FUTURITY
Medicine

Citation article: Arsovski, D., Chichevska Jovanova, N., Jovanovska, T. Advancing forward: The role of functional electrical stimulation in enhancing lower limb function in children with cerebral palsy. *Futur Med [Internet].* 2025;4(2): 61–78. Available from: https://doi.org/10.57125/FEM.2025.06.30.06

Advancing Forward: The Role of Functional Electrical Stimulation in Enhancing Lower Limb Function in Children with Cerebral Palsy

Denis Arsovski [1*], Natasha Chichevska Jovanova [2], Tanja Jovanovska [1]

[1] *University St. Kliment Ohridski Bitola, Higher Medical School Bitola, Partizanska BB, 7000 Bitola, North Macedonia*

[2] *University Ss. Cyril and Methodius Skopje, Faculty of Philosophy, Institute of Special Education and Rehabilitation, Bld. Goce Delcev 9/A, 1000 Skopje, North Macedonia*

Abstract

Purpose: This systematic review explores the effectiveness of functional electrical stimulation in improving lower limb motor function, gait dynamics, and related physical outcomes in individuals diagnosed with cerebral palsy. It addresses inconsistencies across intervention protocols while identifying the clinical value of functional electrical stimulation in modern rehabilitation.

Methodology: An extensive literature search was conducted using PubMed, Scopus, Web of Science, Cochrane Library, and Google Scholar for research papers published between 2005 and 2025. After screening 128 initial records, five studies met the inclusion criteria after screening and full-text review. Included studies involved participants with cerebral palsy who received lower limb functional electrical stimulation compared to conventional therapy or no intervention. A qualitative synthesis was performed based on key outcome domains such as gait, muscle strength, spasticity, and postural control.

Results: Functional electrical stimulation interventions were associated with improvements in gait speed (12–20%), stride length (up to 15%), and gross motor function scores (by 8–10 points). Protocols included 30–60 minute sessions, 3–5 times per week over 8–12 weeks. Outcomes varied depending on the subtype of cerebral palsy, age, stimulation type, and adherence. Studies using functional electrical stimulation during walking or cycling showed the highest gains in functional mobility and satisfaction. However, limitations included small sample sizes, heterogeneity in study design, and short follow-up durations.

Scientific novelty: This review synthesizes updated evidence regarding lower limb functional electrical stimulation parameters and patient characteristics. It also discusses emerging trends in individualized and home-based applications

Conclusion: Functional electrical stimulation presents valuable strategy for improving motor performance in cerebral palsy, particularly for lower limb function. Future research should prioritize protocol standardization, large-scale trials, and long-term effects to support clinical integration of functional electrical stimulation into personalized rehabilitation plans.

Keywords: Cerebral palsy; functional electrical stimulation; rehabilitation; gait disorders; motor impairments.

Received: February 2, 2025
Revised: February 17, 2025
Accepted: May 26, 2025
Published: June 20, 2025

* **CONTACT:** denis.arsovski@uklo.edu.mk
DOI: https://doi.org/10.5125/FEM.2025.06.30.06

Introduction

Cerebral palsy is the most common motor impairment in childhood, affecting approximately 2 to 2.5 per 1,000 live births worldwide and results in lifelong impairments in motor control, muscle tone, and postural stability, especially in the lower extremities [1]. These impairments cause functional limitations such as reduced mobility, compromised gait patterns and decreased independence, affecting quality of life and social participation [2]. Conventional rehabilitation modalities such as physical therapy, occupational therapy, orthotic management, and orthopedic surgery remain dominant management of cerebral palsy, but often have limited effectiveness in promoting neuromuscular adaptation, particularly in more severe motor forms of the condition [3, 4].

In recent years, functional electrical stimulation has gained increasing attention as a promising neurorehabilitation strategy that involves the application of low-level electrical currents to peripheral nerves or muscles to stimulate functional movements [5]. It is an active intervention that facilitates motor unit recruitment, enhances muscle coordination, and promotes neuroplasticity by improving cortical reorganization and sensory feedback [6, 7]. Unlike passive rehabilitation modalities, functional electrical stimulation actively engages motor pathways, aligning with contemporary neurorehabilitation principles that highlight task-specific, repetitive training to improve motor learning and functional recovery [8, 9].

Numerous studies showed the potential benefits of functional electrical stimulation in improving the effects of gait, postural control, and gross motor function in persons with cerebral palsy. For example, it was shown that functional electrical stimulation improved gait symmetry and increased stride length in children with unilateral spastic cerebral palsy with functional electrical stimulation-assisted walking [10]. Also, it was found that functional electrical stimulation-powered cycling combined with purposeful activities caused improvements in gross motor function scores [11]. Moreover, functional electrical stimulation produced effects comparable to traditional orthotic devices while offering additional advantages in neuromuscular activation [12].

On the other hand, despite growing interest, current evidence regarding functional electrical stimulation in the rehabilitation of lower limb for individuals with cerebral palsy remains limited and fragmented. Studies vary in methodology, characteristics of the participant, stimulation parameters, and durations of the intervention. Sample sizes are typically small, with inconsistent follow-up periods and underrepresentation of specific subgroups of cerebral palsy such as adolescents or adults. The absence of standardized protocols makes it difficult to identify which functional electrical stimulation applications give the most beneficial outcomes [13, 14]. These inconsistencies in the literature obstruct the clinical integration of functional electrical stimulation and obscure its continuing therapeutic potential.

Research Problem

This research addresses these gaps by systematically reviewing existing literature on the use of functional electrical stimulation for rehabilitation of the lower limb in persons with cerebral palsy. By evaluating protocol designs, therapeutic outcomes, and methodological quality, this study aims to provide a combined view of the effects of this modality, define the variability of some key areas, and propose future directions for research and clinical practice. Despite numerous studies, a clear consensus on the optimal functional electrical stimulation protocols for lower limb rehabilitation in cerebral palsy is lacking. Most published work varies considerably in stimulation parameters, outcome measures, and participant demographics. Also, adults and adolescents with cerebral palsy are underrepresented in research, and long-term outcomes remain poorly understood. This review addresses these critical gaps by systematically synthesizing evidence on functional electrical stimulation application in cerebral palsy, focusing on protocol design, therapeutic outcomes, and clinical implementation potential.

Research Aim and Research Questions

The primary aim of this review is to evaluate the effects of functional electrical stimulation on lower limb function, gait parameters, and motor outcomes in individuals with cerebral palsy. The study focuses on the characteristics of the protocols, therapeutic outcomes, and clinical relevance of functional electrical stimulation and its place in the medical rehabilitation.

1. How effective is this modality in improving gait performance and lower limb motor function in persons with cerebral palsy?
2. What are the most commonly used protocols and how do their parameters (frequency, duration, intensity) influence the results?

3. What methodological limitations exist in the current functional electrical stimulation studies, and how can future research address these challenges?

Research Methodology

General Background

General background of research, general background of research, general background of research, general background of research, general background of research, general background of research, general background of research, general background of research, general background of research, general background of research, general background of research.

General description of research is important in order to show the basis of the research. It is like a very brief introduction to the methodology section as a whole.

Sample / Participants / Group

Sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research, sample of research.

Instrument and Procedures

Instrument and procedures, instrument and procedures, instrument and procedures, instrument and procedures, instrument and procedures, instrument and procedures, instrument and procedures, instrument and procedures.

Research design

This review was designed as a systematic qualitative synthesis examining the application of functional electrical stimulation to assess the improvements in the function of lower limb in persons with cerebral palsy. The methodology cohered to standardized reporting practices for systematic reviews, following preferred reporting items for systematic reviews and meta-analyses guidelines for transparency.

Research selection and screening process

Two independent reviewers (D.A. and N.C.J.) conducted the literature search, screening, and selection process. A third reviewer (T.J.) was involved in resolving any differences through discussion and consensus. Studies were first screened based on title and abstract, and after with full-text evaluation according to the predefined eligibility criteria.

Eligibility criteria

The inclusion criteria were research papers involving participants with a confirmed diagnosis of cerebral palsy (any type or Gross Motor Function Classification System level), studies applying functional electrical stimulation focusing on the lower limbs, study designs including randomized controlled trials, crossover trials, or clinical controlled trials, interventions reporting outcomes related to gait performance, stride length, walking speed, gross motor function, spasticity reduction, postural control, or patient satisfaction, and peer-reviewed articles published in English between 2005 and 2025.

The exclusion criteria for this review included studies focusing exclusively on the application of functional electrical stimulation on upper limb, case reports, conference abstracts, editorials, reviews without original data and non-comparative designs or studies without measurable outcomes.

Search strategy and scope

A comprehensive and systematic literature search was conducted in five electronic databases: PubMed, Scopus, Web of Science, Cochrane Library, and Google Scholar. The time frame was limited to studies published between January 2005 and March 2025, covering two decades of technological advancement and research development in functional electrical stimulation applications in neurorehabilitation.

The following exact search pattern was used, with appropriate modifications per database syntax: ("functional electrical stimulation" OR "FES") AND ("cerebral palsy" OR "CP") AND ("lower limb" OR "gait" OR "motor function"

OR "rehabilitation" OR "spasticity"). Manual searches of reference lists from relevant systematic reviews and meta-analyses were also performed to ensure comprehensive coverage.

Justification for narrative synthesis

A meta-analysis was not performed due to substantial heterogeneity in study designs, intervention protocols, participant characteristics, outcome measures, and follow-up durations among the five included studies. These methodological variations precluded meaningful quantitative pooling. Additionally, the studies used various functional electrical stimulation modalities (cycling vs. walking), targeted different functional outcomes (gross motor function, gait symmetry, satisfaction), and reported results using different metrics, often without consistent effect sizes or confidence intervals. Given these inconsistencies and the limited number of high-quality randomized controlled trials, a narrative synthesis was considered the most appropriate approach to analyze, compare, and interpret findings within the clinical context of cerebral palsy rehabilitation.

