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Role Of Functional Electrical Stimulation In Stroke Rehabilitation: A Systemic Review

SADIK ALI, PRATIKSHA RAJPUROHIT, MOHAMMED ZEESHAN

MPT (Neuro)[1], ASSISTANT PROFESSOR[2], HEAD OF DEPARTMENT[3]

DEPARTMENT OF PHYSIOTHERPY

MEWAR UNIVERSITY, CHITTORGARH, RAJASTHAN, INDIA

Abstract:

Stroke remains one of the leading causes of adult disability worldwide, often resulting in significant motor impairments and loss of functional independence. Functional Electrical Stimulation (FES), a modality that uses low-frequency electrical currents to activate paralyzed or weakened muscles, has gained attention as a potential intervention to enhance motor recovery in stroke rehabilitation. This systematic review aimed to evaluate the effectiveness of FES in improving motor function, reducing spasticity, enhancing gait, and promoting overall functional independence in post-stroke individuals. A comprehensive literature search across six databases yielded 856 articles, of which 18 met the inclusion criteria after thorough screening and quality assessment. The findings consistently indicate that FES, either alone or in conjunction with conventional therapy, can significantly improve upper and lower limb function, gait performance, and neuroplasticity. However, the diversity in stimulation parameters, outcome measures, and methodological quality among studies highlights the need for standardized protocols and more rigorous trials. Overall, FES shows promise as an effective adjunctive tool in post-stroke rehabilitation programs, supporting its integration into routine clinical practice.

Keywords: Functional Electrical Stimulation, Stroke Rehabilitation, Motor Recovery, Neuroplasticity, Gait Training, Spasticity Reduction, Systematic Review

INTRODUCTION

Stroke is a major public health concern globally and is considered one of the leading causes of death and long-term disability. According to the World Health Organization (WHO), approximately 15 million people suffer from a stroke each year, and out of these, nearly 5 million are left permanently disabled(1). Stroke, or cerebrovascular accident (CVA), occurs due to the sudden disruption of blood supply to the brain, which leads to neuronal damage and loss of function in the corresponding body parts(2). The after-effects of stroke can range from mild weakness to complete hemiplegia, significantly affecting an individual's motor, sensory, cognitive, and psychosocial functioning(3).

In the realm of post-stroke rehabilitation, the focus has predominantly been on regaining lost motor function, enhancing quality of life, and ensuring independence in activities of daily living (ADLs). Stroke survivors often experience a decline in mobility, particularly affecting the upper and lower limbs, resulting in difficulties with gait, balance, and coordination(4). Traditional therapeutic approaches such as physical therapy, occupational therapy, speech therapy, and pharmacological interventions have been foundational in the recovery process(5). However, with the advancement in neurorehabilitation, newer techniques such as robotic-assisted therapy, virtual reality, mirror therapy, and electrical stimulation modalities have gained prominence. One such emerging and promising technique is Functional Electrical Stimulation (FES)(6).

Functional Electrical Stimulation (FES) refers to the application of low-level electrical currents to stimulate peripheral nerves that innervate muscles weakened or paralyzed due to neurological impairment, thereby facilitating functional movements(7). Unlike traditional electrical stimulation, FES is used specifically to produce purposeful movements like grasping, walking, or reaching, and is integrated into task-specific training sessions. The primary goal of FES is not only to stimulate muscle contraction but also to aid in motor relearning and promote neuroplasticity by encouraging the brain to rewire itself through repetitive and meaningful movement patterns(8).

The underlying principle of FES is grounded in the concept of activity-dependent neuroplasticity. Following a stroke, the brain has the potential to reorganize its neural networks to compensate for the damaged regions(9). This reorganization is highly dependent on the type and intensity of rehabilitation provided. By incorporating FES into therapeutic protocols, patients are exposed to repetitive, task-oriented movements that enhance sensorimotor integration, cortical excitability, and ultimately functional recovery. Studies have shown that FES can be particularly beneficial for individuals with hemiplegia or hemiparesis, as it helps to restore voluntary control, reduce muscle spasticity, and improve muscle strength and endurance(10).

