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Review Article

Does therapeutic electrical stimulation improve function in children with disabilities? A comprehensive literature review

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Abstract. The use of therapeutic electrical stimulation for medical purposes is not new; it has been described in medical textbooks since the 18th century, but its use has been limited due to concerns for tolerance and lack of research showing efficacy. The purpose of this review is to discuss the potential clinical applicability, while clarifying the differences in electrical stimulation (ES) treatments and the theory behind potential benefits to remediate functional impairments in youth.
The literature review was performed as follows: A total of 37 articles were reviewed and the evidence for use in pediatric diagnoses is reported.
The synthesis of the literature suggests that improvements in various impairments may be possible with the integration of ES. Most studies were completed on children with cerebral palsy (CP). Electrical stimulation may improve muscle mass and strength, spasticity, passive range of motion (PROM), upper extremity function, walking speed, and positioning of the foot and ankle kinematics during walking. Sitting posture and static/dynamic sitting balance may be improved with ES to trunk musculature. Bone mineral density may be positively affected with the use of Functional Electrical Stimulation (FES) ergometry. ES may also be useful in the management of urinary tract dysfunction and chronic constipation. Among all reviewed studies, reports of direct adverse reactions to electrical stimulation were rare.
In conclusion, NMES and FES appear to be safe and well tolerated in children with various disabilities. It is suggested that physiatrists and other healthcare providers better understand the indications and parameters in order to utilize these tools effectively in the pediatric population. MeSH terms: Electrical stimulation; child; review.

Keywords: Spasticity, paraplegia, quadriplegia, cerebral palsy, disability

1. Introduction

The use of neuromuscular electrical stimulation (NMES) for medical purposes is not new. Historical references indicate the ability to use electrical currents to activate muscle since the 18th century. Faraday described the importance of alternating current to avoid tissue necrosis, which in turn allowed Duchenne to use electrical stimulation to understand muscle physiology and localization of peripheral nerve injuries [1–3] Since then, the interest and use of electrical stimulation (ES) as a therapeutic option in medicine has waxed and waned. Initially, without reliable stimulation instruments, practitioners did not fully appreciate the physiological aspects. Now, with technological ad-

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vancement, there are reliable ES machines and a better understanding of appropriate parameters to use with patients.

1.1. Basic electrophysiology

ES has been used for many years in a wide variety of applications [4]. ES has been used to maintain or increase range of motion (ROM), reduce acute localized edema, promote healing of fracture or wounds, reduce effects of spasticity, prevent or reverse disuse atrophy, facilitate movement, and as an orthotic substitution [4–9]. One of the features complicating research and analysis of ES's effectiveness is the confusing nomenclature associated with its different applications. The most common types of ES, as classified by the authors, are listed below. A list of general parameters, can be found in Table 1.

Therapeutic Electrical Stimulation is the use of ES in any therapeutic capacity. It is a broad, non-specific term, which includes all of the following [4]:

- Neuromuscular Electrical Stimulation (NMES) is electricity applied across the surface of the skin over an intact peripheral nerve, evoking an action potential (AP) in the nerve to drive a muscle contraction. NMES is any application of ES with motor goals, ex: stimulation to anterior tibialis to perform dorsiflexion. NMES includes FES [4].
- Functional Electrical Stimulation (FES) is the application of electrical stimulus to the nerve of a paralyzed muscle to restore or achieve function, ex: triggered stimulation to anterior tibialis during gait training. FES is most often used in neurorehabilitation and routinely paired with task-specific practice [4].
- Transcutaneous Electrical Nerve Stimulation (TENS) involves the depolarization of a peripheral sensory nerve to offer an alternate and competing sensation to reduce nociception for pain modulation. Clinically, TENS has been used for lower back pain, neurogenic pain, arthritic pain, and various other forms of pain [4].
- Threshold Electrical Stimulation (TES) is the application of electrical stimulation across the skin to a muscle at the sensory threshold. It does not elicit a muscle contraction. The stimulation is provided over a longer period of time with minimal intensity (2–10 milliamperes [mA]) [10]. With similar acronyms, it is often confused with therapeutic electrical stimulation and TENS. However, it has distinct parameters and different treatment goals.

While ES may be helpful in muscle strengthening and motor retraining, it is important to consider that electrically driven contractions are different from physiologically generated ones. There are two main differences between electrical and physiological contractions. First, while the AP in a physiologic contraction travels only anterograde to the neuromuscular junction, the electrically generated AP, beginning in the middle of the axon, generates a wave of hyperpolarization behind the AP resulting in bidirectional (anterograde and retrograde) conduction [4]. Second, the recruitment of muscle fibers differs in type and number. Physiologic contractions preferentially recruit slow contracting, fatigue resistant (Type I) fibers. Physiologically generated motor unit activation is varied and asynchronous, allowing switching between active and inactive motor units to maintain muscle activity and prevent fatigue. Recruitment of muscle fibers from electrical contractions progresses from large to small fibers, contrary to physiologic contractions, and is largely dependent on proximity [4]. Electrical contractions reflect preferential recruitment of fast fatigue (Type II) muscle fibers and synchronous activation of motor units, which fatigue quickly. Mulcahey et al. [11] showed that a paralyzed muscle with intact peripheral innervation should produce a grade 3 muscle contraction when stimulated at 10–20 Hz (pulse frequency), a pulse width of 200–400 μsec, and intensity as tolerated. In subjects, the effect in the muscle may be affected by, not just the current, but also the size of the muscle, its baseline strength and the sub-cutaneous or adipose tissue present.

1.2. Neurophysiology

Beyond the study of functional changes, there has been much investigation into the impact of ES on the cells, tissues, and systems in the body. The available research is broad and includes multiple types of ES interventions studied in a variety of pediatric diagnoses. The research is, overall, positive and indicates the use of ES to be beneficial.