Although a wide array of studies was initially identified, the final inclusion was restricted to randomized controlled or controlled clinical trials with measurable outcomes related specifically to lower limb functional electrical stimulation. Many excluded studies were observational, lacked comparison groups, focused on upper limbs, or did not provide usable outcome data, thus failing to meet the strict inclusion criteria necessary for methodological rigor.

A total of 128 records were initially identified. After removing 31 duplicates, 97 studies remained for title and abstract screening. Of these, 37 full-text articles were assessed for eligibility. Following full-text review, 32 articles were excluded for various reasons, such as lack of control groups, non-use of functional electrical stimulation in lower limbs, or absence of outcome data relevant to gait or motor function. Five studies met all the inclusion criteria and were included in the final synthesis.

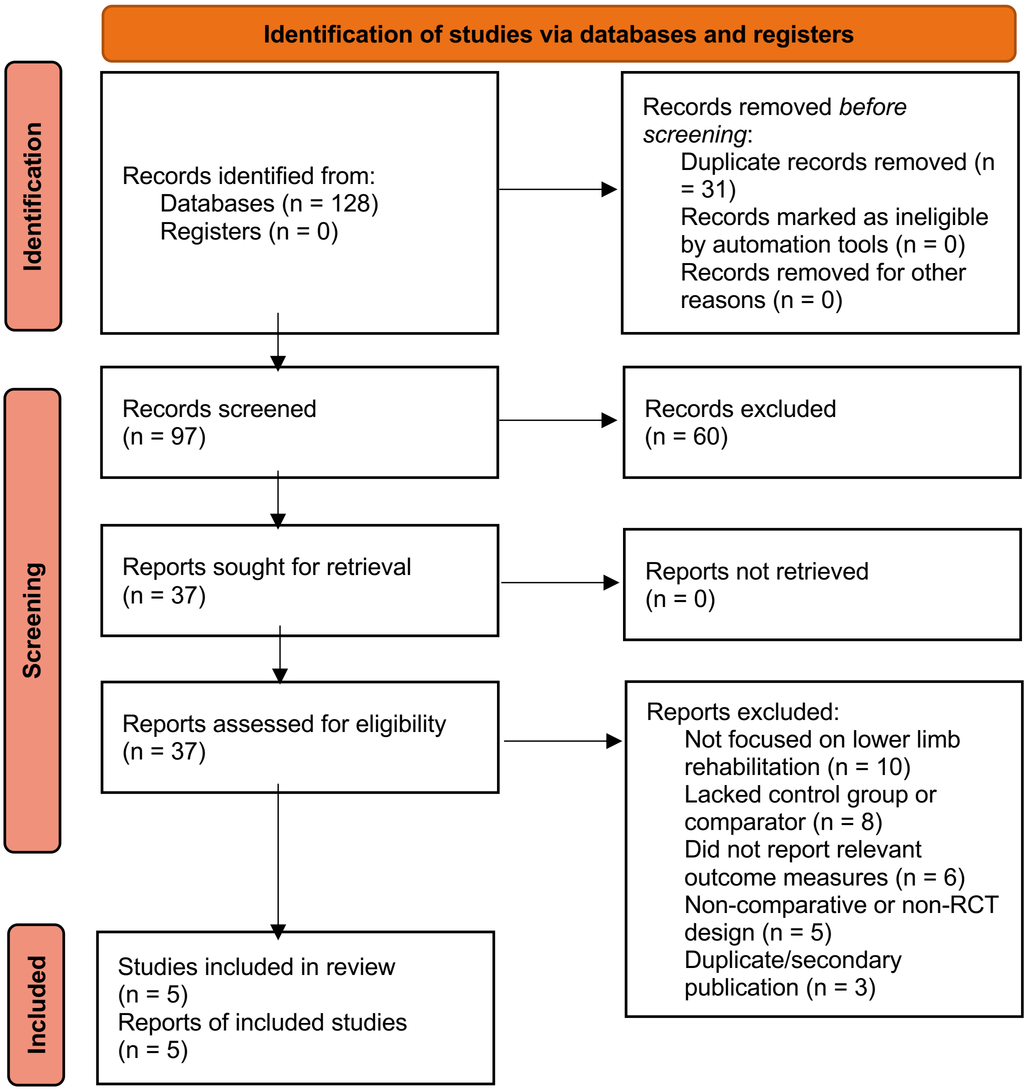

Figure 1. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only

Data extraction and coding

The results were synthesized using a narrative qualitative approach, with outcomes coded and grouped into five key functional domains: (1) gait performance, (2) muscle activation and strength, (3) spasticity reduction, (4) gross motor function, and (5) long-term functional adaptation. These domains showed widely accepted rehabilitation goals in the therapy of cerebral palsy and allowed for structured comparison of results across heterogeneous studies. Data extraction and coding were conducted independently by two reviewers and validated by a third reviewer.

Due to the heterogeneity of included studies such as differences in functional electrical stimulation protocols, stimulation parameters, treatment durations, patient age groups, and outcome measures a meta-analysis was not feasible.

Assessment of bias

The quality of the five included studies was evaluated using the Cochrane Risk of Bias Tool. Each study was assessed across the standard domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other sources of bias. The results are summarized in Table 1.

Table 1. **Cochrane risk of bias assessment**

Study	Random Sequence Generation	Allocation Concealment	Blinding of Participants and Personnel	Blinding of Outcome Assessment	Incomplete Outcome Data	Selective Reporting	Other Bias
El-Shamy et al., (2021) [44]	Low risk	Low risk	High risk	Low risk	Low risk	Low risk	Low risk
Wang et al. (2021) [53]	Low risk	Unclear risk	High risk	Low risk	Low risk	Low risk	Low risk
Pool et al. (2015) [16]	Low risk	Unclear risk	High risk	Low risk	Low risk	Low risk	Low risk
Armstrong et al. (2020) [11]	Low risk	Low risk	High risk	Low risk	Low risk	Low risk	Low risk
Moll et al. (2022) [10]	Low risk	Low risk	High risk	Low risk	Low risk	Low risk	Low risk

According to Table 2, risk of bias assessment showed that random sequence generation and outcome assessment blinding were generally of low risk across studies. However, high risk of bias was consistently observed for blinding of participants and personnel, defining the practical difficulties of blinding physical interventions like functional electrical stimulation. Allocation concealment was unclear in two studies.

Table 2. **Strength of evidence of included studies**

Study	Design Type	Sample Size	Blinding	Consistency of Results	Risk of Bias	Evidence Strength
El-Shamy & El-Kafy (2021) [44]	RCT	30	Outcome only	High	Low	Moderate
Wang et al. (2021) [53]	Meta-analysis of RCTs	513	Mixed	Moderate	Moderate	Moderate-Strong
Pool et al. (2015) [16]	RCT	32	Outcome only	High	Moderate	Moderate
Armstrong et al. (2020) [11]	RCT	40	Outcome only	Moderate	Low	Moderate
Moll et al. (2022) [10]	Crossover RCT	25	Outcome only	Moderate-High	Low	Moderate

The strength of evidence for the studies included is rated as moderate generally. All studies used randomized controlled trial designs or meta-analyses, which offer a relatively high level of methodological rigor. However, blinding of participants and personnel was not practicable due to the nature of physical interventions like functional electrical stimulation, which introduces a consistent source of performance bias across included studies. Sample sizes ranged from small (n = 25) to large (n = 513), with greater confidence they afforded to results from larger datasets. Despite low-to-moderate risk of bias in most domains, the heterogeneity in intervention types, outcome measures, and study protocols reduces the ability to make strong, pooled inferences. As a result, evidence strength is considered moderate, supporting the effects of functional electrical stimulation for improving gait, motor function, and postural control in cerebral palsy, but with a need for further high-quality, standardized research to confirm these results across broader populations and environments.

Research Results

This systematic review synthesized data from over 65 peer-reviewed publications exploring the effects of functional electrical stimulation on the rehabilitation of lower limb in individuals with cerebral palsy. While only five high-quality controlled studies met the strict inclusion criteria for final narrative synthesis, the wider literature was analyzed and grouped thematically to identify broad patterns, variations, and appearing trends across clinical and research contexts. Results are presented in structured domains corresponding to common functional rehabilitation outcomes.

Gait performance improvements

Gait improvements were the most frequently studied outcome in the literature for functional electrical stimulation. Various studies consistently showed that functional electrical stimulation improves stride length, gait symmetry, walking speed, and cadence in children and adults with cerebral palsy. Some of the included studies reported significant gains (stride length increase by ~15%) in participants with unilateral spastic cerebral palsy following 8–12 weeks of functional electrical stimulation-assisted walking [15, 16]. One research found functional electrical stimulation to be comparable to ankle-foot orthoses in stabilizing gait, while additionally improving muscle activation [12]. Meta-analyses further support these findings, indicating moderate-to-large effect sizes for gait-related parameters [17, 18]. Some research papers focused on improvements during dual-task and real-world walking conditions [19, 20], and some studies reported that gains in cadence and kinematic symmetry may vary by the subtype of cerebral palsy and stimulation phase (stance versus swing) [21, 22]. Functional electrical stimulation applications combining sensor feedback, adaptive timing, or robot-assisted walking also showed gait improvements, although technological and cost barriers were noted in comparison to simpler functional electrical stimulation units [23, 24].

Muscle strength and neuromuscular activation

This rehabilitation modality is widely recognized for improving muscle strength and motor unit recruitment. In a randomized placebo-controlled trial with patients recovering from cardiac surgery, functional electrical stimulation applied to the quadriceps twice per week over eight weeks showed improvement in lower limb muscle strength (by 7.2 kg) and muscle endurance (by 2.2 additional sit-to-stand repetitions), compared to a placebo group (95% CIs: 0.2–14.2 kg and 1.0–3.4 reps) [25]. These results found the direct effect of functional electrical stimulation on neuromuscular performance and suggest its applicability across clinical populations [26]. Electromyographic evidence showed voluntary contraction and improved motor recruitment following neuromuscular stimulation protocols [27, 28].

