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# MXene-Based Textile-Integrated Dry Electrodes for Surface Electromyography (sEMG)*

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***Abstract*—This paper proposes a textile-integrated dry sEMG electrode system with a layered MXene-based structure. The design includes a tannic acid pretreatment on the fabric substrate, creating bio-friendly interfacial bridges that reinforce adhesion between the fabric and MXene layers. Morphological and chemical analyses (e.g., FTIR) confirm the efficacy of tannic acid in enhancing active sites, thereby promoting uniform MXene deposition. Mechanical tests, including a tensile peeling assessment, demonstrate stable adhesion across the electrode, while skin-contact impedance measurements confirm reliable signal transmission similar to commercial gel electrodes at the sEMG frequency range. Further, multiple MXene layer electrodes show stronger sEMG signals compared with single MXene layer one, underscoring the advantage of additional conductive layers in maintaining consistent electrical performance.**

***Clinical Relevance*—The resulting electrode structure is comfortable, exhibits no skin irritation or residue during removal, and maintains integrity under repeated mechanical stress, making it a promising candidate for long-term, self-administered sEMG applications. Future work will explore scalable production methods and expanded use in biomedical engineering and human–machine interfacing contexts.**

## I. Introduction

Surface electromyography (sEMG) offers a non-invasive method to evaluate muscle activity, enabling a wide range of biomedical engineering applications in e.g. rehabilitation, sports performance, and human–machine interfaces [1, 2]. sEMG electrodes can be classified as "wet" (gelled) or "dry" electrodes [3]. Conventional sEMG typically relies on Ag/AgCl single-use electrodes, originally designed for electrocardiography (ECG), which includes a conductive gel to improve electrode-to-skin contact. These electrodes have some drawbacks in relation to long-term use, including skin irritation, gel dehydration, and reusability. They also require precise anatomical placement, which often makes self-administered use complicated.

Researchers have explored alternative strategies to achieve good sEMG signal acquisition without extra adhesives or gels [4, 5]. One approach makes use of metallic-based dry electrodes, such as copper foil electrodes, which eliminate the need for gels [4]. However, these solutions often compromise flexibility, comfort and signal quality, which are key requirements for wearable devices, especially during prolonged use or in dynamic environments. Another strategy focuses on polymer-based conductive materials, including polymer composites, which enhance flexibility and biocompatibility [5]. When integrating these materials into textiles, including wiring and connectors, the resulting 'system' functions as a single, ease-to-use wearable product, which reduces the complexity of electrode application and supports self-administered use [6, 7]. However, the integration of polymer-based electrodes into textiles presents challenges. Typically, this integration is realized through coating or polymer deposition of conductive polymers onto a textile substrate to form additional layers. A primary challenge lies in achieving robust interfacial bonding between these layers [8]. Recent studies have further introduced MXene-based nanocomposites, such as hydrogels fabricated via in-situ conformal coating of MXene nanosheets within a PAA/ACC polymer network, and MXene/PDMS composites prepared by solution blending followed by molding and curing, which show great potential for improving stretchability, skin conformity, and signal stability in flexible electrodes [9, 10]. However, these emerging materials still face challenges in balancing electrical performance, long-term durability, and scalable fabrication for wearable applications.

In this paper, we introduce a novel interfacial-enhanced, MXene-based dry electrode featuring a layered structure. It consists of a fabric substrate, a single or multi-layered MXene coating on the fabric, and a top layer of Ecoflex–MXene composite. MXenes, a family of two-dimensional transition metal carbides or nitrides, offer an exceptional 2D structure with excellent electrical conductivity. Tannic acid, a bio-friendly polyphenol rich in functional groups, is used as an interfacial bridging layer to increase the density of active sites and reinforce adhesion between the fabric substrate and the MXene coating. The Ecoflex–MXene composite on the top layer ensures sufficient skin adhesion, thanks to the flexibility and adhesive properties of Ecoflex [11, 12]. As a proof of concept, we integrated the MXene-based electrodes configured in single-, double-, and triple- layers into a textile band substrate. The design also included embroidered wiring, creating a wearable 'system' that allows easy donning and doffing, a key feature in self-administered applications [13]. Initial results demonstrate that multi-layered MXene electrodes outperform single-layered configurations, providing skin-contact impedance comparable to standard Ag/AgCl electrodes and producing adequate sEMG signals in

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the first tests in a single participant. These findings highlight the feasibility and potential of our approach for long-term sEMG monitoring in various wearable healthcare and rehabilitation scenarios.