High frequency, low intensity TENS has been reported to affect sympathetic outflow from the spinal cord by stimulating afferent fibers to increase blood flow to the muscles [55]. This can assist spastic muscles by improving efficiency, oxygen uptake, and waste product removal. TENS is also believed to activate sensory Ia afferent fibers switching on presynaptic inhibition [56], mechanisms leading to reduction in spasticity as measured by a reduction in H-reflex ampli-

Table 1
Parameter ranges for common types of electrical stimulation

Type of stimulation	Treatment goal	Frequency range	Pulse width range
NMES	Motor activation	10–60 Hz	200–1000 μsec
FES	Function	10–60 Hz	200–1000 μsec
TENS	Pain modulation	80–150 Hz	50–200 μsec
TES	Motor bulking (amplitude: 1–5 μA)	35 Hz	300 μsec

NMES: Neuromuscular Electrical Stimulation; FES: Functional Electrical Stimulation; TENS: Transcutaneous Electrical Stimulation; TES: Threshold Electrical Nerve Stimulation.

tude [55]. The H-reflex is a measure of spinal motor neuron excitability. It is postulated that the principle of reciprocal inhibition is responsible for decreasing muscle tone in an agonist spastic muscle when the antagonist muscle receives continuous NMES [57]. It appears to activate Type Ia afferent muscle fibers of the antagonist muscle while inhibiting the motor neurons of the agonist muscle. This can interrupt the constant co-activation of the agonist and antagonist [57] to allow proper movement.

It has been well documented that muscle and bone demonstrate a positive response to FES for individuals with a spinal cord injury. Muscles improve in size, strength [12–14] and composition. Fiber type conversion, from IIB to IIA and I, has been demonstrated in patients with paralysis and atrophy [15], indicating improved oxidative capacity and fatigue resistance. FES lower extremity cycle ergometry results in proportional increases in fiber area and capillary number [16]. Recovery of lost bone mass, especially in the lower limb [17] is also associated with FES. Metabolic benefits have also been demonstrated in response to ES training, including increases in lean muscle mass [6], increased capillary number [18] and decreases in adipose tissue [19]. Beyond body composition, FES has been demonstrated to decrease blood glucose and insulin levels in patients with Spinal Cord Injury (SCI) [6,20,21]. Muscle volume and stimulated strength improved [22] and, although sample sizes are small, bone mineral density shows positive changes [23] in children and adolescents who participated in ES exercise. These improvements in muscle mass, bone density, and body composition may lead to fewer pathological complications, including fractures, pressure ulcers, and infections in impaired populations and enhancement of quality of life.

It has also been demonstrated that the cardiovascular system is highly responsive to training augmented by ES. FES exercise produced a two- fold increase in the oxygen uptake, a three-fold increase in ventilation rate and a five beats per minute increase in heart rate from the resting value in seven volunteers with C5 to T12 spinal cord injury [24]. Peak Oxygen uptake and maximum power output also improves in response to ES training [25]. In children, it has been demonstrated that peak oxygen uptake, lipid and cholesterol levels improve in response to ES training [26]. Finally, it has been observed that ES may play a role in reversing the atherosclerosis associated with paralysis [27].

Finally, and perhaps most significant for function, the nervous system is capable of change in response to stimulation. It has been repeatedly demonstrated in vitro and in animal studies that activity augmented with ES plays a critical role in both development and plasticity within the nervous system, including gene expression [28–32], modification of synaptic strength (e.g., LTP) [33,34], synapse elimination [33], myelination and maintenance of myelination [35–38], and axonal growth [39–41].

The purpose of this review is to discuss the potential clinical applicability of ES, clarify differences in types of ES interventions, and the theory behind potential benefits. Since different diagnoses may present with similar impairments, and therefore indications for ES, this review is structured based on indications for treatment of impairment, rather than by disease, condition, or disability.

2. Methodology of literature review

A search was conducted for English language articles in MEDLINE/PubMed database for the term “electrical stimulation”. Only articles from the last ten years (2003 to 2013), in participants younger than 18 years of age, were included. Articles were excluded if they were reviews, letters, commentaries, and abstracts or if neuromuscular electrical stimulation was not the primary intervention. Where relevant, the discussed literature has been assigned a Level of Evidence [42]. (See Table 2) Percutaneous or implantable electrical stimulation studies were not included due to small numbers of practical applications. The abstracts were reviewed and the articles were divided for thera-

Table 2
Oxford centre for evidence-based medicine – levels of evidence (March 2009) [42]

Level	Type of evidence for therapy
1a	Systematic Review (SR) with homogeneity of Randomized Control Trials (RCTs)
1b	Individual RCT (with narrow Confidence Interval)
1c	All or none*
2a	SR (with homogeneity) of cohort studies
2b	Individual cohort study (including low quality RCT; e.g. $<$ 80% follow-up)
2c	"Outcomes" Research; Ecological studies
3a	SR (with homogeneity) of case-control studies
3b	Individual Case-Control Study
4	Case-series (and poor quality cohort and case-control studies)
5	Expert opinion without explicit critical appraisal, or based on physiology, bench research or "first principles"

(*) Met when all patients died before treatment became available, but some now survive on it; or when some patients died before the treatment became available, but none now die on it. Full references and details can be found at http://www.cebm.net/oxford-centre-evidence-based-medicine-levels-evidence-march-2009/.

peutic application. A total of 37 articles were reviewed. The following describes the findings based on treatment indications across diagnoses. References will be presented based on highest level of evidence available for each functional impairment.

3. Discussion

3.1. Impairments

3.1.1. Muscle weakness

Two randomized studies in 2006 assessed change in muscle strength in children with CP. Kerr et al. (Level of Evidence = 2b) [43] included NMES (stimulation to motor threshold) and TES (stimulation at sub-motor thresholds) groups and compared them with a control group that received mock stimulation. Both groups received ES at a frequency of 5 times per week for a duration of 16 weeks. Participants in the NMES group received continuous ES for one hour during the day and those in the TES group received 8 hours of ES at night. The primary outcome measure was quadriceps muscle peak torque. No differences in peak muscle torque were found between the two groups and the control group, by measuring peak torque. Gross Motor Function Measure (GMFM) and Lifestyle Assessment Questionnaire – Cerebral Palsy (LAQ-CP) were identified as secondary outcome measures. Even though no significant differences, between intervention group, were seen in peak torque or GMFM, both NMES and TES groups showed significant difference, compared to placebo, in LAQ-CP, which measured impact of disability, at the end of treatment and at six weeks of follow-up. Compliance was reported at an average of 38.3% for TES and 71.1% for NMES group. Participants with different types (quadriplegic, diplegic, dystonic, ataxic and non-classifiable) of cerebral palsy (CP) and Gross Motor Function Classification System (GMFCS) levels (I-IV) were included in this study, which may have affected the outcomes. In addition, post-study sample size calculation showed that there were not enough participants to achieve significant power. On the other hand, Ozer et al. [44] (Level of Evidence = 2b) only included patients with hemiplegic CP in their report. NMES to upper extremity antagonistic muscles was applied and compared to patients with dynamic bracing alone, and with those who received NMES and dynamic bracing. The participants that received both NMES and dynamic bracing had significant improvements, in grip strength and posture of upper extremity, in addition to improvements in active range of motion (AROM) and passive range of motion (PROM), velocity of movement and control, throughout treatment period. However, these changes reverted back to pre-treatment values, three months after completion. Small numbers of participants in each group also limit the statistical power of this study.

