

Closed Loop Neuromodulation in Neurological Rehabilitation: Movement-Paired Vagus Nerve and Spinal Cord Stimulation for Motor Recovery

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Abstract: Neurological physiotherapy is increasingly incorporating neuromodulation technologies that aim to enhance activity-dependent neuroplasticity and functional recovery. A recent advancement is the transition from conventional open-loop stimulation toward closed-loop neuromodulation, in which stimulation is temporally linked to voluntary movement, muscle activity, gait events, or neural activity. Movement-paired vagus nerve stimulation (VNS) and transcutaneous spinal cord stimulation (tSCS) represent two emerging approaches with potential applications in neurological rehabilitation. Clinical trials have demonstrated that VNS paired with upper-limb rehabilitation can improve motor impairment after chronic stroke, while recent research has extended this concept toward non-invasive transcutaneous auricular VNS (taVNS), wearable movement-triggered systems, and brain-computer-interface-synchronized stimulation. Similarly, tSCS combined with gait training has shown promising effects on walking-related outcomes, although substantial heterogeneity exists in stimulation parameters and treatment protocols. More recently, electromyography (EMG)-triggered spinal stimulation has introduced a physiological feedback mechanism for timing stimulation during gait. This mini-review discusses the neurophysiological rationale, current evidence, clinical applications, limitations, and future directions of movement-paired VNS and spinal stimulation, with particular emphasis on their integration into neurological physiotherapy.

Keywords: Closed-Loop Neuromodulation; Vagus Nerve Stimulation; Transcutaneous Auricular Vagus Nerve Stimulation; Transcutaneous Spinal Cord Stimulation; Stroke; Neurorehabilitation; Neuroplasticity; Motor Recovery; Neurological Physiotherapy

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Stroke remains a major cause of long-term neurological disability, with persistent impairments in motor control, strength, coordination, gait, balance, and upper-limb function affecting independence and participation. Conventional neurological physiotherapy emphasizes task-specific training, repetitive practice, progressive challenge, motor learning, and functional activity. However, recovery may remain incomplete in individuals with substantial neurological injury, creating interest in interventions capable of modifying neural excitability and enhancing the effects of rehabilitation. Neuromodulation

refers to the modification of nervous-system activity through electrical, magnetic, or other forms of stimulation. Vagus nerve stimulation (VNS), transcutaneous spinal cord stimulation (tSCS), transcranial stimulation, and functional electrical stimulation have all been investigated as adjuncts to neurological rehabilitation. The rationale is that modulation of neural excitability may facilitate the neural processes required for motor learning and recovery.^[1,6]

An important recent development is the transition from open-loop toward closed-loop neuromodulation. In open-loop systems, stimulation is delivered according to predetermined parameters and timing. In a closed-loop system, stimulation is triggered or modified according to information obtained from the patient, such as movement, electromyographic activity, gait events, or neural activity. This creates a temporal relationship between the patient's rehabilitation behavior and neuromodulatory input.^[9] The concept is particularly relevant to physiotherapy because the stimulation can be incorporated directly into active, task-specific rehabilitation rather than being administered independently of functional movement.

1. Concept of Closed-Loop Neuromodulation

Different biological signals can be used to control stimulation. Inertial measurement units (IMUs) can detect movement, EMG can identify muscle activation, gait sensors can identify specific phases of walking, and electroencephalography (EEG) can detect neural activity associated with motor intention.^[4,5,8] This approach differs from simply combining neuromodulation with exercise. In a conventional intervention, stimulation may be delivered during a rehabilitation session but without being controlled by the patient's real-time physiological activity. In a true closed-loop approach, the patient's activity becomes part of the control system. A recent example is SmartVNS, a wearable system that uses a wrist-worn IMU to automatically detect functional upper-limb movements and trigger transcutaneous auricular VNS. In a four-week feasibility study involving nine individuals with stroke or spinal cord injury, the system demonstrated the technical feasibility of automatically delivering movement-paired stimulation during conventional therapy.^[4]

2. Neurophysiological Rationale

The rationale for movement-paired neuromodulation is closely related to activity-dependent neuroplasticity. Motor learning depends on repeated activation of neural networks associated with a specific task. Neuromodulation may potentially enhance the neural response to appropriately timed movement and thereby reinforce the networks involved in motor learning.^[1,2] VNS provides one approach to this concept. Vagal afferent stimulation can influence brainstem neuromodulatory systems, including noradrenergic and cholinergic pathways, which are involved in cortical plasticity and learning. The therapeutic concept is therefore not simply to stimulate the vagus nerve but to pair stimulation with successful motor behavior.^[1,2] Spinal stimulation is based on a different physiological mechanism. tSCS may alter spinal excitability and facilitate the activation of residual descending and spinal motor pathways. When stimulation is combined with gait training, the neuromodulatory input occurs within the context of active motor practice.^[6,7]

However, the precise neurophysiological mechanisms underlying clinical recovery remain incompletely established, and physiological changes should not automatically be interpreted as evidence of clinically meaningful functional improvement.