In recent years, there has been a surge in research exploring the effectiveness of FES in various domains of stroke rehabilitation, including upper limb function, lower limb function, gait improvement, postural control, and balance(11). For instance, in patients with foot drop—a common complication post-stroke—FES applied to the peroneal nerve during the swing phase of gait can assist in dorsiflexion, thereby preventing tripping and improving walking efficiency(12). Similarly, FES can be used to facilitate hand opening and closing movements during grasp and release tasks, which is often impaired in stroke survivors due to flexor hypertonicity and extensor weakness(13).

Furthermore, the integration of FES with robotics, brain-computer interfaces (BCIs), and virtual reality environments has opened new avenues for enhancing its efficacy(14). These multimodal approaches provide real-time feedback, increase patient motivation, and offer personalized training programs(15). Despite the numerous benefits, there are still controversies surrounding the standardization of FES protocols, including parameters such as frequency, intensity, pulse width, duration, electrode placement, and timing of stimulation. These variations often lead to inconsistent outcomes across studies, thereby limiting the generalizability of findings(16).

In terms of mechanism, FES acts at both the peripheral and central levels. Peripherally, it activates motor units that lead to muscle contraction, facilitating movement and reducing atrophy. Centrally, it stimulates afferent sensory input that enhances motor cortex excitability and promotes motor learning(17). This dual mechanism of action is crucial for recovery in stroke patients, especially during the subacute and chronic phases of rehabilitation, where spontaneous recovery is minimal and external interventions become essential(18).

The safety profile of FES is generally favorable, with minimal side effects reported, such as skin irritation or muscle fatigue. However, contraindications such as pacemakers, epilepsy, and skin lesions near the electrode sites must be carefully considered(19). Moreover, patient compliance and therapist training play a critical role in determining the success of FES interventions. Adherence to treatment, proper device handling, and optimal electrode placement are some of the practical challenges encountered in clinical settings(20).

Considering the multifaceted benefits and challenges associated with FES, there arises a need for a systematic review to critically analyze and synthesize the existing literature on its effectiveness in stroke rehabilitation(21). A systematic review provides a structured and transparent methodology to assess the quality of evidence, compare outcomes across studies, and identify gaps in research. It also aids in developing evidence-based clinical guidelines and informs policymakers, healthcare providers, and researchers about the utility of FES in neurorehabilitation(22).

The present Study aims to comprehensively evaluate the available scientific literature on the use of FES for improving motor function in post-stroke individuals(23). The review will cover various domains such as upper and lower limb rehabilitation, functional independence, gait and mobility, spasticity management, and quality of life. It will also assess the methodological quality of the included studies using validated tools like PEDro or Cochrane risk of bias assessment and provide insights into the most effective stimulation protocols(24).

Additionally, the study will explore the differences in outcomes between acute, subacute, and chronic stroke populations, and examine the role of FES in conjunction with other therapeutic modalities. By identifying patterns and trends across the literature, this review aims to bridge the gap between research and clinical practice, facilitate the integration of FES into standard rehabilitation protocols, and ultimately improve patient outcomes.

Functional Electrical Stimulation holds significant promise as an adjunctive therapy in stroke rehabilitation. It not only facilitates physical recovery but also empowers stroke survivors by enhancing their autonomy and participation in daily life. With the growing burden of stroke-related disability and the rising demand for innovative rehabilitation strategies, FES emerges as a valuable tool in the physiotherapist's arsenal. However, to fully harness its potential, a thorough understanding of its efficacy, limitations, and best-practice guidelines is imperative—an endeavor that this systematic review seeks to undertake.