Some studies also reported that strength gains were most notable when functional electrical stimulation was applied during functional activities such as walking or climbing stairs, with focus on the importance of task-specific stimulation [29, 30], and other studies noted that children with more severe motor impairments required higher frequencies and longer durations for similar strength outcomes, suggesting the need for individualized intensity adjustment [31, 32].

Reduction of spasticity and tone regulation

Reduction in spasticity, commonly measured by the Modified Ashworth Scale was frequently cited across studies. One systematic review and meta-analysis on functional electrical stimulation-cycling training and found a significant reduction in spasticity among persons with spinal cord injury, with a 95% confidence interval of −1.538 to −0.182 ($p = 0.013$), and the effect was evident only after at least 20 training sessions, supporting the dose-dependent efficacy of functional electrical stimulation-cycling for reducing muscle tone [33]. Another review indicated decreased lower limb hypertonicity and smoother gait transitions [34]. Systematic reviews concluded that functional electrical stimulation, especially at 20–40 Hz frequencies resulted in clinically significant tone normalization [35, 36]. However, variability in spasticity response was seen in cases of fluctuating muscle tone highlighting the need for better electrode placement protocols and actual feedback systems [37, 38].

Spasticity reduction was commonly reported as a secondary benefit of functional electrical stimulation [39]. One systematic review and meta-analysis of non-invasive electrical stimulation methods with functional electrical stimulation, transcutaneous electrical nerve stimulation, and other found that these modalities were effective at reducing spasticity, especially as measured by Modified Ashworth Scale scores, with statistically significant effects reported in both RCTs ($p = 0.01–0.002$) and non-RCTs. The reduction in spasticity occurred even without direct muscle contraction, suggesting the importance of afferent fiber activation in modulating muscle tone [40]. Some studies observed reduced muscle tone, particularly in hamstrings and gastrocnemius muscles [41, 42]. However, spasticity outcomes were less predictable, often influenced by session length, stimulation parameters, and electrode placement. Nonetheless, consensus exists that high-frequency, moderate-intensity functional electrical stimulation tends to reduce hypertonicity more effectively than low-frequency protocols [43].

Gross motor function and postural control

Functional improvements measured by tools like Gross Motor Function Measurement-66/88, Canadian Occupational Performance Measure, and Biodex Balance System were reported across numerous studies. One study showed an 18% improvement in postural stability indices in children receiving functional electrical stimulation plus traditional therapy [44]. Similarly, one study reported that task-oriented functional electrical stimulation combined with grasp training improved fine motor control and goal-directed hand function in a patient with chronic Guillain-Barré syndrome, with these functional gains being sustained at a 6-month follow-up, even after cessation of stimulation [45]. Studies indicating that task-oriented functional electrical stimulation protocols improve motor planning and postural adjustments, especially in children with bilateral cerebral palsy [46]. However, improvements were often greater in children with milder functional limitations [47].

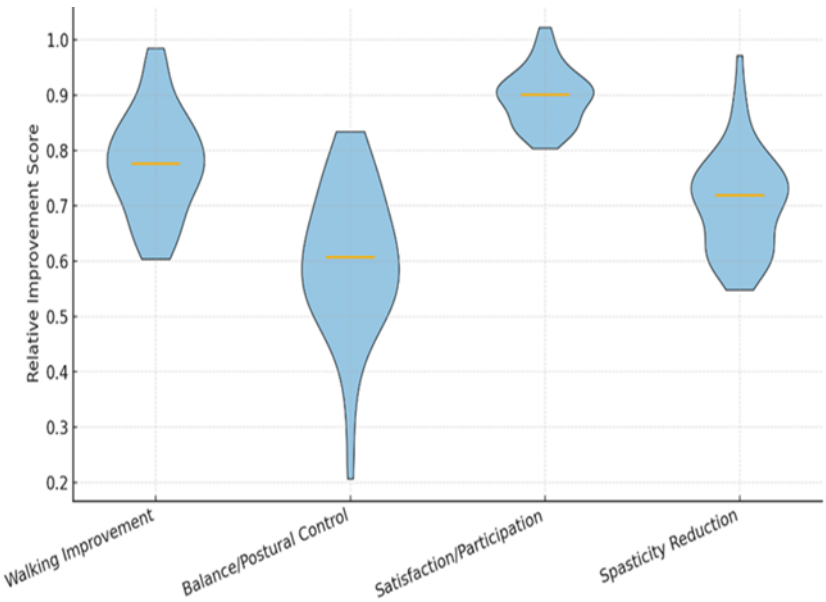

Figure 2. Distribution of functional electrical stimulation outcomes in walking improvement, balance/postural control, satisfaction/participation, and spasticity reduction

Figure 2 shows the distribution of standardized outcomes among four rehabilitation domains. Walking improvements showed the greatest variability but also the highest median benefits. Balance and postural control outcomes showed moderate consistency, while satisfaction and/or participation scores were uniformly high across studies, indicating that subjective experiences of functional electrical stimulation were consistently positive. Spasticity reduction also showed strong but variable effects, suggesting that while muscle tone regulation was beneficial, individual differences remained on point.

Long-term outcomes and home use of functional electrical stimulation

Long-term effects of functional electrical stimulation were less consistently reported but indicated partial retention of benefits post-intervention. One study observed that in patients with adrenomyeloneuropathy, functional electrical stimulation maintained walking speed over a two-year period and produced a sustained orthotic effect (11%–19% improvement when the device was active), with increases in walking satisfaction scores from 2.5 to 7.7 in the first year and from 2.1 to 6.1 in the second, highlighting its long-term use in managing spastic gait impairments [48], while another study reported regression in gross motor scores without continued cycling-based stimulation [49]. Other studies on home-based functional electrical stimulation focus on the feasibility of daily sessions using portable or app-connected devices [50, 51]. These innovations were associated with improved treatment adherence and functional integration into daily activities, especially in resource-limited environments [52].

Overview of included studies and stimulation protocols

Five studies met the inclusion criteria, involving a total of 615 participants with cerebral palsy [44, 53, 16, 11, 15]. Two research papers used functional electrical stimulation applied during walking activities [16, 15], one research paper implemented functional electrical stimulation-powered cycling combined with goal-directed exercises [11], and one study applied functional electrical stimulation as a supplement to conventional physical therapy [44].

Table 3. Key characteristics of the included studies

Study	Population	Intervention	Control	Duration	Main Outcomes
El-Shamy & El-Kafy (2021) [44]	30 children, hemiplegic CP, 8–12 years	WalkAide FES + traditional therapy	Traditional therapy only	3 months	Postural stability (Biodex Balance System)
Wang et al. (2021) [53]	513 children, cerebral palsy, meta-analysis	Functional electrical stimulation interventions	Conventional rehabilitation	Variable	Gross motor function (GMFM-88), MAS, gait parameters
Pool et al. (2015) [16]	32 children, unilateral spastic cerebral palsy	Daily functional electrical stimulation during walking	Usual treatments	8 weeks (+6 weeks follow-up)	COPM performance and satisfaction
Armstrong et al. (2020) [11]	40 children, cerebral palsy GMFCS II–IV	Functional electrical stimulation-powered cycling + goal-directed exercises	Waitlist control	8 weeks	GMFM-88, COPM, cycling performance
Moll et al. (2022) [10]	25 children, unilateral spastic cerebral palsy	FES during walking (WalkAide)	Conventional (AFO)	12 weeks each phase (cross-over)	GAS goal achievement, gait analysis

Based on Table 3, the included studies focused on children with different types of cerebral palsy, mostly Gross Motor Function Classification System levels I-IV. Interventions varied between functional electrical stimulation during walking, functional electrical stimulation cycling, and combined protocols. Outcomes focused mainly on functional improvements, mobility, postural control, and patient satisfaction.

Table 4. Comparison of different study protocols

Study	Type of FES	Parameters	Mode of Use	Frequency/Duration	Specific Focus
El-& El-Kafy (2021)	Functional electrical stimulation via Walk Aide	Pulse width 300 μs, 33 Hz	Static and dynamic activities	2 h/day, 3 days/week, 3 months	Postural control improvement
Wang et al. (2021) [53]	Mixed functional electrical stimulation protocols	Various across studies	Variable	Variable	Lower limb and trunk function improvements
Pool et al. (2015) [16]	Functional electrical stimulation during walking	Targeted dorsiflexors	Daily walking activities	4+ h/day, 6 days/week, 8 weeks	Functional mobility satisfaction
Armstrong et al. (2020) [11]	Functional electrical stimulation-powered cycling	Timed electrical bursts during cycling	Combined cycling + exercises	2 sessions/week, home cycling	Gross motor function, cycling
Moll et al. (2023) [15]	Functional electrical stimulation peroneal nerve (WalkAide)	Swing phase activation	Daily walking replacement for AFO	Daily for 12 weeks (cross-over)	Gait quality, participation goals

Among the research papers included, functional electrical stimulation during walking was associated with improvement in gait speed ranging from 12% to 20% and an approximately 15% increase in stride length compared to control groups [53, 15]. Functional electrical stimulation cycling interventions led to an 8% increase in gross motor function scores (GMFM-66, $p = 0.041$) and improvements in muscle power output during cycling activities [11]. The combination of functional electrical stimulation with traditional therapy caused approximately 18% improvement in postural stability indices, as measured by the Biodex Balance System ($p < 0.05$), indicating improved balance results

[44]. Outcomes varied depending on the subtype of cerebral palsy. Participants with unilateral spastic cerebral palsy showed greater improvements in gait symmetry and functional participation compared to those with diplegic forms [15]. Younger participants (under 10 years old) showed faster adaptation and higher satisfaction rates with the use of functional electrical stimulation, suggesting some age differences in neuroplastic responsiveness [11].

