

Next-generation wearable neuromonitoring technologies: signal acquisition, modalities, and clinical relevance

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This narrative review, based on a non-systematic survey of the current literature, summarizes the current landscape of wearable neuromonitoring modalities—specifically high-density surface electromyography, in-ear electroencephalography, and flexible epidermal sensors. We outline their signal acquisition principles, technical advantages, and potential clinical relevance in scenarios such as postoperative spinal care, stroke neurorehabilitation, and Parkinson’s disease tracking. Furthermore, we discuss artificial intelligence as an emerging tool for processing high-dimensional wearable data, noting that many of these applications remain at an early or exploratory stage. Finally, we address key translational hurdles, including sensor biocompatibility and protocol standardization, that must be resolved to successfully integrate these wearable technologies into routine neurological assessment.

Key words Wearable electronic devices, Neurophysiological monitoring, Electromyography, Artificial intelligence

Introduction

The preservation and restoration of neural function represent primary goals in the management of neurological disorders and the surgical treatment of the central and peripheral nervous systems. Over the past few decades, intraoperative neuromonitoring (IONM)—incorporating modalities such as somatosensory evoked potentials, motor evoked potentials, and electromyography (EMG)—has enhanced surgical safety by providing real-time feedback on the functional integrity of neural pathways [1,2]. Despite its success in minimizing acute iatrogenic injuries, conventional IONM is fundamentally limited by its temporal boundaries; it ceases the moment the surgery concludes. Consequently, clinicians may still encounter delayed postoperative neurological deficits. These deficits often arise hours to days after surgery due to secondary pathophysiological mechanisms, including post-

operative tissue edema, microvascular ischemia, or neuroinflammation, which occur long after the patient has left the highly monitored environment of the operating room [3–5].

Currently, the assessment of postoperative neural recovery or the progression of neurodegenerative diseases relies heavily on intermittent clinical evaluations and invasive neurophysiological testing, such as needle EMG and nerve conduction studies. While these tools possess high diagnostic accuracy, their invasive nature can inflict discomfort on patients, rendering them less suitable for continuous, longitudinal tracking [6,7]. Moreover, assessing a patient in a structured clinical setting may fail to capture the dynamic fluctuations of neural function that manifest during the activities of daily living. Phenomena such as motor fluctuations in Parkinson’s disease, stress-induced dysautonomia, or the complex corticomuscular interactions required for functional mobility post-stroke could benefit from sustained, real-world observation

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[8,9].

The evolution of materials science, microelectro-mechanical systems, and wireless telecommunications has catalyzed the emergence of wearable neuro-monitoring technologies. By transitioning from rigid clinical machines to flexible, skin-conformable sensors, it is increasingly possible to monitor electroencephalography (EEG), EMG, and autonomic parameters in free-living environments [10–12]. Therefore, this review aims to highlight the intersection of these emerging wearable modalities and their clinical relevance. Rather than merely cataloging new devices, we examine how the technological foundations of high-density surface electromyography (HD-sEMG), in-ear EEG, and epidermal sensors may translate into sustained, real-world assessment strategies for post-operative care, neurorehabilitation, and movement disorder tracking. This article is structured as a narrative review; relevant literature was identified through targeted searches of PubMed, Scopus, and Google Scholar using key terms related to wearable neuro-monitoring, surface EMG, in-ear EEG, and epidermal sensors. As this is not a systematic review, the selection of sources was guided by their relevance and recency rather than by a predefined protocol, and the conclusions drawn should be interpreted within this methodological context.

While acute severe trauma leads to immediate nerve disruption detectable by IONM, milder injuries often result in neurapraxia [14]. In the postoperative phase, localized tissue edema can increase interstitial pressure, leading to microvascular compression and delayed ischemia. Because these mechanisms evolve dynamically over several days, intermittent post-operative checks might miss the optimal therapeutic window [15]. In principle, continuous monitoring could detect early signs of motor unit irritability, such as subclinical fasciculations, which may in turn allowing for timelier clinical evaluation, although this application has not yet been validated in prospective clinical studies [16].

Similarly, in the central nervous system, recovery from conditions like stroke relies on neuroplasticity and cortical reorganization [17]. This process is highly activity-dependent and driven by the patient's continuous interaction with their environment. While traditional neuroimaging captures brain activity in constrained moments, wearable tools have been proposed as a means to observe neuroplastic changes during real-world rehabilitation, though direct evidence for this capability remains limited [18]. Consequently, the dynamic nature of these physiological shifts necessitates the transition toward continuous, unobtrusive monitoring modalities.