3. Movement-Paired Vagus Nerve Stimulation

3.1 VNS Paired with Upper-Limb Rehabilitation

The most established clinical evidence for movement-paired neuromodulation comes from VNS combined with upper-limb rehabilitation after chronic stroke.

The VNS-REHAB trial was a randomized, blinded, sham-controlled pivotal trial involving 108 individuals with chronic ischemic stroke and moderate-to-severe upper-limb impairment. Participants received intensive upper-limb rehabilitation paired with either active VNS or sham stimulation. The active VNS group demonstrated greater improvement in Fugl-Meyer Assessment-Upper Extremity scores than the control group, supporting the therapeutic concept of pairing neuromodulation with task-specific rehabilitation.^[11] Longer-term follow-up subsequently reported sustained improvements in upper-limb impairment, activity, participation, and quality-of-life measures at one year.^[13] However, the long-term analysis was not equivalent to a continuously controlled one-year randomized comparison, and therefore should be interpreted accordingly.^[2]

These findings provide an important foundation for closed-loop rehabilitation: neuromodulation appears most clinically

relevant when it is integrated with meaningful motor practice rather than treated as an isolated stimulation intervention.

3.2 Importance of Rehabilitation Dose

An important consideration is that neuromodulation does not eliminate the need for intensive rehabilitation. Analysis of the VNS-REHAB dataset suggested that rehabilitation dosage and stimulation-related factors contributed to upper-limb outcomes, particularly distal motor recovery.^[3] The physiotherapist therefore remains responsible for selecting and progressing the therapeutic task, while neuromodulation potentially enhances the physiological environment in which motor learning occurs.

3.3 Transcutaneous Auricular Vagus Nerve Stimulation

Implanted VNS requires surgical implantation, whereas transcutaneous auricular VNS provides a non-invasive method of stimulating auricular branches associated with the vagus nerve. Recent evidence has expanded considerably.^[12] A 2026 systematic review and meta-analysis included 16 randomized controlled studies involving 708 individuals with stroke. taVNS combined with exercise training was associated with significant improvements in upper-limb motor outcomes, including Fugl-Meyer Assessment–Upper Extremity, Wolf Motor Function Test, and Action Research Arm Test scores, as well as activities of daily living. The authors nevertheless emphasized that optimal stimulation parameters and exercise protocols remain uncertain.^[5]

This evidence supports the use of taVNS as an adjunct to exercise, but it is important to distinguish taVNS paired with exercise from true closed-loop taVNS. A study can synchronize stimulation with a rehabilitation session without actually using real-time physiological information to control stimulation. The development of wearable movement-triggered taVNS represents a more advanced form of closed-loop rehabilitation.^[10]

Lhoste et al. developed SmartVNS, which uses a wrist-worn IMU to detect functional upper-limb movements and automatically trigger taVNS. The four-week feasibility study included nine individuals with stroke or spinal cord injury undergoing conventional therapy. The movement-detection system achieved 76.3% stimulation precision and delivered stimulation during approximately twice as many detected movements as therapist manual triggering. The system was also reported to have high usability and was well tolerated.^[4] The importance of this work is not simply that a wearable VNS device was developed. Rather, it demonstrates the feasibility of making patient movement itself the trigger for neuromodulation.

4. Brain-Computer-Interface-Synchronized Neuromodulation

The next stage of closed-loop rehabilitation involves using neural activity rather than only physical movement as the control signal. BCI systems can detect changes in brain activity associated with motor imagery or attempted movement. When this signal is used to trigger neuromodulation, stimulation may occur even when actual movement is limited. Recent work has explored closed-loop taVNS synchronized with BCI-based motor training after stroke.^[9] Such systems represent a progression from movement-triggered stimulation toward neural-signal-triggered neuromodulation. However, BCI-linked neuromodulation remains an emerging field. Technical complexity, signal variability, calibration requirements, and limited clinical datasets currently restrict routine clinical implementation.

5. Transcutaneous Spinal Cord Stimulation

tSCS has emerged as another non-invasive neuromodulation approach for neurological rehabilitation. Surface electrodes are positioned over the spinal region to modulate spinal neural circuits and excitability. Research in stroke rehabilitation has predominantly investigated tSCS in combination with lower-limb and gait training. A 2026 systematic review found that cathodal transcutaneous spinal stimulation combined with gait training probably improves walking capacity, cadence, paretic lower-limb strength, and walking speed, with moderate-certainty evidence. However, effects on several secondary gait outcomes were limited or uncertain.^[6]

A 2026 scoping review identified 13 studies of tSCS in stroke rehabilitation, including five randomized and eight non-randomized studies. Sample sizes ranged from only two to 21 participants, while stimulation parameters varied substantially with respect to amplitude, frequency, carrier frequency, and pulse width. Most studies focused on lower-extremity function.^[7]

