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REVIEW

Do Electrical Stimulation Devices Reduce Pain and Improve Function?—A Comparative Review

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ABSTRACT

Background: Multiple forms of electrical stimulation (ES) potentially offer widely varying clinical benefits. Diminished function commonly associated with acute and chronic pain lessens productivity and increases medical costs. This review aims to compare the relative effects of various forms of ES on functional and pain outcomes.

Methods: A comprehensive literature search focused on studies of commonly marketed forms of ES used for treatment of pain and improvement of function. Peer-reviewed manuscripts were categorized as "Important" (systematic review or meta-analysis, randomized controlled trial, observational cohort study) and "Minor" (retrospective case series, case report, opinion review) for each identified form of ES.

Results and Discussion: Varying forms of ES have markedly different technical parameters, applications, and indications, based on clinically meaningful impact on pain perception, function improvement, and medication reduction. Despite being around for decades, there is limited quality evidence for most forms of ES, although there are several notable exceptions for treatment of specific indications. Neuromuscular electrical stimulation (NMES) has well-demonstrated beneficial effects for rehabilitation of selective spinal cord injured (SCI), post-stroke, and debilitated inpatients. Functional electrical stimulation (FES) has similarly shown effectiveness in rehabilitation of some stroke, SCI, and foot drop outpatients. H-Wave® device stimulation (HWDS) has moderate supportive evidence for treatment of acute and refractory chronic pain, consistently demonstrating improvements in function and pain measures across diverse populations. Interestingly, transcutaneous electrical nerve stimulation (TENS), the most widely used form of ES,

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demonstrated insignificant or very low levels of pain and functional improvement.
Conclusion: Ten of 13 reviewed forms of ES have only limited quality evidence for clinically significant reduction of pain or improvement of function across different patient populations. NMES and FES have reasonably demonstrated effectiveness, albeit for specific clinical rehabilitation indications. HWDS was associated with the most clinically significant outcomes, in terms of functional improvement combined with reduction of pain and medication use. More rigorous long-term clinical trials are needed to further validate appropriate use and specific indications for most forms of ES.
Level of Evidence: II.

Keywords: Chronic pain; Function; Effectiveness; Electrical stimulation; Neuromuscular electrical stimulation; Functional electrical stimulation; H-Wave®; H-Wave device stimulation; Transcutaneous electrical nerve stimulation

Key Summary Points

Evidence quality remains low for clinically significant effectiveness of many forms of electrical stimulation (ES).

Insignificant or low levels of improvements in pain and function have been consistently reported for some forms of ES [e.g., transcutaneous electrical nerve stimulation (TENS)].

Neuromuscular electrical stimulation (NMES) and functional electrical stimulation (FES) are supported by moderate quality evidence for rehabilitation of stroke, spinal cord injury (SCI), debilitation, and nerve dysfunction.

H-Wave® device stimulation (HWDS) has moderate quality evidence for functional improvement with reduction of pain and medication use in acute and chronic pain conditions.

INTRODUCTION

Chronic pain, defined as a minimum of 3 months duration, is a major source of worldwide suffering, interfering with activities of daily living and overall functioning [1, 2]. The US Centers for Disease Control has estimated the national prevalence of chronic pain to possibly be as high as 40% [3, 4]. While perception of acute pain appropriately notifies the body of imminent danger, chronic pain involves disruptive neural signals which compromise function and lead to debilitation. Chronic pain often results in inability to work and lowers self-esteem, leading to disturbing life events, including a high incidence of divorce and even suicide [5–8]. Within the US an estimated US$560 billion per year in lost productivity has been attributed to the effects of chronic pain [9].

Widely applied treatment regimens for chronic pain promote medications like non-steroidal anti-inflammatory drugs and opioids [10], while non-pharmacological treatment options include physical therapy, exercise, cognitive behavioral therapy, invasive interventions like nerve blocks/ablation, and complementary and alternative medicine, including acupuncture [11–15]. Multimodal regimens are reasonably effective through various treatment combinations. Some pharmacological treatments have disturbing side effects, particularly addiction and overdose with long-term opioids use [10, 16]. With the North American "opioid epidemic", there is a dire need for less toxic treatment options which target primary sources of pain generation [17, 18].