Pathophysiological Foundations of Continuous Neuromonitoring

To contextualize the development of wearable neuromonitoring technologies, it is helpful to briefly outline the temporal dynamics of nerve injury and neuroplasticity that necessitate continuous observation.

During spine or anterior neck surgeries, peripheral nerves and nerve roots may be subjected to mechanical forces such as traction or compression [13].

Emerging Wearable Modalities for Neuromonitoring

The transition from clinical to wearable neuro-monitoring requires overcoming significant biophysical challenges, primarily minimizing motion artifacts and maintaining stable sensor-skin interfaces. This section details three key modalities, focusing on their operational principles, technical characteristics, limitations, and potential applications.

1. High-density surface electromyography

Traditional bipolar surface EMG utilizes two electrodes to measure the global electrical activity of a muscle, which typically lacks spatial resolution and is susceptible to crosstalk [19]. In contrast, HD-sEMG deploys two-dimensional grids comprising tens to hundreds of miniaturized electrodes closely spaced (e.g., 3–8 mm apart). This configuration provides a high-resolution spatiotemporal map of the electrical potential distribution across the skin surface [20].

The primary technical advantage of HD-sEMG lies in its advanced signal processing capabilities. Utilizing mathematical algorithms such as blind source separation, the complex interference pattern recorded at the surface can be decomposed into the discharge trains of individual motor units [21]. This non-invasive extraction of motor unit action potentials and their firing rates mimics some of the diagnostic information traditionally obtained via invasive needle EMG [22].

Despite its potential, wearable HD-sEMG faces technical hurdles. The computational load required for real-time decomposition is substantial, challenging the battery life of wireless sensors. Additionally, maintaining uniform impedance across a large grid during dynamic movements remains difficult, as localized sweating or electrode lift-off can degrade signal quality.

In terms of exploratory applications, flexible HD-sEMG patches have been investigated for tracking physiological markers of reinnervation. As a damaged nerve regenerates, surviving motor neurons undergo collateral sprouting. Conceptually, by wearing an HD-sEMG array, a patient's progressive reinnervation could be quantified over weeks, potentially serving as an objective biomarker for nerve regeneration speed, although clinical validation of this approach is still in its early stages [23].

2. In-ear electroencephalography

Prolonged cortical monitoring is often hampered by the obtrusiveness of conventional scalp EEG systems, which require wet gels and are prone to movement artifacts. In-ear EEG, often integrated into customized earpieces or "hearables," records electrical activity using dry or semi-dry electrodes placed directly within the ear canal or around the auricle [24].

Anatomically, the ear canal is in close proximity to the temporal lobes, providing a stable vantage point for recording auditory evoked potentials, sleep spindles, and certain epileptiform discharges. Because the ear canal is relatively stationary compared to the scalp and naturally holds the sensor securely, in-ear EEG tends to suppress motion artifacts and offers enhanced wearability for long-term daily use [25].

The most significant limitation of in-ear EEG is its low spatial resolution. Due to the small inter-electrode distance and confined anatomical location, it is generally unable to capture focal activities occurring in the frontal or occipital cortices. Furthermore, the limited number of channels restricts complex source localization.

Despite spatial constraints, in-ear EEG has shown preliminary utility in automated sleep staging, which is relevant since sleep architecture is often disrupted post-surgery and in neurodegenerative diseases. Furthermore, clinical studies have highlighted the inherent limitations of intraoperative monitoring in predicting delayed postoperative neurological events [10,16]. To help bridge this gap, it has been proposed that wearable EEG tracking could serve as an adjunctive tool to monitor postoperative arousal and neural network integrity in ambulatory environments, though this application remains largely conceptual at present.

3. Flexible epidermal sensors for autonomic monitoring

Autonomic nervous system dysfunction is a critical component of various conditions, ranging from systemic neuropathies to disorders of gut–brain interaction, where wearable monitoring is increasingly being evaluated [26]. Recent advancements in materials science have led to ultra-thin, flexible epidermal sensors designed specifically for continuous biomarker and autonomic tracking. Utilizing elastomeric substrates embedded with nanomaterials, these sensors exhibit mechanical properties that conform closely to the human epidermis.

For instance, epidermal wearable biosensors have been specifically engineered to continuously monitor biochemical markers in sweat, offering non-invasive tracking capabilities for chronic diseases [27]. Their thin profile makes them minimally obtrusive to the

wearer, supporting high patient compliance in both clinical and home settings.

