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Original Article

Design and Characterization of flexible Electrodes for Long-Term ECG Monitoring

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Long-term, non-invasive electrocardiogram (ECG) monitoring is essential for vulnerable populations such as neonates, pregnant women, and the elderly. Conventional Ag/AgCl gel electrodes, while clinically reliable, are limited by issues including skin irritation, signal degradation, and discomfort during prolonged use. This study presents the development of flexible, dry electrodes with knitted conductive fabric, woven conductive fabric, and thin graphene sheets. The proposed electrode design ensures wearer comfort. The knitted fabric type provides excellent flexibility and stretchability for wearer comfort, whereas the woven type offers superior mechanical strength and durability. Graphene sheets, though mechanically weaker, significantly enhance electrical conductivity.The electrodes are fabricated on a silicone flap substrate developed using biocompatible Liquid Silicone Rubber (LSR) to ensure safe and skin-conformable application. The electrodes undergo comprehensive characterization including surface morphology and elemental composition via Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS), mechanical strength and flexibility through Universal Testing Machine (UTM) testing, and extensive electrical analysis. Electrical properties are evaluated using impedance spectrometry under both dry and wet conditions (after immersion in phosphate-buffered saline), AC conductivity measurements, voltage-frequency response, and four-probe electrical characterization. The impedance analysis reveals reduced contact resistance in wet conditions simulating skin-electrode interface, indicating improved signal conductivity. Among the developed electrodes, graphene based electrodes showed the best signal quality (45.14 dB), clearly exceeding the other types including Ag/AgCl. The results demonstrate that graphene sheets, when integrated with a biocompatible silicone substrate, combine mechanical robustness, electrical stability, and wearer comfort—delivering stable, high-fidelity ECG signals suitable for continuous, real-time cardiac monitoring applications.

Introduction

The global burden of cardiovascular diseases (CVDs) continues to rise, with millions affected across all age groups. According to the World Health Organization, CVDs account for approximately 32% of all global deaths, many of which could be prevented through early diagnosis and continuous health monitoring [1]. Among the instruments for early detection, the electrocardiogram (ECG) is still indispensible for evaluating the cardiac electrical activity and spotting anomalies including arrhythmias, ischemia, and myocardial infarction [2]. Constant ECG monitoring is particularly important for vulnerable groups such as new-borns with congenital heart defects, pregnant women prone to gestational arrhythmias, elderly people with declining cardiovascular resilience, and patients undergoing remote care or rehabilitation [3,4]. In such situations, long-term, non-invasive, pleasant monitoring solutions are required to guarantee continuous health data collecting without generating patient pain or skin-related issues. Conventional Ag/AgCl gel electrodes are not appropriate for continuous monitoring even if they are somewhat common in clinical settings. These electrodes make skin contact using conductive gels, which causes problems like gel dehydration, rising impedance with time, skin maceration, allergic responses, and user discomfort [5,6,16,17]. Moreover, the regular necessity for repositioning and reapplication compromises the feasibility of Ag/AgCl electrodes in long-term or ambulatory monitoring situations [7]. These limitations hinder the effectiveness of traditional ECG systems in wearable healthcare solutions, driving a growing interest in dry electrode alternatives. Textile-based dry

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electrodes represent a promising direction for next-generation bio potential sensing. These electrodes, integrated into garments or patches, offer significant benefits: comfort, flexibility, washability, and mechanical adaptability to body movements [8,9]. Unlike wet electrodes, they eliminate the dependency on gels and reduce maintenance, making them more appropriate for applications in telemedicine, home monitoring, and fitness tracking [10]. However, challenges such as variable contact pressure, motion-induced artifacts, and inadequate electrical performance still persist, particularly in low-signal scenarios or during dynamic movement [11].