Johnston et al. [22] published a randomized control trial (Level of Evidence = 2b) in the use of FES lower extremity (LE) cycle ergometer for children and youth with SCI. Only non-ambulatory children and youth graded as A, B or C on the American Spinal Injury Association (ASIA) International Standard for Neurological Classification of SCI (ISNCSCI) Scale (AIS), defined as presence of voluntary anal contraction and/or minimal proximal muscle movement, were included. They received ES to quadriceps, hamstrings and gluteal muscles, through FES ergometer or stand-alone NMES for 60 minutes, three times a week for a total of six months. Children who received ES through FES ergometer or stand-alone NMES had significant improvements in muscle volume and stimulated strength, compared to passive

ergometry. The children who underwent NMES had significantly greater muscle volume than FES cycle and passive ergometer. The children who underwent FES cycle had significantly greater stimulated strength compared to stand-alone NMES or passive cycling. Even though the hamstring muscles were stimulated, no volume or muscle strength changes were reported as significant. The compliance was reported as an average of $> 80\%$. The small study size may have affected power in this study.

Smaller studies [45–49] (Level of Evidence = 3b & 4) in children with CP, Traumatic Brain Injury (TBI), Myelomeninogocoele (MMC), and SCI have also reported improvements in muscle strength after completing programs with either NMES or FES.

These articles indicate that therapeutic ES can increase muscle strength in children with hemiplegic CP with weakness in their upper extremity, and in children and youth with SCI who have lower extremity weakness when applied through FES ergometers. Even though changes have been reported in muscle volume, strength, and posture, the clinical significance of these changes is not known. In some studies, the effects were temporary, and did not persist during a follow-up period where the participants were no longer receiving the intervention. It is unknown if the effects may last longer with longer treatment duration or may require that the treatment be continued for effects to be maintained. Most of the studies reported utilizing ES for 30 to 60min per day, three to five times per week, for four to six months. A partially preserved peripheral nerve (UMN lesion) is required to be able to elicit a muscle contraction.

3.1.2. Spasticity

Multiple studies have evaluated the use of ES for the management of spasticity, with the majority including children with CP. Alabdulwahab has reported the use of TENS [50] (Level of Evidence = 3b) and NMES [51,52] (Level of Evidence = 2b) on participants with spastic diplegic CP who were ambulatory. A decrease in spasticity was reported after onetime trial and for those receiving a longer duration of ES for 15 minutes, three times a day for one week. Additional details were included in the "Gait dysfunction" section, as spasticity was not the primary outcome for these studies. For all these studies, a significant decrease in spasticity was noticed at time of trial. However, there was no difference between single and multiple applications of NMES program at follow-up. A small study by Katz et al. [53] (Level of Evidence = 3b) included 11 children. The control group was comprised of 6 typically developing children and the intervention group included 5 children with CP (diplegic and hemiplegic types), who completed three months of NMES at home (30 minutes per day for at least five days), to the quadriceps muscle, and continued baseline therapies. Subjects in the study group with CP had significant difference in the pattern of co-contraction and electrically assisted motion when compared to the control group of typically developing children. This difference was not seen after treatment. Participants in the intervention group had a significant increase in average movement speed, and decreased knee jerk (as a measure of spasticity) during movement, and knee torque impulse. Muscle strength was not improved, however, improved "smoothness" of motion (by reported decreased knee torque impulse) was significant when compared to before treatment with NMES.

Additional studies have included the use of ES to potentially increase the uptake of botulinum toxin (BTX) intervention [54]. Pieber et al. [55] (Level of Evidence = 3b) reported the use of NMES and BTX to wrist and finger extensors in subjects with spastic hemiparesis and impaired hand function. The intervention group received BTX injection to forearm flexors, in addition to ES to wrist and hand extensors five to seven days after BTX, for 15 minutes twice a day, at least five times a week for three months. The control group received only BTX. Both groups received usual therapies once a week. While the article refers to the intervention as FES, a review of the parameters utilized in the study finds that the intervention is more consistent with NMES. Both groups had improved AROM/PROM, spasticity, and strength. However, the ES group also showed improved upper limb function per the Movement ABC Checklist. Rha et al. [56] (Level of Evidence = 2b) reported the possibility of earlier denervation in muscles treated with BTX and adjuvant ES. In this study, 23 participants, with spastic diplegic and quadriplegic CP, received BTX to bilateral gastrocnemius muscles followed by the use of NMES to one gastrocnemius muscle and sham stimulation to the other side for 30 minutes per day, every day, for one week. Some participants received low frequency stimulation (4 Hz), while others received higher frequency (25 Hz). The participants underwent electrodiagnostic testing with measurements of compound muscle action potential (CMAP). The areas receiving high and low frequency ES showed earlier decrease in the CMAP area, consistent with earlier denervation, when compared to sham side. A significant decrease in spastic-

ity (30 days after injection) was noted in all groups, including both ES groups and sham group. No significant differences were noted at 30 days between the ES and sham sides, except time for denervation. Clinical parameters of spasticity were not evaluated prior to 30 days after injection. In a smaller study, Kang et al. [57] (Level of Evidence = 3b) utilized BTX followed by NMES to gastrocnemius muscle. The participants had decreased spasticity and improved passive range of motion in the ankle, at two weeks, compared to one month in the control group.

NMES may be useful to temporarily decrease spasticity in patients with upper and lower limb involvement, when used for at least 30 min per day, for three to five times per week. NMES applied to antagonistic muscles, after the spastic agonist muscles have received BTX, may decrease the amount of time it takes for the chemical denervation to occur. Only the combined use of BTX and ES has been shown to potentially improve function and motor control, when compared to BTX alone. If used immediately after BTX injection to the spastic muscle, it may increase BTX uptake. However, the literature is not clear in frequency and dosing of ES to optimize spasticity management.