The authors consequently characterized tSCS as an exploratory adjunct and emphasized the need for adequately powered trials, standardized protocols, stratification by stroke severity and chronicity, and longer follow-up.^[7]

6. EMG-Triggered Spinal Stimulation

One of the most clinically interesting developments is the use of EMG as a real-time trigger for spinal stimulation. EMG provides information regarding the activation of specific muscles. When a predefined muscle-activation pattern is detected, the stimulation system can deliver electrical stimulation at the corresponding point in the movement cycle. Tani et al. evaluated an EMG-triggered transcutaneous spinal cord and hip stimulation system, termed FAST walk, in a randomized controlled trial involving individuals with chronic stroke. Twenty participants were randomized to FAST walk plus treadmill training, spinal stimulation plus treadmill training, or treadmill training alone, with 17 participants completing the study. There was no significant between-group difference in the primary 10-m walking-time outcome. However, the FAST walk group demonstrated significant within-group improvements after intervention and at four-week follow-up.^[8] Therefore, the findings support the feasibility and potential clinical utility of EMG-triggered stimulation but do not establish superiority over conventional treadmill training or other stimulation approaches.^[8,14,15]

This distinction is important when interpreting emerging technologies because statistically significant within-group improvement does not necessarily demonstrate that the technology itself produced an additional treatment effect.

7. Movement-Paired VNS Versus Spinal Neuromodulation

Although both approaches belong to the broader field of closed-loop neuromodulation, their physiological targets and clinical applications differ.

Table 1. Comparison of Movement-Paired Vagus Nerve Stimulation and EMG/Movement-Triggered Spinal Cord Stimulation in Neurological Rehabilitation.

Feature	Movement-paired VNS	EMG/movement-triggered spinal stimulation
Primary target	Vagal afferent pathways and associated neuromodulatory systems	Spinal neural circuits/excitability
Common rehabilitation target	Upper-limb motor recovery	Gait and lower-limb function
Trigger	Movement, therapist command, or neural signal	EMG, movement or gait event
Main clinical evidence	Chronic stroke upper-limb rehabilitation	Emerging stroke gait rehabilitation
Current maturity	Relatively more advanced clinical evidence	Early/emerging
Physiotherapy integration	Task-specific upper-limb training	Gait and task-specific lower-limb training

This comparison also highlights why “closed-loop neuromodulation” should not be treated as a single intervention. Different stimulation modalities, control signals, and rehabilitation tasks may produce different physiological and clinical effects.

The development of closed-loop neuromodulation systems does not replace neurological physiotherapy; rather, it may increase the importance of clinical decision-making because the quality, specificity, and functional relevance of the movement paired with stimulation remain critical to rehabilitation. The neurological physiotherapist plays an important role in patient selection by assessing motor impairment, residual voluntary movement, sensory status, balance, gait capacity, and individual functional goals to determine suitability for technology-assisted rehabilitation. The physiotherapist determines appropriate therapeutic tasks and identifies movements that are meaningful, achievable, and suitable for repeated practice, while progressively modifying movement difficulty through changes in resistance, speed, repetitions, environmental conditions, level of assistance, and task complexity. In addition, physiotherapists collaborate with rehabilitation engineers and other clinicians to optimize sensor placement and interpret movement or electromyographic data within the context of functional performance. Clinical outcome assessment should extend beyond device-generated physiological measures to include impairment, activity, participation, and patient-reported outcomes. Continuous clinical monitoring is also required to

identify fatigue, skin irritation, stimulation intolerance, inappropriate triggering, and changes in neurological status. Thus, as closed-loop technologies evolve, the neurological physiotherapist may increasingly function as the clinical controller of the rehabilitation task, while the neuromodulation system provides automated, physiologically synchronized stimulation.

Conclusion

Closed-loop neuromodulation represents an emerging intersection of neurological physiotherapy, neuroplasticity, wearable technology, and precision rehabilitation. Movement-paired VNS has demonstrated clinically relevant benefits for upper-limb recovery after chronic ischemic stroke, while newer studies are extending the approach toward non-invasive wearable stimulation, EMG-triggered spinal stimulation, and BCI-synchronized neuromodulation.^[1,4,5,8] The major conceptual advance is the transition from predetermined stimulation toward stimulation that is temporally coupled to the patient's own movement or physiological activity. Current evidence is promising but should be interpreted cautiously. VNS has the more mature clinical evidence base, whereas movement-triggered taVNS and EMG-triggered spinal stimulation remain emerging technologies.^[4,7,8] Large randomized trials with standardized stimulation parameters, appropriate control groups, long-term follow-up, and patient-important functional outcomes are required. For neurological physiotherapy, the future application of these technologies is unlikely to involve neuromodulation replacing conventional rehabilitation. Instead, the more plausible model is neuromodulation embedded within intensive, task-specific and individualized physiotherapy, with real-time physiological signals increasingly used to personalize treatment.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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