As an extension of Industry 4.0, and after the discovery of 5G communication, Big Data, the Internet of Things, and Internet-connected devices, there have been several research studies conducted on wearable electronic devices. In particular, wearable devices, textile sensors, mobile computing, and cloud computing are becoming more and more important in personal health monitoring systems. Smart clothing systems combine clothing with membrane electrodes and can be used for various functions, including physical signal sensing, energy storage, temperature and humidity monitoring, and thermal energy management. Common smart clothing systems include electrocardiogram (ECG) and electromyography (EMG) smart clothing. The greatest advantage of ECG smart clothing devices is that they are non-invasive and can still display the complete P-Q-R-S-T waveform, which is commonly used to determine the presence of heart rate or nerve conduction problems, arrhythmia, conduction block, accelerated conduction, and other conditions. In addition, ECG waveforms can provide clinical references to doctors by measuring the interval between R-R waves (time difference between heartbeats) and heart rate (beats per minute). Hence, ECG smart clothing can provide one of the best indicators of physical fitness and heart function. However, traditional bio electrodes use a disposable gel-type Ag/AgCl electrode, which is the most widely used gel-type electrode in clinical applications. The surface adhesive can effectively fix the electrode onto the skin, reducing electrode slippage and enhancing the stability of the impedance between the electrode and skin. Nevertheless, the Ag/AgCl electrode is not conducive to long-term daily monitoring because the hydrogel layer between the skin and electrode degrades over time, leading to a deteriorated signal quality and skin irritation from the adhesive. Moreover, owing to the specific preparation required to connect the cables to the device before measurement, these electrodes can only be used to record signals for up to a few hours. To overcome these problems, researchers have attempted to develop flexible dry electrodes to replace the gel-type one; these can be integrated into textile products. Textile/flexible dry electrodes are needed for long-term bio potential monitoring, especially in vulnerable populations such as neonates, pregnant mothers, and the elderly, as they provide greater comfort. Ungelled electrodes based on textile substrates have gained attention for their seamless integration into garments, enabling unobtrusive, wearable health monitoring. Conductive textiles composed of silver-coated, carbon-infused, or polymer-based fibers exhibit promising electrical conductivity while maintaining softness, stretchability, and biocompatibility [18-21]. Developed a smart garment incorporating textile electrodes, achieving reliable ECG acquisition even under dynamic conditions. To overcome these limitations, graphene - an atomically thin carbon nanomaterial known for its superior electrical and mechanical properties - has been explored for electrode enhancement. Researchers [22, 23], have highlighted graphene's potential for next-generation wearable electronics, including ECG applications to enhance the reliability and performance of dry electrodes, researchers have explored the integration of nanomaterials - especially graphene - into textile substrates. Graphene is a two-dimensional carbon material known for its extraordinary electrical conductivity, large surface area, and excellent mechanical flexibility [12,13]. When used in biosensors, graphene contributes to reduced contact impedance, improved signal-to-noise ratio, and enhanced biocompatibility, all of which are crucial for capturing high-fidelity ECG signals [14,15].

Graphene-coated textiles, or textile-graphene hybrids, offer enhanced surface conductivity, lower skin-electrode impedance, and long-term stability [24,25]. For instance, [24] showed how graphene yarns buried into fabric electrodes lowered contact resistance and enhanced signal quality across a broad frequency range. Similarly, [25] produced printed graphene sensors on flexible materials and showed steady ECG signal capture for more than twenty-four hours. Characterizing hybrid electrodes means verifying homogeneous material integration by means of surface morphological and composition analysis. Detailed topographical and elemental dispersion of the materials is shown by scanning electron microscopy (SEM) and energy dispersion X-ray spectroscopy (EDS [26,27]. While [27] guaranteed uniformity in conductive layers, studies by [26] employed SEM to validate the adherence of graphene coatings on fabric substrates. Apart from structural study, mechanical testing is essential to evaluate the endurance of these electrodes against wear, elongation, and stress. Tensile strength tests of various textile topologies were conducted by researchers such as [28] in order to link elasticity with signal consistency during motion. The fundamental measurement for bio potential electrodes is electrical performance, which is routinely evaluated in simulated physiological environments. Four-probe resistance measurements, AC conductivity testing, and impedance spectroscopy provide information on how well electrodes preserve electrical integrity in dry vs. moist environments - that which phosphate-buffered saline (PBS) [29,30] mimics. For instance, [30] found a relationship between ambient conductivity and impedance decrease via frequency-response tests on textile electrodes under different humidities to mimic sweat or skin moisture. Graphene's conductive performance under such biological simulations has also been explored. To further optimize electrode design and predict behavior under different stress and electrical conditions, simulation tools such as CAD modeling and COMSOL Multiphysics have been increasingly used [31]. COMSOL is used to model current density across flexible electrode substrates, revealing hotspots that inform material optimization [32]. Modelled potential distribution to minimize signal distortion and improve user comfort [33]. Tested textile-based graphene electrodes submerged in PBS and noted reduced skin-electrode impedance and improved signal-to-noise ratio over gel-based controls. These simulations are critical to bridge the gap between laboratory development and real-world deployment.