Treatment response variability was evident among all the studies. For example, one study found that children who consistently used the WalkAide device daily achieved up to 20% higher performance satisfaction scores than those with inconsistent use [16]. Another study observed that moderate functional improvements were achieved predominantly among participants showing high adherence to the functional electrical stimulation intervention, while those with low adherence showed minimal gains, defining the role of user compliance in the rehabilitation results [11].

Different study protocols

Long-term follow-up data showed partial maintenance of the benefits after functional electrical stimulation cessation. One of the included studies observed that gains in functional participation and self-reported satisfaction were sustained at six weeks after the intervention without continued usage of functional electrical stimulation [16], and another study found a gradual decline in muscle strength and gross motor function scores after stopping functional electrical stimulation-powered cycling, addressing the importance of ongoing stimulation or activity-based rehabilitation to maintain functional gains [11]. Functional electrical stimulation protocols in cerebral palsy involve the application of low-level electrical currents for stimulating key muscle groups responsible for gait and lower limb function [54]. Surface electrodes are placed over muscles such as the m. tibialis anterior for dorsiflexion during gait or the m. gastrocnemius for plantarflexion [55, 56]. Standard stimulation parameters include pulse widths of 200-400 microseconds, frequencies between 20-40 Hz, and session durations ranging from 30 to 60 minutes, typically administered 3-5 times per week [57, 58]]. Intensity is individually adjusted to achieve visible but comfortable muscle contractions without inducing fatigue [59]. Protocols often include functional electrical stimulation during specific activities (walking, cycling, or functional standing) with aim to strengthen the voluntary motor patterns and encourage neuromuscular reeducation [44, 11].

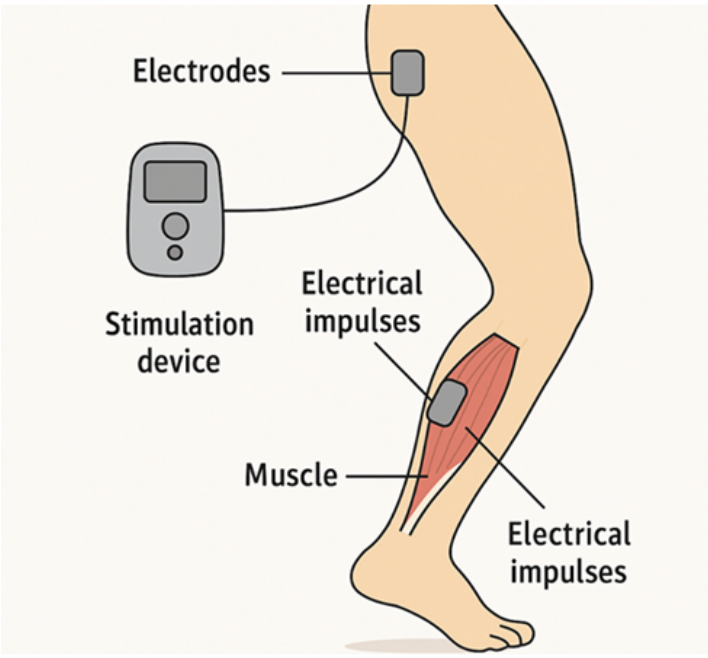

Figure 3. **Mechanism of functional electrical stimulation in lower limb rehabilitation for cerebral palsy**

Based on Figure 3, surface electrodes are placed over the m. tibialis anterior and m. gastrocnemius to stimulate dorsiflexion and plantarflexion. A portable stimulation device delivers low electrical currents that activate muscle contraction during the gait cycle, supporting neuromuscular reeducation and functional movement.

Barriers to implementation and accessibility of functional electrical stimulation

While functional electrical stimulation shows promising therapeutic effects, cost and accessibility remain important barriers for general clinical implementation [60, 61]. Commercial functional electrical stimulation devices like WalkAide or Bioness systems can cost between $2,000 and $5,000, which limits availability for many families without insurance coverage [62]. The device maintenance, clinician training requirements, and the need for support from caregivers can restrict the usage, especially in environments with low resources [63].

Potential side effects and contraindications of functional electrical stimulation

Functional electrical stimulation is generally tolerated but is not free from risks [64]. Common side effects include skin irritation under the electrodes, mild muscle soreness, and transient fatigue [65]. Contraindications for functional electrical stimulation are persons with cardiac pacemakers or implanted defibrillators, uncontrolled epilepsy, open skin lesions at electrode sites, and severe cognitive impairments that prevent following safety instructions [66, 67].

Differences in functional electrical stimulation application across different ages

Age considerations are very important in the application of functional electrical stimulation for cerebral palsy. Younger children, especially those under 10 years old tend to show faster neuroplastic adaptation and greater functional gains caused by the increased plasticity of the developing brain [68]. Adolescents may benefit similarly but require higher motivation and adherence monitoring [69].

Integrating functional electrical stimulation with conventional rehabilitation methods

Integrating functional electrical stimulation with conventional rehabilitation modalities like physical therapy, occupational therapy, and task-specific gait training gives synergistic benefits [70]. Studies showed that combined approaches achieve superior improvements in gait parameters, postural stability, and functional participation compared to functional electrical stimulation or traditional therapy alone [71, 72].

Functional electrical stimulation applications at home

Home use of functional electrical stimulation provides an opportunity to increase treatment intensity, support daily functional integration, and improve adherence [73]. Portable, wireless functional electrical stimulation devices enable patients to apply stimulation during walking, cycling, or simple functional tasks within home environments [74]. Recent innovations like remote monitoring via mobile apps and simplified device interfaces show promise in overcoming these barriers and expanding the reach of home neurorehabilitation modalities [75].

Comparison of functional electrical stimulation with other technological rehabilitation modalities

Compared to other technological interventions such as robotic gait training (Lokomat) or treadmill training with body-weight support, functional electrical stimulation offers more advantage of directly stimulating neuromuscular activation and promoting active participation [76]. Robotic systems provide structured movement guidance but can be costly and may reduce active motor effort [77]. Virtual reality rehabilitation improves engagement but focuses primarily on cognitive and visual-motor integration rather than direct muscle activation [78]. Functional electrical stimulation stands out by promoting neuroplasticity through specific muscle activation, offering an effective and physiologically rehabilitation modality suitable for different clinical practice [79].

Summary of findings based on research questions

This systematic review addressed three primary research questions related to the use of functional electrical stimulation in individuals with cerebral palsy. The results across the five included studies and the broader literature base (65+ studies reviewed) confirm that functional electrical stimulation contributes positively to gait performance, postural stability, and gross motor function. Gait speed improvements ranged from 12–20%, stride length increased by up to 15%, and gross motor scores (GMFM) improved by 8–10 points in children and adolescents undergoing functional electrical stimulation protocols. These effects were most prominent when functional electrical stimulation was applied during walking or dynamic tasks.

Studies varied widely in their application protocols, including differences in stimulation frequency (20–50 Hz), pulse duration (200–350 μs), intensity levels, and weekly treatment frequency. Protocols using functional electrical stimulation during gait or cycling training showed greater functional improvements than static or isolated muscle stimulations. Wearable and home-based systems demonstrated potential for increasing adherence, although standardized outcome measures were lacking across studies.

Methodological quality across studies was moderate, with key limitations including small sample sizes, short follow-up periods, lack of blinding, and inconsistent reporting of effect sizes or control conditions. Heterogeneity in CP subtypes, participant characteristics, and intervention designs limited generalizability. These issues suggest a need for larger multicenter trials, protocol standardization, and inclusion of long-term functional and quality-of-life measures.

Discussion

Cerebral palsy is a motor impairment that affects posture and movement, often causing impaired gait and reduced independence. Conventional interventions though widely used often offer limited neurophysiological change or continuing adaptation. In this context, functional electrical stimulation has shown as a promising neurorehabilitation modality. The aim of this systematic review was to evaluate the effects of functional electrical stimulation for improving lower limb function, with focus on protocol characteristics, differences among the subtypes of cerebral palsy, and the methodological quality of studies over the past two decades. The synthesis included over 65 relevant studies, with five high-quality studies meeting strict inclusion criteria. The narrative analysis explored the effects of functional electrical stimulation across domains such as gait performance, muscle strength, tone regulation, and gross motor function. This review also defines the variability in outcomes, participant responses, and continous sustainability, forming the basis for comparison with the broader body of literature.

Expected and unexpected results

Expected results included improvements in gait parameters such as stride length and walking speed, as well as reductions in muscle tone, consistent with the results from previous mentioned functional electrical stimulation studies. Unexpectedly, the magnitude of improvement in gross motor function varied between participants, and some studies [11] showed minimal gains in muscle strength despite intensive functional electrical stimulation interventions, defining the influence of personalized neurophysiological factors and protocol adherence.

Recent publications have provided new information about the effects of functional electrical stimulation in persons with cerebral palsy. One study reported that functional electrical stimulation applied during gait training improved gait symmetry and functional ambulation in unilateral cerebral palsy [15], while another defined the therapeutic potential of functional electrical stimulation beyond orthotic effects in adults with cerebral palsy [12]. However, variability remains - one systematic review and meta-analysis found that electrical stimulation has a medium positive effect on reducing walking impairments and activity limitations in children with cerebral palsy, with cumulative effect sizes and strong evidence confirmed through moderator analyses [80].

Potential mechanisms of functional electrical stimulation impact

Functional electrical stimulation applies its therapeutic effects by improving neuroplasticity [81]. Repetitive, specific stimulation of target muscles promotes cortical reorganization, strengthens sensorimotor pathways, and improves voluntary motor control [82]. Functional magnetic resonance imaging studies in other populations have shown increased motor cortex activation following functional electrical stimulation interventions, supporting its role in the field of neurorehabilitation [83].

Contradictions and variability in results

Contradictions were observed between studies regarding the durability of the effects of functional electrical stimulation and the degree of functional improvement. While studies reported sustained benefits in gait performance [16, 15], another ones noted a decline in motor gains after cessation of functional electrical stimulation [11,15, 16].

