Journal of Electronic Research and Application, 2026, Volume 10, Issue 8
http://ojs.bbwpublisher.com/index.php/JERA
Online ISSN: 2208-3510
Print ISSN: 2208-3502

Exploration of the Application Value of Flexible Carbon Nanotube Electromyography Electrodes in Health Monitoring

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Abstract: The development of wearable devices has posed new requirements for surface electromyography (EMG) electrodes, including long-term, comfortable, and high-fidelity signal acquisition. Traditional Ag/AgCl wet electrodes suffer from limitations such as skin irritation and signal attenuation. Carbon nanotubes (CNTs), with their excellent conductivity, flexibility, and biocompatibility, have emerged as ideal materials for constructing flexible dry EMG electrodes. This paper systematically reviews the material properties, preparation strategies, and signal acquisition performance of flexible CNT EMG electrodes, analyzes their application value in scenarios such as muscle function assessment, gesture recognition, motion monitoring, and multimodal integrated monitoring, discusses challenges such as scalable preparation, long-term stability, and standardized evaluation, and looks forward to directions such as self-powered systems, artificial intelligence integration, and smart textiles. This paper suggests that the electrode is expected to become the core sensing element of the next generation of wearable health monitoring systems, promoting the clinical translation of non-invasive monitoring technologies.

Keywords: Carbon nanotubes; Flexible electrodes; Electromyography signals; Health monitoring Classification Code: G712 Document Code: A

Online publication: Sept 3, 2026

1. Introduction

Electrophysiological signal detection, including electrocardiography (ECG), electromyography (EMG), and electroencephalography (EEG), represents a critical clinical testing method for assessing human health status and enabling real-time monitoring of patient well-being [1]. With the advancement of wearable medical monitoring technologies, bioelectronics has found widespread applications in health detection, medical supervision, and motion detection [2,3]. The efficient acquisition of high-quality electrophysiological signals has become a research focus [4].

Currently, commonly used surface bioelectrodes have limitations. Gel electrodes rely on conductive gel to reduce impedance, but gel drying during long-term monitoring can easily cause skin allergies and increase noise [5]. Wet electrodes require skin preparation for long-term use, and sweat can also lead to signal degradation [6,7]. Dry electrodes offer convenience and long-term wearability advantages, but they suffer from poor skin conformity, high impedance, and are prone to motion artifacts during movement [2,8]. Penetrating electrodes can reduce artifacts, but they lack mechanical stability and comfort [7,9].

An ideal skin electrode should possess high conductivity, high stretchability, softness, skin adhesion, and excellent biocompatibility [6,10]. Carbon nanotubes (CNTs), with their unique honeycomb lattice structure endowing them with excellent carrier mobility, mechanical flexibility, and chemical stability, have emerged as ideal materials for constructing flexible dry bioelectrodes. In recent years, researchers have successfully prepared various types of flexible CNT EMG electrodes through multiple strategies, achieving significant progress in signal acquisition and application expansion.

This paper systematically reviews the research progress of flexible CNT EMG electrodes in the field of health monitoring, starting from material properties and preparation methods, analyzing signal acquisition performance, discussing application prospects in scenarios such as muscle function assessment, gesture recognition, motion monitoring, and multimodal integrated monitoring, summarizing challenges, and looking forward to development directions.

2. Material Properties and preparation methods of carbon nanotube electromyography electrodes

2.1. Basic electrical and mechanical properties of carbon nanotubes

Carbon nanotubes (CNTs) are formed by rolling up single or multiple layers of graphene, with their honeycomb lattice structure composed of sp^2 hybridized carbon atoms endowing them with exceptional properties. Electrical properties: The conductivity of single-walled carbon nanotubes (SWCNTs) can reach 10^2–10^4 S/cm, owing to their unique electronic band structure that allows carrier mobility with minimal scattering limitations [1]. Mechanical properties: Their Young’s modulus can exceed 1 TPa, enabling them to withstand significant bending and stretching deformations, making them suitable for compounding with flexible substrates to adapt to dynamic skin deformations. Chemical stability and biocompatibility: CNTs are resistant to corrosion or degradation in physiological environments. PDMS/SWCNT/RGO composite electrodes have demonstrated cell counts comparable to control groups in studies on connective tissue cell viability, with some composite materials exhibiting in vitro cell survival rates exceeding 80%, indicating that properly designed CNT-based electrodes possess a safety foundation for long-term skin contact [11,12].