The novelty of this study lies in the electrode design that balances comfort, robustness, and signal quality. Knitted fabric electrode, with their high stretchability and conformability, are suited for dynamic anatomical regions, whereas woven type provide tensile strength and durability. Graphene sheet layers further enhance conductivity and reduce skin–electrode impedance.

The objectives of the study include, (a) to design and fabricate flexible electrodes variants by embedding conductive knitted fabric, woven type and graphene layers in biocompatible silicone flaps to improve comfort and electrical performance for ECG monitoring; (b) to evaluate the mechanical properties of the developed electrodes through tensile testing; (c) to verify material composition and structural integration using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS); (d) to characterize the electrical performance of the electrodes under dry and wet conditions using impedance spectroscopy, AC conductivity analysis, and four-probe measurements; and (e) to compare the performance of the developed wearable electrodes with conventional Ag/AgCl wet electrode based on electrical characteristics and signal fidelity

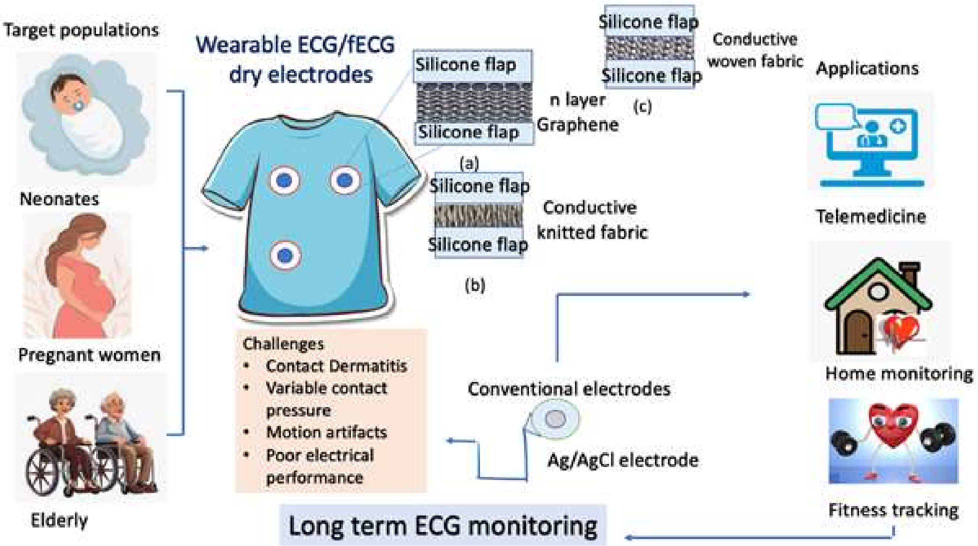

Figure 1: General framework of graphene/conductive fabric based wearable electrode

The scope of this work encompasses both material-level innovations and system-level evaluations. The goal is to develop a viable textile-electrode platform that can replace traditional Ag/AgCl electrodes in long-term, continuous monitoring scenarios - especially where wearability, patient comfort, and stable bio potential signal acquisition are paramount. By bridging the gap between material science and wearable healthcare technology, this study contributes to the growing ecosystem of intelligent, patient-centric medical devices.

