Ubiquitous Embroidered Electrodes: An Open-Source Platform for Biopotential Measurement

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***Abstract*— Biopotential measurement, including electrocardiograph (ECG), electroencephalograph (EEG), electromyograph (EMG), etc., is a generic tool for health monitoring, diagnosis, human-robot interface, etc. This paper presents an open-source platform for designing and fabricating dry-contact textile electrodes using programmable embroidery, which provides an accessible tool for ubiquitously embroidering textile electrodes on fabrics according to users' needs. Our method allows for precise control of geometric parameters, including stitch pattern and filling density, to optimize electrode performance. The results demonstrate that by varying the filling density of conductive threads, the electrode impedance can be systematically controlled. The experimental results showed that our embroidered electrodes achieved low skin-electrode impedance. In real-time ECG monitoring, these electrodes produced high-quality signals, which are comparable to gel electrodes. In addition, these electrodes can be quickly embroidered onto different fabric substrates such as clothes, sheets, pillows, etc., without the need for extra fabrication steps. These findings validate our platform as a feasible method for producing cost-effective, comfortable, reliable embroidered electrodes suitable for long-term wearable health monitoring. We open source the platform to make it accessible to the research community.**

Keywords—Embroidered electronics, open-source platform, biopotential measurement, dry, contact, and ECG.

I. Introduction

In recent years, wearable sensors have started to change the way we think about personal health. Instead of getting a health checkup only once in a while at hospitals, these devices allow us to monitor physiological signals throughout our daily lives continuously. This is where smart textiles have emerged as a promising solution. Smart textiles are flexible, comfortable, and can be integrated directly into clothes and other fabrics in everyday life, and thus are a promising solution for long-term health monitoring, chronic management, and assistive device control [1]-[3]. Recent advancements in electronic textile materials and fabrication techniques have generated a number of remarkable studies on developing flexible sensors on woven or nonwoven fabrics, as well as integrating systems into clothing [4]. Among different textile fabrication techniques, embroidery offers excellent potential for transferring desired patterns to fabric substrates.

For decades, medical-grade biopotential measurements have relied on conventional gel electrodes, which use adhesive and conductive gels to make a good connection with the human skin. Embroidered electrodes provide an alternative dry contact solution for placement in various wearable or other fabric substrates, enabling ubiquitous monitoring. However, there are still major challenges that have slowed the widespread use of these dry textile electrodes, including the unclear impedance and skin-electrode impedance for textile electrodes and the uncontrolled fabrication process that can result in different performances.

To address these challenges, this paper presents a programmable design and fabrication platform for embroidered electrodes that can be quickly embroidered onto common fabrics. The proposed programmable electrodes offer several advantages, including the ease of fabrication, reusability, cost-effectiveness, and compatibility with different body types, enabling real-time biopotential measurement with an improved skin-electrode interface to ensure accurate signal acquisition across various skin conditions, such as dry, moist, and wet skin. In addition, the size, shape, and stitch patterns can be precisely controlled for optimization for different users and usage conditions [5]. Our platform, including both hardware and software, is open-sourced, aiming to enable ubiquitous monitoring in daily life.

The remainder of this paper is organized as follows: Section II describes the electrode design, fabrication process, and our open-source platform. Section III presents the experimental setup and results, and Section IV concludes the work.

II. Embroidered Electrode Design and Fabrication

A. Embroidery for Textile Electronics Fabrication

Embroidery is a textile manufacturing method that uses individual fibers or threads and subsequently introduces them into fabric substrates to achieve desired patterns. Unlike other textile electronics fabrication techniques such as screen-printing, ink jet printing [6], embroidery provides precise, repeatable control over the z-axis (stitch penetration), creating robust conductive paths. However, standard embroidery software is optimized for visual aesthetics, not for controlling the electrical properties required for functional sensors. To address this gap, we developed an open-source software tool to streamline the creation of high-performance embroidered