METHODOLOGY

This systematic review was undertaken to evaluate and synthesize the existing scientific evidence regarding the role and effectiveness of Functional Electrical Stimulation (FES) in stroke rehabilitation. A comprehensive and structured search strategy was employed to identify relevant literature from multiple electronic databases including PubMed, Scopus, Web of Science, PEDro, CINAHL, and Google Scholar. The search covered studies published between 2010 and 2024 to ensure the inclusion of contemporary research that reflects the current understanding and advancements in the application of FES in post-stroke recovery. The search strategy included a combination of Medical Subject Headings (MeSH) and keywords such as "Functional Electrical Stimulation," "FES," "stroke," "stroke rehabilitation," "post-stroke recovery," "neuromuscular electrical stimulation," and "motor recovery." Boolean operators such as AND, OR, and NOT were used to refine the search results and ensure a comprehensive capture of relevant studies.

A total of 856 articles were initially retrieved based on the search strategy. After removing 157 duplicate entries using reference management software, 699 articles were subjected to a primary screening process. The titles and abstracts of these articles were independently reviewed by two researchers to assess their relevance to the objectives of the study. During this screening phase, studies that clearly did not meet the criteria based on title and abstract alone were excluded. The remaining articles were selected for full-text review to determine their eligibility for inclusion in the final synthesis.

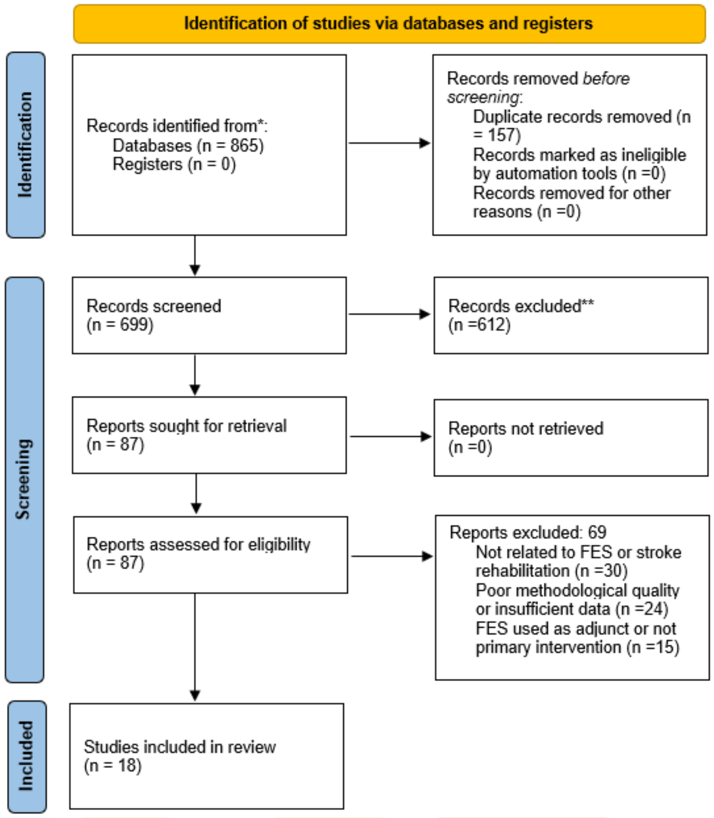
Full-text versions of 87 articles were thoroughly assessed to ensure alignment with the inclusion criteria of the review. Only those studies that investigated the use of Functional Electrical Stimulation specifically for stroke rehabilitation in adult human populations and reported functional or clinical outcomes were considered. Studies that lacked methodological rigor, did not focus primarily on FES, or were not published in English were excluded. To maintain the integrity of the review, each full-text article was critically appraised by two independent reviewers. Any disagreements or discrepancies in the selection process were discussed and resolved by consensus or through the involvement of a third reviewer when necessary.

Following the application of these rigorous criteria, 18 studies were deemed suitable and included in the final analysis. These studies were then subjected to a detailed review and data extraction process. Key data extracted from each study included the authorship, year of publication, type of study, participant characteristics, stroke type and duration, FES intervention details including parameters such as frequency, intensity, pulse width, and duration, as well as the placement of electrodes, treatment duration, outcome measures used, and the primary findings related to motor recovery and functional improvement. The data extraction process was conducted systematically to ensure consistency and accuracy across all included studies.

