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Neuromuscular Electrical Stimulation in Stroke Rehabilitation: Current Evidence, Clinical Applications, and Future Directions

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Abstract

Stroke remains one of the leading causes of long-term disability worldwide and continues to place a significant physical, emotional, and economic burden on individuals, their families, and healthcare systems. Although advances in emergency stroke care and medical management have improved survival rates, many stroke survivors continue to experience long-term impairments such as muscle weakness, impaired motor control, spasticity, balance deficits, gait abnormalities, and limitations in performing activities of daily living. These persistent impairments emphasize the importance of comprehensive rehabilitation aimed at restoring functional independence and improving quality of life.

Conventional physiotherapy remains the cornerstone of stroke rehabilitation and focuses on improving movement through strengthening exercises, balance training, gait re-education, task-oriented practice, and functional mobility training. However, recovery is often incomplete, particularly in individuals with moderate to severe neurological deficits. Consequently, several adjunctive rehabilitation approaches have been introduced to enhance motor recovery and promote neuroplasticity. Among these, neuromuscular electrical stimulation (NMES) has gained increasing attention because of its ability to facilitate muscle contraction, improve voluntary motor control, reduce muscle atrophy, and support functional recovery.

The purpose of this narrative review is to summarize the current evidence regarding the role of NMES in stroke rehabilitation, describe its physiological mechanisms, discuss its clinical applications, and highlight future research directions. A comprehensive literature search was conducted using PubMed, Scopus, PEDro, and Google Scholar, focusing primarily on studies published between 2015 and 2026. Randomized controlled trials, systematic reviews, meta-analyses, and clinical practice guidelines involving adult stroke survivors were reviewed to provide a comprehensive overview of the available evidence.

Current literature indicates that NMES, particularly when combined with conventional physiotherapy and task-specific training, can improve upper and lower limb motor function, muscle strength, gait performance, balance, and functional independence in appropriately selected stroke survivors. Evidence suggests that early application of NMES may further enhance recovery by promoting neuroplasticity and improving neuromuscular activation, although beneficial effects have also been reported in individuals with chronic stroke. Nevertheless, considerable variability exists in stimulation parameters, treatment duration, patient selection, and outcome measures, making it difficult to establish standardized clinical protocols.

Overall, NMES should be considered a valuable adjunct to conventional physiotherapy rather than a replacement for it. When incorporated into individualized rehabilitation programs, it has the potential to enhance functional recovery and improve long-term outcomes after stroke. Future multicenter randomized controlled trials with standardized treatment protocols, larger sample sizes, and extended follow-up periods are needed to determine optimal stimulation parameters and strengthen the evidence supporting its routine clinical use.

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INTRODUCTION

Stroke is one of the most common neurological disorders and remains a leading cause of long-term disability worldwide. Despite considerable advances in preventive strategies, acute medical management, and reperfusion therapies, stroke continues to affect millions of individuals each year and is associated with significant physical, psychological, social, and economic consequences. Improvements in emergency stroke care have increased survival rates, resulting in a growing population of stroke survivors who require comprehensive rehabilitation to restore functional independence and improve quality of life. Consequently, rehabilitation has become an essential component of stroke management, extending beyond survival to focus on maximizing recovery and facilitating community reintegration.

Motor impairment is the most frequent and disabling consequence of stroke. Approximately 70–80% of individuals experience weakness or paralysis of the upper and/or lower limbs during the acute phase, while many continue to have residual deficits months or even years after the initial event. These impairments commonly include reduced voluntary muscle activation, abnormal muscle tone, impaired coordination, diminished balance, gait dysfunction, decreased endurance, and difficulty performing activities of daily living. Such deficits substantially restrict independence and often increase caregiver burden while reducing participation in social and occupational activities.

The primary objective of stroke rehabilitation is to promote functional recovery by enhancing neuroplasticity—the nervous system's capacity to reorganize neural pathways in response to injury and experience. Functional recovery depends on repeated, task-specific, intensive, and meaningful practice that stimulates cortical reorganization and facilitates motor relearning. Conventional physiotherapy remains the cornerstone of rehabilitation and includes interventions such as range-of-motion exercises, strengthening programs, balance training, gait retraining, task-oriented therapy, proprioceptive exercises, and functional mobility training. Although these interventions have demonstrated clinical benefits, many patients continue to experience incomplete recovery, particularly those with moderate to severe motor impairments. Consequently, adjunctive rehabilitation techniques have gained increasing attention as strategies to augment conventional therapy and optimize functional outcomes.

Among these adjunctive interventions, neuromuscular electrical stimulation (NMES) has become one of the most widely investigated therapeutic modalities in neurorehabilitation. NMES involves the application of electrical impulses through surface electrodes placed over peripheral nerves or motor points to elicit controlled muscle contractions. Initially developed to prevent muscle atrophy during periods of immobilization, NMES is now used extensively in neurological rehabilitation to improve muscle strength, facilitate voluntary movement, enhance motor control, reduce spasticity, and support functional task performance. The repeated activation of paretic muscles, combined with enhanced sensory input to the central nervous system, is believed to promote cortical reorganization and facilitate motor recovery following stroke.

The therapeutic effects of NMES extend beyond muscle strengthening. Experimental and clinical studies suggest that electrical stimulation increases afferent sensory feedback, enhances corticospinal excitability, promotes synaptic plasticity, improves motor unit recruitment, and facilitates motor learning. When synchronized with voluntary movement or functional task practice, NMES may reinforce neural pathways involved in movement execution, thereby improving the efficiency of rehabilitation. Consequently, NMES has been incorporated into rehabilitation programs targeting upper limb recovery, lower limb function, gait training, balance rehabilitation, prevention of shoulder subluxation, and management of foot drop.