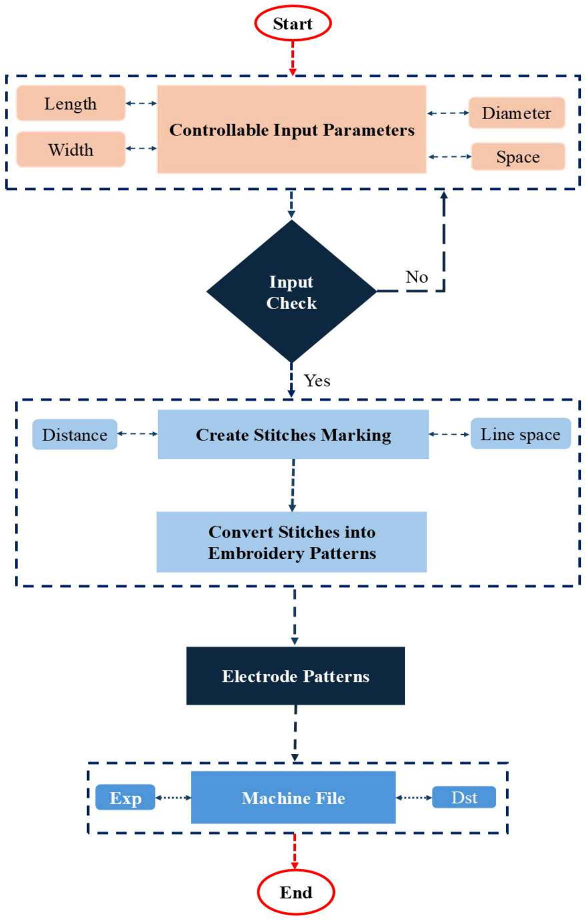


Fig. 1. Programmable embroidery flowchart for creating the machine code for design to fabrication translation.

electrodes. This tool automates the generation of complex stitch patterns from a simple set of user-defined inputs, moving beyond manual design challenges. Figure 1 illustrates the workflow diagram. Our approach provides systematic input control over electrode geometry and filling density parameters that are directly correlated with the skin-electrode impedance matching and improving the signal-to-noise ratio of the embroidered electrode.

Our design tool, built in Python using the Pyembroidery library, translates high-level parameters into precise, low-level machine instructions. The core of the tool's algorithm generates a series of parallel or cross-hatched stitch lines within a defined geometric boundary. A user first specifies the electrode's shape and dimensions (e.g., a 30 mm diameter circle). They then input the desired filling density as a percentage, which the tool translates into a specific input spacing distance between stitch lines. For example, a 100% density corresponds to the minimum possible stitch spacing before stitches overlap, while a 50% density doubles this spacing. Before generating the final file, the tool can perform validation checks, such as flagging a stitch spacing that is too small (<1.0 mm), which could risk thread breakage or damage to the substrate fabric. The electrode design is composed of two functional parts: a primary circular sensing