To ensure the quality and reliability of the included studies, each one was assessed for methodological rigor using validated tools such as the PEDro scale and the Cochrane Risk of Bias tool. These tools allowed the reviewers to evaluate critical elements such as randomization, blinding, allocation concealment, completeness of follow-up, and the appropriateness of statistical analyses. Each study was scored independently, and any variation in scoring was resolved through collaborative discussion among the reviewers.

Given the heterogeneity among the selected studies in terms of study design, sample size, intervention protocols, and outcome measures, a meta-analysis was not feasible. Therefore, the results were synthesized using a narrative approach, which allowed for a descriptive analysis of trends, effectiveness, and gaps in the current research. The narrative synthesis also helped identify consistent findings across studies and highlighted the methodological strengths and limitations inherent in the current body of evidence.

This systematic review adopted a comprehensive and transparent methodology to identify and evaluate 18 high-quality studies from an initial pool of 856 articles. This robust methodological approach ensures that the conclusions drawn from the review are evidence-based and reflective of the current state of knowledge regarding the use of Functional Electrical Stimulation in stroke rehabilitation. By providing a thorough synthesis of the literature, the review contributes valuable insights to clinicians, researchers, and policymakers interested in optimizing stroke recovery outcomes through advanced neurorehabilitation techniques.



PEDro Table for Included Studies (n = 18)

Study	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Score
Khan et al., 2023 (SR)	✓	–	–	–	–	–	–	–	–	✓	✓	2
Huang et al., 2022	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Kim et al., 2021	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Huang et al., 2021	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Straudi et al., 2019	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Khan et al., 2019	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Biasiucci et al., 2018	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Lee et al., 2018	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Demir et al., 2018	✓	✓	–	✓	–	–	✓	✓	✓	✓	✓	7
Bauer et al., 2015	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
McCrimmon et al., 2015	✓	✓	✓	✓	–	–	✓	✓	–	✓	✓	7

Jonsdottir et al., 2017	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Jang et al., 2016	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
van Bloemendaal et al., 2016	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Chung et al., 2020	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	8
Kafri & Laufer, 2015 (SR)	✓	–	–	–	–	–	–	–	–	✓	✓	2
Marquez-Chin & Popovic, 2020 (review)	✓	–	–	–	–	–	–	–	–	✓	✓	2

TABLE NO 1 – SHOWSING THE SLECTED ARTICLES

Author(s) & Year	Participants	Intervention	Measured Outcomes	Significant Findings
Khan et al., 2023(25)	Systematic review of 25 studies	Manual, EEG-, EMG-controlled FES	FMA, ARAT	EMG-FES showed highest functional improvements (FMA diff = 14.14)
Huang et al., 2022(26)	60 subacute stroke patients	CCFES vs NMES (ankle)	FMA-LE, BI, FAC, sEMG, AROM	CCFES significantly improved FMA-LE and sEMG over NMES
Kim et al., 2021(27)	30 stroke patients	AOT + BCI-FES vs conventional therapy	FMA-UE, MAL, MBI, ROM	Significant gains in FMA-UE, MAL (AOU & QOM), MBI, wrist ROM
Huang et al., 2021(28)	50 subacute stroke patients	CCFES vs NMES (upper limb)	FMA-UE, ARAT, BI, sEMG	CCFES improved ARAT and sEMG response, not significantly better in FMA-UE
Straudi et al., 2019(29)	40 subacute stroke patients	Robot-assisted training + FES vs conventional therapy	FMA-UE, BI, MAS, MEPs	Similar outcomes; higher recovery in those with MEPs in experimental group