Over the past decade, numerous randomized controlled trials, systematic reviews, and meta-analyses have evaluated the effectiveness of NMES in stroke rehabilitation. While many studies have demonstrated improvements in motor recovery, walking ability, muscle strength, and functional independence, others have reported modest or inconsistent benefits. Variations in patient characteristics, stroke severity, intervention timing, stimulation parameters, treatment duration, and outcome measures have contributed to these conflicting findings. Therefore, clinicians continue to face uncertainty regarding the optimal implementation of NMES in routine clinical practice.

In recent years, advances in rehabilitation technology have further expanded the potential applications of NMES. Wearable stimulators, wireless systems, closed-loop stimulation, robotics-assisted rehabilitation, virtual reality integration, brain–computer interfaces, and artificial intelligence-assisted rehabilitation are increasingly being explored to deliver individualized, task-specific therapy. These innovations have the potential to improve treatment precision, increase patient engagement, and extend rehabilitation beyond traditional clinical settings through home-based programs and telerehabilitation.

Given the growing body of evidence and the rapid evolution of rehabilitation technologies, an updated synthesis of current knowledge is warranted. This narrative review aims to summarize contemporary evidence regarding the role of NMES in stroke rehabilitation, describe its physiological mechanisms, examine its clinical applications across different functional domains, discuss its advantages and limitations, and highlight future directions that may enhance its integration into evidence-based neurorehabilitation practice.

SEARCH STRATEGY

A comprehensive literature search was conducted to identify relevant studies evaluating the role of neuromuscular electrical stimulation (NMES) in stroke rehabilitation. Electronic databases including PubMed, Scopus, PEDro, Google Scholar, and Web of Science were searched for articles published between January 2015 and June 2026. Additional relevant articles were identified by manually reviewing the reference lists of selected studies and review papers.

The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords, including **"stroke," "cerebrovascular accident," "neuromuscular electrical stimulation," "NMES," "functional electrical stimulation," "FES," "stroke rehabilitation," "motor recovery," "upper limb rehabilitation," "lower limb rehabilitation," "gait training," "balance,"** and **"physiotherapy."** Boolean operators (AND/OR) were used to combine search terms and optimize retrieval of relevant publications.

The review primarily included randomized controlled trials, systematic reviews, meta-analyses, clinical practice guidelines, and high-quality observational studies involving adult individuals with ischemic or hemorrhagic stroke. Studies that investigated the effects of NMES alone or in combination with conventional physiotherapy on motor recovery, muscle strength, gait, balance, upper limb function, lower limb function, spasticity, or activities of daily living were considered. Only articles published in English and available in full text were included.

Studies involving pediatric populations, animal models, conference abstracts, editorials, opinion articles, unpublished theses, and studies lacking sufficient methodological details were excluded. Articles focusing exclusively on other neurological conditions without separate stroke-related findings were also excluded.

The selected literature was critically reviewed to summarize the current evidence regarding the physiological mechanisms, therapeutic applications, clinical effectiveness, advantages, limitations, and future directions of NMES in stroke rehabilitation. As this is a narrative review, formal quality assessment and meta-analysis were not performed. Instead, emphasis was placed on synthesizing evidence from high-quality and clinically relevant publications to provide a comprehensive overview of the current role of NMES in evidence-based stroke rehabilitation.

PATHOPHYSIOLOGY OF STROKE

Stroke is a neurological condition that occurs when the blood supply to a part of the brain is interrupted or reduced, resulting in insufficient oxygen and nutrient delivery to brain tissue. Within minutes of the interruption in blood flow, brain cells begin to lose their function, and prolonged ischemia can lead to irreversible neuronal damage. Depending on the location and extent of the brain injury, stroke can produce a wide range of motor, sensory, cognitive, perceptual, and communication impairments that significantly affect an individual's functional independence and quality of life.

Stroke is broadly classified into two major types: ischemic stroke and hemorrhagic stroke. Ischemic stroke accounts for approximately 80–85% of all stroke cases and occurs when a cerebral artery becomes blocked by a thrombus or embolus, preventing adequate blood flow to the brain. Hemorrhagic stroke accounts for the remaining 15–20% of cases and results from the rupture of a blood vessel within or around the brain, leading to bleeding and increased intracranial pressure. Although the underlying mechanisms differ, both types of stroke can cause substantial neuronal injury and long-term neurological deficits.

The neurological impairments observed after stroke depend on the specific brain region affected. Damage to the primary motor cortex, corticospinal tract, internal capsule, cerebellum, or brainstem commonly results in motor deficits such as muscle weakness, impaired voluntary movement, abnormal muscle tone, poor coordination, and reduced postural control. Upper limb dysfunction is particularly common and often persists longer than lower limb impairment, making activities such as reaching, grasping, dressing, eating, and writing challenging. Lower limb involvement may lead to gait abnormalities, decreased balance, reduced walking speed, and an increased risk of falls, all of which limit community participation and independence.

One of the hallmark features of post-stroke motor impairment is hemiparesis or hemiplegia, which results from disruption of the corticospinal pathways responsible for voluntary movement. In the early stages following stroke, many patients experience flaccid paralysis due to spinal shock and reduced neural activation. As recovery progresses, abnormal muscle tone and spasticity may develop because of impaired inhibitory control within the central nervous system. These changes are often accompanied by muscle shortening, joint stiffness, contracture formation, weakness, and reduced endurance, further limiting functional performance.

In addition to motor impairments, stroke can adversely affect sensory function, proprioception, cognition, language, vision, and perception. Deficits in proprioception and somatosensory feedback reduce movement accuracy and motor learning, while cognitive and perceptual impairments may interfere with participation in rehabilitation. These multiple impairments often coexist, highlighting the need for a comprehensive, multidisciplinary rehabilitation approach tailored to each individual's needs.