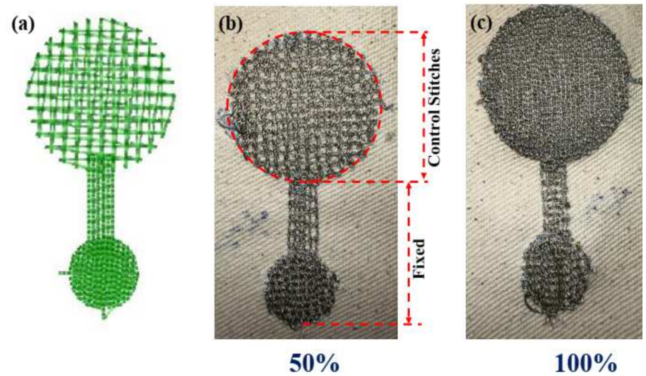


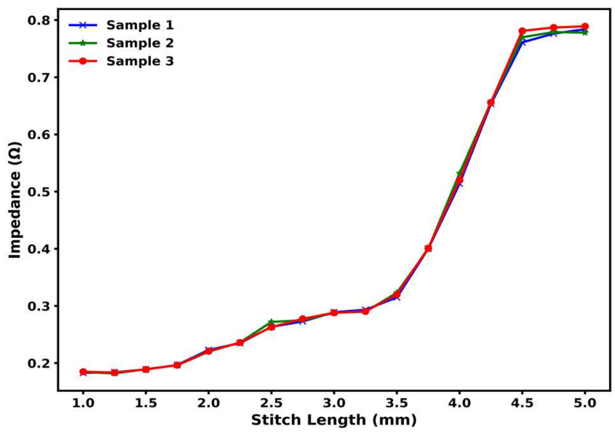
Fig. 2 Design to manufacturing translation. (a) Generated controllable stitch pattern as machine code; (b) fabricated embroidered electrode with 50% filling; (c) 100% filling.

area where the filling density is experimentally varied, and a small, fixed connection tab. This tab is always embroidered at maximum density to create a mechanically stable and electrically reliable point (< 0.3 Ω) for attaching measurement clips, minimizing contact resistance at the instrumentation interface. The tool then exports the complete design into standard machine-readable files (dst, .exp types of files).

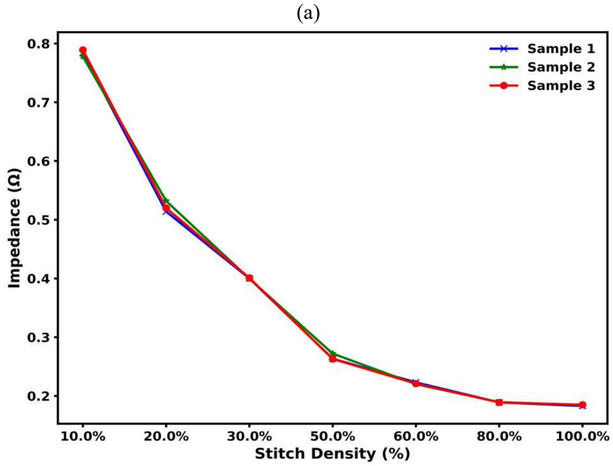
For physical fabrication, we selected materials to optimize the trade-off between electrical conductivity, mechanical durability, and user comfort. We chose Madeira's HC-12 conductive thread, a silver-plated polyamide multifilament, for its low linear resistance (< 100 Ω/m) and its superior flexibility compared to stiffer metallic threads. The electrodes were fabricated on a standard, non-conductive 100% cotton substrate using a JANOME embroidery machine. We employed a crucial two-thread embroidery technique, using a durable polyester thread as the top thread and the HC-12 conductive thread in the bobbin. This method is important for e-textile fabrication as it protects the delicate conductive thread from the high mechanical tension and abrasion of the needle path, placing it predominantly on the bottom (skin-facing) surface of the fabric. This ensures a direct conductive path to the skin while maintaining the structural integrity of the sensor. Using this optimized process, we produced four distinct sets of electrodes with filling densities of 30%, 50%, 80%, and 100% to evaluate their performance.

B. *Open Source Platform*

This platform addresses a key limitation in conventional embroidery software, which is primarily designed for decorative purposes rather than functional sensor or electronics design and fabrication. Our proposed tool empowers researchers to user-define stitch geometry and density with precision parameters for sensor or electrode optimizations. The GitHub repository [5] tool provides the complete Python code, electrode design files tested in our study, and raw and processed ECG data to ensure reproducibility. Step-by-step instructions are also included to facilitate user adoption. Through this initiative, we aim to support the bioelectronics and wearable device community and encourage collaborative development under an open-science framework.



(a)



(b)

Fig. 3 Embroidered electrode impedance characteristics. (a) Electrode impedance versus stitches distance; (b) electrode impedance versus filling stitches densities.