2.2. Preparation strategies for flexible electrodes

Based on the assembly methods and processing techniques of carbon nanotubes, the preparation strategies for flexible carbon nanotube electromyography electrodes can be summarized into the following main approaches [13].

Direct synthesis method: Growing CNTs directly on flexible substrates can achieve good adhesion, but is limited by the contradiction between growth temperature and substrate thermal stability. The blown aerosol chemical vapor deposition method enables high-yield production of self-supporting dry films in a roll-to-roll manner, with controllable adjustment of thickness, sheet resistance, and light transmittance [14].

Transfer method: Patterned transfer of pre-grown CNT films onto flexible substrates allows independent optimization of growth conditions and substrate selection. Patterning with a resolution of 200 μm can be achieved using laser-cut masks [14].

Solution processing method: CNTs are dispersed in a solvent and formed into films through coating, printing, or spraying. MWCNT/PDMS composite electrodes are prepared using a low-cost solution processing method, which is simple and easy to scale up [15].

Composite preparation method: CNTs are compounded with a polymer matrix to form composite materials that combine conductivity and flexibility, with performance adjustable by controlling doping concentration and dispersion state [13]. Laser irradiation can reduce the resistance of SWCNT/RGO/PDMS composite materials by 13 times to 8 ± 2 kΩ [11].

2.3. Typical electrode configurations

Thin-film electrodes: Ultra-thin conformal CNT dry electrodes exhibit high transparency (> 90%) and good conductivity (60 Ω/sq), enabling them to adhere to the skin in the form of temporary tattoos for ECG, EMG, and EEG monitoring [14].

Composite electrodes: MWCNT/PDMS composite electrodes demonstrate interface impedance comparable to that of Ag/AgCl electrodes in the frequency range of 20–1 kHz [15]. The elastic modulus of PDMS/SWCNT/RGO composite electrodes (180.0 ± 5.3 kPa) is highly matched with that of the skin [11]. MXene/CNT composite electrodes construct a three-dimensional structure with low impedance and high signal-to-noise ratio [16].

Multi-channel array electrodes: A 64-channel three-dimensional Ti_3C_2 MXene/CNT composite electrode array exhibits exceptional flexibility, enabling seamless conformity to skin curvature. Its contact impedance at 100 Hz is 10 times lower than that of Ag/AgCl gel electrodes, providing a hardware foundation for fine gesture recognition [16]. Fabric electrodes: CNTs combined with textiles form electrodes that combine conductivity and breathability, allowing direct integration into everyday clothing.

Electronic fabrics based on in-situ growth of CNTs on carbonized silk fabrics can monitor pulse waves and joint movements in real time [17]. Ultrathin nanosheets assembled from single-walled CNT networks on elastomers exhibit good water vapor permeability, allowing sweat to pass through during exercise [18].

3. Signal acquisition performance of flexible carbon nanotube electromyography electrodes

3.1. Skin-electrode interface impedance

Interface impedance directly affects signal fidelity and signal-to-noise ratio (SNR). The three-dimensional MXene/CNT composite electrode exhibits a contact impedance 10 times lower than that of the Ag/AgCl gel electrode at 100 Hz [16]. The MWCNT/PDMS composite electrode demonstrates comparable performance to traditional Ag/AgCl electrodes within the frequency range of 20–1 kHz [15]. The ultrathin CNT dry electrode achieves a contact impedance of 100 $k\Omega \cdot cm^2$ at 10 Hz, comparable to that of commercial wet electrodes [14]. Increasing mechanical pressure (0–100 mmHg) reduces impedance across the entire frequency range [15]. The PDMS/SWCNT/RGO composite electrode maintains impedance stability during 7 days of simulated sweat exposure [11].