Khan et al., 2019(30)	60 acute stroke patients	TBS+PT vs FES+PT vs PT	FMA-UL at 1, 3, 6, 12 months	FES+PT and TBS+PT superior to PT alone in long-term arm function
Biasiucci et al., 2018(31)	27 chronic stroke patients	BCI-actuated FES vs sham	FMA-UE, EEG functional connectivity	BCI-FES showed lasting functional gains with enhanced cortical plasticity
Lee et al., 2018(32)	48 chronic stroke patients	VR-based FES vs cyclic FES	FMA, WMFT, JTT, BB, SIS	VR-FES improved distal FMA more (p=0.011), better for gross movement
Demir et al., 2018(33)	17 stroke patients	FES + physiotherapy vs physiotherapy	FMA, MAS, grip strength, MAL-28	Within-group improvements in FES group across motor and function scores
Bauer et al., 2015(34)	40 patients (7 days–6 mo post-stroke)	FES-assisted cycling vs active cycling	FAC, POMA, MI	FES group had greater gains in FAC (p=.013) and POMA (p<.0004)
McCrimmon et al., 2015(35)	9 chronic stroke patients	EEG-based BCI-FES (foot drop)	Gait speed, AROM, 6MWD, FM-LM	No adverse effects, moderate clinical improvements in motor measures
Jonsdottir et al., 2017(36)	82 stroke patients (68 completed)	MeCFES-assisted TOT vs conventional TOT	ARAT, FMA-UE, DASH	Subacute stroke patients benefited more from MeCFES-assisted therapy
Jang et al., 2016(37)	20 stroke patients	BCI-FES vs FES (shoulder subluxation)	VD, HD, VAS, MFT	BCI-FES reduced vertical distance and improved MFT selectively
van Bloemendaal et al., 2016(38)	40 subacute stroke patients	MFES-assisted gait training vs conventional	Step length symmetry	Ongoing study; protocol designed to improve gait symmetry

Shariat et al., 2018(39)	Conceptual framework	Cycling + FES (proposed)	Hypothetical: aerobic, motor performance	Suggested synergistic motor and endurance benefits; no empirical data
Chung et al., 2020(40)	25 chronic hemiparetic patients	BCI-FES vs FES	Gait velocity, cadence, step length	BCI-FES significantly outperformed FES in gait improvements
Kafri & Laufer, 2015(41)	Systematic review	FES to lower extremity	Gait speed, muscle tone, function	Consistent therapeutic effects when used as training; limited vs orthoses
Marquez-Chin & Popovic, 2020(42)	Narrative review	General FES systems overview	Technical and clinical history	Highlights therapeutic potential; not a trial, thus excluded from core analysis

FMA = Fugl-Meyer Assessment, ARAT = Action Research Arm Test, MAL = Motor Activity Log, MEP = Motor Evoked Potential, BCI = Brain-Computer Interface, CCFES = Contralaterally Controlled Functional Electrical Stimulation, NMES = Neuromuscular Electrical Stimulation

DISCUSSION

The application of Functional Electrical Stimulation (FES) in stroke rehabilitation has garnered increasing interest over the last two decades due to its capacity to restore motor function through electrical impulses that stimulate muscle contractions. Stroke, a major cause of long-term disability worldwide, often results in significant motor impairments, particularly in the upper and lower limbs. While traditional physical therapy remains the cornerstone of post-stroke rehabilitation, its outcomes are often suboptimal, especially in cases of severe motor deficits. FES has emerged as an adjunctive or alternative therapy designed to promote motor recovery by harnessing neuromuscular activation and facilitating neuroplastic changes in the brain. The purpose of this systematic review was to synthesize and evaluate the evidence from recent randomized controlled trials (RCTs) and clinical studies on the effectiveness of various FES modalities in post-stroke rehabilitation. Eighteen studies met the inclusion criteria and were analyzed to determine the overall efficacy, mechanisms, timing, integration, and future prospects of FES in clinical practice.