Materials and Methods

The figure 1 outlines the research workflow, starting from electrode fabrication with conductive textiles and graphene sheets, followed by mechanical, morphological, and electrical characterizations, leading to simulation, performance evaluation, and potential biomedical applications.

The research workflow begins by identifying target populations - such as neonates, pregnant women, and the elderly - who require long-term, non-invasive ECG or fetal ECG (fECG) monitoring. To address limitations of conventional Ag/AgCl gel electrodes, including contact dermatitis, variable contact pressure, motion artifacts, and poor electrical performance, wearable dry electrodes are developed and integrated into clothing. These electrodes are fabricated using biocompatible silicone flaps combined with textile/graphene sheet to enhance comfort, flexibility, and signal quality. Once embedded in garments, these electrodes enable continuous, high-fidelity biopotential signal acquisition suitable for various applications, including telemedicine, home health monitoring, and fitness tracking. This integrated approach bridges advanced material design with practical wearable healthcare solutions, supporting long-term ECG monitoring without the drawbacks of traditional wet electrodes.

To construct the flexible dry electrodes, three distinct materials were employed: knitted conductive fabric, woven conductive fabric, and thin graphene sheets shown in figure 2(a), (b) and (c). These were selected for their complementary mechanical, electrical, and physiological properties essential for wearable ECG applications. The sensing elements were integrated onto a biocompatible silicone flap, serving as the substrate, to ensure flexibility, durability, and comfort during long-term skin contact.

Knitted conductive fabric

The knitted conductive fabric [36-38] is selected for its exceptional elasticity and ability to conform closely to the body's contours, making it particularly suitable for wearable biomedical applications. Constructed using silver-coated nylon yarns, the fabric offers a combination of electrical conductivity and soft texture, ensuring both functional efficiency and user comfort. Its interlocked loop

Figure 2(a): Woven conductive fabric with copper and nickel plated Nylon (b) Knit Jersey conductive fabric with cotton, silver, yarn and spandex (c) conductive graphene sheet

Table 1: Comparison of materials used in development of wearable electrodes

Property	Knitted Fabric	Woven Fabric	Graphene Sheet
Material Composition	Silver-coated nylon	Silver-plated polyester	CVD-grown or solution-processed graphene
Thickness	0.0091 cm / 0.091 mm / 91 µm	0.0410 cm / 0.410 mm / 410 µm	0.0025 cm / 0.025 mm / 25 µm
Surface Resistance	~0.1–0.5 Ω/sq	~0.2–0.6 Ω/sq	< 50 Ω/sq
Flexibility	Very High (Multidirectional stretch)	Moderate (Low stretch, high stiffness)	High (conformal, flexible layer)
Mechanical Durability	Moderate (prone to deformation under strain)	High (retains shape under stress)	Moderate (requires careful handling)
Breathability	High	Moderate	N/A (dependent on substrate)
Biocompatibility	High (skin-friendly yarns)	High	Very High (excellent for skin contact)
Primary Function	Ensures contact stability during motion	Provides structural integrity	Enhances electrical conductivity & signal quality
Use Case in Electrode	Outer/Contact Layer	Structural/Base Layer	Intermediate Conductive Layer

structure allows multidirectional stretchability, which helps maintain consistent skin contact even during body movements. Obtaining steady and strong biopotential signals depends on this attribute. With a surface resistivity ranging from around 0.1 to 0.5 Ω/sq. and a thickness of 0.0091 cm (91µm), the fabric has high stretchability, breathability, and skin-friendly qualities - all of which help to explain this material's fit for long-term wearable ECG monitoring uses - are among its key benefits.

Woven conductive fabric

The electrode design using woven conductive fabric [39,40] provides enhanced electrical conductivity, mechanical support, and dimensional stability. Silver-plated polyester fibers which were densely interwoven to create a strong and durable construction make up this fabric. Although the woven material lacked the suppleness of knitted materials, its great structural rigidity made it perfect for preserving shape and performance during lengthy usage and under mechanical stress. Its 0.0410 cm (410 µm) fabric thickness and surface resistivity between 0.2 and 0.6 Ω/sq shown outstanding tensile strength, resilience to repeated washing, and consistent shape retention, qualities vital for durable and dependable wearable electrode systems.