Several forms of ES stimulate muscles that may be atrophied by disuse or neurological compromise and are intended primarily for functional rehabilitation and training. These include neuromuscular electrical stimulation (NMES), functional electrical stimulation (FES), and electrical muscle stimulation (EMS). Numerous other forms of ES emit widely varying electrical pulses and current into and beneath the skin over a painful anatomical target, to reduce pain and/or improve function in a potentially safer and more physiological

manner than with drugs. These electrotherapies, primarily intended for pain and/or to improve function and applied stand-alone or as adjuncts, include transcutaneous electrical nerve stimulation (TENS), H-Wave® device stimulation (HWDS), interferential current (IFC) or therapy (IFT), noninvasive interactive neurostimulation (NIN), pulsed magnetic field therapy (PMFT) or pulsed electromagnetic field therapy (PEMF) or pulsed electrical stimulation (PES), galvanic current stimulation (GCT) or direct current (DC), microcurrent electrical nerve stimulation (MENS), percutaneous electrical nerve stimulation (PENS), percutaneous neuromodulation therapy (PNT) or peripheral nerve stimulation (PNS) or peripheral nerve field stimulation (PNFS), and transcranial direct current stimulation (tDCS).

Most of these forms of ES are non-invasive or subcutaneous modalities, each designed to either reduce pain and improve function or to assist with rehabilitation and training [19]. There is an urgent need for such innovative modalities and treatment paradigms, based on best available clinical evidence, to improve and maximize overall patient outcomes and healthcare. The purpose of this scoping, comparative review is to critically analyze the literature regarding the relative effectiveness of currently available forms of ES, particularly focusing on pain and functional improvement. Basic recommendations will follow regarding appropriate use for different conditions and patient populations.

METHODS

A scoping literature search of all published studies from 2000 to 2023 was conducted using PubMed, Web of Science, Embase, and the Cochrane Library, with the intention of providing an extensive and comprehensive overview and categorization of various forms of available ES, something currently unavailable in the literature. Inclusion criteria included studies primarily focusing on the use of ES for treatment of pain and improvement of functional status. ES was defined as use of a medical device to send electrical pulses to an anatomical target (i.e., nerve, muscle, vessel) with the intention to influence nerve conduction and/or muscle contraction. Some forms of ES have been described in the literature by several different names, so every effort was made to thoroughly cover available related technologies. Articles retrieved from the searches were evaluated independently by one reviewer using predefined standardized data extraction forms, and then data were evaluated again by a second independent reviewer. Following article retrieval, studies were categorized as "Important" (systematic review or meta-analysis, randomized controlled trial, observational cohort study) and "Minor" (retrospective case series, case report, opinion review). This article is based on previously conducted studies and does not contain any studies with human participants or animals performed by any of the authors.

RESULTS

Evidence for each form of ES is categorized and recorded in Table 1.

Marketed Primarily for Neurological or Disuse Functional Rehabilitation and Training

Neuromuscular Electrical Stimulation (NMES) NMES alternates depolarization and repolarization primarily to decrease muscle spasm and prevent disuse atrophy [20]. NMES emits a mid-frequency rectangular waveform with pulse duration around 500 μs [21]. This form of ES stimulates muscles to repeatedly contract, simulating real exercise, which can lead to rapid fatigue and tetany when applied for longer periods [30]. NMES is prescribed for physical rehabilitation, mostly for patients with prolonged inpatient immobilization and for muscle strengthening in patients with spinal cord injuries [20–22]. A meta-analysis using NMES for cerebral palsy children suggested improvements in gross motor function (sitting and standing), although studies were of low quality [23]. Systematic reviews of NMES for muscle weakness in hospitalized adults with advanced disease indicated general effectiveness in

Table 1 Evidence categorization for forms of electrical stimulation; important studies include systematic review (*SR*) and/or meta-analysis (*MA*), randomized controlled trial (*RCT*), and observational cohort study (*OCS*), while minor studies include retrospective case series, case report and opinion review