Recovery after stroke depends on several factors, including the severity and location of the brain lesion, the patient's age, overall health status, timing of rehabilitation, intensity of therapy, and the ability of the nervous system to reorganize through neuroplasticity. Early rehabilitation is particularly important because the brain demonstrates heightened plasticity during the first few months after stroke. During this period, repetitive, task-specific, and goal-directed interventions can facilitate cortical reorganization, strengthen remaining neural pathways, and improve functional recovery.

Understanding the pathophysiological changes that occur following stroke provides the foundation for selecting appropriate rehabilitation strategies. Since many post-stroke deficits arise from impaired motor control, muscle weakness, reduced sensory input, and altered neural activation, interventions that enhance neuromuscular function and promote neuroplasticity are of particular clinical importance. Neuromuscular electrical stimulation (NMES) is one such intervention that has gained widespread attention because of its ability to activate paretic muscles, provide sensory feedback, and facilitate motor relearning when integrated with conventional physiotherapy.

NEUROPLASTICITY AND MOTOR RECOVERY AFTER STROKE

Recovery following stroke is largely dependent on the brain's ability to reorganize and adapt after injury, a process known as **neuroplasticity**. Neuroplasticity refers to the capacity of the central nervous system to modify its structure and function by forming new neural connections, strengthening existing pathways, and reorganizing cortical networks in response to injury, learning, and repetitive practice. This remarkable ability enables undamaged areas of the brain to partially compensate for lost functions and forms the scientific basis of modern stroke rehabilitation.

Immediately after a stroke, the affected brain tissue undergoes a series of complex biological changes, including neuronal death, inflammation, edema, and disruption of neural pathways. Despite this initial damage, the brain possesses an inherent ability to recover through spontaneous repair mechanisms. During the first few weeks and months after stroke, the nervous system enters a period of heightened plasticity in which surviving neurons establish new synaptic connections and previously inactive neural pathways may become functionally active. This period provides an important opportunity for rehabilitation interventions to maximize recovery.

Motor recovery after stroke is influenced by several mechanisms of neuroplasticity. These include synaptic plasticity, cortical reorganization, axonal sprouting, dendritic remodeling, and increased excitability of surviving motor pathways. Repetitive practice of functional movements stimulates these adaptive changes, allowing patients to gradually regain voluntary motor control. The principle of **"use it or lose it"** emphasizes that regular activation of affected muscles helps preserve and strengthen neural circuits, whereas prolonged inactivity may lead to further deterioration of motor function.

One of the key principles of stroke rehabilitation is **task-specific training**, in which patients repeatedly perform meaningful functional activities such as reaching, grasping, standing, and walking. Repetition of these tasks promotes motor learning by enhancing communication between the brain and muscles. The intensity, frequency, and specificity of rehabilitation exercises play a crucial role in stimulating cortical reorganization and improving functional outcomes. Therefore, rehabilitation programs increasingly emphasize active participation, high repetition, and goal-oriented practice.

Sensory feedback also plays an essential role in motor recovery. Information received from muscles, joints, tendons, and skin continuously travels to the central nervous system, allowing the brain to monitor movement and make appropriate adjustments. Following stroke, impaired sensory input often contributes to poor motor control and reduced movement accuracy. Rehabilitation interventions that increase afferent sensory stimulation can enhance sensorimotor integration and facilitate motor relearning by improving communication between peripheral tissues and the brain.

Neuromuscular electrical stimulation (NMES) is particularly valuable because it combines muscle activation with enhanced sensory feedback. Electrical stimulation produces repeated contractions of paretic muscles while simultaneously activating sensory receptors, thereby increasing afferent input to the central nervous system. This continuous sensory stimulation is believed to improve corticospinal excitability, strengthen remaining neural pathways, and promote cortical reorganization. When NMES is synchronized with voluntary movement or incorporated into task-specific training, it may further reinforce motor learning and improve functional performance.

Research over the past decade has demonstrated that rehabilitation interventions promoting neuroplasticity are associated with better functional recovery, particularly when initiated during the early stages after stroke. Nevertheless, meaningful improvements can also be achieved during the chronic phase, provided that rehabilitation is intensive, individualized, and functionally relevant. Factors such as patient motivation, treatment intensity, stroke severity, age, and cognitive status all influence the extent of neuroplastic changes and overall recovery.

A thorough understanding of neuroplasticity is essential for physiotherapists when designing rehabilitation programs for individuals with stroke. It highlights the importance of delivering repetitive, task-oriented, and evidence-based interventions that actively engage the nervous system. As an intervention capable of simultaneously enhancing muscle activation, sensory input, and motor learning, NMES has become an important adjunct to conventional physiotherapy and continues to gain recognition as a valuable tool for facilitating post-stroke motor recovery.

NEUROMUSCULAR ELECTRICAL STIMULATION: PRINCIPLES AND PHYSIOLOGICAL MECHANISMS

Neuromuscular electrical stimulation (NMES) is a therapeutic intervention that uses controlled electrical impulses to stimulate peripheral motor nerves and produce muscle contractions. The electrical impulses are delivered through surface electrodes placed over the motor points or peripheral nerves of the targeted muscles. Unlike voluntary muscle contraction, which is initiated by signals from the brain, NMES directly activates motor neurons, allowing muscle contraction even when voluntary movement is limited or absent. This characteristic makes NMES particularly valuable in the rehabilitation of individuals with stroke who have impaired motor control and muscle weakness.