3.1.3. *Contracture management/Prevention of deformity*

Two studies (Level of Evidence = 3b) evaluated the use of NMES on children with different types of CP. They reported increased PROM to the hamstrings with ES applied to the quadriceps muscles [58], and increased PROM and AROM to ankle dorsiflexion and foot with ES applied to the anterior tibialis [59] ES was compared to passive stretch intervention.

The use of ES in the management of congenital muscular torticollis (CMT) was evaluated by Kim et al. [60] (Level of Evidence = 3b). In this study, the intervention group received 30 minutes of ES to the sternocleidomastoid (SCM) muscle in addition to stretching for two minutes. The control group got 30 minutes of manual stretching. They demonstrated a significant decrease in crying during therapy, improved tilt angle in supine, and neck rotation in supine. By providing the ES to the subject's muscle, the muscle may require, fewer manual stretching time, resulting in better tolerance. Adjuvant ES may help increase PROM when compared to passive stretch alone.

One study [61], (Level of Evidence = 4) examined infants with idiopathic congenital talipes equinovarus, commonly known as clubfoot. ES was applied to the ankle evertor muscles in six week phases for 30 minutes a day in addition to bracing. Significant improvements in ankle dorsiflexion PROM and improvements in calf circumference were noted. Authors observed that by adding the ES protocol, potential for relapse of clubfeet while wearing foot abduction braces related to the Ponseti method may be decreased.

Appropriate patient selection for utilization of ES for contracture management includes children with UMN lesions leading to spasticity with poor hamstring extensibility and limited passive or active dorsiflexion. Infants with CMT who have poor extensibility of the SCM muscle may benefit from the addition of ES in addition to traditional therapy for improved range of motion and better tolerance (less crying) during therapy.

3.1.4. *Upper limb dysfunction*

All of the studies that have evaluated the use of ES for improvements of upper limb function have included children with spastic hemiplegic CP. Two of these studies also included children with TBI and/or stroke. A randomized controlled trial by Xu et al. [62] (Level of Evidence = 1b) allocated children to one of three groups: constraint-induced movement therapy plus electrical stimulation (CIMT + ES), CIMT only, or traditional occupational therapy only. Participants in the CIMT+ES received ES to wrist extensors of the affected arm for 20 minutes, five times a week, for two weeks. All three groups made significant improvements overall. The CIMT + ES group showed the greatest improvements in all upper limb functional tests, including the Nine-Hole Peg Test and the visual-motor integration subsection of the Peabody Developmental Motor Scale. The CIMT dosage in this study may have been too low, which should be considered. When compared to CIMT for upper extremity function, both may improve AROM, PROM, spasticity and strength, but changes in function have only been reported when adjuvant ES is used.

A small prospective study by Mäenpää et al. [63] (Level of Evidence = 2b) used ES to the infraspinatus and the wrist and elbow extensor muscles in children with hemiplegic CP. Participants completed 12 sessions of ES for 30 minutes during therapy. All participants showed significant improvements in the tested movements of the Zancolli Classification for hand function immediately after completion of treatment and three months later. They also had improved active elbow extension and forearm supination. Rodriguez-Reyes et al. [64] (Level of Evidence = 3b) added ES for 20 minutes per session to wrist extensors after BTX

intervention to wrist flexors. Other muscle groups, such as pronators and elbow flexors were included as well in some participants. All participants had statistically significant improvements in hand function on the Jebsen Hand Test, but no statistically significant improvements were seen on Modified Ashworth Scale (MAS) and PROM.

Pieber et al. [55], (Level of Evidence = 3b) compared the use of BTX only and use of NMES after BTX intervention in children with CP and stroke *(for details see Spasticity section)*. The group who underwent adjuvant ES had improvements in their upper limb function, as determined by the Movement ABC Checklist, when compared to BTX only. However, no formal statistical analysis was performed.

Okafor et al. [65] evaluated upper extremity function in participants with neonatal brachial plexus palsy (NBPP) when provided with an ES program (Level of Evidence = 1b). The participants, ages 0 to 60 days old with NBPP, were randomized into two groups for six weeks. One group received conventional therapies consisting of passive mobilization and soft tissue manipulation, while the other group received an NMES program. Active range of motion in shoulder abduction, elbow flexion, wrist extension, and arm circumference were evaluated at baseline, three weeks, and six weeks after treatment. There were no statistically significant differences at baseline. At three weeks, the ES group showed significant improvements in shoulder abduction, when compared to the control group. There were significant findings in all variables in the ES group when compared to the control group after six weeks of intervention.

Children with spastic hemiplegic CP, TBI, or Stroke with decreased upper extremity function when measured via the 9-Hole peg test, Peabody Developmental Motor Scale, and the Jebsen Hand Test may benefit from ES when provided for at least 20min per day, five times per week, for two to six weeks. Those with hemiplegic CP may further benefit from the use of ES when applied in conjunction with CIMT. Additionally, infants with NBPP, despite having a lower motor neuron injury (LMN), may benefit from ES to improve active shoulder abduction, elbow flexion, and wrist extension.

3.1.5. Gait deficits

Multiple prospective, controlled trials reported improvements in gait parameters in participants with CP. Arya et al. [66] (Level of Evidence = 2b) included children with hemiplegic and diplegic CP. Participants underwent ES to the quadriceps femoris and anterior tibialis for 30 minutes a session, four to five times a week, for four weeks in addition to standard physical therapy. The control group received standard physical therapy only. Those in the intervention group demonstrated improvements in walking speed, cadence, and the Gross Motor Function Measure (GMFM) within participants and when compared to the control group.

Alabdulwahab reported consistent improvements in step length and speed in two different studies with children with spastic diplegia. The 2009 study [52] included younger children, five to nine years of age, while the one in 2011 [51] included another cohort of older children, ages eight to thirteen years of age (Level of Evidence = 2b, for both). Therapeutic ES was provided to bilateral hip adductors and abductor muscles during walking, at home after a trial for 15 minutes, and then for 15 minutes three times a day for one week. Both studies had two control groups for gait parameters, one with ambulatory children with spastic diplegic CP and the other with typically developing children. At baseline, gait performance was significantly different from the typically developing control group, but not the spastic diplegic CP control group. Significant improvements in step length and gait speed of the therapeutic ES group were reported in both studies. In the 2011 study, the therapeutic ES group also showed significant decrease in spasticity of the hip adductors (Modified Ashworth Scale). At the beginning of the study, both groups walked with scissoring gait. At the end of one week, the knees of the ES group were able to move, more than 2 cm laterally, while walking, decreasing the scissoring. The control group remained stable.