Important studies	Minor studies
Neuromuscular electrical stimulation (NMES)	
MA on children with cerebral palsy: improved standing and sitting	Several reports describe technology
2 SRs for muscle weakness in debilitation: effective inpatient adjunct to primary rehabilitation protocol	
RCT for cervical spondylosis: questionable effect in reducing pain versus sham treatment	
SR for patellofemoral pain syndrome: no evidence to support	
Functional electrical stimulation (FES)	
2 SR/MA on stroke: improved upper arm outcomes, no effects on pain	Report on walking speed (foot drop): moderate evidence to support
SR on youth with spinal cord injury (SCI): moderate quadricep strength improvement	
RCT on SCI: increased walking ability and muscle reactivation	
RCT on SCI: two times greater quality of life (QoL) improvement compared to stretching	
RCT on acquired brain injury: no improvement on mobility	
RCT on foot drop: moderate evidence to support, superior results compared to ankle–foot orthosis (AFO)	
Electrical muscle stimulation (EMS)	
SR on electrotherapy for neck pain: very low-quality evidence, ineffective compared to placebo for disability or pain	
Transcutaneous electrical nerve stimulation (TENS)	
SR on chronic pain: no benefit for reduction, disability, or QoL	Several reports describe technology
3 MAs on chronic back pain: negligibly improved symptoms relative to controls	Diabetic neuropathy: weak evidence as adjunct therapy
SR on phantom limb pain: no effect	Post-herpetic neuralgia: weak evidence as adjunct therapy
SR on spasticity: mild improved activity and spasticity-related outcome measures	
SR on multiple sclerosis (MS): marginal effects for treating pain	
SR on neuropathic pain: low-quality evidence with no recommendations	
SR/MA on total knee arthroplasty: reduced post-op pain and opioid use up to 24 h, but no longer-term effects	
H-Wave® device stimulation (HWDS)	

Table 1 continued

Important studies	Minor studies
SR on chronic or neuropathic pain and dysfunction: moderate improvement in function, pain reduction and decreased medication usage	Pre-clinical basic science studies describe technology
2 RCTs on diabetic peripheral neuropathy: moderate reduction in chronic pain	
OCS on functional benefit in first responders: reduction in pain and work-related performance improvement	
OCS on end-stage chronic pain: QoL benefits and pain reduction for up to 2 years	
Interferential current (IFC) or therapy (IFT)	
SR for musculoskeletal pain: no evidence to support	Several reports describe technology
SR for acute and chronic pain: no evidence to support	
SR for knee osteoarthritis: weak evidence to support	
8 RCTs on jaw, shoulder, back, neck and knee: limited effectiveness	
2 RCTs on chronic low back pain: mild effects in pain and disability reduction	
RCT on adhesive capsulitis: similar effectiveness as low-current TENS	
Noninvasive interactive neurostimulation (NIN)	
RCT in lateral ankle sprain: questionable benefit	Several reports of technology limitations and lack of long-term effectiveness
RCT in post-TKA patients: some reported pain reduction	
SR/MA in plantar fasciitis: most effective in pain reduction of 5 different modalities	
Pulsed magnetic field therapy (PMFT) or pulsed electromagnetic field therapy (PEMF) or pulsed electrical stimulation (PES)	
SR in electromagnetic fields for osteoarthritis: possible mild benefit	Several reports describe technology
SR/MA in osteoarthritis: limited improved function but no effects in pain reduction	Reports of excessive non-ionizing radiation exposure in several European systems
AHRQ comparative effectiveness review: no effects on disability or pain	
Galvanic current stimulation (GCT) or direct current (DC)	
SR in neck pain: low-quality evidence, does not reduce disability or pain compared to placebo	
Microcurrent electrical neurostimulation (MENS)	
RCT in elderly patients: short-term improvement in grip strength and heel rise (no long-term improvement seen)	
Percutaneous electrical nerve stimulation (PENS)	

Table 1 continued

Important studies	Minor studies
RCT for low back pain: no difference in pain reduction compared to conditioning and exercise	General review lacks quality evidence
RCT for knee pain: poor evidence to support	
2 RCTs for migraine and neck pain: limited reported pain reduction and range-of-motion improvement	
Percutaneous neuromodulation therapy (PNT) or peripheral nerve stimulation (PNS) or peripheral nerve field stimulation (PNFS)	
SR for chronic pain: limited evidence to support (some higher-quality evidence for migraines)	General review raises concerns
Transcranial direct current stimulation (tDCS)	
3 SRs on chronic pain: no evidence to support	2 general reviews describe technology
MA on chronic back pain: no evidence to support	
MA on stroke patients: reported improvements in QoL and arm function	
SR/MA on fibromyalgia pain: tentative evidence only	

combination with other rehabilitation methods, with proven safety for critically ill patients when properly applied [24, 25]. The effectiveness of NMES for pain relief, noting isolated reports of reduced neck pain in cervical spondylosis patients compared to sham treatment, remains questionable, with the majority of clinical studies being of low quality and failing to report adverse outcomes related to tetanic muscle contractions [26, 27].