III. Experiment and Results

This section details the comprehensive experimental validation of the embroidered electrodes, beginning with the characterization of their intrinsic electrical properties, followed by a description of the real-time ECG acquisition system, and concluding with an analysis of the recorded signal quality compared to standard gel electrodes. The results also showed that the given open-sourced stitch patterns can be quickly embroidered onto different fabric substrates for various application scenarios, including shirts and compression sleeves, sheets, etc.

A. Embroidered Electrode Characteristics

To evaluate the performance of the fabricated embroidered electrodes, we conducted two sets of experiments: First, we characterized the intrinsic resistance of the electrodes themselves, and second, we recorded real-time ECG signals to compare their performance against standard gel electrodes. To characterize the electrodes' conductive properties, both the intrinsic impedance and the skin-electrode impedance in tight contact conditions were measured across each patch using a two-point probe method. Figure 3 shows the relations between the electrodes' impedance and the stitch pattern parameters. The results showed that with the stitch length increasing, the impedance rises, while increasing the filling density causes the impedance to decrease significantly. The 100% filled electrodes exhibited the lowest resistance of approximately 0.18 Ω, confirming that a higher density of conductive thread creates a more conductive surface.

We also measured skin-electrode impedance to understand the contact condition for ensuring successful biopotential measurement. In a resting condition with compressive sleeves, the skin-electrode impedance was measured at 13.39 kΩ. We also recognized motion artifacts and other noise sources, which are not the main focus of this paper. We studied them in our previous work [7].

B. ECG Monitoring Hardware Setup

To validate the performance of the embroidered electrodes for biopotential monitoring, a dual-channel system was developed to record ECG signals simultaneously from both the embroidered electrodes and commercial Ag/AgCl gel electrodes, allowing for a direct, time-synchronized comparison. First of all, we set up the signal conditioning and acquisition system using Olimex ECG shields, each connected to an Arduino microcontroller. The signal from the electrode first passed through a protection stage. A multi-stage amplification process using instrumental amplifiers and high-pass filters was followed. The final stage was a third-order Bessel low-pass filter with a 40 Hz cut-off frequency, which effectively reduced high-frequency noise and prevented signal aliasing. The sampling frequency was 250 Hz.

C. Results of ECG Acquisition

ECG signals were recorded from a healthy subject in a resting state using a standard Lead I electrode configuration (right arm, left arm, and a reference electrode). To investigate the critical role of the skin-electrode interface, each textile electrode was tested under two distinct conditions: a "relaxed state" with only casual contact, and a "tight state", where a gentle, consistent pressure was applied using an elastic band to ensure a stable physical connection.

The recorded ECG waveforms are presented in Fig. 4 (for 30% and 100% filling densities). The results demonstrate two key findings: First, for all electrode types, applying firm pressure in the "tight state" dramatically improved signal quality by reducing baseline wander and suppressing motion artifacts. This confirms that a stable mechanical interface is essential for reliable signal acquisition with dry electrodes.

Second, there is a strong correlation between the electrode's filling density and the resulting signal fidelity. The lower-density electrodes (30% and 50%) produced detectable but noisy ECG signals. In contrast, the 80% and, most significantly, the 100% filled electrodes delivered exceptionally clean and stable waveforms. This performance improvement is directly linked to the lower intrinsic resistance and larger conductive surface area of the higher-density designs. The signal from the 100% filled electrode in the "tight state" (Fig. 4d) is of note, as its clean morphology, with well-defined P, QRS, and T waves, is qualitatively indistinguishable from the signal produced by the gold-standard Ag/AgCl gel electrode. These results conclusively validate that by optimizing the physical design through high filling density and ensuring a stable mechanical interface, embroidered electrodes can achieve a level of performance comparable to clinical-grade electrodes, making them a viable and practical solution for wearable health monitoring.

