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The Future of Wearable Neurotechnology: A Study on Neurostimulation Suits

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Abstract: *This report provides a comprehensive literature review and comparative analysis of wearable neurotechnology, with a specific focus on neurostimulation suits. The study examines the historical trajectory of the field, analyzes the core principles and clinical applications of current devices, and critically evaluates the primary challenges to their widespread adoption. By synthesizing data from academic research, clinical trials, and industry reports, the report projects the future of the field, highlighting the transformative role of artificial intelligence, advanced materials, and closed loop systems. Key findings indicate that wearable neurostimulation is evolving from simple, open loop devices to intelligent, multi modal systems capable of delivering personalized, real time therapy. Leading examples, such as the Exopulse Mollii Suit for spasticity and the CUE Device for Parkinson's disease, demonstrate clinical efficacy, albeit with highly individualized outcomes. The analysis reveals that the most significant barriers to adoption are not solely technical, but rather economic, regulatory, and ethical. High device costs, a fragmented reimbursement landscape, and the absence of harmonized regulatory frameworks pose substantial hurdles. Furthermore, the increasing use of these technologies for human enhancement, beyond their therapeutic applications, raises profound questions concerning data privacy, equitable access, and cognitive liberty. The future of this market is poised for significant growth, driven by a convergence of AI, the Internet of Things (IoT), and continued miniaturization. For this potential to be fully realized, a concerted effort is required to address current research gaps, streamline regulatory pathways, and establish robust ethical governance*

Keywords: Closed Loop Systems, Adaptive Deep Brain Stimulation (aDBS), Neural Decoding, Multivariate Classifiers, Generative AI, Internet of Things (IoT)

I. INTRODUCTION

1.1. Defining Wearable Neurotechnology and Neurostimulation Suits

Wearable neurotechnology represents a rapidly expanding category of devices that function at the interface of the human nervous system and digital technology. The term "neurotechnologies" is formally defined as "devices and procedures used to access, monitor, investigate, assess, manipulate and/or emulate the structure and function of the neural systems of natural persons".1 A key distinction is that many wearable neurotechnologies are "direct to consumer" (DTC), meaning they can be purchased without a medical prescription or the intervention of a clinical professional. While some companies may make "para clinical claims" regarding their health benefits, these devices are, by definition, not regulated as medical devices in the same way as traditional implants. This creates a complex regulatory and ethical landscape.

Neurostimulation suits are a specialized subset of wearable neurotechnology, characterized by their full body or multi limb garment design. These suits integrate multiple electrodes, sensors, and a central control unit to deliver therapeutic electrical or mechanical stimuli to a user's body. They represent a significant advancement from single point of contact devices, such as the simple transcutaneous electrical nerve stimulation (TENS) units, and are designed for a more comprehensive and holistic effect on the nervous and muscular systems.

1.2. Scope, Objectives, and Rationale of the Study

This report serves as a qualitative literature review and comparative analysis of wearable neurostimulation suits. The study's primary objectives are to:

- Review the historical and scientific foundations of neurostimulation to provide essential context.
- Analyze the current state of technology, comparing the mechanisms and clinical applications of leading neurostimulation suits and related devices.
- Identify and discuss the technical, economic, and regulatory challenges that currently impede the widespread adoption of these technologies.
- Examine the complex ethical and societal implications of a direct to consumer neurotechnology market.
- Propose future directions and emerging trends, including the impact of artificial intelligence and new materials.

The rationale for this report is rooted in the burgeoning market for wearable neurotechnologies and the need for a nuanced, expert level document to guide strategic decisions in research and development, investment, and policy. As these devices move from niche medical applications to mainstream consumer products, a critical assessment is required to understand their true potential and the multifaceted challenges that must be overcome.

II. LITERATURE REVIEW / COMPARATIVE STUDY

2.1. The Evolution of Neurostimulation: From Ancient Practices to Modern Innovation

The concept of using electrical stimuli to modulate the body's functions is a practice with a long history, dating back nearly 2,000 years to ancient Greece. In 63 AD, Scribonius Largus documented the use of live black torpedo fish which produce an electric discharge for pain relief, a practice that highlights a rudimentary understanding of bioelectricity. The scientific exploration of this phenomenon was formalized in the 18th century. In 1746, Jean Jallabert used a Leyden jar to stimulate muscle fibers in a paralyzed limb, inducing involuntary contractions that led to muscle regeneration and increased blood flow. A few years later, in 1771, Italian physician Luigi Galvani's experiments on frog leg muscles, where he observed twitching upon electrical application, effectively launched the modern study of bioelectricity.