In 2003, van der Linden et al. [67] (Level of Evidence = 2b) evaluated ambulatory participants with all types of CP. Participants were randomized into one of two different groups, one that underwent NMES to the gluteal muscles for 60 minutes, six times a week, for eight weeks, while the other group received usual physical therapy. No significant differences in gait kinematics, gluteus maximus muscle strength, hip PROM, or GMFM measures were reported for the group who underwent NMES. In this study, parameters for NMES included a pulse width of 75 to 100 μsec with frequency of 10 to 30Hz. Based on the recommended parameters, these settings are not likely to evoke motor responses *(see Table 1 for appropriate motor parameters)*. In a later study, van der Linden et al. [68] (Level of Evidence = 2b) included children with diplegic or hemiplegic CP who were able

to ambulate. ES and FES were used to stimulate ankle dorsiflexors (ADF) and quadriceps for 60 minutes, six days a week, for ten weeks. Programmed frequency was 40 Hz with a pulse width of 100 μsec to ADF and 150 μsec to the quadriceps. For the first two weeks, the patient incorporated the ES to both muscles after being trained by physical therapist. Then, the participants switched from ES to FES for foot drop with a footswitch (Odstock Dropped Foot Stimulator) for the remaining eight weeks. The control group did not receive intervention. Both groups underwent gait analysis. In the intervention group, peak ankle dorsiflexion was significantly improved, and a decrease in knee flexion during stance phase was noticed. There was also a trend toward improvement in the Gillette Gait Index.

Alabdulwahab et al. [50] (Level of Evidence = 3b) also completed a smaller study where the intervention group received TENS, rather than ES, to hip adductors and compared them to similar control as described above. They reported significantly improved step length and speed, while no changes were noted on step width.

Kang et al. [57] (Level of Evidence = 3b, previously referenced in the Spasticity section) evaluated young children with CP with equinus foot deformity. All children received BTX to the gastrocnemius muscles with one group receiving ES to the injected muscles. Both groups had improvements in spasticity when assessed with the MAS and improved ankle PROM. The participants who underwent adjuvant ES with BTX had improved gait kinematics in foot equinus and crouched gait. Galen et al. [69] (Level of Evidence = 3b) evaluated qualitative changes in gait of ambulatory children with hemiplegic and diplegic CP after adding FES to the anterior tibialis following BTX injections to gastrocnemius muscles. A trend towards improvements were noted at the ankle angles and foot positioning. Findings did not reach statistical significant differences.

Seifart et al. [58] (Level of Evidence = 4) measured walking speeds and muscle strength in children with hemiplegic CP. FES was applied to the anterior tibialis and gastrocnemius muscles, using the Odstock 2 Channel Stimulator (O2CHSPI version 3.0, United Kingdom). Subjects started FES program to muscles at varying time intervals (between three and 35 days) after receiving botulinum toxin to ankle plantarflexors. The subjects incorporated FES at home with walking for 30 minutes perday, five times per week for four weeks. No changes in walking speed were noticed with addition of FES to both agonist and antagonist musculature, as adjuvants to standard management with only therapy.

Ambulatory children with spastic hemiplegic and diplegic CP who have poor knee control, decreased cadence and speed, foot equinus, and crouched gait during walking may benefit from the incorporation of ES with or without BTX. ES may assist in functional changes and developing motor patterns in patients with spasticity, when provided for 30 to 60 min per day, five to six times per week, for at least four weeks. Earlier denervation and longer effects may be seen when combining BTX and ES.

3.2. Foot drop

Two prospective studies evaluated the use of an FES device to the common fibular nerve (WalkAide; Innovative Neurotronics, Austin, TX, USA) in children with CP. Prosser et al. [59] (Level of Evidence = 2b) included ambulatory children (GMFCS I-II) with all types of CP who had foot drop. Participants wore the device for an average of 5.6 hours a day (range 1.5 to 9.4 hours a day), every day for four months. Their gait was analyzed in a gait laboratory prior to incorporation of FES device, in their own footwear, with braces if applicable. Most subjects wore no braces or only lifts/SMOs at baseline. Only one subject used an AFO. FES device was incorporated at three months after traditional interventions. Gait was re-assessed at four months (one month since FES incorporation) and seven months (three months after incorporating FES device). Significant improvements in ankle dorsiflexion during swing with preservation of ankle plantarflexors at toe-off were noted during the use of FES device, when compared with non-FES condition. Their gait speed did not change, as they maintained a self-selected walking speed at 0.3 mph and fast walking speed at 0.45 mph. FES device was not compared to traditional AFO in this study since only one subject used AFO at baseline.

Meilahn's [70] (Level of Evidence = 2b) study included children with hemiplegic CP. The same type of FES device as described above (WalkAide) was fit to each participant. The majority of participants (70%) wore the FES device for completion of the study (three months). Wear time was reported with an average of 8.4 hours per day during the first three weeks, and then an average of 5.8 hours per day for the remainder of the study. Their gait paremeters were analyzed, but comprehensive motion analysis study was not completed.

Gait velocity increased in 50% of the participants and ankle kinematics were normalized in about 30% of the participants. Data was compared to baseline gait analysis obtained two weeks prior to initiation of trial. However, study does not mention if subjects wore any bracing at baseline analysis. Two participants reported skin irritation from electrodes.

Two lower level studies were found that investigated the use of heel switches as an intervention for foot drop. Postans and Granat [71] (Level of Evidence = 3b) evaluated ambulatory children with diplegic or hemiplegic CP that received FES via heel switch (computer-controlled stimulator by the University of Strathclyde) during walking for gait analysis. Improvements in ADF in swing phase were noted along with improvements in foot positioning and increased knee extension during stance phase. Ho et al. [72] (Level of Evidence = 3b) also analyzed the use of FES heel switch (Respond II Select) in ambulatory children with CP. Participants' gait was statistically compared with gait parameters of typically developing children. It was reported that study participants improved the impulse generated during push-off. Both studies had equal stimulation parameters with pulse width of 300 μs and frequencies of 32 to 50 Hz.