Functional Electrical Stimulation (FES)

FES emits various programmed sequences of nerve stimulation eliciting distinct muscle contractions, which resemble some normal functional movements, for stroke recovery and highly motivated spinal cord injury patients (SCI) [28, 29]. A systematic review of 34 clinical trials concluded that FES was superior in improving movement scores of stroke patients with upper limb dysfunction when compared to other modalities including TENS, NMES, and tDCS [30]. FES cycling as an adjunct therapy for chronic SCI patients demonstrated a marked increase in daily functional measures compared to stretching, in contrast to outcomes of another multi-center trial in acquired brain injury patients which failed to demonstrate any improved mobility [31, 32]. FES is most utilized to stimulate muscles of the anterior compartment of the leg, causing functional dorsiflexion for patients with peroneal nerve palsy, effectively resulting in increased walking speed [33, 34]. The addition of FES to a conventional foot drop rehabilitation program showed greater reduction of lower extremity spasticity, with motor strength recovery being superior to use of an ankle–foot orthosis [29, 35, 36]. FES is not currently indicated as a treatment modality for pain, with more research needed to understand long-term therapeutic effects [28, 30].

Electrical Muscle Stimulation (EMS)

EMS has a similar design to TENS but with stronger stimulation intensity which causes muscle contractions. The most common

application of EMS is for facial muscles (e.g., Bell's palsy), although it has been proposed to treat neck and upper back conditions. A systematic review noted an extremely low quality of evidence, which has suggested ineffectiveness compared to placebo, with no reduction of disability or pain [37].

Marketed Primarily for Pain Relief and/or Function Improvement

Transcutaneous Electrical Nerve Stimulation (TENS)

TENS is a widely promoted intervention for chronic pain and spasticity, most commonly being prescribed for temporary relief of neck and low back pain. A TENS device emits variable electrical impulses, with most applications using higher frequencies between 40 and 150 Hz, with a short rectangular-shaped pulse duration typically around 50 μs. Low frequencies between 1 and 4 Hz with high intensity are less commonly used in a theoretical attempt to inhibit peripheral large-diameter, nociceptive transmission neurons [38–40]. Given the variability of application protocols, TENS evidence continues to be compromised by inconsistency in parameters, dosing, and testing populations, which have not been standardized in reported trials [41]. A 2019 systematic review of TENS for chronic pain found the quality of the evidence to be incredibly low, while it has not been demonstrated to be harmful or beneficial for pain control, disability, health-related quality of life (QoL), or in reducing use of pain-relieving medications [42]. Meta-analyses reported that TENS negligibly improved symptoms of chronic back pain relative to control treatments, but was less effective than other neurostimulation device forms [16, 43]. Another meta-analysis of TENS for chronic low back pain reported only very slight pain relief (< 1 on 1–10 pain scale), also noting little beneficial effect over 5 weeks of treatment [41]. One systematic review and meta-analysis suggested that the addition of TENS, as an adjunct to a multi-modal pain protocol following total knee arthroplasty, might help reduce reported pain and narcotic use during the first 24 h, although no beneficial effect was noted at 2-weeks [44].

H-Wave® Device Stimulation (HWDS)

HWDS, a unique form of ES, has different pain-relieving high-frequency (60 Hz) effects than TENS, with primary low-frequency (2 Hz) muscle effects being notably distinct from NMES. HWDS has a much different waveform compared to other forms of ES, emitting a very prolonged (5000 μs) pulse width/duration, being orders of magnitude longer than with other devices. While high-frequency mode effects can produce effective anesthesia/analgesia, low-frequency mode does not cause muscle weakness or tetany with extended use like NMES [45]. Pre-clinical studies demonstrated that the exponentially decaying biphasic waveform causes non-fatiguing muscle contractions and positive physiological effects on blood and lymph flow (vasodilation, angiogenesis), as well as nerve function [46, 47]. A 2021 systematic review of HWDS clinical trials found that low- to moderate-quality studies consistently reported clinically significant improvements in pain and function, as well as a reduction in pain medication use over a spectrum of acute and chronic pain disorders. Noting an excellent safety profile and relative cost-effectiveness, consideration of HWDS as part of a multimodal pain management program was suggested [45]. A cohort survey study of first responders using HWDS made available at the job site demonstrated multiple work-related performance improvements [48]. A large observational cohort study of end-stage workers' compensation chronic (mean 8 years) pain patients found that HWDS treatment led to significant QoL gains, in terms of improved function, reported pain, and decreased medication use [49].