Initially, NMES was primarily used to prevent muscle atrophy in individuals with prolonged immobilization. Over time, its application has expanded considerably, and it is now widely incorporated into neurological rehabilitation programs. In stroke rehabilitation, NMES is commonly used to improve muscle strength, facilitate voluntary movement, enhance motor control, reduce muscle atrophy caused by disuse, improve circulation, and promote functional recovery. Rather than replacing conventional physiotherapy, NMES is most effective when integrated into a comprehensive rehabilitation program that includes task-oriented training, strengthening exercises, balance activities, and functional mobility practice.

The therapeutic effects of NMES are based on both peripheral and central mechanisms. At the peripheral level, electrical stimulation activates motor nerves, producing repeated muscle contractions that help maintain muscle mass, improve muscle strength, increase endurance, and reduce the effects of prolonged inactivity. Repeated contractions also improve local blood circulation, enhance oxygen delivery to muscles, and may reduce edema by promoting venous and lymphatic return. These physiological effects contribute to improved muscle performance and prepare patients for active rehabilitation.

At the central nervous system level, NMES provides continuous sensory input through stimulation of cutaneous and proprioceptive receptors. This increased afferent feedback travels to the spinal cord and cerebral cortex, where it contributes to sensorimotor integration and cortical reorganization. Repeated sensory stimulation is believed to enhance corticospinal excitability, facilitate activation of surviving neural pathways, and strengthen communication between the brain and affected muscles. These neurophysiological changes support activity-dependent neuroplasticity, which is essential for motor relearning after stroke.

One of the major advantages of NMES is its ability to combine passive muscle activation with active patient participation. When electrical stimulation is synchronized with the patient's voluntary effort or incorporated into functional activities such as reaching, grasping, standing, or walking, the combined motor and sensory input may

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produce greater improvements than either intervention alone. This approach reinforces normal movement patterns and enhances the effectiveness of task-specific rehabilitation.

Several stimulation parameters influence the effectiveness of NMES, including waveform, pulse duration, frequency, intensity, ramp time, duty cycle, and treatment duration. Although optimal parameters may vary depending on the treatment goal and individual patient characteristics, most clinical studies in stroke rehabilitation have used frequencies ranging from **20 to 50 Hz**, pulse durations between **200 and 400 microseconds**, and stimulation intensities sufficient to produce a visible and comfortable muscle contraction. Treatment sessions typically last **20 to 60 minutes**, with interventions performed several times per week over a period of **4 to 12 weeks**. Careful adjustment of these parameters is essential to achieve effective muscle contraction while minimizing discomfort and fatigue.

NMES can be applied to various muscle groups depending on the patient's functional limitations. In individuals with upper limb impairment, stimulation is commonly applied to the wrist extensors, finger extensors, deltoid, and shoulder stabilizers to improve reaching, grasping, and upper extremity function. For lower limb rehabilitation, muscles such as the tibialis anterior, quadriceps, hamstrings, and gluteal muscles are frequently targeted to improve gait, balance, standing ability, and functional mobility. Stimulation of the tibialis anterior is particularly effective in managing foot drop during walking and is often incorporated into gait training programs.

The effectiveness of NMES depends on appropriate patient selection and integration with active rehabilitation. Individuals with residual motor pathways, preserved peripheral nerve function, and the ability to participate in rehabilitation generally demonstrate better outcomes. Conversely, factors such as severe cognitive impairment, complete lower motor neuron lesions, uncontrolled epilepsy, cardiac pacemakers (unless medically cleared), active malignancy at the treatment site, open wounds, or impaired skin integrity may limit the safe application of NMES.

Current evidence suggests that NMES is most beneficial when initiated early after stroke, during the period of enhanced neuroplasticity. However, research has also demonstrated meaningful improvements in muscle strength, motor function, gait performance, and functional independence in individuals with chronic stroke. These findings indicate that the nervous system retains the capacity for adaptation even in later stages of recovery when rehabilitation is intensive, repetitive, and task-oriented.

Overall, NMES represents a scientifically supported rehabilitation modality that combines muscle activation with enhanced sensory feedback to facilitate motor recovery after stroke. By improving neuromuscular activation, promoting cortical reorganization, and supporting functional movement, NMES serves as an effective adjunct to conventional physiotherapy. As rehabilitation technology continues to advance, its integration with robotics, virtual reality, wearable devices, and brain-computer interface systems is expected to further enhance its role in evidence-based stroke rehabilitation.

CLINICAL APPLICATIONS OF NEUROMUSCULAR ELECTRICAL STIMULATION IN STROKE REHABILITATION

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Neuromuscular electrical stimulation (NMES) has become an integral component of contemporary stroke rehabilitation because of its ability to address various motor impairments commonly observed after stroke. Depending on the patient's clinical presentation and rehabilitation goals, NMES can be applied to different muscle groups to improve muscle activation, voluntary movement, functional performance, and overall independence. Current evidence suggests that the greatest benefits are achieved when NMES is incorporated into individualized rehabilitation programs and combined with conventional physiotherapy and task-specific training.

UPPER LIMB REHABILITATION

Upper limb dysfunction is one of the most disabling consequences of stroke and often persists long after lower limb function has improved. Many stroke survivors experience weakness of the shoulder, elbow, wrist, and hand muscles, making everyday activities such as reaching, grasping, dressing, eating, writing, and personal hygiene difficult. Because hand function is essential for independence, improving upper limb recovery remains a major goal of stroke rehabilitation.

NMES has been widely used to facilitate muscle activation in the affected upper limb. Electrical stimulation is commonly applied to the wrist extensors, finger extensors, deltoid, biceps, triceps, and shoulder stabilizing muscles to improve voluntary movement and functional use of the arm. Repeated muscle contractions generated by NMES help strengthen weakened muscles, reduce disuse atrophy, and provide continuous sensory input that promotes cortical reorganization and motor relearning.

