13,14] while other studies did show significant, though sometimes transient, improvements in function relative to controls.[12,17] The beneficial effects of cyclic NMES seem to be more apparent in patients who have some residual movement at baseline.[12,18] In a study of 95 subacute patients, initial motor severity (i.e., baseline Fugl-Meyer score) was identified as the most significant predictor of improvement in upper limb function after 4 weeks of cyclic NMES.[17] Studies of cyclic NMES in *chronic* hemiplegia have typically been relatively small case series designs (i.e., no control group), but have also demonstrated improvements in various upper limb motor impairment measures.[18,19]

EMG (electromyographic)-triggered NMES attempts to make stimulated hand opening coincide with the patient's own effort to open the hand. Surface EMG recording electrodes are placed over the wrist and/or finger extensors of the paretic side to detect EMG signals when the patient attempts to open the hand. When the processed EMG signal surpasses a pre-set threshold, electrical stimulation ramps on to a pre-set stimulation intensity that produces full hand opening. After several seconds the stimulation turns off and the patient is prompted with visual and/or audio cues to try to open the hand again, repeating the EMG-triggered NMES cycle. Thus, EMG-triggered stimulation facilitates repetitive and volitionally initiated exercises of the hemiparetic upper extremity and provides cutaneous and proprioceptive feedback time-locked to each attempted movement,[20] which may be important for motor relearning.[21] Like cyclic NMES, EMG-triggered NMES is not typically used to mediate functional task practice because the intensity and duration of stimulation are not controlled by the patient (Table 1). And because EMG-triggered NMES requires the patient to be able to produce discernable EMG signals consistently, it may not be applicable to the most severely impaired patients.[21]

EMG-triggered NMES has been shown to improve upper limb motor *impairment*. An early case series study of 69 chronic patients reported improvement in wrist active range of motion and extensor EMG activity in response to EMG-triggered NMES integrated with conventional therapy.[21] The participants who received a greater dosage (i.e., sessions per week) of EMG-triggered NMES had greater increases in voluntary extensor EMG amplitude. RCTs in chronic hemiplegia also show that EMG-triggered NMES improved performance on one or more measures of motor impairment (e.g., Fugl-Meyer score, Box and Blocks score, extensor and grip strength) as compared to conventional therapy, though not all studies agree on which outcomes improve relative to controls.[22–25] Most of the trials in chronic patients did not assess upper limb *function* (i.e. activity limitation) or the persistence of effect. In acute and subacute patients, a RCT showed greater improvement on impairment measures but not on upper limb function relative to conventional therapy,[20] but another study showed the opposite – improvement on function (i.e., ARAT) but not on impairment measures relative to usual care.[26] Nearly all of the RCTs of EMG-triggered NMES have had small sample sizes (i.e., < 10 per group), and like cyclic NMES, the improvements relative to controls are generally modest and of questionable clinical relevance.

Although EMG-triggered NMES might be expected to improve upper limb movement and function more than cyclic NMES,[27] several RCTs that directly compared the two treatments showed no significant difference in the outcomes of cyclic and EMG-triggered NMES, whether in chronic[28,29] or subacute[30,31] subjects. Explanations for why no differences in outcomes were found between cyclic and EMG-triggered NMES include: 1) EMG-triggered NMES may not require enough active involvement (i.e., patients only trigger stimulation, not control duration or intensity) to create a large enough contrast with cyclic NMES,[28] 2) the cyclic NMES group may have also been exerting effort during stimulation, further reducing the contrast between the two treatments,[28] 3) with EMG-triggered NMES, any time delays between the attempt to extend the wrist and fingers and the initiation of stimulation may negate any neurophysiological advantage the treatment might have had over cyclic NMES.