Interferential Current (IFC) or Therapy (IFT)

IFC, sometimes called IFT, uses differing medium-frequency electrical currents to reduce tissue impedance, theoretically allowing higher penetration into target tissues to inhibit the nervous system, supposedly resulting in muscle relaxation, pain suppression, and accelerated

healing [50]. However, IFC has provided no additional clinical benefits for first-line conservative treatment of patients with low back or lower extremity pain, or for subacromial impingement syndrome [51–53]. While two older systematic reviews suggested marginal benefit, non-standardized protocols, heterogeneity, and other methodological limitations have significantly undermined the quality of IFC evidence in musculoskeletal pain and knee osteoarthritis [54, 55]. A more recent IFC systematic review found no statistically significant reduction in treatment of acute and chronic pain [56].

Noninvasive Interactive Neurostimulation (NIN)

NIN reportedly stimulates A, delta, and C nerve fibers, emitting larger currents through areas of lower impedance [57, 58]. Specialized attachments can be interchanged to access different nerve regions, including a probe, an elastic band with sensors, and a cranium comb. Compared to TENS and IFC, this form of ES has a higher amplitude of stimulation, where it has been suggested that NIN therapy may supplement a standard rehabilitation protocol to decrease pain over the short term in post-TKA patients [59]. One meta-analysis of different treatment modalities for plantar fasciitis reported that NIN seemed to be the most effective in reducing pain [60]. However, this product is not easily accessible and quite expensive, the mechanism of action is poorly understood, and there are insufficient trials demonstrating long-term effectiveness [58, 60, 61].

Pulsed Magnetic Field Therapy (PMFT) or Pulsed Electromagnetic Field therapy (PEMF) or Pulsed Electrical Stimulation (PES)

PMFT, also called pulsed electromagnetic field therapy or pulsed electrical stimulation, emits subsensory pulsed electric potentials that supposedly alter the homeostatic balance of cartilage degradation and synthesis, stimulating repair in degenerative conditions like osteoarthritis [19, 62, 63]. One systematic review concluded that PMFT might result in mild benefit for some knee osteoarthritis patients [64]. Another systematic review and meta-analysis reported that PMFT might have limited effectiveness in improving physical function in knee osteoarthritis patients, but there was no effect on pain reduction, with the authors acknowledging that the strength of evidence was low for physical function and extremely low for pain [62]. A Comparative Effectiveness Review by the Agency for Healthcare Research and Quality concluded that PMFT failed to improve disability (low evidence) or pain (moderate evidence) [65]. Concerns have also been reported about possible excessive non-ionizing radiation exposure with several European PMFT systems [66].

Galvanic Current Stimulation (GCT) or Direct Current (DC)

GCT, also called direct current, has been experimented with over several centuries and is still used in some treatments of the skin, being promoted for inhibiting nociceptor activity. It is also believed to help transport ionized substances through the skin, particularly topical anti-inflammatory drugs (iontophoresis). Systematic reviews have reported low-quality evidence that GCT does not reduce disability or pain compared to placebo [37].

Microcurrent Electrical Neuromuscular Stimulation (MENS)

MENS is a sub-sensory very low-level current that is purported to mimic naturally occurring electrical body impulses to decrease pain and to facilitate healing processes. Despite some brief duration improvement in grip strength and heel rise in elderly patients compared to sham, no subsequent clinical improvement was noted [67]. This ES form has a notable paucity of evidence in the literature.