However, translating these devices to daily use requires overcoming mechanical limitations. Maintaining long-term durability necessitates robust, wireless, skin-integrated system designs that can function reliably across various physical healthcare environments [28].

From a neurophysiological perspective, integrating the continuous measurement of electrodermal activity and heart rate variability provides a direct window into assessing autonomic function and sympathovagal balance [29]. Consequently, this modality extends the reach of neuromonitoring beyond motor and sensory pathways, providing a potential window into stress-induced physiological changes and autonomic neuropathies.

Table 1 summarizes the key characteristics of the major wearable neuromonitoring modalities, including their signal acquisition principles, strengths, limitations, and representative clinical relevance.

Table 1. Characteristics of emerging wearable neuromonitoring modalities

Modality	Primary target signal	Signal acquisition principle	Main advantages	Main limitations	Representative clinical relevance
HD-sEMG	Motor unit electrical activity	Two-dimensional arrays of closely spaced surface electrodes record spatially distributed muscle electrical potentials, which can be decomposed into individual motor unit discharge patterns	High spatiotemporal resolution; non-invasive assessment of motor unit behavior; reduced crosstalk compared with conventional bipolar sEMG; potential for longitudinal tracking of reinnervation	High computational demand for signal decomposition; susceptibility to electrode lift-off and sweating; difficulty maintaining uniform impedance during dynamic movement	Postoperative motor monitoring after spine or peripheral nerve surgery; longitudinal assessment of reinnervation and motor recovery
In-ear EEG	Cortical electrical activity	Dry or semi-dry electrodes placed within the ear canal or around the auricle record EEG signals from a relatively stable anatomical site	Improved wearability for long-term monitoring; reduced motion artifact compared with conventional scalp EEG; feasibility for continuous monitoring in free-living environments	Limited spatial resolution; inability to capture broad cortical activity reliably; restricted source localization due to limited channel number	Continuous sleep staging; adjunctive monitoring of postoperative arousal and neural network integrity; potential application in neurorehabilitation and neurodegenerative disease monitoring
Flexible epidermal sensors	Autonomic and biochemical signals, including EDA, HRV, skin temperature, and sweat biomarkers	Ultra-thin skin-conformal sensors based on elastomeric substrates and nanomaterials continuously detect physiological and biochemical signals from the skin surface	Comfortable long-term wear; minimal motion-related signal degradation; suitability for ambulatory monitoring; ability to extend neuromonitoring to autonomic function	Limited long-term durability; mechanical degradation with repeated stretching or moisture exposure; need for robust wireless skin-integrated designs	Continuous autonomic monitoring; assessment of sympathovagal balance; detection of stress-related physiological changes and autonomic neuropathies

HD, high-density; sEMG, surface electromyography; EEG, electroencephalography; EDA, electrodermal activity; HRV, heart rate variability.

Representative Clinical Applications

While the technological capabilities of wearable sensors are expanding, their ultimate value lies in clinical translation. This section highlights representative clinical scenarios where these technologies could provide meaningful insights.

1. Postoperative care in spine and peripheral nerve surgery

Surgeries for cervical radiculopathy and myelopathy carry a risk of postoperative complications, such as C5 palsy, which typically manifests 2 to 7 days post-surgery. IONM has established the utility of tracking motor-evoked potentials to predict upper extremity motor paresis during such procedures [30,31]. Drawing upon these established IONM principles, it is conceivable that a wearable HD-sEMG array on the deltoid muscle could allow clinicians to extend motor unit recruitment monitoring into the postoperative ward. In this exploratory framework, observing a delayed drop in recruitment efficiency might alert the surgical team to impending neuropraxia. Similarly, building on the concepts of intraoperative recurrent laryngeal nerve assessment [32], wearable sensors placed on the neck could theoretically be used to track the postoperative recovery trajectory of vocal fold neuropraxia after thyroidectomy. It should be noted, however, that these postoperative applications have not yet been validated in controlled clinical trials and remain at a conceptual stage.

2. Neurorehabilitation and corticomuscular coherence

In stroke rehabilitation, assessing whether motor improvements stem from true neurological recovery or compensatory movements is challenging. Corticomuscular coherence (CMC) provides a mathematical measure

of the functional coupling between the primary motor cortex (via EEG) and the contracting muscle (via EMG) [33]. By deploying a multimodal wearable system, clinicians could estimate CMC continuously during rehabilitative exercises. A progressive increase in beta-band CMC (15–30 Hz) over weeks of therapy has been hypothesized to reflect functional rewiring of the corticospinal tract, and could, if validated, serve as a digital biomarker to help time adjunct therapies such as robot-assisted training [34].