The modern era of neurostimulation began in the early 1960s, driven by a paradigm shift in the understanding of pain. The publication of Melzack and Wall's gate control theory of pain in 1965 was a defining event, providing a more informed framework for clinical neurostimulation. The theory suggested that pain was the result of complex dynamic processes in the nervous system rather than a simple, hard wired system, which led to a move away from destructive surgical treatments and towards reversible, modulatory therapies. This period saw the development of deep brain stimulation (DBS) and spinal cord stimulation (SCS) for intractable pain. The journey from using fish and Leyden jars to sophisticated, FDA approved devices in the late 1960s illustrates a continuous trajectory of innovation and deepening scientific understanding.

2.2. Core Principles and Mechanisms of Wearable Neurostimulation

The technology underpinning modern wearable neurostimulation is diverse, encompassing a variety of energy sources and physiological mechanisms. While the goal is consistent to modulate neural activity the means to achieve this differ significantly.

2.2.1. Electrical and Electromyographic Stimulation

Electrical stimulation remains the most common modality for neurostimulation suits. The Exopulse Mollii Suit, for instance, uses low level electrical current delivered through 58 embedded electrodes to produce a "basic tension in the musculature". Its primary mechanism of action is a process called "reciprocal inhibition". This technique involves stimulating the antagonist muscle to a spastic one, which activates inhibitory interneurons in the spinal cord, thereby reducing the excitability and spasticity of the agonist muscle. This approach is similar in principle to traditional TENS (Transcutaneous Electrical Nerve Stimulation), which is widely used for pain relief.

The fundamental principle of electrical stimulation is rooted in bioelectricity, where applied current directly influences the electrophysiology of nerve and muscle cells. The parameters of this current, such as pulse width, pulse shape, and

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frequency, are critical for determining the outcome. The Exopulse Mollii Suit, for example, operates at a fixed frequency of 20 Hz with a square pulse shape.

2.2.3. The Rise of Closed Loop and Adaptive Systems

A significant trend in modern neurotechnology is the shift from "open loop" systems, which deliver continuous or pre programmed stimulation, to "closed loop" or adaptive systems. These next generation platforms use sensors and advanced algorithms to monitor physiological or neural data in real time and dynamically adjust stimulation parameters to optimize therapeutic effect.

This evolution represents a fundamental change in the relationship between the device and the user. Earlier devices were passive delivery mechanisms, but the integration of artificial intelligence (AI) and machine learning transforms them into intelligent, personalized therapeutic agents. The Smart Neurostimulation System (SNS), for example, is a wireless, 60 channel, AI enabled brain computer interface (BCI) designed to decode brain activity and predict momentary memory lapses, triggering stimulation in real time to enhance cognitive function. Similarly, adaptive deep brain stimulation (DBS) for Parkinson's disease uses AI algorithms to detect abnormal neural patterns, such as the onset of a tremor, and then automatically adjusts stimulation strength on the fly. This ability to learn an individual's unique "neural fingerprints" allows for a level of personalized, on demand therapy that was previously impossible. The development of these systems illustrates a direct causal link between the advancement of sensor technology and AI analytics and the emergence of more sophisticated, effective, and tailored treatments.

2.3. Clinical Applications: Efficacy and Comparative Analysis

The focus of neurostimulation has expanded dramatically, moving from general pain relief to highly specialized, personalized interventions across motor and cognitive domains.

2.3.1. Case Study: The Exopulse Mollii Suit for Spasticity in MS and CP

The Exopulse Mollii Suit is a prominent example of a modern neurostimulation suit. It is an assistive medical device designed for both pediatric and adult users with neurological disorders such as cerebral palsy (CP), multiple sclerosis (MS), and stroke, who suffer from spasticity and muscle weakness.

The suit is a functional lycra garment with 58 embedded silicone rubber electrodes and a detachable control unit. The device is individually programmed for each user to target specific muscle groups and intensities, with settings saved in the control unit for simple at home use. The technical specifications include a low frequency of 20 Hz, a square pulse shape, and a pulse width of 25 175 µs.