Several randomized controlled trials and systematic reviews have reported that combining NMES with conventional physiotherapy leads to greater improvements in upper limb motor function than conventional therapy alone. Patients receiving NMES have demonstrated better performance in reaching, grasping, object manipulation, and functional arm activities. Improvements have also been observed in clinical outcome measures such as the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), the Action Research Arm Test (ARAT), the Wolf Motor Function Test (WMFT), and the Box and Block Test (BBT). The benefits are generally more pronounced when NMES is initiated during the early stages of recovery and integrated with repetitive task-oriented practice.

LOWER LIMB REHABILITATION

Lower limb weakness following stroke contributes significantly to impaired mobility and reduced independence. Weakness of the quadriceps, hamstrings, gluteal muscles, and ankle dorsiflexors often results in difficulty standing, transferring, climbing stairs, and walking safely. These impairments increase the risk of falls and reduce participation in daily activities.

NMES is frequently applied to lower limb muscles to improve strength, muscle activation, postural stability, and functional mobility. Electrical stimulation of the quadriceps can enhance knee stability during standing and walking, while stimulation of the gluteal muscles contributes to improved pelvic stability and balance. Strengthening these muscle groups helps patients perform functional activities more efficiently and confidently.

Clinical studies have demonstrated that NMES combined with strengthening exercises and gait training can significantly

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improve lower limb motor recovery, walking ability, and functional mobility. Improvements have been reported in muscle strength, walking speed, endurance, and lower limb motor scores. Commonly used outcome measures include the Lower Extremity Fugl-Meyer Assessment (FMA-LE), Timed Up and Go (TUG) test, Six-Minute Walk Test (6MWT), Five Times Sit-to-Stand Test (FTSTS), and Functional Ambulation Category (FAC).

GAIT REHABILITATION AND MANAGEMENT OF FOOT DROP

Gait impairment is one of the most common functional limitations after stroke. Abnormal walking patterns often result from muscle weakness, impaired coordination, decreased balance, and inadequate ankle dorsiflexion during the swing phase of gait. One of the most frequently observed gait abnormalities is foot drop, which increases the risk of tripping and falls while reducing walking efficiency.

NMES has been extensively used to improve gait by stimulating the tibialis anterior muscle during the swing phase of walking. This facilitates ankle dorsiflexion, improves toe clearance, and promotes a more symmetrical gait pattern. In many rehabilitation settings, NMES is synchronized with walking to produce functional muscle activation during gait training.

Evidence from clinical trials indicates that NMES can improve walking speed, stride length, cadence, gait symmetry, and overall walking efficiency. Patients often demonstrate greater confidence while walking and reduced dependence on assistive devices. Functional improvements have been measured using the Ten-Meter Walk Test (10MWT), Six-Minute Walk Test (6MWT), Functional Gait Assessment (FGA), Dynamic Gait Index (DGI), and Functional Ambulation Category (FAC).

BALANCE AND POSTURAL CONTROL

Impaired balance is another major challenge following stroke and is closely associated with an increased risk of falls and reduced functional independence. Damage to the motor and sensory systems affects postural control, weight shifting, and coordination, making it difficult for patients to maintain stability during standing and walking.

NMES contributes to balance rehabilitation by improving activation of lower limb muscles involved in maintaining posture, including the quadriceps, gluteal muscles, and ankle musculature. Enhanced muscle strength and improved proprioceptive feedback help patients achieve better postural control and more symmetrical weight distribution.

Several studies have shown that incorporating NMES into conventional balance training leads to greater improvements in static and dynamic balance than exercise alone. Improvements are commonly assessed using the Berg Balance Scale (BBS), Functional Reach Test (FRT), Mini-BESTest, and Postural Assessment Scale for Stroke Patients (PASS). Better balance often translates into improved confidence, safer mobility, and a reduced risk of falls.

SHOULDER SUBLUXATION AND SHOULDER PAIN

Shoulder pain and glenohumeral subluxation are common complications during the early stages after stroke, particularly in individuals with severe upper limb weakness. These conditions may interfere with rehabilitation by limiting

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active movement and reducing participation in therapy.

NMES is frequently used to stimulate the supraspinatus and posterior deltoid muscles to improve shoulder stability and maintain proper alignment of the glenohumeral joint. By strengthening these muscles and enhancing neuromuscular control, NMES may help reduce shoulder subluxation, alleviate pain, and improve upper limb function.

Clinical evidence suggests that early application of NMES can reduce the severity of shoulder subluxation and improve patient comfort. Although findings regarding pain reduction are somewhat variable, many studies support its use as part of a comprehensive shoulder rehabilitation program that includes positioning, range-of-motion exercises, and functional training.

MANAGEMENT OF SPASTICITY

Spasticity is a common secondary complication following stroke and is characterized by increased muscle tone and exaggerated stretch reflexes. It can interfere with voluntary movement, reduce joint mobility, and impair functional performance.

NMES may help reduce spasticity by promoting reciprocal inhibition of overactive muscles, improving muscle activation patterns, and enhancing voluntary motor control. When combined with stretching, positioning, and active exercise, NMES has shown beneficial effects in reducing muscle stiffness and improving movement quality in selected patients. However, the degree of improvement varies among individuals, and further research is needed to establish standardized treatment protocols.

ACTIVITIES OF DAILY LIVING AND FUNCTIONAL INDEPENDENCE

The ultimate goal of stroke rehabilitation is to improve the patient's ability to perform activities of daily living independently and participate fully in family and community life. Improvements in muscle strength and motor control are clinically meaningful only if they translate into better functional performance.