Switch-triggered NMES is a modality intended to facilitate functional task practice. Switches (or button presses) allow the patient[32] or therapist[33] to control both the initiation and termination of stimulation sequences (i.e., the timing of the stimulated movement, Table 1) with button presses so that the device can be used in assisting task practice during therapy sessions.[34] The intensity of stimulation is not controlled by the patient, but is pre-set. The Bioness H200 (Bioness Inc., Valencia, CA) is an example of a switch-triggered device that stimulates finger and thumb extensors and flexors through surface electrodes that are mounted inside a wrist-forearm orthosis, which also houses the stimulator. The patient turns stimulation on and off to the extensors and flexors by pressing buttons on a separate control unit with their unaffected hand. Stimulation sequences that produce different hand opening and closing postures can be programmed and selected to match the task to be performed. Significant therapeutic effects were reported on several measures of motor impairment (e.g., Box and Blocks score, Ashworth score) and function (e.g., timed Jebsen-Taylor Hand Function tasks) in chronic patients after 5 weeks of home exercise and task practice with the Bioness H200.[35] Several follow-up RCTs in acute[34,36] and subacute[32] patients found that switch-triggered NMES with therapy had greater improvements than therapy alone on measures of spasticity, wrist extension, Box and Blocks score, Fugl-Meyer score, and timed tasks. Although the Bioness H200 can be used as a neuroprosthesis and has been shown to have a significant neuroprosthetic effect,[37] it is typically used and studied as a motor relearning tool.

Another switch-triggered NMES approach uses stimulation only as needed to assist first with repetitive reaching tasks (stimulating shoulder and elbow muscles), and then with grasping tasks (stimulating wrist, finger, and thumb muscles), progressively decreasing the use of NMES as the patient improves.[38] The treating therapist uses button switches to activate the stimulation sequences that are needed to perform tasks. Greater therapeutic effects were measured in acute patients who had 12–16 weeks of this switch-triggered NMES approach as compared to patients who received conventional task-specific occupational therapy.[33]

Sensor- and EMG-*controlled* NMES modalities use controllers that are designed to let the patient control the timing *and* intensity of stimulation to their hand in a way that can be fluid with task practice, which may result in greater sensorimotor integration and superior motor relearning (i.e., therapeutic effects). Such systems may also be suitable as neuroprostheses to assist with activities of daily living. Indeed, the earliest NMES devices for upper limb stroke rehabilitation used a sensor mounted to the contralateral shoulder to let the patient proportionally control the intensity of stimulation to the forearm extensors as they practiced tasks.[39] Electrogoniometers, bend sensors, touch-sensitive mats, and accelerometers are among the external sensors that have been incorporated into NMES systems for upper limb stroke rehabilitation.[40–43] Researchers also continue to explore the use of EMG signals from the impaired upper limb to not merely *trigger* the onset of a pre-set intensity and duration of stimulation, but to *control* the intensity and timing of stimulation.[44,45] A challenge for EMG-controlled NMES modalities is that the effort required from the patient to contract the muscle that operates the controller may induce flexor synergies or hypertonia, which can overpower the electrical stimulation of extensors and result in reduced degrees of stimulated hand opening.[44,46]

Contralaterally controlled NMES is a unique version of sensor-controlled stimulation that uses movement from the unimpaired side to control the timing and intensity of stimulation to the paretic side (Table 1).[43] The hand system consists of a glove with bend sensors worn on the *non-paretic* hand and a multi-channel stimulator that delivers stimulation to the *paretic* hand extensors with an intensity that is proportional to the degree of opening of the glove (Fig. 2). This modality enables repetitive hand opening exercise and functional task practice with the paretic hand. The control strategy gives the user intimate proportional control of the stimulation intensity without requiring any residual movement or EMG signals from the paretic hand. Therefore, the likelihood of triggering flexor synergy patterns may be less than sensor-controlled or EMG-controlled stimulation devices that require control signals from the paretic limb. Contralaterally controlled NMES produced larger improvements in maximum voluntary finger extension and other measures of upper extremity impairment and activity limitation than cyclic NMES in a RCT of subacute patients.[47]