Thin graphene sheet

Integration of a thin graphene sheet into the electrode assembly serves as a conductive enhancement layer; its high quantum capacitance facilitates efficient capacitive coupling of ECG signals between the skin and the sensor, improving signal acquisition.Owing to its atomic-scale thickness and exceptional electrical conductivity, graphene significantly reduced the skin–electrode impedance and enhanced the clarity of biopotential signals [41,42]. The graphene is either CVD-grown or solution-processed and subsequently applied to the textile substrates through thermal lamination or spray coating methods, depending on the compatibility of the base fabric. With a sheet thickness of 0.0025 cm (25/µm) and a sheet resistance of less than 50Ω/sq, the graphene layer offered outstanding electrical performance, high biocompatibility, and excellent conformability to the underlying textile surface, making it a critical component in achieving stable and high-fidelity ECG signal acquisition.

The table 1 highlights key differences among the three sensing elements, knitted fabric, woven fabric, and graphene sheet, in terms of thickness, surface resistance, flexibility, mechanical strength, and biocompatibility.

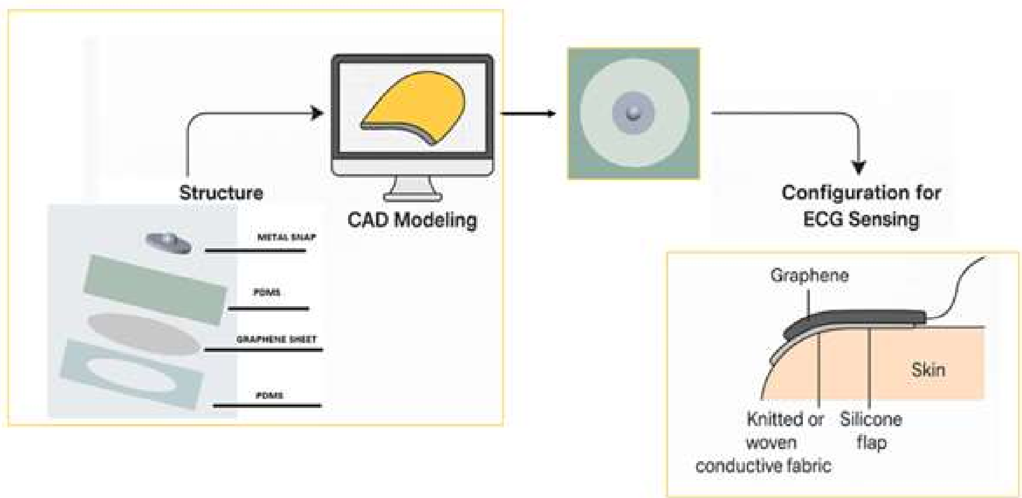

Figure 3: Schematic illustration of textile/graphene electrode design

Electrode design and fabrication

Figure 3 shows the schematic depiction of the textile/graphene electrode design, illustrating the integration of knitted conductive fabric, woven conductive fabric, or a graphene layer on a silicone flap for ECG sensing.

Electrode structure

At the top, the metal snap serves as the electrical signal connector, followed by a Polydimethylsiloxane(PDMS)layer providing insulation and support for subsequent layers. Positioned beneath the PDMS layer, the sensing elemnet, with a diameter of 2 cm, that functions as the primary conductor. Additionally, another layer of PDMS, featuring a 1.5 cm diameter opening at the center, is located further down, exposing the graphene sheet for direct external surface contact. This design ensures the effective and reliable detection of ECG signals while prioritizing user comfort and flexibility. The sensing element is encased in PDMS layers. The utilization of soft and flexible materials in these electrodes enhances user comfort, rendering them more tolerable for extended wear.