By enhancing upper and lower limb function, gait, balance, and coordination, NMES contributes to greater independence in daily activities such as walking, transferring, dressing, bathing, eating, and personal care. Several clinical studies have demonstrated significant improvements in functional outcome measures, including the Modified Barthel Index (MBI), Functional Independence Measure (FIM), Barthel Index (BI), and Stroke Impact Scale (SIS), when NMES is combined with conventional rehabilitation.

Overall, current evidence supports the use of NMES as an effective adjunct to conventional physiotherapy across multiple domains of stroke rehabilitation. While the magnitude of improvement varies according to stroke severity, treatment timing, stimulation parameters, and patient characteristics, NMES consistently demonstrates positive effects on motor recovery and functional performance. Individualized treatment planning and integration with task-specific rehabilitation remain essential for achieving optimal clinical outcomes.

CURRENT EVIDENCE FROM RANDOMIZED CONTROLLED TRIALS, SYSTEMATIC REVIEWS, AND META-ANALYSES

Over the past decade, a substantial number of randomized controlled trials, systematic reviews, and meta-analyses have investigated the effectiveness of neuromuscular electrical stimulation (NMES) in stroke rehabilitation. Collectively, the available evidence suggests that NMES is a beneficial adjunct to conventional physiotherapy, particularly when incorporated into task-specific rehabilitation programs. Although the magnitude of improvement varies across studies, most research demonstrates positive effects on motor recovery, muscle strength, gait performance, balance, and functional independence.

Several randomized controlled trials have reported that the addition of NMES to conventional physiotherapy results in greater improvements in upper limb motor function compared with conventional therapy alone. Patients receiving NMES have shown significant gains in voluntary muscle activation, hand function, reaching ability, and performance of functional tasks. Improvements have commonly been reported using standardized outcome measures such as the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), and Box and Block Test (BBT). These findings suggest that repeated electrically induced muscle contractions, combined with active movement practice, facilitate motor relearning and improve upper limb function.

Evidence supporting the use of NMES for lower limb rehabilitation has also increased considerably. Clinical studies have demonstrated improvements in quadriceps strength, ankle dorsiflexion, walking speed, gait symmetry, and functional mobility following NMES interventions. Stimulation of the tibialis anterior muscle has been particularly effective in managing foot drop, improving toe clearance during the swing phase of gait, and reducing the risk of falls. Several studies have also reported improvements in walking endurance and community ambulation when NMES was integrated into gait training programs.

Balance and postural control are other important areas in which NMES has shown promising results. Improvements in static balance, dynamic balance, weight-bearing symmetry, and postural stability have been observed when electrical stimulation is combined with conventional balance exercises. Better balance contributes to increased confidence during mobility, reduced fall risk, and greater independence in daily activities.

Numerous systematic reviews have evaluated the overall effectiveness of NMES across different stages of stroke rehabilitation. Most reviews conclude that NMES provides clinically meaningful improvements in motor function, particularly when initiated during the acute or subacute phases of stroke recovery. Early intervention appears to maximize the benefits of neuroplasticity, allowing repeated muscle activation and sensory stimulation to promote cortical reorganization. Nevertheless, evidence also indicates that individuals with chronic stroke can achieve functional improvements when NMES is incorporated into intensive rehabilitation programs.

Meta-analyses published in recent years generally support the positive role of NMES in improving motor recovery, muscle strength, gait performance, and activities of daily living. These studies report small to moderate effect sizes for several functional outcomes, with the greatest benefits observed when NMES is combined with task-oriented exercises rather than being used as a stand-alone intervention. The findings reinforce the concept that electrical stimulation should complement active rehabilitation instead of replacing conventional physiotherapy.

Despite these encouraging results, the available literature demonstrates considerable heterogeneity among studies. Differences in participant characteristics, stroke severity, time since stroke onset, stimulation parameters, treatment duration, frequency of intervention, electrode placement, and outcome measures make direct comparison difficult. In addition, variations in methodological quality, sample size, and follow-up periods contribute to inconsistent findings across individual studies. These factors partly explain why some clinical trials report greater benefits than others.

Another important consideration is patient selection. Current evidence suggests that individuals with preserved peripheral nerve function, residual voluntary movement, and the ability to actively participate in rehabilitation tend to achieve better outcomes with NMES. Patients receiving early, intensive, and individualized rehabilitation programs also appear to experience greater functional improvements than those receiving delayed or less intensive interventions.

Recent research has increasingly focused on combining NMES with other rehabilitation technologies to enhance treatment effectiveness. Hybrid interventions involving robotic-assisted therapy, functional electrical stimulation (FES), virtual reality, mirror therapy, brain-computer interface systems, wearable sensors, and telerehabilitation have demonstrated encouraging results in improving patient engagement and functional recovery. These integrated approaches may represent the future direction of stroke rehabilitation by providing more personalized and task-specific treatment.

Overall, the current body of evidence supports the use of NMES as a safe, effective, and evidence-based adjunct to conventional physiotherapy for individuals with stroke. While further high-quality research is needed to establish standardized treatment protocols and identify the most effective stimulation parameters, existing literature consistently indicates that NMES can contribute to meaningful improvements in motor recovery, mobility, and functional independence. Continued advances in rehabilitation technology and individualized treatment approaches are expected to further expand the role of NMES in evidence-based stroke rehabilitation.

ADVANTAGES AND LIMITATIONS OF NEUROMUSCULAR ELECTRICAL STIMULATION

Neuromuscular electrical stimulation (NMES) has become an important adjunct in stroke rehabilitation because of its ability to enhance conventional physiotherapy and improve motor recovery. Over the years, increasing clinical evidence has supported its use in managing upper and lower limb impairments, gait abnormalities, muscle weakness, and functional limitations following stroke. Despite its numerous benefits, NMES also has certain limitations that should be considered when planning individualized rehabilitation programs.