Clinical evidence on the Exopulse Mollii Suit is mixed but promising. A study evaluating the effectiveness of a single 60 minute session found no significant effect on spasticity at a group level. However, the study noted a highly variable effect at the individual level, with some patients, particularly those with severe baseline spasticity, exhibiting reduced neural components. User reports and testimonials corroborate these findings, with some users stating that the suit "greatly reduce[s] his spasticity" and "reduces the pain a lot and makes moving and walking less exhausting". This variability underscores the need for personalized stimulation protocols and highlights a critical research gap: while the technology may be effective, understanding and predicting its effect on a given individual requires further study.

2.3.2. Applications in Motor and Cognitive Rehabilitation

The use of neurostimulation for rehabilitation extends beyond chronic pain, with a growing body of research exploring its potential to restore motor and cognitive function after neurological injury or disease.

Researchers are exploring how non invasive neuromodulation can enhance physical therapy outcomes for patients with neurological injuries. For stroke and spinal cord injury (SCI) survivors, the field is moving toward integrated systems that combine multiple technologies. A clinical trial investigates the use of a robotic orthosis, a non invasive brain computer interface (BCI), and functional electrical stimulation (FES) to improve motor function in paralyzed limbs. This system uses a BCI to decode a patient's imagined movement, triggering the robotic orthosis to move the paralyzed arm, which is then accompanied by FES to activate the muscles. This integrated approach aims to leverage the brain's plasticity

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by creating a feedback loop between intention, movement, and stimulation. The success of these therapies appears to be highly dependent on the timing and phase of recovery, suggesting that stimulation should be precisely tailored to the patient's individual state to achieve the greatest, most consistent benefit. Furthermore, neuromodulation, such as Functional Neuromuscular Electrical Stimulation (FNMES), has shown superiority over traditional rehabilitation swallowing therapy in improving motor and sensory function in the pharyngeal phase of swallowing.

2.3.3. Addressing Movement Disorders: The CUE Device for Parkinson's Disease

The CUE Device, developed by Charco Neurotech, represents a distinct approach to neurostimulation for movement disorders. It is a non invasive, wearable medical device designed to alleviate the symptoms of Parkinson's disease, including slowness, stiffness, and rigidity. Unlike the electrical stimulation of the Exopulse Mollii Suit, the CUE Device uses "pulsed cueing and high frequency focused vibrotactile stimulation" to modulate the peripheral nervous system.

Pilot tests of the device showed that users improved their MDS UPDRS scores by an average of 7.8 points, which is considered a clinically significant improvement. The device, which is the size and weight of a small pebble, is worn discreetly on the sternum and can be customized via a smartphone app that also provides symptom and medication tracking. The device is priced at £795, with subscription required for adhesive patches.

2.4. Comparative Device Matrix

Device Name	Target Condition	Core Technology	Mechanism of Action	Efficacy Metrics	Cost & Accessibility
Exopulse Mollii Suit	Spasticity (CP, MS, Stroke), Pain	Electrical Stimulation	Reciprocal Inhibition: Stimulates antagonist muscle to relax agonist muscle	Variable, with some users reporting reduced pain and spasticity. One study found no consistent group effect, but individual benefits were noted in severe cases.	High cost (~€7,000). Not approved by all insurance providers.
Charco CUE Device	Parkinson's Disease	Vibrotactile Stimulation, Cueing	Modulates the peripheral nervous system to ease stiffness and slowness.	Users improved MDS UPDRS scores by an average of 7.8 points, considered clinically significant.	Priced at £795, with subscription for patches. VAT exemption available for some users.
Teledyne PeakSleep™	Insomnia, Sleep onset Latency	Transcranial Electrical Stimulation (tES)	Repetitive electrical stimulation to enhance brainwave patterns for sleep.	Pilot trial on 23 participants showed a reduction in sleep onset latency with a large effect size (Cohen's)	Prototype, not commercially available.
TENS Units	Chronic Pain	Electrical Stimulation	Delivers low voltage electrical current to block pain signals from reaching the brain.	Effective for symptomatic relief of chronic pain; Medicare coverage available after trial.	Low cost therapy, often covered by insurance for long term use.

