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STIMEL-03 WHITE PAPER SERIES

White Paper 1

Functional Electrical Stimulation and Motor Relearning After Stroke

Mechanisms and Clinical Outcomes

Abstract

Stroke rehabilitation faces a fundamental physiological barrier. Many patients cannot generate sufficient voluntary muscle activation to perform the repetitions required for effective neuroplastic recovery. When voluntary activation is weak, therapy intensity decreases and motor relearning slows.

Functional Electrical Stimulation (FES) provides a method for restoring movement by activating peripheral motor nerves and producing muscle contractions that mimic voluntary action. Traditional stimulation systems, however, operate independently of patient intent and therefore do not fully reinforce the neural relationship between motor command and movement.

Emerging neuromuscular rehabilitation approaches integrate electrical stimulation with physiological feedback signals such as electromyography (EMG). These closed-loop systems detect voluntary motor intent and synchronize stimulation with patient effort. By linking neural intention with assisted movement, this approach reinforces motor pathways and supports neuroplastic adaptation.

Closed-loop EMG-triggered stimulation has been shown to improve functional recovery and upper-limb motor performance compared with passive stimulation approaches in stroke rehabilitation settings [4-6].

The Stimel-03 system integrates Functional Electrical Stimulation, Neuromuscular Electrical Stimulation, and real-time EMG biofeedback within a single rehabilitation platform. By synchronizing stimulation with voluntary effort, the system strengthens the relationship between neural intent and muscle activation.

This white paper reviews the physiological foundations of Functional Electrical Stimulation in stroke rehabilitation, explains the mechanisms through which stimulation supports motor relearning, and describes how EMG-guided systems such as Stimel-03 contribute to modern neuromuscular rehabilitation strategies.

Clinical Problem in Stroke Rehabilitation

Stroke rehabilitation is often limited by a fundamental challenge: many patients cannot generate sufficient voluntary muscle activation to perform the repetitions required for effective motor relearning. Conventional therapy depends on active participation, yet weak neural signals frequently fail to produce meaningful muscle contractions during the early and subacute stages of recovery.

As a result, therapy intensity is reduced, functional movements cannot be practiced effectively, and the reinforcement of neural pathways required for neuroplastic recovery becomes limited.

Technologies that can assist movement while simultaneously reinforcing voluntary motor intent offer a potential solution to this limitation.

Stroke and Motor Impairment

Stroke disrupts neural pathways responsible for voluntary motor control. Damage to cortical and subcortical motor networks often results in weakness, paralysis, abnormal muscle tone, and impaired coordination. Many stroke survivors develop hemiparesis or hemiplegia that significantly limits upper or lower limb function [1].

Recovery following stroke depends largely on neuroplasticity, the ability of the brain to reorganize neural circuits and recruit alternative motor pathways. Repeated activation of motor networks strengthens emerging neural connections and supports the gradual restoration of voluntary movement [2].

Rehabilitation programs therefore emphasize repetitive, task-specific training. However, early after stroke many patients cannot generate sufficient muscle activation to participate effectively in active therapy. Weak neural signals fail to produce meaningful muscle contractions, limiting the intensity and effectiveness of rehabilitation exercises.

Electrical stimulation provides a mechanism for overcoming this limitation by artificially activating peripheral motor nerves and enabling functional muscle contractions even when voluntary control is limited [3].

Mechanisms of FES-Driven Motor Relearning

Functional Electrical Stimulation activates motor nerves using controlled electrical pulses delivered through surface electrodes. These pulses depolarize peripheral motor neurons and trigger muscle contractions similar to voluntary activation [3].

Several mechanisms explain how FES supports neurological recovery.

- First, stimulation increases the number of effective movement repetitions during therapy. By enabling movement even when voluntary activation is weak, patients can perform more functional repetitions during rehabilitation sessions [3].
- Second, stimulation enhances sensory feedback. Muscle contractions activate proprioceptive receptors that transmit afferent signals back to the central nervous system. These signals reinforce motor pathways and contribute to cortical reorganization [2].
- Third, stimulation supports associative learning. When electrical stimulation is synchronized with voluntary effort, the pairing of neural intent and successful movement strengthens the neural circuits responsible for motor control [6].
- Finally, repeated stimulation helps maintain muscle physiology. Muscles that remain inactive after stroke rapidly lose strength and endurance. Electrical stimulation preserves muscle mass and prevents disuse atrophy, ensuring that muscles remain capable of responding to voluntary neural signals during recovery [3].