3. Tracking progression in neurodegenerative diseases

Optimizing dopaminergic medication in Parkinson's disease requires an accurate understanding of the patient's "On" and "Off" times, which typically relies on subjective patient diaries [8,11]. Wearable kinematics combined with surface EMG have been explored as an objective method to capture resting tremor characteristics, bradykinesia, and muscle rigidity under naturalistic conditions [35]. Over time, repeated sampling of these parameters can generate a personalized record of motor symptom fluctuations. While this continuous peripheral data is also being investigated for its potential to inform advanced closed-loop stimulation parameters [36], its primary near-term value lies in providing clinicians with an objective, continuous metric to guide routine medication adjustments.

Table 2 summarizes representative clinical scenarios in which wearable neuromonitoring technologies may provide meaningful longitudinal information beyond conventional intermittent assessment.

Table 2. Representative clinical applications of wearable neuromonitoring technologies

Clinical scenario	Wearable modality	Target parameter(s)	Expected clinical utility	Current limitation(s)
Postoperative care after spine and peripheral nerve surgery	HD-sEMG	Motor unit recruitment pattern, spontaneous activity, reinnervation-related signal changes	Continuous postoperative monitoring beyond the operating room; early detection of delayed neurological deterioration; longitudinal tracking of motor recovery	Limited clinical validation in postoperative wards; susceptibility to motion artifact and electrode instability; high computational demand for real-time analysis
Post-thyroidectomy functional follow-up	Wearable neck sensors / surface EMG-based monitoring	Voice-related acoustic parameters, superficial muscle electrical activity	Longitudinal tracking of vocal fold or recurrent laryngeal nerve functional recovery; adjunctive postoperative follow-up in ambulatory settings	Mostly conceptual or early-stage application; lack of standardized wearable protocols; uncertain signal specificity
Stroke neurorehabilitation	Multimodal EEG-EMG wearable system, including in-ear EEG	CMC, beta-band coupling, muscle activation pattern	Distinguishing true neurological recovery from compensatory movement; monitoring functional rewiring during rehabilitation; supporting timing of adjunct therapies	Limited standardization of signal acquisition and analysis; low spatial resolution of wearable EEG; need for longitudinal validation
Parkinson's disease monitoring	Wearable kinematics combined with surface EMG	Tremor characteristics, bradykinesia, rigidity-related fluctuation, On/Off state variability	Objective continuous tracking of motor symptom fluctuation; improved guidance for medication adjustment; development of individualized motor profiles	Variability across devices and algorithms; challenges in interpreting real-world movement data; incomplete integration into routine practice
Autonomic dysfunction monitoring	Flexible epidermal sensors	EDA, HRV, skin temperature, sweat-related biomarkers	Continuous assessment of autonomic imbalance and stress-related physiological change in free-living environments	Limited durability for long-term use; need for robust skin-integrated systems; limited disease-specific clinical validation

HD-sEMG, high-density surface electromyography; EMG, electromyography; EEG, electroencephalography; CMC, corticomuscular coherence; EDA, electrodermal activity; HRV, heart rate variability.

Artificial Intelligence as an Enabling Tool

The integration of wearable continuous monitoring generates large volumes of high-dimensional data, rendering manual interpretation impractical. Consequently, artificial intelligence (AI) and machine learning (ML) are increasingly recognized as important enabling tools for signal processing and pattern recognition in this context, although their integration into wearable neuromonitoring workflows remains largely at the research and development stage.

1. Signal pre-processing and noise reduction

Real-world ambulatory data is inherently noisy and

complex. AI algorithms, such as hybrid neural autoencoders, have been utilized to process and encode complex sensory and neural data efficiently [37]. In the context of wearable devices, the application of similar neural network architectures has the potential to assist in isolating physiological signals from background noise and baseline drift, which is a necessary step before any reliable clinical interpretation can occur. However, prospective validation of such pipelines on ambulatory wearable data remains limited.

2. Pattern recognition and prognostic assessment

Once the data is pre-processed, ML models can be utilized to handle the temporal dependencies of physiological time-series data. By analyzing extracted

features, AI models may identify latent patterns related to patient mobility and neurological status. For instance, ML algorithms analyzing continuous gait parameters and wearable sensor data have demonstrated the ability to assess fall risk accurately among vulnerable populations [38,39]. Furthermore, AI methodologies have demonstrated robust capabilities in predicting severe neurological outcomes in critical care scenarios, such as post-cardiac resuscitation [40]. While originating from acute care, this illustrates the broader prognostic potential of AI in neurological monitoring; by applying similar pattern recognition frameworks to ambulatory wearable data, ML may in the future assist clinicians in stratifying patients based on objective digital biomarkers. At present, however, this translational step has not been broadly demonstrated, and further clinical studies are needed to establish the reliability and generalizability of such approaches.