NMES Modalities for Lower Limb Rehabilitation

Cyclic, EMG-triggered, and contralaterally controlled NMES applied to paretic lower limb muscles while the subject is seated or side-lying have been evaluated for therapeutic effects. In a randomized placebo-controlled trial of 46 acute hemiplegic subjects, cyclic NMES was applied to the quadriceps, hamstring, tibialis anterior, and medial gastrocnemius in an activation sequence that mimicked normal gait while the subjects were side-lying with their lower extremity supported by a sling.[48] Significantly greater improvement in ankle dorsiflexion torque and EMG activity and significantly less spasticity and co-contraction were demonstrated after 3 weeks of multi-channel cyclic NMES as compared to the control group. Also, a significantly greater percentage of subjects in the cyclic NMES group were able to complete a timed walking task by the end of the 3-week treatment and 5 weeks later as compared to the control group. EMG-triggered NMES of paretic ankle dorsiflexors has been shown to have positive effects on ankle strength, range of motion, balance, and ambulation in chronic patients.[21,49,50] Contralaterally controlled NMES, where the patient controlled the intensity of stimulation to the paretic ankle dorsiflexors by dorsiflexing their non-paretic ankle while seated, was first tested in a case series[51] and later in an RCT.[52] Contralaterally controlled NMES was shown to increase lower extremity Fugl-Meyer score, maximum dorsiflexion angle and moment while seated, and performance on the modified Emory Functional Ambulation Profile in chronic patients, but not more than cyclic NMES.

Applying NMES to the paretic ankle dorsiflexors (i.e., peroneal nerve) *during* the swing phase of gait was first described by Liberson and associates in 1961.[53] The common peroneal nerve was stimulated with a pair of electrodes, one placed just below the head of the fibula and the other over the tibialis anterior. A heel switch worn in the shoe of the paretic side turned the stimulation on when the foot was lifted off the ground, and turned the stimulation off at heel strike and during the stance phase of gait. Currently there are 3 FDA approved surface electrode NMES systems for preventing footdrop during gait: the Odstock Dropped-Foot Stimulator (Odstock Medical Limited, Salisbury, UK), WalkAide (Innovative Neurotronics Inc., Austin, TX), and Bioness L300 Footdrop System (Bioness Inc., Valencia, CA). These devices utilize either a heel switch or a tilt sensor below the knee to synchronize the timing of stimulation to the swing phase of gait (Fig. 3).[54,55] Two multi-channel footdrop systems with implanted electrodes and stimulator have the CE mark in Europe. One is a dual-channel device developed by the University of Twente (Netherlands) that stimulates the deep and superficial branches of the common peroneal nerve for better control of ankle dorsiflexion, eversion, and inversion.[56] The other is a fourchannel device, developed at Aalborg University (Denmark) and utilizes a 4-channel nerve cuff electrode surgically placed around the common peroneal nerve.[57]

Peroneal nerve stimulation (PNS) during gait has positive neuroprosthetic and therapeutic effects on ambulation. *Neuroprosthetic* effects have been shown in a number of case series studies and several RCTs, with outcome measures ranging from gait kinematic and spatio-temporal parameters to metabolic cost indices.[54,55,58–60] According to a systematic review, there is a positive neuroprosthetic effect of PNS on walking speed.[61] A recent multicenter clinical trial of 99 chronic patients showed that after 42 weeks of PNS during gait, 67% of participants had a gain of ≥ 0.1 m/sec (the minimal clinically important difference) in comfortable gait speed when walking with PNS.[62] *Therapeutic* effects associated with PNS during gait have also been observed since the earliest studies. That is, PNS during gait produces not only positive neuroprosthetic effects (i.e., the effects on gait observed when the stimulator is on), but also “carry-over” or therapeutic effects after the device has been turned off. Such effects have been observed in multiple case series studies, and include improvements in ambulation function, normalization of EMG muscle activation patterns, emergence of EMG signals in previously silent muscles, and decreased co-contraction of antagonist muscles.[53–55,63–68] After 30 weeks of PNS during gait, 29% of 99 chronic stroke patients had a therapeutic effect on comfortable walking speed of ≥ 0.1 m/sec.[62]