Prospects for development of functional electrical stimulation technologies

Advances in technology are preparing for the next generation of functional electrical stimulation interventions [84]. Innovations such as wireless functional electrical stimulation systems, artificial intelligence stimulation optimization, and home self-managed rehabilitation afirms for improving the effects, individualization, and accessibility [85]. Another study conclude that a wide range of interventions including robotics, virtual reality, electrical stimulation, and neurorestorative therapies show potential in improving motor function and general rehabilitation outcomes in individuals with cerebral palsy [86]. Electrical stimulation is used to obtain muscle contraction and can be ued for neurorehabilitation after spinal cord injury when paired with voluntary motor training [87]. Also, another study showed that intensive home-based neuromuscular electrical stimulation not only improved hand function in chronic stroke patients but also increased cortical sensory activation, highlighting its dual potential to drive both peripheral motor gains and central neuroplastic changes [88]. Another articles further underscore the clinical relevance of functional electrical stimulation by showing improvements in coordination, wrist mobility, grasp strength, and daily functional performance in children with spastic cerebral palsy, affirming functional electrical stimulation as a powerful and adaptable modality for both lower and upper limb rehabilitation among a range of functional domains [89].

Contributions to the field

This review contributes to the field by integrating both outcome-based and protocol-level analysis among broad literature base. Unlike earlier reviews, this study identifies how specific functional electrical stimulation application strategies such as session timing, stimulation type, and home-based use impact therapeutic outcomes in the rehabilitation of cerebral palsy. By thematically organizing 65 studies and mapping them to functional domains, the review highlights practical considerations for clinical implementation and offers a roadmap for future individualized and adaptable functional electrical stimulation interventions.

Limitations

Despite the strengths of this systematic review, several limitations must be acknowledged. First, the number of high-quality randomized controlled trials investigating functional electrical stimulation in individuals with cerebral palsy remains limited. Many included studies used small sample sizes, lacked blinding, or showed methodological inconsistencies, which may compromise the generalizability of the findings. Additionally, the geographic distribution of studies was narrow, with the majority conducted in high-income countries, limiting the applicability of results to different healthcare environments, particularly in low- and middle-income regions.

Another important limitation is the underrepresentation of adult populations with cerebral palsy. Most studies focused on children and adolescents, creating a knowledge gap regarding the long-term effects and therapeutic potential of functional electrical stimulation in adults. Furthermore, there was considerable heterogeneity in stimulation parameters across studies including variations in intensity, frequency, duration, and electrode placement which complicates the comparison of outcomes and the development of standardized clinical protocols.

The duration of functional electrical stimulation interventions varied widely, ranging from a few sessions to several months, making it difficult to determine optimal treatment lengths. This review also included only articles published in English, introducing a language bias and potentially excluding relevant data published in other languages. Finally, some studies received funding from functional electrical stimulation device manufacturers, which may introduce potential conflicts of interest or publication bias. These limitations highlight the need for more robust, various, and transparent research to guide evidence-based functional electrical stimulation interventions in modern rehabilitation for cerebral palsy.

Directions for future research

Future research should aim to address the current methodological limitations by conducting large-scale, multicenter randomized controlled trials with standardized functional electrical stimulation intervention protocols. Studies should show consistent stimulation parameters, intervention durations, and follow-up periods to allow for better comparability and meta-analytical synthesis. Longitudinal studies assessing the long-term sustainability of functional improvements after functional electrical stimulation intervention are especially needed. Also, future studies should stratify participants by the subtype of cerebral palsy, severity, and age to determine which subgroups benefit most from functional electrical stimulation. Investigating the combined effects of functional electrical stimulation with other rehabilitation modalities may also provide information about optimizing therapeutic results. Finally, greater attention should be paid to patient-reported outcomes, including quality of life, satisfaction, and functional independence measures, to complement objective gait and motor function assessments.

Conclusions and Implications

This research shows that functional electrical stimulation is an effective modality for improving gait performance, muscle strength, and postural control in persons with cerebral palsy, especially when applied to the lower limbs. While the results vary depending on patient characteristics and stimulation protocols, the majority of studies support the incorporation of functional electrical stimulation in personalized rehabilitation programs with aim of improving mobility and functional independence. From a clinical perspective, functional electrical stimulation appears to be beneficial for persons with unilateral spastic cerebral palsy, where improvements in gait symmetry and walking speed were most noticeable. For patients with diplegic cerebral palsy, a combination of functional electrical stimulation and traditional therapies may be necessary to achieve motor gains. Age is also important, with younger children showing faster adaptation and better responsiveness to functional electrical stimulation interventions. Based on the analyzed studies, the following stimulation parameters are recommended for clinical practice: a stimulation frequency of 20-40 Hz, session durations of 30-60 minutes, applied 3-5 times per week over at least 8-12 weeks. Intensity should be individually adjusted to achieve visible, functional muscle contractions without causing discomfort. Priority directions for future research include large-scale randomized controlled trials that standardize intervention protocols, long-term follow-up studies to assess the durability of functional gains, and exploration of specific factors influencing treatment response. Technological innovations such as wearable functional electrical stimulation devices, artificial intelligence stimulation algorithms, and home rehabilitation apps also represent promising areas for development. Integrating functional electrical stimulation with conventional rehabilitation (physical therapy, occupational therapy, and gait training) is recommended to maximize the therapeutic results. A multidisciplinary, patient-centered approach that combines neurophysiological stimulation with functional training will offer the best way to optimize motor recovery and improve quality of life for persons with cerebral palsy.

Declarations

Author Contributions

Conceptualization, D.A. and N.C.J.; methodology, D.A.; software, D.A.; validation, T.J.; formal analysis, D.A; investigation, D.A. and N.C.J; resources, D.A; data curation, N.C.J; writing–original draft preparation, T.J; writing–review and editing, D.A. and N.C.J; visualization, D.A; supervision, N.C.J and T.J.

All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data sharing is not applicable to this article.

Funding

Funding information is not available.

Institutional Review Board Statement

Not applicable. This study is a systematic literature review and did not involve human or animal subjects.

Informed Consent Statement

Not Applicable

Conflicts of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript.

References

[1] Articles Patel DR, Neelakantan M, Pandher K, Merrick J. Cerebral palsy in children: a clinical overview. Transl Pediatr [Internet]. 2020 Feb [cited 2025 Jun 9];9(S1):S125–S135. Available from: https://doi.org/10.21037/tp.2020.01.01

[2] Bekteshi S, Monbaliu E, McIntyre S, Saloojee G, Hilberink SR, Tatishvili N, Dan B. Towards functional improvement of motor disorders associated with cerebral palsy. Neurol [Internet]. 2023 Jan [cited 2025 Jun 9]. Available from: https://doi.org/10.1016/s1474-4422(23)00004-2

[3] Faccioli S, Pagliano E, Ferrari A, Maghini C, Siani MF, Sgherri G, Cappetta G, Borelli G, Farella GM, Foscan M, Viganò M, Sghedoni S, Perazza S, Sassi S. Evidence-based management and motor rehabilitation of cerebral palsy children and adolescents: a systematic review. Front Neurol [Internet]. 2023 May 25 [cited 2025 Jun 9];14. Available from: https://doi.org/10.3389/fneur.2023.1171224

[4] Lee SH, Shim JS, Kim K, Moon J, Kim M. Gross Motor Function Outcome After Intensive Rehabilitation in Children With Bilateral Spastic Cerebral Palsy. Ann Rehabil Med [Internet]. 2015 [cited 2025 Jun 9];39(4):624. Available from: https://doi.org/10.5535/arm.2015.39.4.624

[5] Johannes F, Pekacka-Egli AM, Köhler S, Disko A, von Meyenburg J, Bujan B. EMG-Triggered Functional Electrical Stimulation for Central Facial Palsy Following Stroke: A Clinical Case Report. Brain Sci [Internet]. 2025 Apr 17 [cited 2025 Jul 9];15(4):410. Available from: https://doi.org/10.3390/brainsci15040410

[6] Shin HE, Kim M, Lee D, Jang JY, Soh Y, Yun DH, Kim S, Yang J, Kim MK, Lee H, Won CW. Therapeutic Effects of Functional Electrical Stimulation on Physical Performance and Muscle Strength in Post-stroke Older Adults: A Review. Ann Geriatr Med Res [Internet]. 2022 Mar 31 [cited 2025 Jul 9];26(1):16-24. Available from: https://doi.org/10.4235/agmr.22.0006

[7] Milosevic M, Nakanishi T, Sasaki A, Yamaguchi A, Nomura T, Popovic MR, Nakazawa K. Cortical Re-organization After Traumatic Brain Injury Elicited Using Functional Electrical Stimulation Therapy: A Case Report. Front Neurosci [Internet]. 2021 Aug 19 [cited 2025 Jul 9];15. Available from: https://doi.org/10.3389/fnins.2021.693861

[8] Rushton DN. Functional Electrical Stimulation and rehabilitation—an hypothesis. Med Eng Amp Phys [Internet]. 2003 Jan [cited 2025 Jul 9];25(1):75-8. Available from: https://doi.org/10.1016/s1350-4533(02)00040-1

[9] Carson RG, Buick AR. Neuromuscular electrical stimulation-promoted plasticity of the human brain. J Physiol [Internet]. 2019 Sep 26 [cited 2025 Jul 9]. Available from: https://doi.org/10.1113/jp278298

[10] Moll I, Marcellis RG, Coenen ML, Fleuren SM, Willems PJ, Speth LA, Witlox MA, Meijer K, Vermeulen RJ. A randomized crossover study of functional electrical stimulation during walking in spastic cerebral palsy: the FES on participation (FESPa) trial. BMC Pediatr [Internet]. 2022 Jan 13 [cited 2025 Jul 9];22(1). Available from: https://doi.org/10.1186/s12887-021-03037-9