The reviewed articles suggest that candidates for the use of ES to address foot drop in gait are ambulatory children with UMN lesions, particularly diplegic and hemiplegic CP. It is recommended that the child use the device for a trial period to evaluate the effectiveness, ramp up parameters appropriate for the individual, and optimize tolerance of the device. FES neuroprostheses should be used for an average of six hours a day, for at least three weeks. The incorporation of ES for gait training may improve walking speed, positioning of foot, and ankle kinematics.

3.2.1. Poor trunk control

Karabay et al. [73] evaluated sitting balance, Gross Motor Function Measure (GMFM) sitting score, and Cobb and sacral angles in two groups of participants with spastic diplegic CP (Level of Evidence = 2b). Both groups received conventional physical therapy, and the treatment group also received NMES to abdominal and posterior back muscles for 30 minutes daily (at least five times a week) for four weeks, during therapy. Both groups had improvements in GMFM sitting score, while the ES group had greater significant improvement. Similar results were reported for Cobb and kyphosis angles while sitting. No changes in the sacral angle were observed in either group.

Sitting and balance may be improved with ES to trunk musculature for children with spastic diplegic CP, provided for 30 minutes a day, five times per week, for at least four weeks.

3.2.2. Deconditioning

Improvements in resting heart rate and oxygen uptake have been reported by Johnston et al. [26,47] in two different studies (Level of Evidence = 1b & 4). Both studies compared children with SCI who underwent ES without cycling, lower extremity FES cycle ergometry (RT300), or passive cycle ergometry without ES. Participants in the FES and ES group received stimulation to the gluteal, hamstrings and quadriceps muscles. Treatment duration time in both studies was sixty minutes, three times per week, for six months. The groups that used FES ergometers showed greater percent of change improvement in oxygen uptake when compared to participants who cycled passively (Level of Evidence = 1b) [26]. The ES group showed declines in cholesterol levels compared to the FES and passive ergometer groups (Level of Evidence = 1b) [26]. ES may assist with conditioning, including improved oxygen uptake for children with SCI and potentially for other children who have decreased lower extremity selective control and decreased ambulatory ability.

3.2.3. Disuse osteopenia/osteoporosis

Improvements in bone mineral density (BMD) values have been reported in two different studies for children with SCI. Johnston et al. [47] (Level of Evidence = 4, also referenced above in the Conditioning section) evaluated BMD between participants who participated in FES ergometry to passive cycling only. At the end of the six months, improved BMD, muscle volumes and strength, and resting heart rates were observed for the participants undergoing FES ergometry, as compared to those in passive ergometry. Later, Lauer et al. [23] (Level of Evidence = 1b) replicated these results in a randomized-control trial. The participants were allocated to three interventions: FES ergometers, passive ergometer, or NMES only. The treatment times and duration were for 60 minutes, three times per week, for six months. Other baseline activities, such as walking or standing with braces were permitted. All participants underwent Dual Energy X-Ray Absorptiometry (DEXA) examination. Non-significant trends for improved BMD were reported for participants who underwent either passive or FES ergometry. While these results are not statistically significant, these trends may

be of clinical significance as BMD improved by 0.9–10% with exercise only, 29% with passive ergometer, and 33% with FES ergometry. Proximal femur changes were observed in both groups, either passive or FES cycling, but only the FES ergometry group had improvements in proximal tibia BMD. Bone mineral density may be positively affected with the use of FES ergometry.

FES ergometry may be beneficial for children with SCI who are at risk for or who have disuse osteopenia or osteoporosis.

3.2.4. Dysphagia

The use of ES for dysphagia has been widely reported in the adult literature. Christiaanse et al. [74] evaluated the use of NMES (VitalStim®) in children with dysphagia (Level of Evidence = 2b). These participants had dysphagia due to a variety of underlying conditions. ES was provided to neck musculature for 30 to 45 minute sessions, twice a week for, ten weeks (total of 22 sessions). Because this was a retrospective study, participants who underwent usual oromotor training, without ES, for dysphagia were used as historical controls. The participants were divided in primary versus acquired dysphagia for additional comparisons. Participants with acquired dysphagia who underwent oromotor training and NMES improved more in their Functional Oral Intake Scale, obtained with video-fluoroscopic swallowing study, than similar control children. Therefore, children with acquired dysphagia, rather than primary dysphagia may be better candidates for VitalStim®.

3.3. Appropriate patient selection

Patients who are the best candidates for treatment with ES present with functional deficits related to weakness, spasticity, or poor motor control. Additionally, patients with low muscle mass, bone mineral density (BMD), cardiovascular deconditioning, or contracture may benefit from therapeutic ES to address these deficits. This may include patients with cerebral palsy (CP), traumatic brain injury (TBI), stroke, spinal cord injury (SCI), myelomeningocele (MMC), brachial plexopathy [65], and orthopedic abnormalities [75,76]. While a patient exclusively with lower motor neuron syndrome, that is presence of hypotonicity, denervation atrophy, and absent reflexes, may not be the best candidate for remediation of functional deficits with ES, it may still be worth considering as an adjunct to traditional therapy. Kern et al. [77] found that home-based FES of denervated muscle resulted in rescue of muscle mass and tetanic contractility in a 2-year longitudinal prospective study of 25 adult participants with complete conus/cauda equina lesions. They also found important immediate benefits for the participants, including improved cosmetic appearance of lower extremities and the enhanced cushioning effect for seating [77]. No studies have been published with pediatric LMN injury population.

No article reviewed here presents a lower age limit for treatment with ES. The youngest participants in the articles reviewed were two days old, for the treatment of brachial plexus palsy, and 16 months old, for the treatment of spasticity. Very young children may tolerate ES better, as they do not have the anxiety associated with perceived discomfort that older children do. As with all patients, very young children should be carefully monitored for signs and symptoms of adverse responses (see below).