The research on PNS during gait has progressed to RCTs comparing the effects of PNS to standard of care, which is an ankle-foot-orthosis (AFO). In order for PNS to challenge standard of care practice, definitive evidence would be necessary to show that PNS provides either an equivalent neuroprosthetic effect on walking or a superior therapeutic effect restoring volitional gait. Four large clinical trials have recently been published comparing PNS to AFO. Sheffler et al. compared the therapeutic effects of 12 weeks of PNS and AFO on lower limb impairment, ambulation, and quality of life in 110 chronic patients and found significant but similar *therapeutic* effects on ambulation and quality of life from both PNS and AFO.[69] Kluding et al. compared the effects of 30 weeks of PNS and AFO in 197 chronic patients and found both groups to improve similarly on walking speed with their assigned device (*neuroprosthetic* effect). They also noted significant but similar *therapeutic* effects on walking speed for both groups.[70] Everaert et al. enrolled 121 patients who were less than 1 year post-stroke and found similar improvements in walking speed between PNS and AFO groups.[71] Bethoux et al. reported a 30-site study that enrolled 495 chronic stroke patients who wore a PNS device or an AFO for 6 months.[72] Both groups had significant improvements in gait velocity while wearing their device (AFO or PNS), but no between-group differences were found.

Based on these four large RCTs, PNS during gait for 12–30 weeks can have significant therapeutic effects on functional mobility and walking speed. Wearing the PNS device can further increase walking speed and walking endurance beyond the therapeutic effects. However, no significant differences were found between PNS and AFO on walking speed or functional ambulation, although questionnaires showed that patients preferred PNS over AFO with respect to long-term use, all-day use, confidence on inclines, and ease of donning/doffing.[71]

Since gait deviation in hemiplegia is not limited to ankle dysfunction, multichannel stimulation systems have been investigated for therapeutic effects. Early work used surface electrodes and demonstrated improvements in qualitative and quantitative measures of gait after training with a 6-channel surface system that activated ankle dorsiflexion and plantarflexion, knee flexion and extension, and hip extension.[73,74] However, as the number of electrodes increases, surface systems become increasingly difficult to implement due to difficulty of donning and doffing of multiple electrodes, pain of stimulation, and poor repeatability of electrode placement and muscle contractions. Therefore, multichannel percutaneous systems have also been explored for motor relearning.[75] A single-blinded RCT of 32 chronic stroke patients demonstrated that multi-channel percutaneous NMES-mediated ambulation training in combination with body-weight supported treadmill training (BWSTT) improved gait components and knee flexion coordination more than BWSTT without NMES,[76] and that the gains were maintained at 6 months post-treatment.[77]

Peripheral and Central Effects of NMES in Stroke Rehabilitation

The mechanisms by which NMES reduces motor impairment and activity limitation have not been fully elucidated, but therapeutic effects are probably due to a combination of peripheral and central effects. Peripheral effects of NMES include increase in contractile force and fatigue resistance,[78,79] increase in muscle mass,[80] reduction of edema,[81] conversion of fast-twitch fast-fatiguing glycolytic type II muscle fibers to slow-twitch fatigue-resistant oxidative type I muscle fibers,[79] and enhanced hyperemic arterial response and endothelium-dependent cutaneous vasodilation.[82] These peripheral effects can reverse disuse atrophy and may explain in part some improvements stroke patients experience after various NMES treatments.