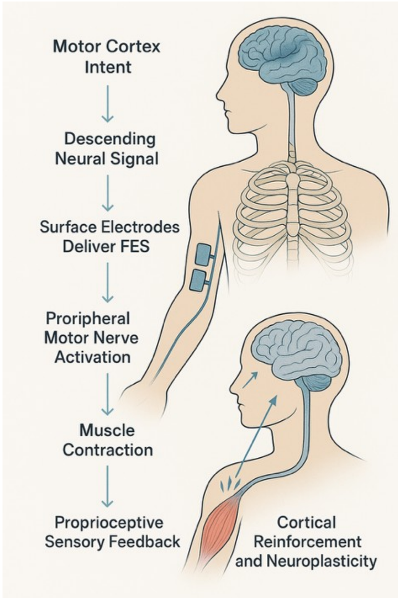


Figure 1. Functional Electrical Stimulation Mechanism Loop *This figure illustrates the physiological loop underlying Functional Electrical Stimulation. Electrical stimulation activates peripheral motor nerves, producing muscle contraction and generating proprioceptive feedback that reinforces neural pathways involved in motor control.*

Closed-loop neuromuscular rehabilitation extends the principles of Functional Electrical Stimulation by synchronizing stimulation with voluntary motor intent. Rather than delivering stimulation passively, these systems detect physiological signals associated with patient effort and trigger stimulation only when voluntary activation is attempted. This synchronization strengthens the temporal relationship between neural intent and muscle contraction, reinforcing associative motor learning and supporting more effective neuroplastic adaptation.

Closed-Loop EMG-Guided Rehabilitation

Traditional electrical stimulation systems deliver stimulation according to predefined programs without considering patient effort. While these systems can strengthen muscles, they do not directly reinforce voluntary motor intent.

Modern neuromuscular rehabilitation systems incorporate electromyographic monitoring. Surface EMG sensors detect electrical signals generated when a patient attempts to activate a muscle. Even weak voluntary signals can be identified and used to trigger therapeutic stimulation [6].

When stimulation is triggered by voluntary EMG activity, rehabilitation becomes a closed-loop process. The patient attempts a movement, the EMG signal confirms the attempt, and electrical stimulation assists the intended movement.

This timing-dependent pairing between neural intent and assisted muscle contraction is believed to strengthen sensorimotor integration and enhance cortical reorganization during rehabilitation.

This synchronization links cortical motor commands with peripheral muscle activation. Over repeated therapy sessions, this association strengthens neural pathways responsible for voluntary movement and contributes to motor relearning.

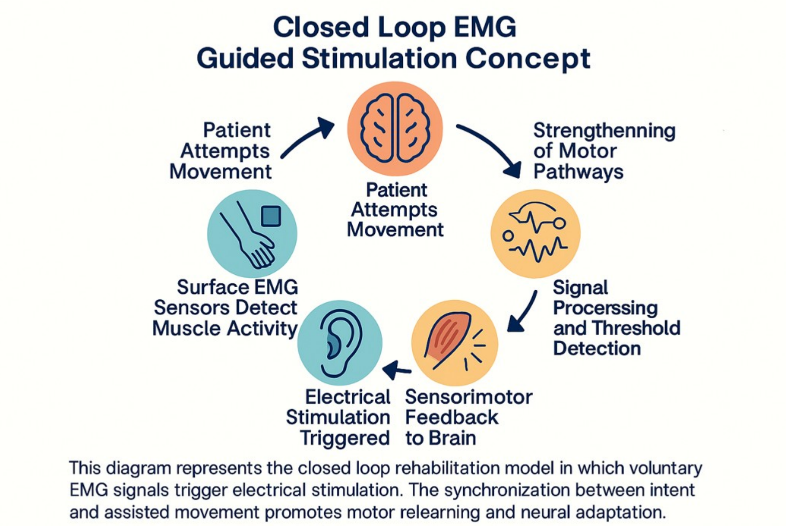


Figure 2. Closed-Loop EMG-Guided Stimulation *This diagram illustrates the closed-loop rehabilitation model in which voluntary EMG signals trigger electrical stimulation. Synchronization between motor intent and assisted movement reinforces neural pathways involved in motor control.*

Key Differentiators of Stimel-03

Stimel-03 integrates stimulation, EMG monitoring, and biofeedback within a single neuromuscular rehabilitation platform. This integration allows stimulation to be synchronized with voluntary motor intent during therapy.