Percutaneous Electrical Nerve Stimulation (PENS)

PENS, unlike TENS, uses needles that are inserted around or immediately adjacent to the targeted nerve, making it indistinguishable from electro-acupuncture. Randomized controlled trials of PENS have reported limited clinical improvement in migraine and neck pain

patients, but less so for low back and knee pain [68–71]. PENS lacks quality evidence demonstrating any sustained benefit, so when trialed should only be with a licensed and trained therapist after more conventional treatments have failed [72].

Percutaneous Neuromodulation Therapy (PNT) or Peripheral Nerve Stimulation (PNS) or Peripheral Nerve Field Stimulation (PNFS)

PNT and its variations including PNS and PNFS, involve electrodes placed percutaneously or deeper in the region of targeted peripheral nerves for treatment of postoperative pain, neuropathic pain, or complex regional pain syndrome. Clinical evidence for this form of ES has been mostly limited to case reports/series and retrospective reviews, with insufficient evidence to support safety and effectiveness, with reported complications when older open nerve exposure techniques were used for electrode placement, resulting in multiple revisions from lead migration or failure [73, 74]. A more recent systematic review of PNS, typically using ultrasound lead placement, specifically noted a lack of high-quality RCTs with methodological limitations and heterogeneity, but indicated some potential benefit for chronic migraines, cluster headaches, post-amputation pain, chronic pelvic pain, and possibly for chronic low back and lower extremity pain [75].

Transcranial Direct Current Stimulation (tDCS)

tDCS uses surface cranial leads to stimulate the sensorimotor cortex, reportedly altering gamma-aminobutyric acid neurotransmission and resting membrane potential, resulting in either depolarization or hyperpolarization, depending on flow and axon orientation. This ES form contrasts with the efferent and afferent peripheral nerve stimulation of many other ES forms [76, 77]. Studies have reported cathode tDCS improvement in QoL and arm function in stroke patients, but only tentative evidence for pain reduction in fibromyalgia patients [78, 79]. A 2020 meta-analysis concluded that existing evidence was underwhelming and that tDCS was ineffective for reducing chronic back pain [80]. Previous systematic reviews of non-invasive brain stimulation techniques highlighted that tDCS had minimal short-term effects on chronic pain, noting multiple sources of research bias [81, 82]. Another systematic review questioned whether tDCS had any effect at all, noting only one demonstrable effect on a single neurophysiological monitoring measure, motor-evoked potential amplitude [83].

Miscellaneous ES Forms Unrelated to Pain and Function

The forms of ES selected for this review have focused strictly on devices that have been designed and marketed to improve pain and/or function, where there has been some medical evidence to draw reasonable conclusions regarding relative effectiveness and clinical indications. Literature searches led to numerous other FDA-cleared ES device forms for other unrelated indications, primarily for use by physical and wound therapists or for treatment of psychological disorders. Physical and wound therapy-related examples include the following: Iontophoresis, Faradic ES (muscle reeducation/atrophy), Russian ES (e.g., Olympic muscle enhancement), EMG-triggered stimulation (partial functioning nerves), reciprocal EMG-triggered stimulation (over-stimulated nerves), high-voltage ES (wound healing), and high volt pulsed current (edema, decubitus wounds). Examples of ES forms used for psychological disorders include the following: electroconvulsive therapy (severe depression), deep brain stimulation (severe depression, neurological disorders), repetitive transcranial magnetic stimulation (depression, severe OCD), and vagus nerve stimulation (depression, PTSD).

DISCUSSION

Comparison of ES Types and General Recommendations

Function

Functional loss can occur because of direct neurological and/or motor deficit resulting from stroke, SCI, nerve injury, and muscle disease or disuse. Another common reason for

functional compromise is from any sustained perception of pain, which similarly leads to guarding and relative disuse. As such, clinical research which focuses on objective functional outcome measures probably represents a more reliable indicator of overall effectiveness than basic recording of various subjective pain measures. Some forms of ES that address recovery of muscle or nerve dysfunction do not simultaneously provide pain relief. This review highlighted that several of the more effective ES forms had a greater impact on functional measures than reported pain.

Of the three recommended forms of ES, NMES has proven effectiveness in the rehabilitation of SCI and immobilized/debilitated inpatients, as well as for cerebral palsy patients, but does not seem to reduce pain significantly [20–27]. FES is another effective ES tool for stroke recovery and with highly motivated SCI outpatients, as well as for functional treatment of foot drop (peroneal nerve palsy), although no pain relief should be expected [28–30, 33, 34]. Several moderate-quality HWDS studies have shown statistically significant gains in functional measures, being somewhat higher by percentage than the recorded reductions in pain measures [45, 48, 49].