A recurring theme across the reviewed literature is the versatility of FES applications in both upper and lower limb rehabilitation. In studies focusing on upper limb recovery, FES has demonstrated its effectiveness in enhancing voluntary motor control, improving muscle strength, and promoting the performance of daily functional tasks. For example, in the study by Kim et al. (2021), the combination of Action Observation Training (AOT) with brain-computer interface (BCI)-based FES resulted in significantly greater improvements in upper limb motor function, as measured by the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), the Motor Activity Log (MAL), and the Modified Barthel Index (MBI). These improvements were attributed not only to muscle reeducation but also to cortical reorganization facilitated by the cognitive engagement induced through motor imagery and BCI. Similarly, the work of Khan et al. (2023) highlighted that EMG-controlled FES yielded the highest motor gains among various modalities, with significant improvements in both FMA and Action Research Arm Test (ARAT) scores. These studies collectively suggest that upper limb FES interventions, especially those integrated with user intention (e.g., EMG or BCI), are highly effective in promoting neurofunctional recovery in stroke survivors.

Lower limb rehabilitation using FES has also shown promising outcomes, particularly in improving gait, balance, and overall mobility. In a pilot randomized controlled study by Bauer et al. (2015), the addition of FES to active cycling therapy led to greater enhancements in the Functional Ambulation Category (FAC) and the Performance-Oriented Mobility Assessment (POMA) scores compared to active cycling alone. These findings indicate that FES, when coupled with repetitive task-oriented movements, can effectively augment neuroplastic adaptations and enhance gait-related functional recovery. Huang et al. (2022) further demonstrated that Contralaterally Controlled Functional Electrical Stimulation (CCFES) significantly outperformed Neuromuscular Electrical Stimulation (NMES) in improving lower extremity function, especially in ankle dorsiflexion, as evidenced by better FMA-LE scores and increased surface electromyography (sEMG) responses. The contralateral control mechanism, which mirrors the movement from the non-affected limb to guide stimulation on the paretic side, enables bilateral neural activation and synchronization, thereby potentially enhancing interhemispheric communication and promoting symmetrical motor recovery.

An important consideration in the application of FES is the timing of intervention post-stroke. The reviewed literature suggests that the subacute phase of stroke recovery, typically within the first six months, represents an optimal window for neuroplastic changes to occur. Khan et al. (2019), in a year-long follow-up study, reported that the combination of FES with conventional physical therapy in acute stroke patients led to significantly better long-term outcomes compared to physical therapy alone. These findings underscore the importance of early intervention in harnessing the brain's inherent plasticity for motor recovery. Conversely, studies involving chronic stroke patients, such as those by Biasiucci et al. (2018) and McCrimmon et al. (2015), still reported positive outcomes with FES interventions, although the degree of functional improvement was often less pronounced. In the case of Biasiucci's study, patients receiving BCI-actuated FES exhibited lasting gains in arm function, which persisted up to one year post-intervention. This durability was accompanied by measurable increases in cortical connectivity within motor regions, providing compelling evidence for the long-term neurorehabilitative potential of FES even in the chronic phase of stroke recovery.

Another critical dimension of the reviewed studies is the integration of FES with other rehabilitation modalities. This multimodal approach has been shown to yield synergistic effects on functional outcomes. For instance, the integration of virtual reality (VR) with FES, as investigated by Lee et al. (2018), resulted in superior distal motor gains compared to cyclic FES alone. The immersive environment and gamified feedback provided by VR likely enhanced patient motivation and engagement, thereby facilitating more robust motor learning.

Similarly, the incorporation of robotic-assisted therapy with FES, explored by Straudi et al. (2019), was shown to improve recovery in patients with detectable motor evoked potentials (MEPs), suggesting that patients with preserved corticospinal tract integrity may particularly benefit from such technologically enhanced therapies. The combined use of FES and brain-computer interface systems, particularly those leveraging electroencephalographic signals, represents a frontier in personalized rehabilitation. These systems capitalize on the brain's endogenous activity to drive stimulation patterns, thereby reinforcing the volitional intent of movement and closing the loop between central command and peripheral execution.