- Hybrid EMG and stimulation architecture enables the system to detect voluntary muscle activity and deliver stimulation using the same electrode interface.
- BioRhythmIQ signal processing. The system is built on the BioRhythmIQ principle, enabling detection of extremely weak neuromuscular signals so therapy can begin even when voluntary contraction is minimal.
- Unified electrode architecture. The same electrode interface can be used for both EMG detection and stimulation delivery, simplifying setup and improving clinical workflow.
- Real-time voluntary effort visualization allows patients to observe their EMG activity and actively participate in therapy by increasing voluntary activation.
- Adaptive threshold detection allows the system to identify small EMG signals and trigger stimulation once voluntary effort exceeds predefined thresholds.
- Multi-channel coordinated stimulation enables clinicians to activate multiple muscle groups to support functional movement patterns.
- Flexible clinical programming allows therapists to adjust stimulation parameters including frequency, amplitude, and timing to match individual rehabilitation needs.

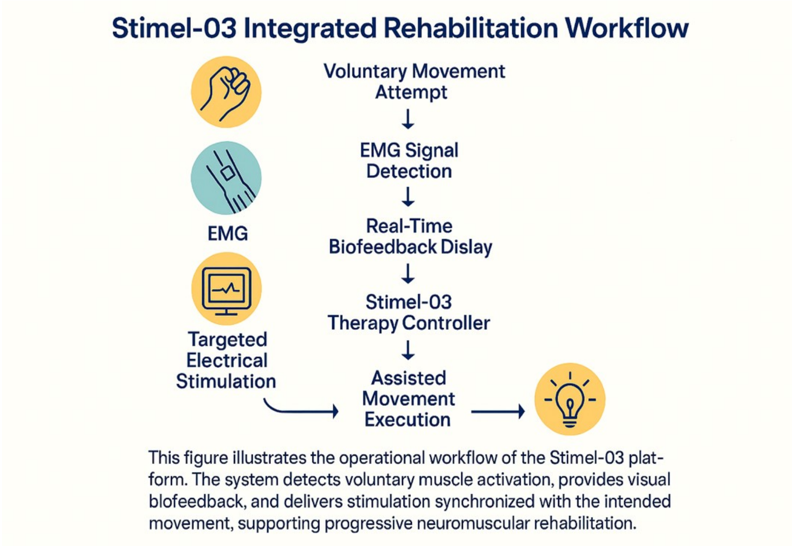


Figure 3. Stimel-03 Rehabilitation Workflow *This figure illustrates the operational workflow of the Stimel-03 system. The platform detects voluntary EMG activity, provides visual biofeedback, and delivers stimulation synchronized with patient intent.*

Clinical Applications in Stroke Rehabilitation

Functional Electrical Stimulation is widely used to address several common motor impairments following stroke. When integrated with EMG-guided rehabilitation platforms such as Stimel-03, stimulation can be synchronized with patient effort, allowing therapy to reinforce voluntary motor intent while assisting functional movement.

In upper limb rehabilitation, therapy often focuses on restoring wrist extension, finger opening, and coordinated grasping. Stimel-03 can assist these movements during occupational therapy exercises by detecting voluntary activation attempts in the forearm muscles and delivering stimulation that supports hand opening and wrist stabilization. This approach allows patients with weak voluntary control to perform task-oriented training such as reaching, grasping, and object manipulation.

Lower limb rehabilitation frequently targets ankle dorsiflexion and knee extension, movements essential for safe walking and gait training. During therapy sessions, Stimel-03 can activate the appropriate muscle groups in response to voluntary activation signals, supporting more stable stepping patterns and improving foot clearance during walking exercises.

Electrical stimulation can also be used in the early stages of rehabilitation when voluntary muscle activation is extremely limited. In these situations, the Stimel-03 platform allows clinicians to initiate assisted muscle activation while simultaneously monitoring EMG activity. As voluntary signals improve, stimulation can be progressively synchronized with patient effort to reinforce emerging motor pathways.

Because the system integrates stimulation with real-time biofeedback, patients can observe their own muscle activity and learn to increase voluntary activation over time. This interactive rehabilitation process supports both neuromuscular strengthening and motor relearning.