3.4. Adverse reactions and contraindications

The majority of the population included in these reviewed studies was patients with cerebral palsy with intact sensation. Therefore, the idea that patients who have appropriate sensation are poor candidates to undergo interventions with ES may be a misconception. No adverse reactions were reported in most of the studies. In fact, Kim et al. [60], reported that participants who received ES better tolerated stretching and therapies. Postans et al. [71] reported two participants who dropped out of their study due to difficulties with tolerance, though no details were provided about trial and ramp up sessions. How the therapists incorporate an ES trial, the use of parameters and ramp up may improve ability for younger children to tolerate the intervention. Another study by Seifart et al. [58] reported that two participants refused to put the electrodes on their skin. Meilahn [70] reported two participants who developed skin irritation associated with the use of electrodes. Hypoallergenic electrodes are now commercially available for patients with sensitive skin or tolerance issues with traditional carbon electrodes. Johnston et al. [22] reported two distal femur fractures during their 2011 study. They associated both of these fractures to the strength testing and not directly with the use of ES. Children are susceptible to the same adverse reactions as adults, which may include withdrawal response, increase in tone, respiration or heart rate, autonomic dysreflexia, neurostorming, increase in seizures (especially patients with poorly controlled

epilepsy), mottled erythema, and other forms of skin irritation.

This is not an all-inclusive list, but highlights some of the most inquired precautions for pediatric patients with disabilities.

3.4.1. Electronic implants

Providers should consider extreme caution in the use of ES with active pacemakers or implantable cardioverter-defibrillators. The literature has shown that ES may affect the pacemaker rhythm and output. It may trigger an on-demand pacemaker or affect its timing. Few studies have included subjects with pacemakers [78]. If its use is being considered, cardiology clearance, electrocardiogram, and pacemaker interrogation may be warranted [79,80].

No literature was found to the use of diaphragmatic stimulation through implantable phrenic nerve stimulator or local pacing, and NMES/FES. Electrical stimulation directly above implantable devices, such as the aforementioned pacemakers and others, including intrathecal baclofen pumps, should be avoided. When in doubt, manufacturer information, such as contraindications, recommendations, and warranties should be reviewed prior to using ES.

3.4.2. Tumors

Multiple textbooks present cancer as a relative contraindication for the use of ES. ES increases circulation and cell proliferation, which theoretically could lead to uncontrolled cell growth and metastases [81]. Very few studies have actually examined the results of NMES, TENS, or FES in patients with cancer. None of these adult studies assessed tumor burden or disease progression as part of their outcome measures [82,83]. Local use of ES away from known malignancies (ex: to ankle dorsiflexors with kidney cancer) may be considered a precaution, not an absolute contraindication [81]. ES has been used to drive in chemotherapeutic agents into target organs [84,85].

3.4.3. Infection

Since ES results in angiogenesis and increased blood flow, stimulating directly above an area of infection, including osteomyelitis, may lead to increased pain (due to increased swelling), and propagation of infection. Therefore, ES may increase the risk of sepsis, if used directly over an infected area and its use should be avoided [81].

3.4.4. Hip subluxation

Johnston et al. [86] specifically evaluated hip migration indices with the incorporation of FES cycle, passive cycle, or ES to lower extremity muscles. Participants underwent 60 minutes of intervention, three times per week for six months. There were no changes in hip migration as long as the hips were appropriately positioned (with avoidance of hip adduction and/or internal rotation) during cycling activities.

4. Clinical applicability

ES has been demonstrated to be a useful modality in treating a wide range of dysfunction in children with functional impairments. ES may be used frequently as an adjunct to therapies to maximize strength (including core strength and trunk/sitting balance), maintain or improve muscle mass, and ROM. ES may be used with or without BTX for spasticity management, either with strengthening of antagonist muscles or by stimulating agonist muscles to accelerate and prolong the effects of chemodenervation.

As indicated in this review, it is generally well tolerated, even by very young children, and adverse events are modest. Provider education and comfort with use still present barriers to implementation, but ES should be considered for the treatment of children with paralysis, weakness, spasticity, or motor control issues.

It is difficult to compare studies, since nomenclature for the use of ES and treatment parameters has not been consistent through the years. Hopefully, with greater education and training, practitioners may become more familiar and increase its use, both in the clinical and research arenas. In addition, with better understanding of parameters to be used according to the goals of treatment, dosing needs to be addressed in future research, as well.

In order to make definitive conclusions regarding ES, NMES or FES as an intervention, careful detail needs to go into selection of appropriate parameters, since this may either limit or maximize ES as an intervention. This can be difficult due to lack of standardization of protocols and/or dosing. As different patient populations with diverse impairments and/or disabilities may benefit from ES as an intervention, appropriate outcome measures need to be taken into consideration.

The majority of the studies reported good tolerance and acceptability of ES. Studies that did not have a clear goal for the implementation of ES and that required ES to be used for a prolonged period of time had decreased acceptability [46]. Therefore, it is highly

Table 3
Details for articles reviewed

Author	Year	Diagnosis	Impairment evaluated	Type of ES	Pulse width	Pulse frequency	Treatment duration & frequency	Level of evidence
AlAbdulwahab et al.	2011	CP (di)	Gait; Spasticity	NMES	50 μsec	20 Hz	15 min/session 3x/day Daily for 1 wk	2b
AlAbdulwahab et al.	2010	CP (di)	Gait; Spasticity	TENS (reported; though consistent with NMES after review of parameters)	250 μsec	100 Hz	15 min/session 3x/day Daily for 1 wk	3b
AlAbdulwahab et al.	2009	CP (di)	Gait; Spasticity	NMES	50 μsec	20 Hz	15 min/session 3x/day Daily for 1wk	2b
Arya et al.	2012	CP (hemi and di)	Gait	NMES	200 μsec	20 Hz for QF; 40 Hz for TA	20–30 min/day 4–5x/ wk for 4 wks	2b
Christiaanse et al.	2011	All diagnosis, primary and acquired	Dysphagia	NMES	100–700 μsec	80 Hz	30–45 min/day 2x/ wk for 10 wks	2b
Galen et al.	2012	CP (hemi and di)	Gait	FES	300 μsec	30 Hz	20–30 min/day 7x/ wk for 8 wks (first wk to build tolerance)	3b
Gelfer et al.	2010	Club feet	Contracture	NMES	330 μsec	40 Hz	30 min/day 7x/ wk for 18 wks	4
Ho et al.	2006	CP (all walkers)	Foot Drop	FES with heel switch	300 μsec	32 pps	min/day 15 trials with FES and walking	3b
Johnston et al.	2011	SCI	Weakness	FES cycle and NMES	150–300 μsec	33 Hz	60 min/day 3x/wk for 6 months	1b
Johnston et al.	2008	SCI	Weakness; Deconditioning, Osteoporosis	FES cycle	150 μsec	33 Hz	60 min/day 3x/wk for 6 months	4
Johnston et al.	2009	SCI	Deconditioning	FES cycle or NMES	150–300 μsec	33 Hz	60 min/day 3x/wk for 6 months	1b
Kamper et al.	2006	TBI + CP	UL dysfunction; Spasticity; Weakness	NMES	280 μsec	35 Hz	15–30 min/day 6x/wk for 12 wks	3b
Kang et al.	2007	CP	Gait; Spasticity; Contractures	NMES	300 μsec	40 Hz	30 min/day 2x/ wk for 2 wks	3b
Karabay et al.	2012	CP (di)	Poor Trunk Control	NMES	250 μsec	25 Hz	30 min/day 5x/ wk for 4 wks	2b
Katz et al.	2008	CP	Spasticity; Weakness	NMES	250 μsec	20 Hz	30 min/day 5–7x/wk for 3 months	3b
Kerr et al.	2006	CP (all)	Gait; Weakness	NMES and TES	300 μsec	35 Hz	1 hr/day (NMES); 8 hr/ night (ThES: $<$ 10 mA) 5x/wk for 16 wks	2b
Khalili et al.	2008	CP	Spasticity; Contracture	NMES	400 μsec	30 Hz	30 min/day 3x/ wk for 4 wks	2b
Kim et al.	2009	Torticollis	Contracture	NMES	not mentioned	8 Hz	30 min/day 3x/ wk for 2 wks	3b
Lauer et al.	2011	SCI (C4-T11)	Osteoporosis	FES cycle or NMES	150–300 μsec	33 Hz	60 min/day 3x/wk for 6 months	1b