## II. Design and Methods

### A. Preparation of MXene-based electrode

The electrodes were prepared to investigate both the interfacial properties of the coated MXene layer on textile substrates (knitted spandex fabric) and the skin-electrode adhesion of the top Ecoflex-MXene layer. A robust coating is essential for withstanding repeated use, including washing and routine maintenance, while sufficient skin–electrode adherence reduces motion induced noise and enhances signal quality. Fig. 1 shows the fabrication process of the electrode. This electrode features a layered structure and is designed as a square patch with a 15×15 mm size. The base layer consists of a flexible textile substrate chosen for its breathability, and ability to conform to human body contours. To prepare the substrate, a 20×20 mm black fabric sample was thoroughly cleaned with soap to remove surface impurities and then immersed in a 5% tannic acid solution for two hours.

Subsequently, an MXene solution (0.02 g MXene per 10 g water) was drop-coated on the textile and allowed to air dry. The functional groups on the surface of MXene provide a stable interface between the textile substrate and conductive Ecoflex-MXene composite layer. Various compositions of this Ecoflex-MXene composite (7.5, 10, 12.5, and 15 wt%) were then applied by coating and cured at 60 °C in a vacuum oven. This layering procedure was repeated once or twice to achieve multiple layers, aiming for improved adhesion and overall performance.

### B. Integration of the electrodes into a wearable prototype

To demonstrate the feasibility for sEMG recording, we designed a minimal viable wearable prototype. i.e. a textile band. The prototype included two MXene-based electrodes using the same fabrication methods described in the previous section and connecting wires and connectors at the wire ends for data acquisition. Wires and connectors were made by embroidering silver-based conductive yarns (Shieldex® 117/17 HCB, Shieldex, Germany); coating was applied at the other end of the wires to make a strong connection between the electrode areas and the connectors. The electrode dimensions are 15 mm × 15 mm, with an inter-electrode distance of 25 mm.

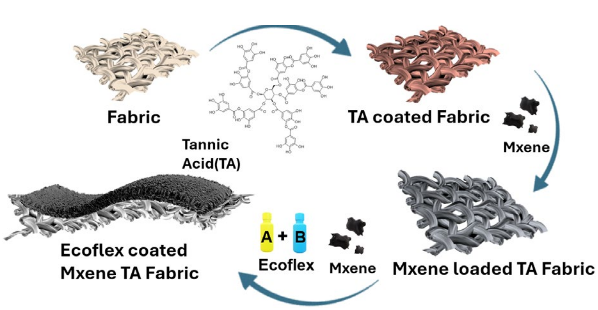


Figure 1. Schematic illustration of fabrication of the textile-integrated sEMG dry electrode.

The embroidered wires are 0.5 mm in width and 50 mm in length, while the connectors are 3 mm × 9 mm in size. The embroidery stitches were chosen for low resistance and minimal tension, reducing the risk of breakage during use.

### C. Characterization of interfacial properties

The enhancement of the fabric interface through polyphenol treatment was investigated through Fourier transform infrared spectroscopy (FTIR, Nicolet iS10 FTIR spectrometer, Thermo Fisher Scientific Inc., Madison, WI, USA). The functional groups and bonding were analyzed to show the interfacial bridge layer formed by tannic acid, a bio-friendly polyphenol, and to reveal the increasing active site density for strengthening adhesion between the fabric substrate and the MXene layer.

To evaluate the effectiveness of the tannic acid treatment, electrical surface resistance on both the front and back sides of the fabric was measured using a two-point method, using a digital multimeter with a 1 cm distance between the two probes. The average resistance values, obtained from three different locations, were then compared between samples with and without tannic acid treatment.

Tensile peeling tests were conducted on an Instronr. 101 (Instron, Massachusetts, USA) universal testing machine with a 10 N load cell. Tensile adhesion spectra for electrodes were tested under a 90-degree peel test, with skin as the substrate, referencing the ASTM D6862 guideline, i.e. 1) Cut the conductive fabric into uniform strips (e.g., 25 mm × 100 mm) and 2) clean the skin surface, 3) attach the fabric to the skin, ensuring even pressure, and 4) secure the skin in the lower grip of a tensile testing machine. 5) attach the fabric's free end to the upper grip at a 90-degree angle, then 6) peel the fabric away at a constant rate (e.g., 25 mm/min) while recording the force. 7) Monitor for skin damage, residue, or fabric tearing, and 8) calculate peel resistance as the average force divided by width.

### D. Experimental setup for skin-contact impedance measurement and sEMG signal acquisition

Skin contact impedance was conducted on a human forearm and measured over a frequency range of 0.1 Hz to 1 MHz using a three-electrode setup. The impedance values were recorded on an electrical impedance spectroscope (PGSTAT 204 with FRA 32M module, Metrohm Autolab, Netherlands) under the potentiostatic mode. The single MXene-based electrode was tested with commercial Ag/AgCl electrodes (Cardinal Health Kendall™) as the counter and reference electrodes, placed 9 cm and 2 cm from the working electrode, respectively [14]. The electrode design includes extra edges for clips to connect to the sEMG detection device.