Mechanical characterization

Tensile qualities and durability of the produced textile electrodes are evaluated by mechanical characterization. Following the ASTM D5035, generally accepted for textile break and elongation testing, tensile strength and elongation tests were conducted using a Shimadzu AG-X Universal Testing Machine with a 10 kN load cell. Testing was done with a constant rate of extension of 100mm/min with a gauge length of 100cm. Important criteria for wearable biomedical electrodes, this test evaluates mechanical strength, flexibility, elongation at break, and material deformation behavior under stress.

During the test, force and elongation were continuously monitored and recorded. The system captured real-time stress-strain data. Observations included any delamination or structural failure, particularly relevant for composite samples. The mechanical test results, including tensile strength and elongation at break, were used for comparative analysis of the different textile configurations. These findings were instrumental in identifying the most mechanically robust and skin-compliant structure suitable for long-term ECG monitoring applications.

Morphological and elemental analysis

Scanning Electron Microscopy (SEM) serves as a powerful tool for analyzing the surface morphology of the textile-based electrodes. The Carl Zeiss EVO 18 Research model provided high-resolution imaging. To ensure optimal conductivity and imaging contrast, a thin gold coating covered each sample using a sputter coater. Operating under a high vacuum with an accelerating voltage of 15 kV, the instrument revealed distinct morphological features:The woven electrode displayed tightly packed, linear fiber arrangements with minimal surface irregularities, offering high tensile integrity.The knitted electrode exhibited interconnected looped structures, confirming its inherent flexibility and extensibility. The graphene sample showed a continuous wrinkled film structure, indicating strong interfacial adhesion. This morphological data confirms the feasibility of the sensing elements for stable and conformable ECG monitoring electrodes.

Energy dispersive x-ray spectroscopy (EDS) complements SEM by identifying and quantifying the elemental composition of the electrode surfaces. EDS analysis enabled the detection of key elements contributing to conductivity and material performance.

Electrical characterization

Electrical characterization evaluates how effectively the textile electrodes conduct electrical signals across various operating conditions. This section outlines the impedance, conductivity, voltage-frequency behavior, and four-probe resistance profiling under dry and PBS-wet conditions.

To investigate frequency-dependent electrical resistance, impedance measurements were performed using the Solartron 1260A Impedance/Gain-Phase Analyzer. The test frequency ranged from 1 Hz to 10 kHz, suitable for biopotential signal analysis such as ECG.Under dry (normal) conditions, the conductivity (ó) and resistivity (ñ) of the electrode material are related by:

$$\sigma = \frac{1}{\rho} \qquad (1)$$

Using the geometric configuration of the sample, resistance (R) is derived from:

$$R = \frac{\rho l}{A} \qquad (2)$$

where, l = length of the sample, A = cross-sectional area.

Impedance (Z) at a given frequency is computed by:

$$Z = \frac{V}{I} \qquad (3)$$

with both voltage (V) and current (I) measured in relation to frequency. Graphene-based electrodes exhibited significantly lower impedance across all frequencies compared to knitted and woven fabrics, confirming superior electron transport properties and interfacial charge mobility.

In PBS-wet conditions, samples were pre-immersed in phosphate buffered saline (PBS) for 10 minutes before testing. The PBS environment simulated the ionic strength and osmolarity of human sweat, resulting in reduced impedance due to improved ionic pathways between electrode and surrounding medium.

AC conductivity (σ_{AC}) is calculated directly from impedance data, considering the geometric structure of the electrode:

$$\sigma_{AC} = \frac{1}{Z \cdot A} \qquad (4)$$

Here, Z = impedance at a given frequency, A = contact area of the sample.

Graphene electrodes maintained high conductivity across the entire spectrum, even under PBS-wet conditions, validating the uniform distribution of conductive pathways.