3.2. Signal-to-noise ratio and signal quality

The MXene/CNT electrode exhibits lower baseline noise and higher SNR when acquiring surface electromyography (sEMG) signals from the arm, maintaining a high SNR of approximately 25 dB across different gestures [16]. The ultrathin CNT dry electrode achieves an SNR of 67 dB for ECG monitoring, outperforming the 60 dB of Ag/AgCl wet electrodes [14]. The ECG signals recorded by the PDMS/SWCNT/RGO composite electrode are comparable in quality to those of Ag/AgCl electrodes, with sharper peak amplitudes [11]. Carbon nanomaterial-based dry electrodes combine excellent mechanical flexibility, high conductivity, and wear comfort due to their gel-free design [12].

3.3. Signal stability under dynamic conditions

The ultrathin profile and good skin adhesion reduce sensitivity to motion noise, effectively overcoming common motion artifacts associated with dry electrodes [2]. Flexible dry electrodes based on CNT/PDMS composites and wrinkled structures effectively control dynamic artifacts [5]. CNT-based dry electrodes exhibit high stability against motion artifacts, which typically arise from the inability of thicker rigid dry electrodes to conform to skin deformations [8]. The ultrathin electrode composed of single-walled CNT networks allows for the transmission of sweat vapor, reducing sweat accumulation at the interface [18].

3.4. Long-term monitoring reliability

The gel-free dry design fundamentally avoids signal attenuation caused by gel drying [14]. The PDMS/SWCNT/RGO composite electrode shows no degradation in ECG signals during 7 days of continuous wear, with no observed skin reactions and stable impedance changes recorded over 14 days [11]. The MWCNT/PDMS composite dry electrode outperforms commercial Ag/AgCl electrodes in ECG and EMG measurements, making it suitable for ubiquitous health monitoring [15]. The mechanical durability of CNT materials supports stable performance under repeated deformation cycles [13].

4. Applications of flexible carbon nanotube electromyography electrodes in health monitoring

4.1. Muscle function assessment and rehabilitation monitoring

Surface electromyography signals contain rich information about neuromuscular function and can be used to assess muscle fatigue, coordination, and functional status. Flexible carbon nanotube electromyography electrodes provide a new means for long-term, dynamic assessment of muscle function.

In the field of neurological rehabilitation, continuous sEMG monitoring holds significant clinical value for assessing rehabilitation progress. Carbon nanotube-based dry electrodes, which do not require conductive gel and can be worn for extended periods, are suitable for rehabilitation scenarios requiring continuous monitoring over days to weeks [2]. The ultrathin CNT dry electrode can adhere to the skin in the form of a temporary tattoo, enabling simultaneous monitoring of ECG, EMG, and EEG [14]. Its low-burden wearability facilitates patients maintaining natural movement states, allowing for the acquisition of more ecologically valid EMG data.

In sports medicine, CNT-based fabric electrodes can be directly integrated into sportswear, enabling real-time tracking of muscle activity during exercise [17]. This eliminates the need for additional electrode attachment, allowing athletes to obtain muscle activity data under natural training conditions.

4.2. Gesture recognition and human-computer interaction

Gesture recognition based on sEMG signals has broad application prospects in intelligent prosthesis control, sign language recognition, and virtual reality interaction [10]. Carbon nanotube-based electromyography electrodes, with their high SNR and good dynamic stability, provide high-quality signal input for gesture recognition.