As a proof-of-concept, the wearable prototype was used to record sEMG signal from the biceps of one of the authors. Single-, double-, and triple- Mxene-layer electrodes were tested to investigate how additional coating layers might affect signal quality. A commercial Ag/AgCl electrode was used as a reference electrode placed on the bony part of the elbow (olecranon). For comparison, sEMG was also recorded with Ag/AgCl electrodes in the same bipolar configuration. A setup time of 3 minutes was used before measurement for both the prototype electrodes and the commercial Ag/AgCl electrodes. The wearable system was secured to the skin using Velcro to maintain consistent and repeatable contact and minimize motion artifacts, while sEMG signals were sampled at 1 kHz using the Neuromotus$^{TM}$ (Integrum AB, Mölndal, Sweden).

To ensure a repeatable and comparable muscle activation, the test subject started with the elbow in 90◦ flexion without activating the muscle. The sEMG signal was visually inspected to ensure a minimal noise level. sEMG data was then recorded while the subject performed a maximal voluntary contraction (elbow flexion) for 5 seconds, followed by a 5-second rest, repeated three times. The sEMG measurements were conducted with a 5-minute interval (including setup time) between successive electrode applications to minimize skin effects and ensure consistency.

## III. Results and Discussion

The MXene-based electrode with a layered structure was evaluated in terms of its morphological, chemical, and functional properties, as well as its performance under its intended use conditions.

### *A. Tannic acid enhanced interfacial properties between MXene layers and textile substrate*

The FTIR spectra of the treated fabric revealed the characteristic peaks of tannic acid, including a broad O-H stretching vibration (~3200–3500 cm$^{-1}$) and prominent peaks associated with C=O stretching (~1700 cm$^{-1}$) and aromatic C=C vibrations (~1600 cm$^{-1}$), as shown in Fig. 2. These functional groups effectively increase the activation sites on the fabric surface, which can facilitate the robust attachment of layered MXene functional groups in the subsequent deposition processes. Its polymerization also regulates MXene penetration into the textile, through which the adhesion shifts from a purely weak physical bond to a stronger chemical anchoring, thereby ensuring uniform conductivity and preventing detachment during drying.

Electrical surface resistance measurement showed that the untreated fabric exhibited a relatively low resistance (~30 kΩ) on the front side but a significantly higher resistance (~6 MΩ) on the backside, indicating poor conductivity homogeneity. Visual inspection showed that in untreated samples, the MXene layer was loosely stacked on the surface and easily removed, primarily due to reliance on physical deposition with minimal chemical bonding. In contrast, tannic acid-treated fabric demonstrated similar resistance on both sides (~250 kΩon the front and ~220 kΩ on the back), indicating improved homogeneous conductivity distribution on the surface and across the fabric. This enhancement is attributed to the ability of tannic acid to introduce additional activation sites on fibres to react with MXene flakes and, therefore, to strengthen surface interactions for increasing affinity of fabric yarns and fibres for the MXene solution.

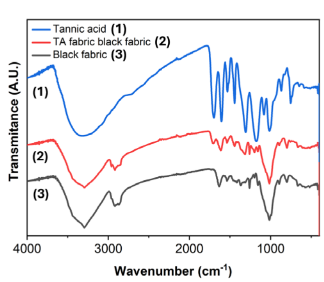


Figure 2. FTIR spectra of TA, TA pretreated fabric, and fabric.

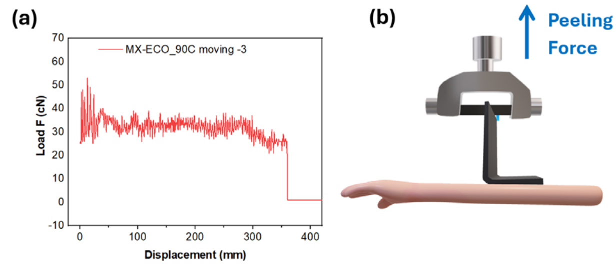


Figure 3. (a) Tensile adhesion spectrum for MXene-based electrode under a 90-degree peel test, (b) scheme of the tensile peeling test.

### *B. Adhesive properties between skin and electrodes*

For the tensile peeling test, the force-displacement curve of the electrodes exhibited an adhesion force of ~50 cN and maintained stable adhesion during peeling (~30–50 cN), as shown in Fig. 3. The electrode demonstrates a consistent force-displacement curve, revealing the uniformity of adhesion across the fabric surface and its interaction with the skin under mechanical stress, indicating strong resistance to detachment. Layered electrode structures, incorporating intermediate bonding layers exhibit enhanced peel resistance. First, these intermediate layers penetrate deep into the fabric substrate, creating stronger bonding that improves adhesion. Second, the multi-layered design reinforces structural integrity, making the electrodes less prone to tearing under mechanical stress. The cohesive forces within the layered system effectively distribute mechanical stresses, minimizing the risk of delamination during peeling. Moreover, the multiple layers also have potential to provide great durability to resist deformation and material fatigue under repeated mechanical forces. Notably, we observed no discomfort with no skin irritation when peeling off. Meanwhile, there is no residue, and no tearing of the fabric, which reveals the good durability and skin-friendliness of the electrode design.

