MXene-Based Textile-Integrated Dry Electrodes for Surface Electromyography (sEMG): Structural and Electrical Stability After Repeated Washing

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***Abstract*— This study investigated the washability and durability of a textile-integrated dry surface electromyography (sEMG) electrode system based on layered MXene-based materials. Building on prior work using tannic acid pretreatment to improve MXene–textile adhesion, the electrodes were further developed with optimized cross-linking and reinforced deposition. The electrodes retained structural and electrical performance after ten laundering cycles. The results show improvements over earlier textile-integrated electrodes, ensuring consistent sEMG detection through repeated use. Enhanced washability supports application in long-term rehabilitation, athletic monitoring, and human-machine interfaces.**

I. Introduction

Surface electromyography (sEMG), i.e. to capture myoelectric activity via non-invasive electrodes placed on the skin over the muscle, is widely applied in rehabilitation, sports science, prosthetics, and human-machine interaction [1]. Traditional gel-based electrodes, though effective, require precise placement and have limited reusability due to gel drying, residue, and skin irritation, making them unsuitable for long-term or self-administered use [2].

Dry textile-integrated electrodes offer a promising alternative, combining flexibility, comfort, and potential for garment integration [3]. Among candidate materials, MXenes, a class of two-dimensional transition metal carbides and nitrides, stand out for their electrical conductivity, processability via solution methods, and mechanical flexibility [4]. Yet, achieving durable, uniform integration of MXene coatings on textiles is challenging, and ensuring that the integrated textile structures to maintain stability and performance under repeated mechanical stress and washing adds further complexity [5].

We have previously introduced a tannic acid pretreatment to enhance MXene adhesion on textile substrates [6]. This plant-

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derived polyphenol, rich in hydroxyl and carboxyl groups, increases active site density on the fabric surface, improving MXene coating uniformity and bonding [7]. By introducing a multilayered electrode design according to our previous study, we achieved strong adhesion, low skin-contact impedance comparable to Ag/AgCl electrodes, and stable sEMG signals [6]. However, their long-term washability was not yet evaluated. Repeated washing can cause coating delamination, disrupt bonding, and degrade performance.

This study addresses that gap by investigating the durability of these electrodes after repeated hand washing. Through multilayer construction, chemical surface reinforcement, and an ecoflex-MXene adhesive interface, we demonstrate a washable, textile-integrated sEMG electrode system that maintains structural and electrical integrity. These improvements support its potential for reusable electronic textiles (e-textiles) in home-based applications and long-term human-machine interfacing.

II. Materials and Methods

A. Surface Modification, Electrode Manufacturing and Wearable Prototype Integration

The electrodes were designed to improve both MXene-textile adhesion and skin contact, while withstanding repeated washing. A layered structure was built on spandex fabric, selected for its flexibility. Fabric squares (20 × 20 mm) were pretreated in 5 wt% tannic acid for two hours, coated with 0.02 g/10 g MXene solution via drop-casting, and air-dried. An ecoflex-MXene composite (7.5-15 wt%) was then applied and cured at 60 °C. This process was repeated to create multilayered electrodes. Each 15 × 15 mm patch was integrated into a textile band for sEMG testing, following previous design validation [6]. Conductive silver yarn (Shieldex® 117/17 HCB) was embroidered under the coated areas in a 0.5 × 50 mm pattern and connected to 3 × 9 mm contact pads for snap button connector attachment.

B. Hand Wash Protocol

A hand wash simulation, based on ISO 6330:2012 guidance, was performed using a 20 °C water bath with 2 g L^{-1} detergent and a 1:20 liquor ratio. Electrodes were manually stirred for 10 minutes, rinsed with clean water at the same temperature, blotted with tissue, and air-dried flat at room temperature. Performance, such as covering surface morphology, adhesion, and sEMG signal quality, was assessed over 10 wash cycles.

C. Mechanical Characterisation and sEMG Acquisition

Adhesion was measured via a 90° peel test (ASTM D6862) using an Instron 101 (Instron, Massachusetts, USA) with a 10 N load cell at 25 mm min^{-1}. For sEMG testing, paired MXene electrodes were placed on the biceps of one author, with positions marked for consistency. Signals were recorded at 1 kHz using a Neuromotus™ system (Integrum AB, Sweden), with an Ag/AgCl reference electrode on the olecranon (Cardinal Health Kendall™). Each session included three 3-second maximal contractions with 3-second rest, performed before washing and after 1, 2, 3, 4, 5, and 10 wash cycles.

III. Results and Discussion

A. Morphological Analysis

Electrode morphology was assessed after repeated hand washing. Coating uniformity was maintained through five cycles, with slight edge lifting observed by the tenth, indicating surface erosion but not structural failure. Inner layers remained well-bonded. As demonstrated previously, tannic acid pretreatment introduces functional groups that enhance bonding with MXene, improving interfacial adhesion and mechanical stability. The reduced detachment seen in multilayered electrodes compared to single-layer ones confirms the value of layered designs in shielding the conductive coating from wash-related damage and mechanical stress.