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Device Name	Target Condition	Core Technology	Mechanism of Action	Efficacy Metrics	Cost & Accessibility
Smart Neurostimulation System (SNS)	Memory Loss / Cognitive Enhancement	AI Enabled BCI (Wireless, 60 channel implant)	Closed loop system: Classifiers decode neural data (LFP spectral power) to predict memory lapses, triggering real time electrical stimulation.	Designed to enhance cognitive function and memory performance. Preclinical/Trial phase.	Advanced prototype/trial; high complexity hardware (Implant + Wearable EP).
VIBRAINT RehUp / Neostim 5	Paralysis (Stroke, Spinal Cord Injury)	Robotic Orthosis + BCI + Transcutaneous SCS/FES	BCI decodes motor intention; triggers robotic movement synchronized with electrical stimulation to modulate spinal and cortical plasticity.	Aims to improve motor function in paralyzed limbs. Currently under clinical investigation.	Complex, multi modal system; currently for clinical trial use only.
Transcutaneous Vagus Nerve Stim (tVNS)	Enhancing Physical Therapy Outcomes	Non invasive Electrical Stimulation (Earbud)	Delivers mild electrical pulses to the outer ear, activating the Vagus Nerve to modulate inflammation and maintain physical improvements.	Preliminary outcomes suggest more durable benefits from physical therapy.	Wearable, small, non invasive; potentially lower cost than traditional VNS.

III. CONCLUSION

The field of wearable neurotechnology, and especially neurostimulation suits, is moving through a period of remarkable change. What began as simple open-loop systems has evolved into intelligent, adaptive technologies that can tailor therapy to each individual's needs. Devices like the Exopulse Mollii Suit and the CUE Device have already shown encouraging results in reducing spasticity and improving motor control. However, their effects often differ from person to person, reminding us that the human nervous system is far too complex for one uniform approach to work for everyone. The main obstacles to wider adoption are not purely technological. High device costs, limited insurance coverage, and complicated regulatory processes continue to make these systems difficult to access for many who could benefit from them. At the same time, as these suits become more advanced and capable of collecting sensitive neural data, new questions arise about privacy, data ownership, and how to ensure fair access to such powerful technology.

Looking ahead, progress in this field will depend on how well researchers, clinicians, and policymakers can work together to overcome these barriers. Studies that focus on long-term, real-world outcomes will be essential to understand how these devices perform outside controlled lab environments. Equally important is the creation of clear ethical and regulatory frameworks that protect users while allowing innovation to thrive.

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Another critical consideration is how these technologies integrate into daily life. Long-term user compliance, comfort, and ease of operation are just as important as clinical effectiveness. Future designs must focus on human-centered engineering creating lightweight, flexible, and intuitive systems that users can wear naturally without discomfort or dependency on technical expertise. Collaboration between engineers, neuroscientists, physiotherapists, and even fashion technologists could redefine how these suits are designed and perceived, making them both therapeutic and socially acceptable.

As artificial intelligence and neural networking technologies advance, wearable neurostimulation systems are poised to become more adaptive, predictive, and personalized. Integrating AI can enable real-time learning from each session, allowing the suit to automatically fine-tune stimulation levels or electrode configurations based on the user's ongoing physiological feedback. Such intelligent systems could revolutionize rehabilitation by providing continuously optimized therapy, enhancing neuroplasticity, and improving long-term outcomes. However, this vision will only succeed if AI is developed and deployed responsibly with transparency, safety validation, and clinician oversight.

The future of wearable neurotechnology depends on collective effort. Researchers must continue to conduct long-term, real-world trials that capture the practical and emotional experiences of users. Policymakers and regulators need to establish unified global standards that balance innovation with safety. Industry stakeholders must work toward affordable pricing models and equitable access. Only through this multidisciplinary collaboration can wearable neurotechnology mature from a promising innovation into a reliable, ethical, and life-changing therapeutic tool.

Ultimately, the promise of neurostimulation suits lies not only in the technology itself but in their potential to restore autonomy, dignity, and confidence to individuals living with neurological challenges. If developed with empathy, scientific rigor, and ethical foresight, these systems can do more than stimulate nerves they can reignite hope, independence, and quality of life for countless people around the world.