Voltage–frequency response

Voltage-frequency analysis provides insights into electrode stability under varying signal conditions. A Tektronix AFG3022B Dual-Channel Arbitrary/Function Generator supplied input voltages of 20 mV, 50 mV, 500 mV, 1 V, and 1.5 V, with frequencies ranging from 4 Hz to 1 kHz. Figure 4, the electrical characterization setup shows (a) impedance measurement using an LCR meter and (b) voltage-frequency analysis using a function generator and oscilloscope with a 2 cm textile electrode sample.

The output response is captured using a KEYSIGHT InfiniiVision MSOX4054A mixed signal oscilloscope. A 2 cm diameter circular sample is clipped between: an input electrode connected via a metal snap, and a sensing electrode made from a circular copper-plated PCB of matching dimensions.The results indicated that the graphene electrodes preserved signal amplitude and phase integrity

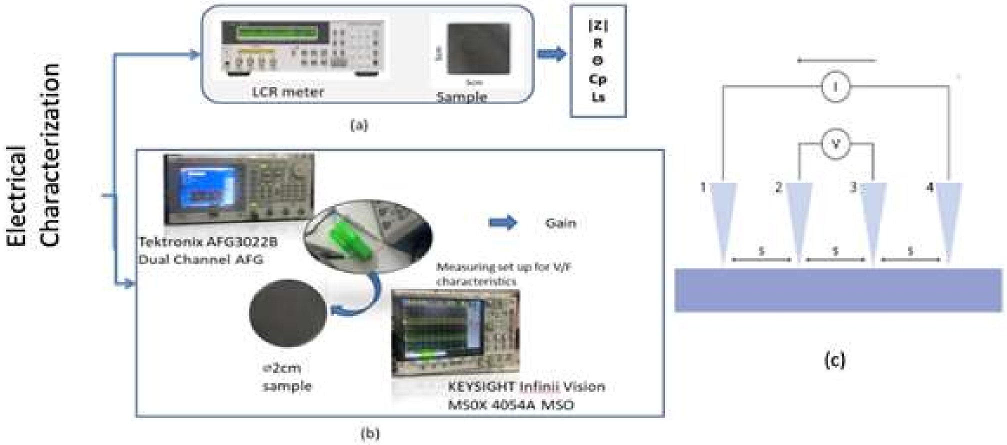

Figure 4: (a),(b) Electrical characterization setup (c) Schematic representation of 4 probe configuration

across the tested frequency band, while woven and knitted fabrics showed noticeable attenuation at higher frequencies.

Four-probe method

The four-point probe method eliminates contact resistance and enables accurate measurement of intrinsic material resistivity.

Probe 1 and 4: Inject constant current (I),

Probe 2 and 3: Measure voltage drop (V).

The resistivity (ñ) is determined using the formula:

$$\rho = \frac{\pi t V}{\ln(2) I} \quad (5)$$

Where, t = thickness of the sample, V = voltage measured, I = applied current.

Figure 4 (c) provides a schematic representation of the four-probe configuration. The setup ensures uniform probe spacing (s) and clean electrical contact. Graphene electrodes showed the lowest sheet resistance, followed by woven and then knitted structures.

Phosphate Buffered Saline (PBS) solution replicates the ionic conductivity of human sweat and extracellular fluid, enabling standardized simulation for testing bioelectronic electrodes. PBS serves three key functions: mimics ionic strength and osmolarity of the human body, maintains pH stability at 7.5, and provides non-toxic, non-reactive behavior during testing. Although not chemically identical to sweat, PBS offers consistency in simulating electrolyte-based skin conditions.

Prior to testing, the textile samples were submerged in PBS for 10 minutes to ensure full wetting and electrolyte absorption.