One of the major advantages of NMES is its ability to activate paretic muscles in patients who have limited or no voluntary muscle contraction. By producing repeated muscle contractions, NMES helps maintain muscle mass, improve muscle strength, reduce disuse atrophy, and prevent secondary complications associated with prolonged inactivity. This is particularly beneficial during the early stages of stroke rehabilitation when voluntary movement is often severely impaired.

Another important benefit of NMES is its role in promoting neuroplasticity. Repeated electrical stimulation provides continuous sensory input to the central nervous system, enhancing afferent feedback and facilitating cortical reorganization. When NMES is combined with voluntary effort and task-specific exercises, it reinforces motor learning and improves neuromuscular control. This combined approach allows patients to practice functional movements more effectively, ultimately contributing to improved motor recovery.

NMES is also a non-invasive and relatively safe intervention when applied appropriately. Surface electrodes are easy to use, treatment can be individualized according to the patient's needs, and adverse effects are generally mild and uncommon. Most patients tolerate NMES well, making it suitable for use in both inpatient and outpatient rehabilitation settings. In recent years, portable and wearable NMES devices have further increased accessibility by allowing selected patients to continue rehabilitation in home-based environments under professional guidance.

Another advantage is the versatility of NMES. It can be incorporated into various rehabilitation programs targeting upper limb function, lower limb strengthening, gait training, balance rehabilitation, shoulder stabilization, and functional task practice. It can also be combined with other evidence-based interventions such as robotic-assisted therapy, virtual reality, mirror therapy, treadmill training, and task-oriented exercises to maximize rehabilitation outcomes.

Despite these advantages, NMES is not without limitations. One of the primary challenges is the lack of standardized treatment protocols. Considerable variation exists among published studies regarding stimulation frequency, pulse duration, intensity, electrode placement, treatment duration, and session frequency. This heterogeneity makes it difficult to determine the optimal treatment parameters and limits direct comparison between clinical studies.

Patient selection is another important consideration. Not all stroke survivors respond equally to NMES. Individuals with severe cognitive impairment, complete peripheral nerve injury, advanced muscle contractures, or significant sensory loss may experience limited benefits. The effectiveness of NMES also depends on factors such as stroke severity, lesion location, time since stroke onset, patient motivation, and adherence to rehabilitation.

Some patients may experience discomfort during electrical stimulation, particularly when higher intensities are required to achieve effective muscle contractions. Mild skin irritation, redness, or electrode-related discomfort may occur, although these effects are usually temporary and resolve after treatment. Proper electrode placement, gradual adjustment of stimulation intensity, and regular skin assessment help minimize these problems.

There are also several contraindications and precautions associated with NMES. It should be used cautiously or avoided in individuals with cardiac pacemakers or implantable electronic devices unless medical clearance has been obtained. Stimulation should not be applied over areas of active malignancy, thrombosis, open wounds, infected skin, or regions with severely impaired sensation. Careful clinical assessment is therefore essential before initiating treatment.

Although numerous studies support the effectiveness of NMES, the overall quality of evidence remains variable. Many clinical trials have relatively small sample sizes, short intervention periods, and limited long-term follow-up. Differences in study design and outcome measures further contribute to inconsistent findings. Consequently, additional high-quality multicenter randomized controlled trials are required to establish standardized clinical guidelines and identify the patient

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populations most likely to benefit from NMES.

From a practical perspective, successful implementation of NMES also requires adequate clinician training and patient education. Physiotherapists must have a thorough understanding of stimulation parameters, electrode placement, treatment progression, and safety precautions to ensure effective and appropriate application. Educating patients about the purpose of NMES, expected outcomes, and the importance of active participation can improve treatment adherence and maximize rehabilitation benefits.

In summary, NMES offers several advantages as an adjunct to conventional stroke rehabilitation, including improved muscle activation, enhanced neuroplasticity, better motor recovery, and increased functional independence. However, its effectiveness depends on appropriate patient selection, individualized treatment planning, correct application techniques, and integration with comprehensive physiotherapy programs. Recognizing both the strengths and limitations of NMES enables clinicians to make evidence-based decisions and optimize rehabilitation outcomes for individuals recovering from stroke.

FUTURE DIRECTIONS

Stroke rehabilitation continues to evolve with rapid advancements in rehabilitation technology, neuroscience, and digital health. Although neuromuscular electrical stimulation (NMES) has already established its role as an effective adjunct to conventional physiotherapy, ongoing research is focused on improving its clinical effectiveness, accessibility, and long-term outcomes. Future developments are expected to refine treatment protocols, personalize rehabilitation programs, and integrate NMES with emerging technologies to maximize functional recovery after stroke.

One of the major areas of future research is the development of standardized NMES protocols. Current studies use a wide variety of stimulation parameters, including differences in frequency, pulse duration, intensity, electrode placement, treatment duration, and session frequency. This variability makes it difficult to compare results across studies and to establish clear clinical guidelines. Future multicenter randomized controlled trials should aim to identify the most effective stimulation parameters for different stages of stroke recovery and various levels of motor impairment.

Personalized rehabilitation is another promising direction. Stroke survivors present with diverse clinical characteristics, including differences in age, stroke severity, lesion location, functional deficits, and recovery potential. Rather than applying a single treatment approach to all patients, future rehabilitation programs are likely to use individualized NMES protocols based on each patient's neurological status, rehabilitation goals, and functional abilities. Such personalized treatment strategies may improve patient outcomes while making rehabilitation more efficient.