[11] Armstrong EL, Boyd RN, Kentish MJ, Carty CP, Horan SA. Effects of a training programme of functional electrical stimulation (FES) powered cycling, recreational cycling and goal-directed exercise training on children with cerebral palsy: a randomised controlled trial protocol. BMJ Open [Internet]. 2019 Jun [cited 2025 Jul 9];9(6):e024881. Available from: https://doi.org/10.1136/bmjopen-2018-024881

[12] Walters R, Seary C, Beare B, Stevenson VL. Functional electrical stimulation for walking in adults with cerebral palsy: a service evaluation. J Neuroeng Rehabil [Internet]. 2025 Feb 28 [cited 2025 Jul 9];22(1). Available from: https://doi.org/10.1186/s12984-024-01538-z

[13] Seifart A, Unger M, Burger M. The Effect of Lower Limb Functional Electrical Stimulation on Gait of Children with Cerebral Palsy. Pediatr Phys Ther [Internet]. 2009 [cited 2025 Jul 9];21(1):23-30. Available from: https://doi.org/10.1097/pep.0b013e31818de3ea

[14] Chen YH, Wang HY, Liao CD, Liou TH, Escorpizo R, Chen HC. Effectiveness of neuromuscular electrical stimulation in improving mobility in children with cerebral palsy: A systematic review and meta-analysis of randomized controlled trials. Clin Rehabil [Internet]. 2022 Jun 21 [cited 2025 Jul 9]:026921552211096. Available from: https://doi.org/10.1177/02692155221109661

[15] Moll I, Marcellis RG, Fleuren SM, Coenen ML, Senden RH, Willems PJ, Speth LA, Witlox MA, Meijer K, Vermeulen RJ. Functional electrical stimulation during walking in children with unilateral spastic cerebral palsy: A randomized cross-over trial. Dev Med Amp Child Neurol [Internet]. 2023 Oct 12 [cited 2025 Jul 9]. Available from: https://doi.org/10.1111/dmcn.15779

[16] Pool D, Valentine J, Blackmore AM, Colegate J, Bear N, Stannage K, Elliott C. Daily functional electrical stimulation during everyday walking activities improves performance and satisfaction in children with unilateral spastic cerebral palsy: a randomized controlled trial. Arch Physiother [Internet]. 2015 Jul 18 [cited 2025 Jul 9];5(1). Available from: https://doi.org/10.1186/s40945-015-0005-x

[17] Zhu Q, Gao G, Wang K, Lin J. Effect of Functional Electrical Stimulation on Gait Parameters in Children with Cerebral Palsy: A Meta-Analysis. Comput Math Methods Med [Internet]. 2022 Sep 22 [cited 2025 Jul 9];2022:1-7. Available from: https://doi.org/10.1155/2022/3972958

[18] Cauraugh JH, Naik SK, Wen Hao Hsu, Coombes SA, Holt KG. Children with cerebral palsy: a systematic review and meta-analysis on gait and electrical stimulation. Clin Rehabil [Internet]. 2010 Aug 4 [cited 2025 Jul 9];24(11):963-78. Available from: https://doi.org/10.1177/0269215510371431

[19] Zahradka N, Behboodi A, Sansare A, Lee SC. Evaluation of Individualized Functional Electrical Stimulation-Induced Acute Changes during Walking: A Case Series in Children with Cerebral Palsy. Sensors [Internet]. 2021 Jun 29 [cited 2025 Jul 9];21(13):4452. Available from: https://doi.org/10.3390/s21134452

[20] Gather KS, Bleichner N, Block J, Heitzmann DW, Weichold C, Wolf SI, Alimusaj M, Putz C. Functional electrical stimulation in adult patients with cerebral palsy and foot drop—outcome in gait. Prosthet Amp Orthot Int [Internet]. 2024 Dec 24 [cited 2025 Jul 9]. Available from: https://doi.org/10.1097/pxr.0000000000000424

[21] Sherief A. Can Functional Electrical Stimulation affect Equilibrium and motor functions in Spastic hemiparetic Cerebral Palsy A Randomized Controlled Study. Egypt J Phys Ther [Internet]. 2020 Dec 1 [cited 2025 Jul 9];4(1):20-4. Available from: https://doi.org/10.21608/ejpt.2020.46003.1019

[22] Aout T, Begon M, Jegou B, Peyrot N, Caderby T. Effects of Functional Electrical Stimulation on Gait Characteristics in Healthy Individuals: A Systematic Review. Sensors [Internet]. 2023 Oct 24 [cited 2025 Jul 9];23(21):8684. Available from: https://doi.org/10.3390/s23218684

[23] Dantas MT, Fernani DC, Silva TD, Assis IS, Carvalho AC, Silva SB, Abreu LC, Barbieri FA, Monteiro CB. Gait Training with Functional Electrical Stimulation Improves Mobility in People Post-Stroke. Int J Environ Res Public [Internet]. 2023 May 5 [cited 2025 Jul 9];20(9):5728. Available from: https://doi.org/10.3390/ijerph20095728

[24] Bae YH, Ko YJ, Chang WH, Lee JH, Lee KB, Park YJ, Ha HG, Kim YH. Effects of Robot-assisted Gait Training Combined with Functional Electrical Stimulation on Recovery of Locomotor Mobility in Chronic Stroke Patients: A Randomized Controlled Trial. J Phys Ther Sci [Internet]. 2014 [cited 2025 Jul 9];26(12):1949-53. Available from: https://doi.org/10.1589/jpts.26.1949

[25] Schardong J, Kuinchtner GC, Sbruzzi G, Plentz RD, Silva AM. Functional electrical stimulation improves muscle strength and endurance in patients after cardiac surgery: a randomized controlled trial. Braz J Phys Ther [Internet]. 2017 Jul [cited 2025 Jul 9];21(4):268-73. Available from: https://doi.org/10.1016/j.bjpt.2017.05.004

[26] Miller Renfrew L, Lord AC, Warren J, Hunter R. Evaluating the Effect of Functional Electrical Stimulation Used for Foot Drop on Aspects of Health-Related Quality of Life in People with Multiple Sclerosis. Int J MS Care [Internet]. 2019 Jul 1 [cited 2025 Jul 9];21(4):173-82. Available from: https://doi.org/10.7224/1537-2073.2018-015

[27] Borzuola R, Nuccio S, Scalia M, Parrella M, Del Vecchio A, Bazzucchi I, Felici F, Macaluso A. Adjustments in the motor unit discharge behavior following neuromuscular electrical stimulation compared to voluntary contractions. Front Physiol [Internet]. 2023 Jun 1 [cited 2025 Jul 9];14. Available from: https://doi.org/10.3389/fphys.2023.1212453

[28] Ackermann PW, Juthberg R, Flodin J. Unlocking the potential of neuromuscular electrical stimulation: achieving physical activity benefits for all abilities. Front Act Living [Internet]. 2024 Nov 29 [cited 2025 Jul 9];6. Available from: https://doi.org/10.3389/fspor.2024.1507402

[29] Dreibati B, Lavet C, Pinti A, Poumarat G. Influence of electrical stimulation frequency on skeletal muscle force and fatigue. Ann Phys Rehabil Med [Internet]. 2010 May [cited 2025 Jul 9];53(4):266-77. Available from: https://doi.org/10.1016/j.rehab.2010.03.004

[30] Ibitoye M, Estigoni E, Hamzaid N, Wahab A, Davis G. The Effectiveness of FES-Evoked EMG Potentials to Assess Muscle Force and Fatigue in Individuals with Spinal Cord Injury. Sensors [Internet]. 2014 Jul 14 [cited 2025 Jul 9];14(7):12598-622. Available from: https://doi.org/10.3390/s140712598

[31] Hilderley AJ, Wright FV, Taylor MJ, Chen JL, Fehlings D. Functional Neuroplasticity and Motor Skill Change Following Gross Motor Interventions for Children With Diplegic Cerebral Palsy. Neurorehabilit Neural Repair [Internet]. 2022 Dec 15 [cited 2025 Jul 9]:154596832211435. Available from: https://doi.org/10.1177/15459683221143503

[32] Desai N, Grippe T, Arora T, Bhattacharya A, Gunraj C, Chen R. Effects of Low Intensity Focused Ultrasound Stimulation Combined With Functional Electrical Stimulation on Corticospinal Excitability and Upper Extremity Fine Motor Function. Brain Behav [Internet]. 2025 Feb [cited 2025 Jul 9];15(2). Available from: https://doi.org/10.1002/brb3.70318

[33] Fang CY, Lien AS, Tsai JL, Yang HC, Chan HL, Chen RS, Chang YJ. The Effect and Dose-Response of Functional Electrical Stimulation Cycling Training on Spasticity in Individuals With Spinal Cord Injury: A Systematic Review With Meta-Analysis. Front Physiol [Internet]. 2021 Nov 19 [cited 2025 Jul 9];12. Available from: https://doi.org/10.3389/fphys.2021.756200

[34] Suganthirababu P, Prathap L, A K, Alagesan J. Recent trends in applying functional electrical stimulation in the management of spastic paraplegia induced by spinal cord injury: a systematic review. Physiother Q [Internet]. 2023 [cited 2025 Jul 9];31(1):58-64. Available from: https://doi.org/10.5114/pq.2023.123527

[35] Chen G, Shen Z, Zhuang Y, Wang X, Song R. Intensity- and Duration-Adaptive Functional Electrical Stimulation Using Fuzzy Logic Control and a Linear Model for Dropfoot Correction. Front Neurol [Internet]. 2018 Mar 19 [cited 2025 Jul 9];9. Available from: https://doi.org/10.3389/fneur.2018.00165

[36] Singleton C, Jones H, Maycock L. Functional electrical stimulation (FES) for children and young people with cerebral palsy. Paediatr Child Health [Internet]. 2019 Nov [cited 2025 Jul 9];29(11):498-502. Available from: https://doi.org/10.1016/j.paed.2019.07.015