Some NMES treatments may also affect the central nervous system and how it controls movement. For example, NMES may promote motor relearning by uniquely providing an artificial way of ensuring synchronized presynaptic and postsynaptic activity (Hebbian plasticity), especially if the electrical stimulation is paired with simultaneous voluntary effort that activates the residual upper motor neurons.[83] Indeed, cortical excitability, as assessed by measuring motor evoked potentials in response to transcranial magnetic stimulation, has been shown to increase more when NMES is paired with voluntary muscle contraction than with NMES alone.[84] This finding suggests that the effect of NMES on cortical excitability is improved by concurrent voluntary cortical drive. Whether the increase in cortical excitability is due to changes at the spinal level, cortical reorganization, or both is unclear. Several researchers have hypothesized that EMG-triggered NMES may produce functional cortical reorganization by inducing long-term potentiation in sensorimotor cortex caused by proprioceptive and cutaneous afferent feedback occurring concurrently with attempted movements.[20,21,23] A regimen of EMG-triggered NMES to the upper extremity has been shown to increase metabolic activity (measured by positron emission tomography) in the *contralesional* supplementary motor area, primary motor cortex, and primary somatosensory cortex,[85] and to increase the intensity of hand related cortical activity (measured by fMRI) in *contralesional* somatosensory cortex.[24] In contrast, a shift in the laterality index toward the *ipsilesional* sensorimotor cortex was shown after EMG-triggered NMES,[22] and brain cortical perfusion (measured by near-infrared spectroscopy) was greater in the *ipsilesional* sensorimotor cortex *during* EMG-controlled NMES than during cyclic NMES or voluntary attempts to extend the wrist and fingers.[86]

There is also evidence that NMES when unpaired with voluntary effort may produce changes in the brain. For example, progressively increasing the intensity of surface NMES of the quadriceps muscle from sensory threshold to maximum motor response produced proportional increases in cortical activity in specific areas of interest, including primary somatosensory and motor cortices, as shown by fMRI.[87] Another study showed that stimulation of the common peroneal nerve at 25Hz with intensities above motor threshold for 30 minutes while seated at rest increased the motor-evoked potential (MEP) in the tibialis anterior by 50% at a transcranial magnetic stimulation (TMS) intensity that initially gave a half-maximum MEP. This effect was evident after 10 minutes of stimulation and persisted for at least 30 minutes after stimulation ended.[88] Follow-up experiments provided evidence that the increase in excitability did not occur at the level of motorneurons, but rather at the cortical level.[88,89] Long-term use of a footdrop stimulator has been found to increase both MEPs elicited by TMS and maximum voluntary contraction of the tibialis anterior in stroke patients, evidence that regular use of a PNS device strengthens activation of motor cortical areas and their residual descending connections.[90]

These and other studies provide mounting evidence that there is a cortical component to NMES, but more studies are needed to elucidate the precise mechanisms at work under specific NMES modalities and patient characteristics.

Emerging Directions for NMES in Stroke Rehabilitation

New NMES techniques for upper and lower limb stroke rehabilitation continue to be developed, especially those that use sensors to trigger stimulation when patients achieve some minimum volitional movement.[42,91,92] It is highly doubtful that any single NMES modality used in isolation from other motor rehabilitation therapies will lead to substantial motor recovery. Therefore, there is a growing trend toward combining NMES with other emerging therapeutic strategies that have shown promise. Examples include combining NMES with mirror therapy,[93] repetitive transcranial magnetic stimulation,[94] constraint-induced movement therapy,[95] robot-assisted movement therapy,[96] motor imagery,[30,85] bilateral movement training,[97] virtual reality games,[98] transcranial direct current stimulation,[99] and body-weight-supported treadmill training.[77,100] Perhaps the best stroke rehabilitation program would have a defined sequence of therapies and combination therapies that become suitable for stroke patients as they progress from severe impairment to complete motor recovery, NMES being an important component in the slate of rehabilitation therapies and techniques.

At the present time, a clinically viable upper extremity neuroprosthesis for daily long-term use as an assistive device is not available for persons with hemiparesis. Implantable microstimulator[40,101] or multi-channel implantable pulse generator[44] approaches may be suitable for stroke patients who have been carefully screened for prohibitive flexor hypertonia. But most patients will not be able to realize a robust neuroprosthetic effect unless a means of suppressing flexor hypertonia is incorporated. Emerging technology that uses nerve cuff electrodes to deliver high-frequency stimulus waveforms to block action potentials in nerves may prove capable of suppressing hypertonia.[102] Adding such spasticity suppressing stimulation to an NMES system could considerably improve its neuroprosthetic effect and widen its applicability.