Technological innovations are also expanding the clinical applications of NMES. Wearable and wireless stimulation devices are becoming increasingly available, allowing patients to continue rehabilitation outside the hospital or rehabilitation center. These portable systems have the potential to increase treatment intensity, improve patient compliance, and support long-term rehabilitation in home-based settings. As telehealth services continue to grow, integrating NMES with telerehabilitation may improve access to physiotherapy, particularly for individuals living in rural or underserved areas.

The integration of NMES with robotic-assisted rehabilitation represents another important advancement in neurorehabilitation. Robotic devices provide repetitive, task-specific movements that complement the muscle activation produced by NMES. Combining these technologies may enhance motor learning, improve movement quality, and increase patient participation during therapy sessions. Several recent studies have reported encouraging results, although additional research is needed to determine the most effective methods for combining these interventions.

Another emerging area is the use of brain–computer interface (BCI) technology in combination with NMES. BCI systems detect signals generated by the brain during movement intention and use these signals to trigger electrical stimulation of the affected muscles. This synchronized activation strengthens the connection between motor intention and muscle contraction, potentially enhancing cortical reorganization and promoting more effective motor recovery. Although this technology is still developing, it represents an exciting direction for future stroke rehabilitation.

Artificial intelligence (AI) and machine learning are also expected to influence the future of NMES. Intelligent rehabilitation systems may analyze patient performance in real time, automatically adjust stimulation parameters, monitor progress, and provide individualized treatment recommendations. Such adaptive systems could improve treatment precision while reducing the workload of healthcare professionals. Although these technologies are currently in the early stages of clinical application, they hold considerable promise for improving rehabilitation outcomes.

Virtual reality (VR) and augmented reality (AR) are increasingly being combined with NMES to create engaging and interactive rehabilitation environments. These technologies encourage patients to actively participate in meaningful functional tasks while receiving electrical stimulation. Increased motivation, greater treatment intensity, and immediate visual feedback may further enhance motor learning and improve adherence to rehabilitation programs.

Future clinical research should also focus on long-term outcomes. Many existing studies evaluate improvements immediately after treatment, while relatively few investigate whether these benefits are maintained over several months or years. Long-term follow-up studies are essential to determine the durability of functional improvements and to identify the most effective maintenance strategies for stroke survivors.

In addition, future studies should include larger and more diverse patient populations. Many currently available clinical trials involve relatively small sample sizes, limiting the generalizability of their findings. Multicenter studies involving participants from different geographical regions, healthcare settings, and stages of stroke recovery would provide stronger evidence to guide clinical practice.

Cost-effectiveness is another important area for future investigation. Although NMES has demonstrated positive clinical outcomes, limited information is available regarding its economic impact. Evaluating the cost-effectiveness of NMES in relation to improved functional independence, reduced caregiver burden, shorter rehabilitation duration, and enhanced quality of life will help policymakers and healthcare organizations make informed decisions regarding its wider implementation.

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Overall, the future of NMES in stroke rehabilitation is highly promising. Continued advances in neuroscience, biomedical engineering, and rehabilitation technology are expected to make NMES more precise, accessible, and individualized. Future research should prioritize standardized treatment protocols, larger multicenter clinical trials, long-term follow-up, and integration with emerging technologies such as robotics, brain–computer interfaces, artificial intelligence, and telerehabilitation. These developments have the potential to further strengthen the role of NMES as an essential component of evidence-based stroke rehabilitation and improve functional outcomes for individuals recovering from stroke.

CONCLUSION

Stroke remains one of the leading causes of long-term disability worldwide, and effective rehabilitation is essential for improving functional independence and quality of life among stroke survivors. Although conventional physiotherapy continues to be the cornerstone of stroke rehabilitation, the growing body of evidence suggests that adjunctive interventions such as neuromuscular electrical stimulation (NMES) can further enhance motor recovery and functional outcomes when incorporated into comprehensive rehabilitation programs.

The literature reviewed in this article indicates that NMES has beneficial effects on upper and lower limb motor function, muscle strength, gait performance, balance, and activities of daily living. These improvements are primarily attributed to enhanced muscle activation, increased sensory feedback, and the promotion of neuroplasticity, which together facilitate motor relearning and functional recovery. Current evidence also suggests that the effectiveness of NMES is greatest when it is initiated early after stroke, combined with task-specific training, and delivered as part of an individualized physiotherapy program. Nevertheless, meaningful improvements have also been reported in individuals with chronic stroke, highlighting the continued potential for recovery even in the later stages of rehabilitation.

Despite these encouraging findings, several challenges remain. Variations in stimulation parameters, treatment duration, patient characteristics, and outcome measures have resulted in considerable heterogeneity across clinical studies. Furthermore, many published trials include relatively small sample sizes and limited long-term follow-up, making it difficult to establish standardized clinical protocols. Additional high-quality multicenter randomized controlled trials are therefore needed to determine the optimal stimulation parameters, identify patient populations most likely to benefit, and evaluate the long-term effectiveness and cost-effectiveness of NMES.

Recent advances in rehabilitation technology, including wearable stimulation devices, robotic-assisted therapy, virtual reality, brain–computer interfaces, artificial intelligence, and telerehabilitation, have expanded the potential applications of NMES and opened new opportunities for delivering personalized and accessible stroke rehabilitation. The integration of these technologies with conventional physiotherapy may further improve patient engagement, treatment intensity, and functional recovery.

In conclusion, NMES represents a safe, practical, and evidence-based adjunct to conventional physiotherapy in stroke rehabilitation. While it should not be considered a replacement for established rehabilitation approaches, its integration into individualized, task-oriented rehabilitation programs can significantly enhance motor recovery and functional independence. As research continues to evolve and rehabilitation technologies advance, NMES is expected to play an increasingly important role in evidence-based neurorehabilitation, contributing to improved clinical outcomes and a better quality of life for individuals recovering from stroke.

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