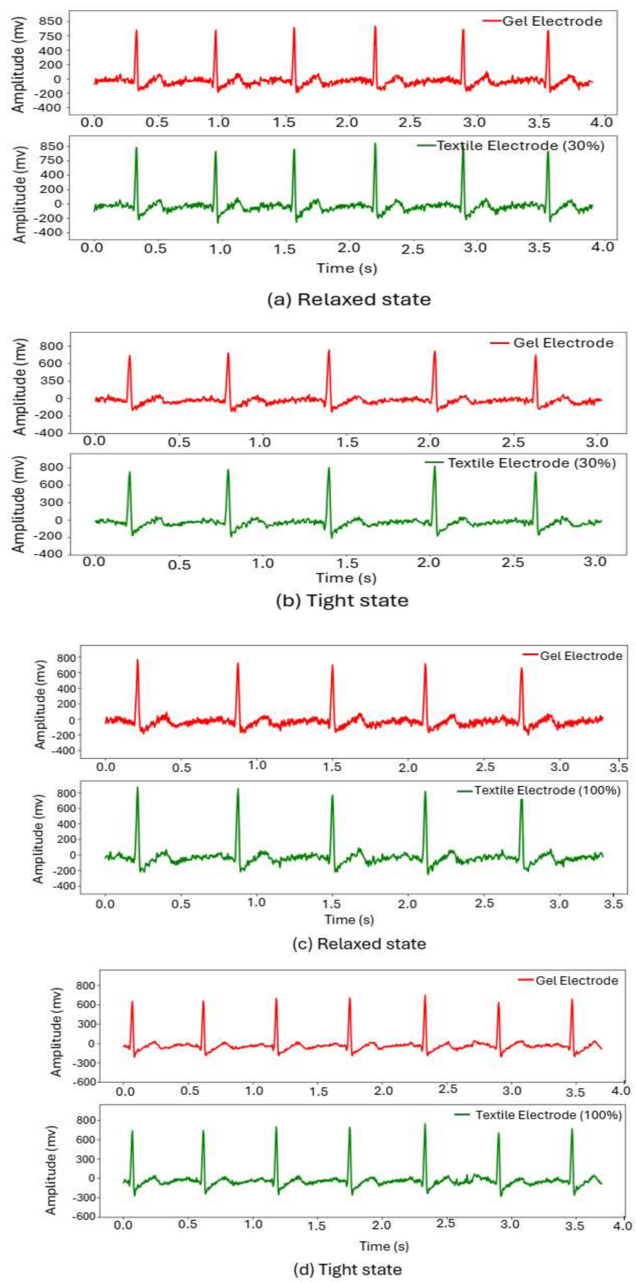


Fig. 4 ECG signals recordred with gel and embroidered electrodes using with different material filling percentages and conditions. a) 30% filled compared with gel electrodes in relaxed state; b) 30% filled vs gel electrodes in tight state; c) 100% filled compared with gel electrodes in relaxed state; d) 100% filled vs gel electrodes in tight state.

D. Results of Different Substrates

In addition to ECG measurement, our embroidered electrodes can be utilized for other types of biopotential measurement in various scenarios. For example, we also embroidered the open-sourced patterns onto multiple cases, including a compression wrist for EMG sensing, a shirt sleeve as a touch sensor, cushion fabric for seats, etc. The designs and results demonstrated that the proposed embroidered electrodes are a viable and cost-effective option for wearable and/or at-home and driving monitoring. The ease of fabrication, reusability, and adaptability, particularly their ability to deliver smooth and reliable biopotential measurement, make them promising candidates for continuous health monitoring. We hope that open-sourcing the code and patterns can provide the research community with a practical tool for clinical and other applications.

IV. Conclusion

This work presents a programmable embroidery-based approach for fabricating dry-contact textile electrodes for biopotential monitoring. By systematically controlling design parameters such as stitch geometry, filling density, conductive thread selection, the proposed embroidered electrodes demonstrated comparable electrical performance to gel-based ones. Real-time ECG acquisition confirmed the effectiveness of the embroidered electrodes, with signal quality improving significantly under tight skin contact, particularly when supported by an elastic band. The open-source platform enables low-cost, customizable electrode design and supports seamless integration into fabric substrates, enabling ubiquitous monitoring in daily life and clinical applications.

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