Translational Challenges and Future Directions

Despite their potential, several critical translational hurdles remain to be resolved before wearable neuromonitoring achieves widespread clinical adoption.

Firstly, the biocompatibility and long-term durability of the sensor-skin interface require further refinement. Prolonged adhesion may cause skin irritation or signal degradation due to epidermal turnover and sweat accumulation. Continued research into breathable materials and stable conductive hydrogels is necessary to maintain low impedance without compromising patient comfort [23,28].

Secondly, rigorous clinical validation and standardization are urgently needed. Many current studies are proof-of-concept trials involving small cohorts. To establish wearable metrics as validated digital biomarkers, large-scale longitudinal trials are imperative. Additionally, standardizing data acquisition protocols,

Table 3. Translational challenges for the clinical implementation of wearable neuromonitoring technologies

Challenge domain	Key issue	Clinical implication	Potential direction for improvement
Sensor-skin interface	Prolonged adhesion may cause skin irritation, signal instability, and impedance changes due to sweat and epidermal turnover	Reduced signal reliability during long-term monitoring; decreased patient comfort and adherence	Development of breathable materials, skin-compatible conductive hydrogels, and low-irritation adhesive interfaces
Mechanical durability	Flexible sensors may degrade with repeated stretching, motion, and moisture exposure	Shortened device lifespan; inconsistent signal quality in ambulatory settings	Robust skin-integrated designs, improved encapsulation strategies, and mechanically resilient nanomaterial-based systems
Signal quality in real-world environments	Motion artifact, electrode lift-off, environmental noise, and variable contact conditions may distort signals	Reduced interpretability of continuous data; risk of false-positive or false-negative signal patterns	Advanced signal pre-processing, adaptive filtering, artifact rejection algorithms, and multimodal signal fusion
Computational burden and data overload	Continuous multimodal monitoring generates large, high-dimensional datasets requiring intensive processing	Difficulty in real-time analysis and clinical interpretation; limited feasibility in routine practice	Edge computing, efficient machine learning pipelines, automated feature extraction, and cloud-assisted analysis
Clinical validation	Many existing studies remain proof-of-concept and involve small or selective cohorts	Limited generalizability and uncertain clinical utility across diverse patient populations	Large-scale longitudinal studies and multicenter validation in representative clinical settings
Standardization	Lack of uniformity in sensor placement, acquisition protocols, and feature extraction methods	Poor comparability across studies and difficulty establishing validated digital biomarkers	Consensus-based protocols, standardized reporting frameworks, and disease-specific normative datasets
Data privacy and cybersecurity	Continuous wireless transmission of neural and physiological data may expose sensitive health information	Barriers to patient trust, regulatory approval, and clinical adoption	Secure encryption, local or federated processing, privacy-aware device architecture, and regulatory compliance frameworks

sensor placement, and feature extraction algorithms is essential to account for inter-individual variability in ambulatory settings [11,12].

Lastly, the continuous wireless transmission of neural data raises valid privacy and cybersecurity concerns. Robust encryption protocols and decentralized data processing techniques—where models are trained locally on the user's device—should be further explored to safeguard patient data and comply with medical privacy regulations [11,18].

Table 3 outlines the major translational challenges that must be addressed before wearable neuromonitoring technologies can be implemented reliably in routine clinical practice.

Conclusion

The emergence of multimodal wearable neuromonitoring represents a notable technological advancement, offering the potential to shift certain aspects of neurological assessment from the clinic to the patient's natural environment. By leveraging the signal acquisition capabilities of HD-sEMG, in-ear EEG, and flexible epidermal sensors, researchers and clinicians may eventually gain sustained, real-world insights into postoperative nerve recovery, corticomuscular neuroplasticity, and disease progression, provided that the current exploratory evidence is substantiated by rigorous clinical validation. As an enabling tool, AI provides the necessary framework to process these complex datasets. Overcoming the remaining translational hurdles, particularly regarding sensor durability, standardized clinical validation, and data security, will be crucial for translating these modalities into clinical practice, ultimately providing objective longitudinal tracking and adjunctive decision support.

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Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Data Availability

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Author Contributions

All work was done by PKJ.

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