While many forms of ES preclude recommendation, two warrant mention for preliminary findings related to functional improvement. PMFT might have limited effectiveness in improving physical function in knee osteoarthritis patients [62, 64], and cathode tDCS seemed to result in improvement in QoL and arm function in stroke patients [78, 79].

Pain

While pain measurements (e.g., VAS, BPI) remain problematically subjective, recorded reduction of pain medication use has more potential for objectivity when comparing ES effectiveness. Of the three recommended ES forms, only HWDS demonstrated statistically significant reductions in pain measures, as well as medication reduction [45, 49]. Several other non-recommended ES forms had marginal effects on reported pain. TENS, which is widely implemented for short-term pain relief, reduced reported pain by < 1 on a 1–10 pain scale, and has reportedly been helpful as an early post-operative adjunct following total knee surgery, as part of a multimodal pain control protocol [41, 44]. NIN therapy may similarly help decrease pain over the short term in post-TKA patients, and shows some promise for plantar fascia pain [59, 60]. Limited clinical improvement in migraine and neck pain patients has been reported with PENS [68–71]. PNS may have some potential benefit for chronic migraines and cluster headaches, post-amputation pain, chronic pelvic pain, and possibly for chronic low back and lower extremity pain [75].

Confusion in the Literature and Marketplace

Given the defined scope of this comparative review of ES forms, focused on effectiveness for improving function and decreasing pain, it is important to understand how much misinformation and lack of standardization exists, particularly in marketing materials directed to consumers and providers. Even the multiple names for a single form of ES further obfuscate collective understanding and differentiation between available devices. Further confusion results from insurance coverage decisions, which often reflect an attitude of rejection of all ES devices, regardless of merit, based on best available medical evidence, or common misgrouping of much different ES forms. The FDA clearance process creates another twist, where a system of broad classifications (buckets) is used. Even within one specific classification, it is widely acknowledged in the healthcare community that each class contains significant variation and diversity between cleared devices/drugs, while the FDA never attempts to differentiate or to provide guidance regarding relative clinical or cost-effectiveness between cleared devices/drugs.

In summary, this scoping comparative review presents a thorough overview, currently unavailable in the literature, but has not attempted to present a myriad of technical aspects for each and every distinct ES form. For those more interested, there are many significant design differences, primarily related to

waveform, pulse frequency, and pulse duration. Waveforms are commonly DC, AC, burst or modulated AC, and low-intensity DC, among others, including "exponentially decaying." Pulse frequency (in Hz) is typically low, middle, or high, while pulse duration (in μs) can be short, mid, long, or ultralong. Based on such varying reported clinical outcomes, it seems reasonable to conclude that such notable differences in electrical parameters are important for effective ES form design.

CONCLUSION

Most forms of ES are used as second-line therapies, following the failure of other conventional treatments. When considered as a whole, the majority of ES forms for treatment of pain and loss of function lack highly rigorous research. This may be at least partly attributed to the fact that most are FDA-cleared as Class II medical devices, which have less demanding research requirements than for higher safety risk Class III devices. Nevertheless, several forms of ES appear to be relatively effective for rehabilitation of function, as well as reduction of pain and medication use. This comparative analysis of 13 distinct forms of ES found disappointing clinical results for 10 of them. NMES and FES have demonstrated reasonable effectiveness for the functional rehabilitation of some stroke, SCI, and patients with certain types of nerve compromise. HWDS appears to have the most promising clinical outcomes, in terms of functional improvement combined with reduction of pain and medication use. More higher-quality long-term clinical trials are needed to further validate appropriate use and to identify specific indications for most forms of ES.

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Data Availability. The data used in this review are available from multiple sources, including public databases PubMed, Web of Science, Embase, and the Cochrane Library and are included in the references section of this article.

Declarations

Conflicts of Interest. Stephen M. Norwood and Ashim Gupta are consultants for Electronic Waveform Lab, Inc. (Huntington Beach, CA, USA). The other authors declare that they have no competing interests.

Ethical Approval. This article is based on previously conducted studies and does not contain any studies with human participants or animals performed by any of the authors.

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