As more NMES modalities and technology continue to emerge, more clinical research studies will be needed. With some exceptions, most of the NMES efficacy studies to date have been relatively small and therefore limited in power to make strong conclusions. Large RCTs comparing different NMES modalities as well as comparing NMES to standard of care are still needed. Studies aimed at elucidating the mechanisms of NMES-mediated recovery (i.e., specific effects on the CNS) could lead to treatment optimization. Also studies are needed to define optimum treatment dose and the most likely responders for any given NMES modality.

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Key Points

- Hemiparesis following stroke is associated with significant upper and lower limb impairment, activity limitation, and reduced quality of life
- Neuromuscular electrical stimulation as a motor relearning tool reduces upper and lower limb motor impairment following stroke
- Neuromuscular electrical stimulation as a neuroprosthesis improves ambulation function of stroke survivors, but not more than standard of care ankle-foot-orthoses.
- Research is needed to more firmly establish the effects of electrical stimulation on upper limb activity limitations and quality of life.
- The benefit of upper limb neuromuscular electrical stimulation modalities relative to alternative therapies or standard of care remains to be fully elucidated.

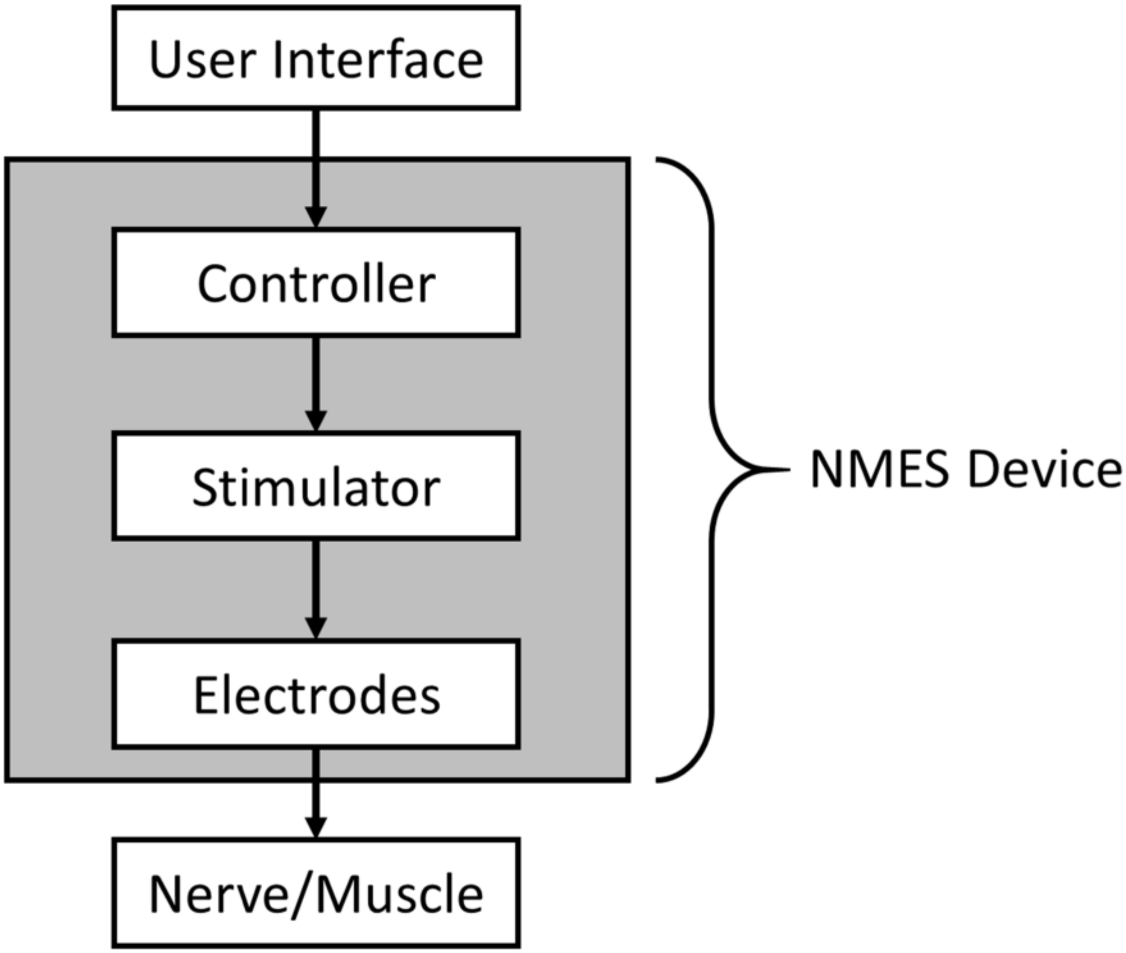

Figure 1.
Diagram of a basic neuromuscular electrical stimulation (NMES) device.

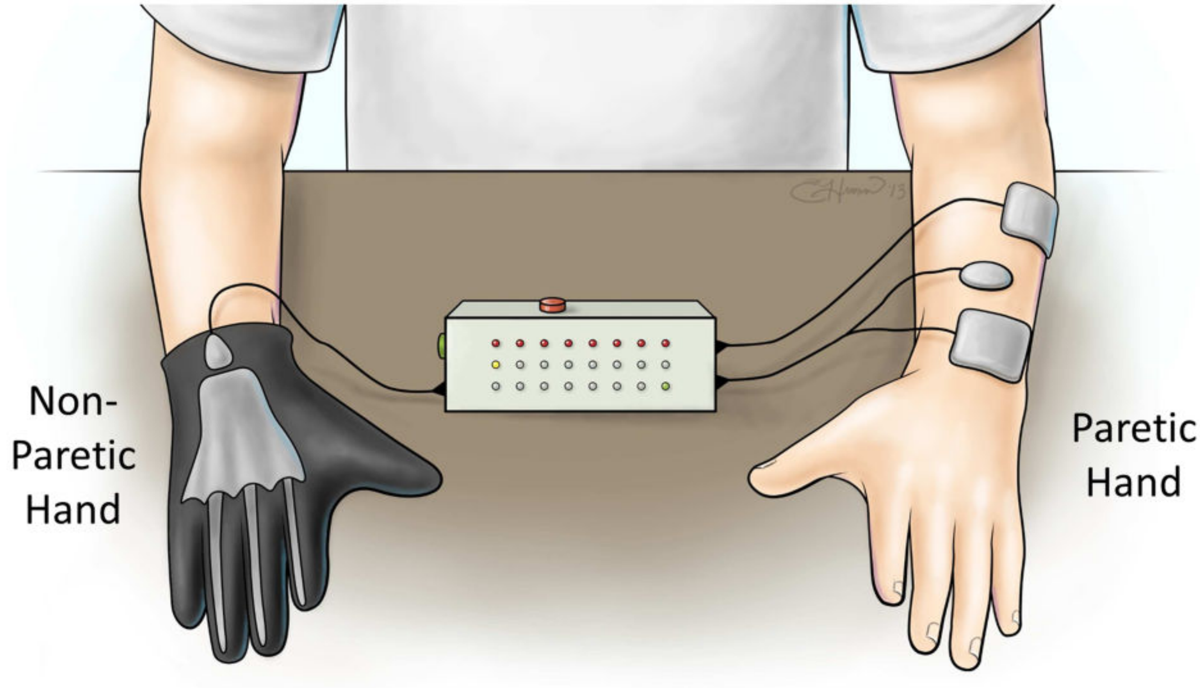

Figure 2.

Contralaterally Controlled NMES System, an example of a sensor-controlled NMES modality. Volitional opening of the non-paretic hand wearing an instrumented glove produces a proportional intensity of stimulation to the paretic hand, giving patients control of the timing and intensity of NMES.