The MXene/CNT electrode achieves an SNR of approximately 25 dB when acquiring sEMG signals for different gestures, with recognition rates exceeding 90% when combined with machine learning [16]. The 64-channel three-dimensional MXene/CNT composite electrode array captures high-resolution spatial distribution information of arm muscle activity, providing a data foundation for fine gesture recognition [16]. A sign language recognition system supported by mixed ion-electron conductive electrodes achieves a classification accuracy of 96.4% [3]. CNT-based dry electrodes combined with machine learning demonstrate high precision and adaptive capabilities in gesture classification [4]. The deep integration of carbon nanotube-based electromyography electrodes with artificial intelligence is driving the development of high-precision, low-latency human-computer interaction interfaces.

4.3. Sports training and physical fitness monitoring

Monitoring physiological signals during sports training is crucial for assessing training effectiveness and preventing sports injuries. The wearability and comfort of carbon nanotube-based electrodes give them unique advantages in sports scenarios [2].

Fabric-type CNT electrodes can be directly integrated into sportswear, enabling real-time tracking of muscle activity during exercise. This avoids the issues of traditional electrode detachment and displacement, ensuring the continuity and reliability of signal acquisition [17]. Single-walled carbon nanotube-SBS nanosheets exhibit excellent resistance to water wiping, which is particularly important for sports scenarios involving frequent sweating and limb friction [10,18].

In the field of ergonomics, CNT-based wearable electromyography electrodes can be used to assess muscle load under different work postures, providing data support for workplace ergonomics optimization [2]. With the increasing awareness of health management, the demand for real-time monitoring of physiological signals in daily life is growing, and CNT-based electromyography electrodes offer an efficient and durable solution for this purpose [6].

4.4. Integrated monitoring of multimodal physiological signals

Single-modality physiological signals are insufficient to comprehensively reflect human health status. The synchronous acquisition and comprehensive analysis of multimodal signals represent an important direction for the next generation of wearable health monitoring systems [17]. Carbon nanotube-based flexible platforms demonstrate unique integration potential in this regard.

CNT-based flexible platforms can construct multimodal sensing platforms through flexible substrates and stretchable conductive materials, enabling synchronous acquisition of multidimensional physiological data such as ECG, EMG, body temperature, and sweat metabolites. This allows for comprehensive health status assessment on a single device [16].

At the signal processing level, CNT-based flexible amplifiers can achieve a gain of up to 1.5×10^5 (approximately 104 dB) [18]. Integrating sensing, amplification, signal processing, and wireless transmission functions into a single flexible platform represents an important development direction for CNT-based wearable health monitoring systems [4,10].

5. Challenges and prospects

5.1. Major current challenges

Although flexible carbon nanotube (CNT) electromyography (EMG) electrodes have made encouraging progress in basic research and application exploration, several key challenges remain in transitioning from the laboratory to practical clinical applications [1].

Scalable Manufacturing: Mass production of high-performance CNT electrodes at low cost remains a bottleneck for their widespread application. Currently, most research is limited to laboratory-scale preparation, lacking mature industrial production processes [13]. How to achieve continuous roll-to-roll, large-area, and low-cost production while maintaining performance is a core engineering issue that needs urgent resolution.

Long-term Stability and Durability: Although some studies have demonstrated continuous monitoring capabilities for 7 days or even 14 days, the long-term performance retention, structural integrity under repeated cleaning and wearing, and practical application scenarios, such as daily use over months or even years, still require systematic validation [11].

Lack of Standardized Evaluation Systems: Currently, there is a lack of unified testing standards and specifications for evaluating the performance of CNT-based electrodes. Differences in impedance measurement conditions, signal-to-noise ratio calculation methods, and long-term monitoring evaluation indicators among different studies make it difficult to compare different electrode systems horizontally [12]. Establishing industry-recognized standard testing methods is crucial for promoting technological maturity and industrialization.

Long-term Verification of Biosafety: Although existing studies indicate that CNT-based materials exhibit good biocompatibility at the skin contact level, more systematic and in-depth toxicological evaluations are needed for long-term, large-area skin contact [11,12]. The potential transdermal absorption pathways and biological effects of carbon nanomaterials still require further clarification [6].