REFERENCES

[1]. OECD. *OECD Neurotechnology Toolkit*. OECD, 2024. Available from: https://www.oecd.org/sti/emerging-tech/neurotech-toolkit.pdf

[2]. *Comparative Analysis of Centralized and Federated Learning Approaches for Smartwatch-Based Stress Detection*. Research Paper, 2025.

[3]. Hobbs Rehabilitation. *Exopulse Mollii Suit*. Available from: https://hobbsrehabilitation.co.uk/neurotechnology/exopulse-mollii-suit/

[4]. Ottobock. *Exopulse Mollii Suit Technical Specifications*. Available from: https://www.ottobock.com/en-ea/exopulse-b2b-obsea

[5]. NeupsyKey. *History of Neurostimulation*. Available from: https://neupsykey.com/history-of-neurostimulation/

[6]. Neuromodulation. *Brief History of Neuromodulation*. Available from: https://www.neuromodulation.com/brief-history-neuromodulation

[7]. D. Eklund et al. The effect of one session of electrical stimulation with the EXOPULSE Mollii suit on spasticity after stroke. *Frontiers in Neurology*, 2021. Available from: https://www.frontiersin.org/journals/neurology/articles/10.3389/fneur.2021.706610/full

[8]. ClinicalTrials.gov. *EXOPULSE Mollii Suit and Exercise in Multiple Sclerosis Spasticity (EXOPULSE-MS)*. Identifier: NCT07126730. Available from: https://clinicaltrials.gov/study/NCT07126730

[9]. Centers for Medicare & Medicaid Services (CMS). *Transcutaneous Electrical Nerve Stimulators (TENS) Coverage Comments*. Available from: https://www.cms.gov/medicare-coverage-database/view/ncacal-public-comments.aspx?ncaid=256

[10]. Vielight. *What are the different types of brain stimulation technologies?* Available from: https://www.vielight.com/blog/types-of-brain-stimulation-technology/

[11]. Charco Neurotech. *A Non-Invasive Wearable Device for People with Parkinson's*. Available from: https://charconeurotech.com/

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[12]. R&D World. *5 neurotech trends to watch in 2025: From paralysis recovery to prosthetics that feel and beyond*. Available from: https://www.rdworldonline.com/5-neurotech-trends-to-watch-in-2025-from-paralysis-recovery-to-prosthetics-that-feel-and-beyond/

[13]. MarketsandMarkets. *Neurostimulation Devices Industry Trends and Forecast*. Available from: https://www.marketsandmarkets.com/ResearchInsight/neurostimulation-devices-industry.asp

[14]. Neuroba. *The Evolution of Wearable Neurotech: What's Next for Consumers*. Available from: https://www.neuroba.com/post/the-evolution-of-wearable-neurotech-what-s-next-for-consumers-neuroba

[15]. Mayo Clinic. *Using AI to improve brain stimulation devices*. Available from: https://www.mayoclinic.org/medical-professionals/neurology-neurosurgery/news/using-ai-to-improve-brain-stimulation-devices/mac-20528554

[16]. P. V. S. Rajamani et al. A wireless, 60-channel, AI-enabled neurostimulation platform. *bioRxiv*, 2025. Available from: https://www.biorxiv.org/content/10.1101/2025.02.04.635298v1.full-text

[17]. K. Blalock et al. Neurostimulation as a potential modality for transitioning patients with chronic refractory pain syndromes off opioid analgesics: A systematic review. *ResearchGate*, 2023. Available from: https://www.researchgate.net/publication/375909869_Neurostimulation_as_a_potential_modality_for_transitioning_patients_with_chronic_refractory_pain_syndromes_off_opioid_analgesics_A_systematic_review

[18]. American Society of Pain and Neuroscience (ASPN). An evidence-based consensus for the use of neurostimulation for the treatment of non-surgical low back pain. *Journal of Pain Research*, 2023. Available from: https://www.dovepress.com/an-evidence-based-consensus-for-the-use-of-neurostimulation-for-the-tr-peer-reviewed-fulltext-article-JPR

[19]. G. L. Musso et al. Enhancing neuroplasticity following stroke: Lessons learned and future directions. *PMC*, 2014. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4121447/

DOI: 10.48175/568

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