B. Mechanical Adhesion Durability

Mechanical adhesion was evaluated via a 90° peel test. As shown in Fig. 1, the unwashed electrode (curve b) exhibited a stable peel force of 30-50 cN, indicating strong interfacial bonding. After 10 washes (curve a), the force dropped to 10-30 cN and became more fluctuating. The peak force values suggest skin adhesion remained stable, while fluctuations can be due to delamination at the fabric-electrode interface. These findings show that although skin contact was maintained, internal adhesion compromised with repeated washing, indicating the need for improved structural reinforcement.

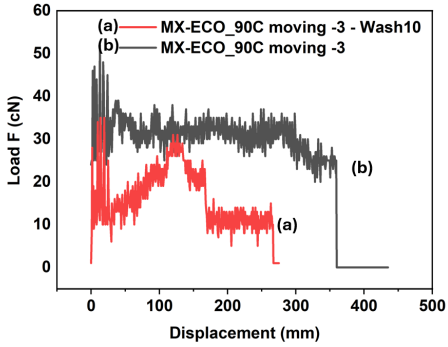

Fig. 1 Peel force-displacement curves of textile-integrated electrodes before and after 10 wash cycles.

C. Washability Assessment - sEMG Signal Performance

To evaluate functional durability, sEMG signals were recorded before and after repeated washing. As shown in Fig. 2, the pristine multilayered electrode (2a) produced consistent signals near ±0.1 mV during voluntary contraction, with minimal change after five washes (2b). After ten cycles, the signal amplitude had declined in the multi-layer sample (2c), while the single-layer electrode failed to detect meaningful activity. These results highlight the improved wash resistance of multilayered designs over time.

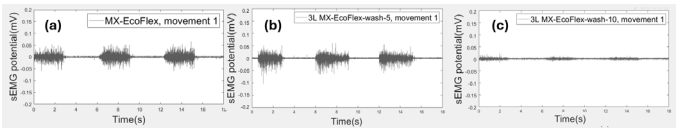

Fig. 2 sEMG signals recorded from textile-integrated electrodes: (a) pristine multilayered, multilayered after (b) 5 washes, and (c) 10 washes.

IV. Conclusions

This study shows that textile-integrated dry sEMG electrodes, enhanced by surface treatment and multilayer design, maintain mechanical and electrical performance after repeated washing. Despite some surface wear after ten cycles, overall integrity was preserved. sEMG results confirmed consistent output, underscoring their potential for reusable wearable applications. Future work will focus on scalable fabrication, sweat and abrasion biocompatibility, and full textile integration for long-term health monitoring and human-machine interaction.

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References

[1] M. Zheng, M. S. Crouch, and M. S. Eggleston, "Surface electromyography as a natural human–machine interface: a review," *IEEE Sensors Journal*, vol. 22, pp. 9198-9214, 2022.

[2] L. Guo, L. Sandsjö, M. Ortiz-Catalan, and M. Skrifvars, "Systematic review of textile-based electrodes for long-term and continuous surface electromyography recording," *Textile research journal*, vol. 90, pp. 227-244, 2020.

[3] J. Shi, S. Liu, L. Zhang, B. Yang, L. Shu, Y. Yang, M. Ren, Y. Wang, J. Chen, and W. Chen, "Smart textile-integrated microelectronic systems for wearable applications," *Advanced materials*, vol. 32, pp. 1901958, 2020.

[4] A. Ahmed, M. M. Hossain, B. Adak, and S. Mukhopadhyay, "Recent advances in 2D MXene integrated smart-textile interfaces for multifunctional applications," *Chemistry of Materials*, vol. 32, pp. 10296-10320, 2020.

[5] S. Uzun, S. Seyedin, A. L. Stoltzfus, A. S. Levitt, M. Alhabeb, M. Anayee, C. J. Strobel, J. M. Razal, G. Dion, and Y. Gogotsi, "Knittable and washable multifunctional MXene-coated cellulose yarns," *Advanced Functional Materials*, vol. 29, pp. 1905015, 2019.

[6] X. Wang, L. Guo, M. Skrifvars, M. B. Kristoffersen, and L. Sandsjö, "MXene-based textile-integrated dry electrodes for surface electromyography (sEMG)," in *Proc. 47th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, 2025, manuscript accepted..

[7] Y. Liu, J. Wang, and Z. Sun, "Aromatic Biobased Polymeric Materials Using Plant Polyphenols as Sustainable Alternative Raw Materials: A Review," *Polymers*, vol. 16, pp. 2752, 2024.