Table 3, continued

Author	Year	Diagnosis	Impairment evaluated	Type of ES	Pulse width	Pulse frequency	Treatment duration & frequency	Level of evidence
Maenpaa et al.	2004	CP (hemi + di)	Contracture	NMES	300 μsec	10–20 Hz	20–60 min/day 5x/wk for 4 wks	3b
Maenpaa et al.	2004	CP (hemi)	UL dysfunction	NMES	300 μsec	40 Hz	20–40 min/session 12 sessions	2b
Meilahn et al.	2013	CP (hemi)	Foot Drop	FES (WalkAide)	50 μsec	not mentioned	8 hr/day (1^{st} 3 wks) then 6 hr/day (2^{nd} 3 wks) for 3 months	2b
Okafor et al.	2008	NBPP	UL dysfunction	NMES	not mentioned	not mentioned	45 min/day 3x/ wk for 6 wks	1b
Ozer et al.	2006	CP (hemi)	UL dysfunction; Spasticity; Contracture; Weakness	NMES	200 μsec	40–60 Hz	30 min/session 2x/day 5x/wk for 16 wks	2b
Pieber et al.	2011	sp hemi (CP + stroke)	UL dysfunction; Spasticity	FES and NEMS	200 μsec	30 Hz	15 min/session 2x/day 5–7x/wk for 3 months	3b
Postans et al.	2005	CP (di + hemi; walkers)	Foot Drop	FES	300 μsec	33 or 50Hz	min/day 10 trials with FES and walking	3b
Prosser et al.	2012	CP	Foot Drop	FES (WalkAide)	25–300 μsec	16.7–33 Hz	5 hr/day Daily for 3 months	2b
Rha et al.	2008	CP (di + quad)	Spasticity	NMES	250 μsec	4–25 Hz	30 min/day 7x/wk for 1 wk	2b
Rodriguez-Reyes et al.	2010	CP	UL dysfunction; Spasticity	NMES	300 μsec	32 Hz	20 min/session 10 sessions	3b
Seifart et al.	2010	CP (hemi)	Gait	FES with foot switch	not mentioned	not mentioned	30 min/day 5x/wk for 4 wks	4
Trevisi et al.	2012	CP	Gait; Spasticity; Weakness	NMES	not mentioned	not mentioned	30 min/day 3x/wk for 7 wks	4
vanderLinden et al.	2003	CP (all walkers)	Gait; Weakness; Contracture	NMES	75–100 μsec	10–30 Hz	60 min/day 6x/wk for 8 wks	2b
vanderLinden et al.	2008	CP (hemi and di)	Gait	NMES or FES	100–150 μsec	40 Hz	60 min/day 6x/wk for 10wks (2 wks of NMES/TES and 8wks of FES)	2b
Vaz et al.	2008	CP (hemi)	UL dysfunction; Weakness	FES	300 μsec	30 Hz	min/day 3x/wk for 8 wks	3b
Walker et al.	2011	MMC	Gait; Weakness; Contracture	TES	280 μsec	35 Hz	6–8 hr/night 6x/wk for 1yr (no one completed 1yr)	4
Xu et al.	2012	CP (hemi)	UL dysfunction	NMES	300 μsec	50 Hz	20 min/day 5x/wk for 2 wks	1b

CP: cerebral palsy; di: diplegia; Gait: gait dysfunction; μsec: microseconds; TES: threshold ES; NMES: neuromuscular ES; hemi: hemiplegia; Contracture: Contracture management/Prevention of Deformity; QF: quadriceps femoris; TA: tibialis anterior; FES: functional electrical stimulation; SCI: spinal cord injury; MMC: myelomeningocele; TBI: traumatic brain injury; UL: upper limb; NBPP: neonatal brachial plexus palsy; sp: spastic; quad: quadriplegia; dx: diagnoses; x/wk: times per week.

beneficial to be goal-oriented for the appropriate implementation and compliance, both in the research and clinical settings. It is essential, also, to appropriately introduce children and youth to the ES devices and electrodes. Using developmentally appropriate ways to explain the procedures and what the patient may feel (for example, "tickling" for the stimulation, "stickers" for the electrodes), can improve tolerability and compliance in the pediatric population.

NMES and FES are safe and well tolerated in children with different disabilities. As practitioners we should better understand how to effectively use this tool. Table 3 includes a list of all articles, level of evidence, type of stimulation reported, parameters used, and impairments treated. ES should be incorporated into therapies to maximize functional progress in order to assist cortical re-organization, train for appropriate motor patterns, and to maximize neurodevelopmental skills for upper and lower extremity function and gait in children. Standardization of terminology and parameters are greatly encouraged in order to be able to compare effectiveness and outcomes. Additional research is required to understand specific outcomes for specific applications, and optimal dosing.

Conflict of interest

The authors have no conflict of interest to declare.

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