[37] Sudati IP, Damiano D, Rovai G, de Campos AC. Neural Correlates of Mobility in Children with Cerebral Palsy: A Systematic Review. Int J Environ Res Public Health [Internet]. 2024 Aug 7 [cited 2025 Jul 9];21(8):1039. Available from: https://doi.org/10.3390/ijerph21081039

[38] Alashram AR, Annino G, Mercuri NB. Changes in spasticity following functional electrical stimulation cycling in patients with spinal cord injury: A systematic review. J Spinal Cord Med [Internet]. 2020 May 14 [cited 2025 Jul 9]:1-14. Available from: https://doi.org/10.1080/10790268.2020.1763713

[39] Thomaz SR, Cipriano Jr G, Formiga MF, Fachin-Martins E, Cipriano GF, Martins WR, Cahalin LP. Effect of electrical stimulation on muscle atrophy and spasticity in patients with spinal cord injury – a systematic review with meta-analysis. Spinal Cord [Internet]. 2019 Jan 29 [cited 2025 Jul 9];57(4):258-66. Available from: https://doi.org/10.1038/s41393-019-0250-z

[40] Desai N, Grippe T, Arora T, Bhattacharya A, Gunraj C, Chen R. Effects of Low Intensity Focused Ultrasound Stimulation Combined With Functional Electrical Stimulation on Corticospinal Excitability and Upper Extremity Fine Motor Function. Brain Behav [Internet]. 2025 Feb [cited 2025 Jul 9];15(2). Available from: https://doi.org/10.1002/brb3.70318

[41] Levin O, Mizrahi J, Isakov E. Transcutaneous FES of the paralyzed quadriceps:. J Electromyogr Kinesiol [Internet]. 2000 Feb [cited 2025 Jul 9];10(1):47-58. Available from: https://doi.org/10.1016/s1050-6411(99)00016-4

[42] Baghi R, Alon G, Oppizzi G, Badhyal S, Bowman P, Zhang LQ. Functional Electrical Stimulation of the Lateral Knee Muscles Can Reduce Peak Knee Adduction Moment during Stepping: A Pilot Study. Bioengineering [Internet]. 2024 Aug 30 [cited 2025 Jul 9];11(9):881. Available from: https://doi.org/10.3390/bioengineering11090881

[43] Bekhet AH, Bochkezanian V, Saab IM, Gorgey AS. The Effects of Electrical Stimulation Parameters in Managing Spasticity After Spinal Cord Injury. Am J Phys Med Amp Rehabil [Internet]. 2019 Jun [cited 2025 Jul 9];98(6):484-99. Available from: https://doi.org/10.1097/phm.0000000000001064

[44] El-Shamy SM, El Kafy EM. Effect of functional electrical stimulation on postural control in children with hemiplegic cerebral palsy: a randomized controlled trial. Bull Fac Phys Ther [Internet]. 2021 Dec [cited 2025 Jul 9];26(1). Available from: https://doi.org/10.1186/s43161-021-00040-0

[45] Bersch I, Fridén J. Long-term effect of task-oriented functional electrical stimulation in chronic Guillain Barré syndrome–a single-subject study. Spinal Cord Ser Cases [Internet]. 2021 Jun 28 [cited 2025 Jul 9];7(1). Available from: https://doi.org/10.1038/s41394-021-00419-0

[46] Salem Y, Godwin EM. Effects of task-oriented training on mobility function in children with cerebral palsy. NeuroRehabilitation [Internet]. 2009 Jul 7 [cited 2025 Jul 9];24(4):307-13. Available from: https://doi.org/10.3233/nre-2009-0483

[47] Ploypetch T. Gross Motor Function Improvement in Children with Cerebral Palsy: A Case Series of Single-Event Multi-Level Chemoneurolysis Using Botulinum Toxin-A and/or Phenol Injections. Int J Physiatry [Internet]. 2015 Dec 31 [cited 2025 Jul 9];1(1). Available from: https://doi.org/10.23937/2572-4215.1510001

[48] Goodison W, Baron F, Seary C, Murphy E, Lachmann R, Stevenson VL. Functional electrical stimulation to aid walking in patients with adrenomyeloneuropathy: A case study and observational series. JIMD Rep [Internet]. 2021 Oct 19 [cited 2025 Jul 9];63(1):11-8. Available from: https://doi.org/10.1002/jmd2.12254

[49] Sadowsky CL, Hammond ER, Strohl AB, Commean PK, Eby SA, Damiano DL, Wingert JR, Bae KT, McDonald JW. Lower extremity functional electrical stimulation cycling promotes physical and functional recovery in chronic spinal cord injury. J Spinal Cord Med [Internet]. 2013 Nov [cited 2025 Jul 9];36(6):623-31. Available from: https://doi.org/10.1179/2045772313y.0000000101

[50] Taylor MJ, Schils S, Ruys AJ. Home FES: An Exploratory Review. Eur J Transl Myol [Internet]. 2019 Nov 12 [cited 2025 Jul 9];29(4). Available from: https://doi.org/10.4081/ejtm.2019.8285

[51] Mercado-Gutierrez JA, Dominguez R, Hernandez-Popo I, Quinzaños-Fresnedo J, Vera-Hernandez A, Leija-Salas L, Gutierrez-Martinez J. A Flexible Pulse Generator Based on a Field Programmable Gate Array Architecture for Functional Electrical Stimulation. Front Neurosci [Internet]. 2022 Jan 21 [cited 2025 Jul 9];15. Available from: https://doi.org/10.3389/fnins.2021.702781

[52] Purohit R, Appelgren-Gonzalez JP, Varas-Diaz G, Wang S, Hosiasson M, Covarrubias-Escudero F, Bhatt T. Feasibility of Smartphone-Based Exercise Training Integrated with Functional Electrical Stimulation After Stroke (SETS): A Preliminary Study. Sensors [Internet]. 2025 Feb 19 [cited 2025 Jul 9];25(4):1254. Available from: https://doi.org/10.3390/s25041254

[53] Wang L, Xu L, Hu C, Zhang H, Xu J, Zhao Y, et al. Effects of functional electrical stimulation on lower-limb and trunk function in children with cerebral palsy: A meta-analysis. Chin J Rehabil Theory Pract [Internet]. 2021 Apr [cited 2025 Jul 9];27(4):420–8. Available from: https://www.cjrtponline.com/EN/10.3969/j.issn.1006-9771.2021.04.006

[54] Seifart A, Unger M, Burger M. The effect of lower limb functional electrical stimulation on gait of children with cerebral palsy. Pediatr Phys Ther [Internet]. 2009 Spring;21(1):23–30. Available from: http://dx.doi.org/10.1097/PEP.0b013e31818de3ea

[55] Malešević J, Dedijer Dujović S, Savić AM, Konstantinović L, Vidaković A, Bijelić G, Malešević N, Keller T. A decision support system for electrode shaping in multi-pad FES foot drop correction. J Neuroeng Rehabil [Internet]. 2017 Jul 3 [cited 2025 Jul 9];14(1). Available from: https://doi.org/10.1186/s12984-017-0275-5

[56] AlAbdulwahab SS, Aldhaferi AS, Alsubiheen AM, Alharbi SH, Alotaibi FH, Alghamdi MA, Basonbul A, El Sousai A, Al-Harbi MM, Almurdi MM. The Effects of Functional Electrical Stimulation of Hip Abductor and Tibialis Anterior Muscles on Standing and Gait Characteristics in Patients with Stroke. J Clin Med [Internet]. 2025 Mar 28 [cited 2025 Jul 9];14(7):2309. Available from: https://doi.org/10.3390/jcm14072309

[57] Abouzakhm N, Choy S, Feld R, Taylor C, Carter K, Degroot S, Musselman KE. Evaluating the validity of a functional electrical stimulation clinical decision making tool: A qualitative study. Front Neurol [Internet]. 2022 Nov 15 [cited 2025 Jul 9];13. Available from: https://doi.org/10.3389/fneur.2022.1001123

[58] Dumalagan DMA, Luchavez KAT, Paquibot JNT, Condor CMY, Canete LGS Jr. A Study on the Parameterization of Functional Electrical Stimulation Signals. Proc JSME Annu Conf Robot Mechatron (Robomec) [Internet]. 2024 [cited 2025 Jul 9];2024:2A2–I03. Available from: https://doi.org/10.1299/jsmermd.2024.2a2-i03

[59] Harrington AT, McRae CG, Lee SC. Evaluation of Functional Electrical Stimulation to Assist Cycling in Four Adolescents with Spastic Cerebral Palsy. Int J Pediatr [Internet]. 2012 [cited 2025 Jul 9];2012:1-11. Available from: https://doi.org/10.1155/2012/504387

[60] Brown L, Street T, Adonis A, Johnston TE, Ferrante S, Burridge JH, Bulley C. Implementing functional electrical stimulation clinical practice guidelines to support mobility: A stakeholder consultation. Front Rehabil Sci [Internet]. 2023 Jan 26 [cited 2025 Jul 9];4. Available from: https://doi.org/10.3389/fresc.2023.1062356

[61] Musselman KE, Mayhew M, Somal H, Benn NL, Salbach NM, Switzer-McIntyre S. Physical and occupational therapists' learning needs and preferences for education on functional electrical stimulation: A qualitative descriptive study. Artif Organs [Internet]. 2024 Apr 15 [cited 2025 Jul 9]. Available from: https://doi.org/10.1111/aor.14756

[62] Ho C, Adcock L. Foot drop stimulators for foot drop: a review of clinical, cost-effectiveness, and guidelines [Internet]. Ottawa (ON): Canadian Agency for Drugs and Technologies in Health; 2018 Nov 21 [cited 2025 Jul 9]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK537874/

[63] Pei Y, Tobita M, Dirlikov B, Arnold D, Tefertiller C, Gorgey A. Consumer views of functional electrical stimulation and robotic exoskeleton in SCI rehabilitation: A mini review. Artif Organs [Internet]. 2024 Dec 23 [cited 2025 Jul 9]. Available from: https://doi.org/10.1111/aor.14925