By combining EMG monitoring, biofeedback, and stimulation in a single platform, Stimel-03 enables clinicians to implement closed-loop neuromuscular rehabilitation strategies that support progressive functional recovery after stroke.

Clinical Scenarios

Clinical Scenario 1

A subacute stroke patient with weak wrist extension attempts to open the hand during therapy. EMG sensors detect voluntary activation in the forearm muscles. When the activation exceeds the stimulation threshold, the Stimel-03 system delivers stimulation that assists wrist and finger extension. Over repeated sessions the patient learns to generate stronger voluntary activation, gradually improving independent hand function.

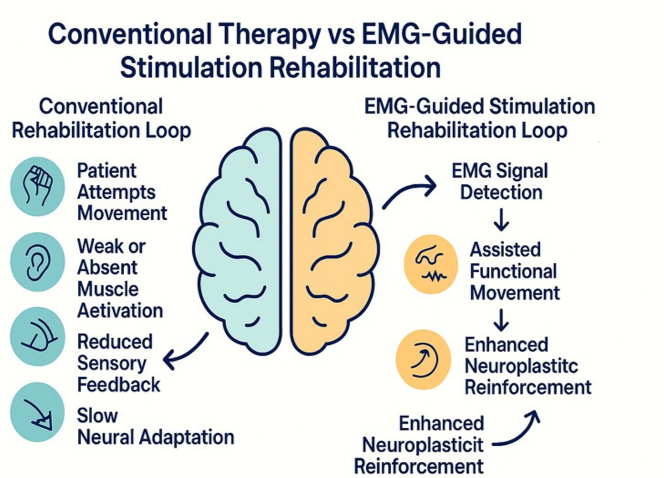
Clinical Scenario 2

A chronic stroke patient with impaired ankle dorsiflexion attempts to lift the foot during gait training. EMG-triggered stimulation activates the tibialis anterior muscle during the swing phase of walking. This synchronized activation improves step clearance and reinforces correct motor timing.

Clinical Impact and Rehabilitation Efficiency

The integration of electrical stimulation into rehabilitation programs increases therapy intensity and patient engagement. Patients receiving stimulation-assisted therapy often perform more repetitions of functional movements during therapy sessions [4].

Earlier activation of weak muscles also allows patients to begin functional training sooner after stroke. This accelerates the transition from passive therapy to active motor rehabilitation. Repeated pairing of voluntary motor intent with successful movement strengthens neural pathways and supports progressive recovery of motor function [5].



This comparison illustrates dif ference between conventional rehabilitation and EMG-guided stimulation therapy. In conventional therapy, weak voluntary activati-on may not generate sufficient movement to reinforce neural pathways, support-

Figure 4. Conventional Rehabilitation vs EMG-Guided Stimulation This figure compares conventional rehabilitation with EMG-guided stimulation therapy. In conventional therapy weak voluntary signals may fail to produce sufficient movement to reinforce neural pathways. In EMG-guided rehabilitation stimulation assists the intended movement, generating stronger sensory feedback and supporting faster motor relearning.

Key Takeaways for Clinicians

- Functional Electrical Stimulation enables early activation of weak muscles after stroke.
- Synchronization of stimulation with voluntary motor intent reinforces neural pathways responsible for movement.
- Closed-loop EMG-guided systems link cortical commands with peripheral muscle activation.
- Increased sensory feedback supports neuroplastic adaptation and motor relearning.
- Integration of stimulation and biofeedback increases therapy engagement and repetition intensity.
- Systems such as Stimel-03 support individualized neuromuscular rehabilitation programs.

Conclusion

The demand for effective stroke rehabilitation continues to grow as healthcare systems face increasing numbers of stroke survivors requiring long-term motor recovery.

Technologies that synchronize therapy with patient intent represent an important evolution in rehabilitation practice. Closed-loop neuromuscular stimulation enables earlier activation of impaired muscles, increased therapy intensity, and stronger reinforcement of neural pathways.

Systems such as Stimel-03 integrate electrical stimulation and physiological feedback to create an adaptive rehabilitation environment that supports progressive motor relearning.

As rehabilitation increasingly shifts toward personalized and home-supported therapy models, intention-synchronized neuromuscular stimulation is likely to become an essential component of modern neurorehabilitation.

References

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