### *C. Skin-electrode impedance and sEMG recording*

Fig. 4.a showed the skin-electrode impedance of MXene-based electrodes over a frequency range of 0.1 Hz to 1 MHz, compared with commercial Ag/AgCl electrodes. Within the 10 Hz to 1 kHz frequency range, the MXene-based electrode exhibits behaviour comparable to that of the commercial Ag/AgCl gel electrode, leading to a similar signal transmission property. This range is critical for sEMG applications, as it encompasses the most relevant frequencies for capturing bioelectrical signals. We attribute this performance in part to the adhesive properties of the top Ecoflex-MXene layer, which promotes conformal skin contact. Furthermore, via the multi-layered synergistic mechanism, the layered structure allows for a uniform distribution of conductive materials. It facilitates

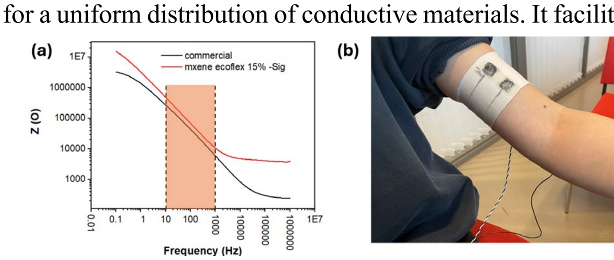


Figure 4. (a) single electrode skin contact impedance diagram comparing with the conventional Ag/AgCl electrode, (b) digital image of sEMG recording.

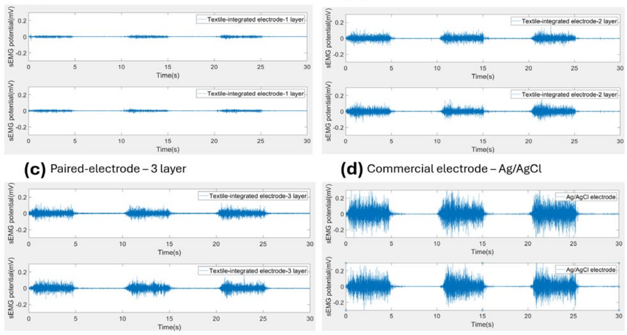


Figure 5. sEMG signals measured from the bicep with paired textile-integrated electrode (a) 1 layers, (b) 2 layers, (c) 3 layers, and (d) conventional Ag/AgCl gel electrode.

efficient electron transmission through the uniform conductive network. By combining high-performance conductive materials with a compact electrode design, interface detachment is minimized, and good electrical performance is maintained.

Fig. 4b shows the sEMG recording setup. Here, the textile band is placed around the subject's upper arm, conforming to the arm's natural contours. The single-layer electrode demonstrated quite poor sEMG signals, with amplitudes fluctuating around ±0.025 mV. On the contrary, the multilayered electrode (2 and 3 layered) demonstrated significantly improved performance (Fig. 5).

The signal was stable, with low noise and clear discernible periods of muscle activity and inactivity, maintaining an amplitude within ±0.1 mV. This multi-layered design enhances the overall sEMG recording performance by providing additional pathways for electron transport, ensuring more consistent signal transmission. Further, by mitigating the impact of structural defects or inconsistencies of the single-layered designs, it also distributes mechanical stress more evenly, improving its durability and resistance to wear during prolonged use.

## IV. Conclusion

This paper proposes an MXene-based, textile-integrated dry electrode system, offering a user-friendly solution to record sEMG signals that overcome the limitations of gel-based electrodes in self-administered applications. The solution strengthens both the skin-electrode interface, through multiple layered enhancement for improved adhesion and contact stability, and the electrode-textile interface, with polyphenol coatings for robust integration with the textile substrate. Despite the sEMG signal quality of our electrode does not fully match that of Ag/AgCl electrode, its consistent and similar behaviour indicates a strong potential for textile integration and embedded wearable applications, offering valuable functionality in real-world scenarios. Future work will focus on improving the scalability and consistency of the electrode fabrication process. Further studies will involve testing with a larger and more diverse user group, as well as assessing long-term durability under practical conditions, such as repeated washing and air permeability tests. These efforts aim to expand the system's usability and integration in biomedical engineering, rehabilitation, and human-machine interfacing.

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## Ethical Approval

The experimental procedures involving human subjects described in this paper were approved by the Swedish Ethical Review Authority.

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