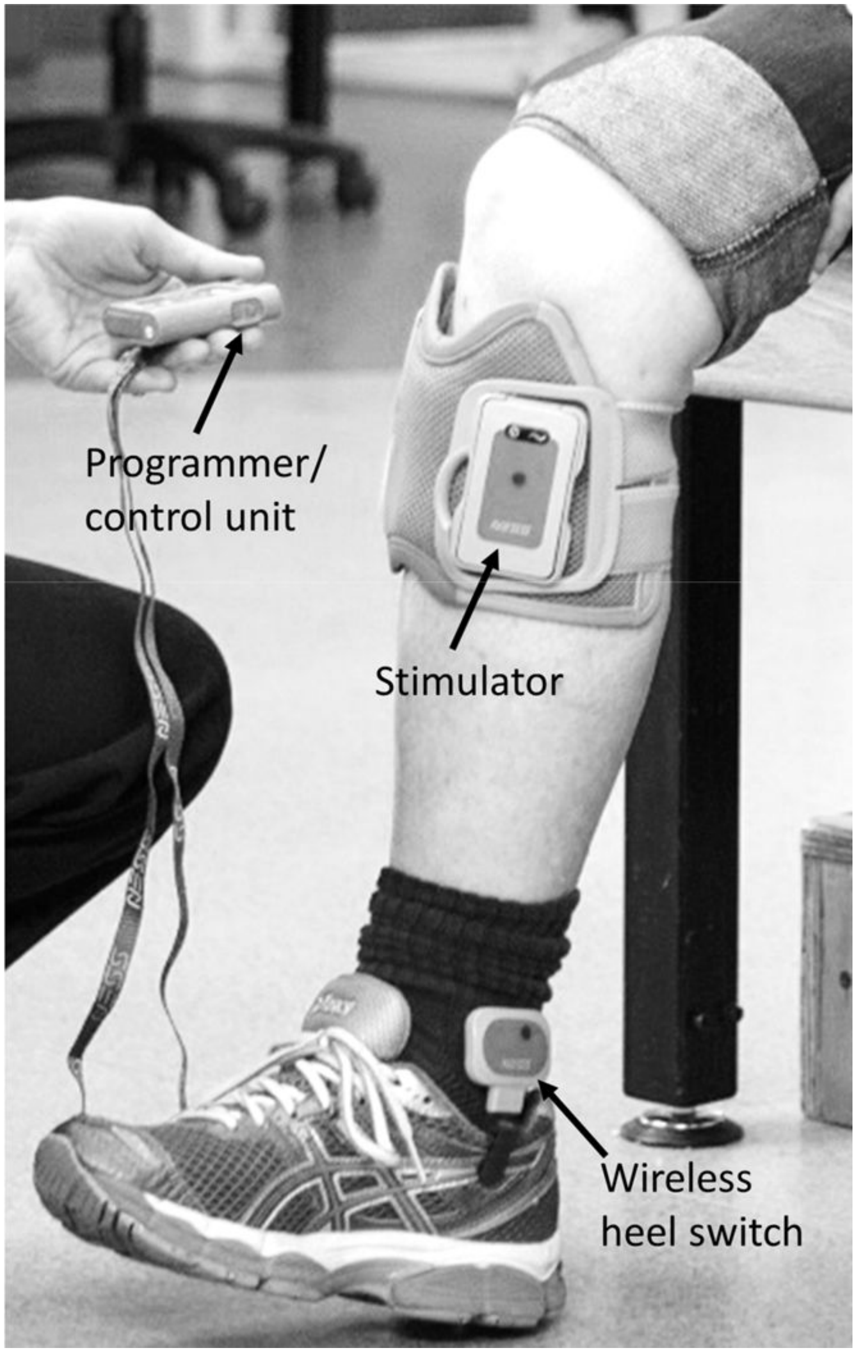

Figure 3.

Example of a peroneal nerve stimulator with a wireless heel switch for dorsiflexing the paretic ankle during gait. (Photograph shows the Bioness L300® Foot Drop System).

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Table 1

Degree of Patient Control for Different Upper Limb NMES Modalities

Patient has real-time control of:	Cyclic NMES	EMG-triggered NMES	Switch-triggered NMES	Contralaterally Controlled NMES
Timing of NMES	No	Onset only	Yes	Yes
Intensity of NMES	No	No	No	Yes