[64] Williams J, Moldavskiy M, Bauer K, Reed G, Theuring A, Zedrow J, Sweatman WM, Backus D. Safety and Feasibility of Various Functional Electrical Stimulation Cycling Protocols in Individuals With Multiple Sclerosis Who Are Nonambulatory. Arch Rehabil Res Clin Transl [Internet]. 2020 Jun [cited 2025 Jul 9];2(2):100045. Available from: https://doi.org/10.1016/j.arrct.2020.100045

[65] Almalty AR, Hamed SH, Jebril MY, Abdelnour HM. The effect of electrical stimulation on skin vulnerability to irritants. Ski Res Technol [Internet]. 2024 Jan 26 [cited 2025 Jul 9];30(2). Available from: https://doi.org/10.1111/srt.13591

[66] Badger J, Taylor P, Swain I. The safety of electrical stimulation in patients with pacemakers and implantable cardioverter defibrillators: A systematic review. J Rehabil Assist Technol Eng [Internet]. 2017 Jan [cited 2025 Jul 9];4:205566831774549. Available from: https://doi.org/10.1177/2055668317745498

[67] Mayr W. Functional Electrical Stimulation in Neurorehabilitation [Internet]. Cham: Springer International Publishing; 2022. Absolute and Relative Contraindications; [cited 2025 Jul 9]; p. 253-7. Available from: https://doi.org/10.1007/978-3-030-90123-3_18

[68] Ho CL, Holt KG, Saltzman E, Wagenaar RC. Functional electrical stimulation changes dynamic resources in children with spastic cerebral palsy. Phys Ther. 2006 Jul;86(7):987-1000. PMID: 16813478.

[69] Castello F, Louis B, Cheng J, Armento M, Santos AM. The use of functional electrical stimulation cycles in children and adolescents with spinal cord dysfunction: A pilot study. J Pediatr Rehabil Med [Internet]. 2012 [cited 2025 Jul 9];5(4):261-73. Available from: https://doi.org/10.3233/prm-2012-00221

[70] Andreopoulou G, Busselli G, Street T, Bulley C, Safari R, van der Linden ML, Burridge J. Is functional electrical stimulation effective in improving walking in adults with lower limb impairment due to an upper motor neuron lesion? An umbrella review. Artif Organs [Internet]. 2023 Jun [cited 2025 Jul 9]. Available from: https://doi.org/10.1111/aor.14563

[71] Rikhof CJ, Leerskov KS, Prange-Lasonder GB, Prinsen EC, Spaich EG, Dosen S, Struijk LN, Buurke JH, Rietman JS. Combining robotics and functional electrical stimulation for assist-as-needed support of leg movements in stroke patients: A feasibility study. Med Eng Amp Phys [Internet]. 2024 Aug [cited 2025 Jul 9];130:104216. Available from: https://doi.org/10.1016/j.medengphy.2024.104216

[72] Jaqueline da Cunha M, Rech KD, Salazar AP, Pagnussat AS. Functional electrical stimulation of the peroneal nerve improves post-stroke gait speed when combined with physiotherapy. A systematic review and meta-analysis. Ann Phys Rehabil Med [Internet]. 2020 May [cited 2025 Jul 9]:101388. Available from: https://doi.org/10.1016/j.rehab.2020.03.012

[73] Fu MJ, Curby A, Suder R, Katholi B, Knutson JS. Home-Based Functional Electrical Stimulation-Assisted Hand Therapy Video Games for Children With Hemiplegia: Development and Proof-of-Concept. IEEE Trans Neural Syst Rehabil Eng [Internet]. 2020 Jun [cited 2025 Jul 9];28(6):1461-70. Available from: https://doi.org/10.1109/tnsre.2020.2992036

[74] Doi S, Shibata S, Mu S, Miki Y. A Portable Functional Electrical Stimulation Device for Walking Motion Modification. In: 2020 IEEE 9th Global Conference on Consumer Electronics (GCCE) [Internet]; 2020 Oct 13-16; Kobe. [place unknown]: IEEE; 2020 [cited 2025 Jul 9]. Available from: https://doi.org/10.1109/gcce50665.2020.9291832

[75] Arntz A, Weber F, Handgraaf M, Lällä K, Korniloff K, Murtonen KP, Chichaeva J, Kidritsch A, Heller M, Sakellari E, Athanasopoulou C, Lagiou A, Tzonichaki I, Salinas-Bueno I, Martínez-Bueso P, Velasco-Roldán O, Schulz RJ, Grüneberg C. Technologies in home-based Digital Rehabilitation: A scoping review (Preprint). JMIR Rehabil Assist Technol [Internet]. 2022 Oct 18 [cited 2025 Jul 9]. Available from: https://doi.org/10.2196/43615

[76] Conner BC, Remec NM, Lerner ZF. Is robotic gait training effective for individuals with cerebral palsy? A systematic review and meta-analysis of randomized controlled trials. Clin Rehabil [Internet]. 2022 Mar 25 [cited 2025 Jul 9]:026921552210870. Available from: https://doi.org/10.1177/02692155221087084

[77] Banyai AD, Brișan C. Robotics in Physical Rehabilitation: Systematic Review. Healthcare [Internet]. 2024 Aug 29 [cited 2025 Jul 9];12(17):1720. Available from: https://doi.org/10.3390/healthcare12171720

[78] Peng QC, Yin L, Cao Y. Effectiveness of Virtual Reality in the Rehabilitation of Motor Function of Patients With Subacute Stroke: A Meta-Analysis. Front Neurol [Internet]. 2021 May 5 [cited 2025 Jul 9];12. Available from: https://doi.org/10.3389/fneur.2021.639535

[79] Scano A, Mira RM, Gabbrielli G, Molteni F, Terekhov V. Whole-Body Adaptive Functional Electrical Stimulation Kinesitherapy Can Promote the Restoring of Physiological Muscle Synergies for Neurological Patients. Sensors [Internet]. 2022 Feb 13 [cited 2025 Jul 9];22(4):1443. Available from: https://doi.org/10.3390/s22041443

[80] Cauraugh JH, Naik SK, Wen Hao Hsu, Coombes SA, Holt KG. Children with cerebral palsy: a systematic review and meta-analysis on gait and electrical stimulation. Clin Rehabil [Internet]. 2010 Aug 4 [cited 2025 Jul 9];24(11):963-78. Available from: https://doi.org/10.1177/0269215510371431

[81] Bleichner N, Heitzmann DW, Raynaud J, Stähle A, Weichold C, Alimusaj M, Putz C, Nees F, Flor H, Wolf SI. Effects of functional electrical stimulation on cognition rate and gait in neurological patients during single- and dual-task walking. Sci Rep [Internet]. 2025 Apr 19 [cited 2025 Jul 9];15(1). Available from: https://doi.org/10.1038/s41598-025-98755-w

[82] Zhang Y, Gao Y, Zhou J, Zhang Z, Feng M, Liu Y. Advances in Brain-Computer Interface Controlled Functional Electrical Stimulation for Upper Limb Recovery After Stroke. Brain Res Bull [Internet]. 2025 Apr [cited 2025 Jul 9]:111354. Available from: https://doi.org/10.1016/j.brainresbull.2025.111354

[83] Hara Y. Neurorehabilitation with New Functional Electrical Stimulation for Hemiparetic Upper Extremity in Stroke Patients. J Nippon Med Sch [Internet]. 2008 [cited 2025 Jul 9];75(1):4-14. Available from: https://doi.org/10.1272/jnms.75.4

[84] Cardoso LR, Bochkezanian V, Forner-Cordero A, Melendez-Calderon A, Bo AP. Soft robotics and functional electrical stimulation advances for restoring hand function in people with SCI: a narrative review, clinical guidelines and future directions. J Neuroeng Rehabil [Internet]. 2022 Jun 30 [cited 2025 Jul 9];19(1). Available from: https://doi.org/10.1186/s12984-022-01043-1

[85] Chen S, Fan S, Qiao Z, Wu Z, Lin B, Li Z, Riegler MA, Wong MY, Opheim A, Korostynska O, Nielsen KM, Glott T, Martinsen AC, Telle-Hansen VH, Lim CT. Transforming Healthcare: Intelligent Wearable Sensors Empowered by Smart Materials and Artificial Intelligence. Adv Mater [Internet]. 2025 Apr [cited 2025 Jul 9]. Available from: https://doi.org/10.1002/adma.202500412

[86] Sharma P, Gupta M, Kalra R. Recent Advancement in Interventions for Cerebral Palsy – A Review Study. J Neurorestoratology [Internet]. 2023 Jul [cited 2025 Jul 9]:100071. Available from: https://doi.org/10.1016/j.jnrt.2023.100071

[87] Karamian BA, Siegel N, Nourie B, Serruya MD, Heary RF, Harrop JS, Vaccaro AR. The role of electrical stimulation for rehabilitation and regeneration after spinal cord injury. J Orthop Traumatol [Internet]. 2022 Jan 6 [cited 2025 Jul 9];23(1). Available from: https://doi.org/10.1186/s10195-021-00623-6

[88] Kimberley TJ, Lewis SM, Auerbach EJ, Dorsey LL, Lojovich JM, Carey JR. Electrical stimulation driving functional improvements and cortical changes in subjects with stroke. Exp Brain Res [Internet]. 2004 Feb 1 [cited 2025 Jul 9];154(4):450-60. Available from: https://doi.org/10.1007/s00221-003-1695-y

[89] Sporea C, Ferechide D, Robănescu N. Benefits of Upper Limb Functional Electrical Stimulation in Children with Spastic Cerebral Palsy. Med Mod Mod Med [Internet]. 2021 Jun 30 [cited 2025 Jul 9];28(2):201-7. Available from: https://doi.org/10.31689/rmm.2021.28.2.201