Motion Artifact Suppression: Although flexible designs have significantly improved signal stability under dynamic conditions, ensuring signal quality during vigorous exercise and extreme sweating remains a technical challenge [8]. Collaborative efforts are needed at multiple levels, including material design, electrode structure optimization, and signal processing algorithms.

5.2. Future development directions

Self-powered Systems: Develop CNT-based self-powered sensors to enable autonomous monitoring without external power sources [1]. CNTs, which function as both electrode materials and energy harvesting components, have potential in self-powering technologies such as triboelectric generation and thermoelectric conversion due to their excellent electrical conductivity and mechanical properties [13]. Self-powered designs will significantly enhance the portability and continuous operation capabilities of wearable devices.

Integration with Artificial Intelligence: Combine machine learning for intelligent signal recognition and disease early warning [16]. The integration of high-density sEMG signals with deep learning algorithms is driving continuous improvements in gesture recognition accuracy [3,16]. In the future, artificial intelligence will not only be used for post-processing analysis of signals but can also be embedded in electrode-side signal preprocessing and feature extraction to enable edge intelligence [4].

Multifunctional Integration: Integrate sensing, amplification, signal processing, and wireless transmission functions into a single flexible platform [10]. Full flexibility and full integration are the development goals of wearable health monitoring systems [12]. CNTs can serve as both sensing materials and components for constructing flexible amplifiers and transistors, providing a material foundation for system-level integration [18].

Smart Textiles: Seamlessly integrate CNT electrodes into daily clothing to enable unobtrusive health monitoring [17]. Transitioning from standalone patch electrodes to fabric electrodes integrated into clothing is an important path to improving user compliance [2]. Future smart clothing will combine daily wearing comfort with continuous physiological signal monitoring capabilities [10].

Clinical Translation: Promote the technological translation from laboratory research to practical medical applications. This requires interdisciplinary collaboration, integrating expertise from material science, electronic engineering, clinical medicine, and data analysis [6]. At the same time, large-scale clinical trials are needed to verify the effectiveness and safety of electrodes in real medical scenarios, obtain regulatory approval, and ultimately achieve a technological leap from hospital monitoring to home health management [2].

6. Conclusion

Flexible carbon nanotube EMG electrodes exhibit significant application value in the field of health monitoring due to the unique electrical, mechanical, and chemical properties of CNT materials. In terms of signal acquisition performance, CNT-based dry electrodes have achieved contact impedance and signal-to-noise ratios comparable to or even better than commercial Ag/AgCl wet electrodes, while overcoming the inherent limitations of wet electrodes, such as gel drying and skin irritation during long-term use. In terms of application scenarios, these electrodes show broad prospects in muscle function assessment and rehabilitation monitoring, gesture recognition and human-computer interaction, sports training and physical fitness monitoring, and integrated monitoring of multimodal physiological signals.

However, to transition from laboratory research to large-scale clinical applications, flexible CNT EMG electrodes still need continuous efforts in scalable manufacturing processes, long-term stability verification, the establishment of standardized evaluation systems, and in-depth research on biosafety. Looking ahead, with the collaborative development of cross-disciplinary fields such as self-powering technologies, artificial intelligence algorithms, and smart textiles, flexible CNT EMG electrodes are expected to become the core sensing elements of the next generation of wearable health monitoring systems, driving a substantial leap in non-invasive health monitoring technology from hospital monitoring to home health management and providing critical technical support for personalized, continuous, and intelligent health management.

Funding

Research Project of the Chongqing Municipal Education Commission on Science and Technology–Research on the Preparation and Performance Optimization of Carbon Nanotube Adhesive Electromyography Electrodes in a Comprehensive Health Monitoring System (Project No.: KJ2025056144525339)

Disclosure statement

The authors declare no conflict of interest.

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