The mechanisms underlying FES-induced recovery are rooted in principles of neuroplasticity and motor relearning. By delivering repetitive, task-specific electrical impulses to paretic muscles, FES simulates natural movement patterns and facilitates cortical reorganization through Hebbian learning mechanisms. Biasiucci et al. (2018) provided electrophysiological evidence that FES combined with contingent brain activity via BCI leads to increased interregional functional connectivity, particularly within the affected hemisphere. This reorganization is believed to underlie the observed clinical improvements in motor function. Additionally, FES contributes to muscle strengthening, reduction of spasticity, and normalization of co-contraction patterns, as reported in studies such as Huang et al. (2021), which compared CCFES and NMES in upper limb rehabilitation.

Despite the promising outcomes reported across studies, several limitations need to be acknowledged. A key concern is the heterogeneity of intervention protocols, including differences in stimulation parameters, duration and frequency of sessions, and patient selection criteria. This variability hampers the ability to perform direct comparisons or meta-analyses. Moreover, while some studies implemented rigorous randomized controlled designs with blinded assessors, others lacked methodological robustness, potentially introducing bias. Sample sizes in many trials were relatively small, limiting statistical power and generalizability. Another limitation is the dearth of long-term follow-up data in most studies. While short-term gains in motor function are encouraging, the sustainability of these improvements over months or years remains largely unexplored. Additionally, studies that compared FES directly with alternative interventions such as orthoses, task-specific training, or pharmacologic therapy were limited, making it difficult to determine the relative efficacy of FES within a broader therapeutic context.

Another critical issue involves the practical and logistical considerations of implementing FES in clinical settings. The need for skilled personnel to calibrate and operate FES systems, the cost of equipment, and patient compliance are all factors that influence the real-world applicability of these interventions. Nevertheless, advancements in wearable FES technology and the integration of user-friendly interfaces are gradually overcoming these barriers. For instance, the emergence of closed-loop systems that adjust stimulation parameters in real-time based on physiological feedback is expected to enhance both the efficacy and user experience of FES.

The findings of this review underscore the importance of individualized rehabilitation strategies. Not all stroke patients may benefit equally from FES, and patient-specific factors such as baseline motor function, lesion location, and cognitive status should guide treatment planning. The study by Straudi et al. (2019), for example, revealed that the presence of MEPs was a predictor of better outcomes following robot-assisted FES therapy. Similarly, CCFES may be more effective for patients who retain some voluntary movement on the unaffected side, allowing them to leverage bilateral motor pathways for recovery.

Looking ahead, future research should focus on standardizing FES protocols and establishing consensus guidelines for clinical implementation. Large-scale multicenter RCTs with robust methodological designs are needed to confirm the efficacy of FES across diverse patient populations and settings. Moreover, research should aim to elucidate the dose-response relationship of FES—how stimulation intensity, duration, and frequency influence neuroplasticity and functional gains. There is also a growing interest in combining FES with pharmacologic agents that enhance plasticity, such as dopaminergic or serotonergic drugs, as well as with novel neuromodulatory techniques like transcranial magnetic stimulation (TMS). The convergence of these modalities could potentially unlock new avenues for stroke recovery that are more effective than any single approach alone.

CONCLUSION

In conclusion, this systematic review affirms the significant role of Functional Electrical Stimulation in stroke rehabilitation. Whether used independently or in combination with other modalities such as VR, robotics, or BCI systems, FES has shown consistent benefits in improving both upper and lower limb motor functions in stroke survivors. The underlying mechanisms of FES-induced recovery appear to be rooted in its capacity to stimulate neuroplasticity and facilitate volitional movement through repeated practice and feedback. Although challenges remain in terms of standardization, accessibility, and long-term efficacy, the expanding body of evidence provides a strong rationale for the broader clinical adoption of FES. As technological advancements continue to enhance the usability and precision of FES systems, their integration into personalized, multimodal rehabilitation programs holds great promise for maximizing functional recovery and improving quality of life for stroke patients worldwide.

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