Results and Discussion

The fabricated flexible dry electrodes were thoroughly characterized through morphological, mechanical, and electrical evaluations. SEM analysis revealed distinct surface morphologies for the woven, knitted, and graphene samples, with EDS confirming elemental compositions specific to each structure. Mechanical testing demonstrated that the woven fabrics exhibited higher tensile strength, while the knitted samples showed superior elongation, and the graphene-enhanced variants provided balanced mechanical and electrical performance. Impedance analysis under dry and PBS-wet conditions highlighted a noticeable decrease in impedance when hydrated, simulating skin contact, with frequency-dependent trends and reduced contact resistance in graphene-integrated samples. Electrical characterizations showed improved AC conductivity and stable voltage-frequency responses in the hybrid electrodes, while four-probe testing validated low resistance and favourable phase angle, capacitance, and inductance values, supporting high-fidelity signal transmission. Compared with conventional Ag/AgCl electrodes, the developed dry electrodes delivered comparable or better signal quality with enhanced comfort, wearability, and long-term usability, making them promising alternatives for continuous ECG monitoring.

SEM and EDS analysis

The surface morphology of the textile electrodes is analyzed using Scanning Electron Microscopy (SEM), while their elemental compositions were determined through Energy-Dispersive X-ray Spectroscopy (EDS). The SEM image of the knitted conductive fabric (Figure 5(a)) reveals a highly entangled fiber structure with overlapping loops, suggesting greater mechanical compliance and enhanced conformability to the skin surface. The woven conductive fabric (Figure 5 (b)), in contrast, exhibits an organized, interlaced pattern with defined rectangular pores, indicating better structural integrity. Meanwhile, the graphene thin sheet (Figure 5 (c)) shows a continuous, wrinkled topology, characteristic of exfoliated graphene sheets, promoting a large surface area for electrical interaction.

EDS spectra further shown in figure 6 confirmed the elemental makeup of the respective samples. The knitted fabric showed dominant peaks for carbon, oxygen, and silver, suggesting the integration of Ag-based conductive materials within a carbonaceous textile base. Table 2 presents the elemental composition of the knitted and woven conductive fabric as determined by EDS analysis. The fabric primarily contains carbon and oxygen, with a significant presence of silver indicating successful integration of conductive material. The woven fabric displayed (figure 6(b)) high concentrations of copper and nickel, indicative of metallic yarns. The woven fabric primarily consists of copper (52.84 wt%) and nickel (36.79 wt%), indicating high conductivity. Minor amounts of carbon and oxygen suggest an organic base material. In the case of the graphene sheet, EDS detected only carbon (figure 6(c)), validating its high-purity structure without contamination. According to the manufacturer's data, the graphene thin sheet consists of 97% carbon,confirming its high purity and suitability for applications requiring excellent electrical conductivity.

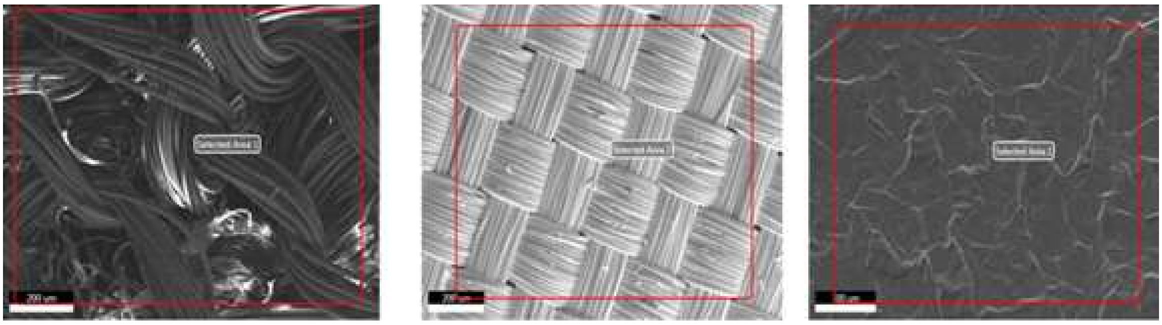

Figure 5: (a) SEM image of knitted conductive fabric (b) SEM image of woven conductive fabric

The SEM and EDS analyses confirmed that the knitted fabric offers high conformability with silver integration, the woven fabric provides structural integrity with copper and nickel content, and the graphene sheet exhibits pure carbon composition ideal for superior conductivity. These findings validate the hybrid electrode materials' suitability for high-performance, long-term ECG monitoring.

Mechanical properties

The mechanical performance (figure 7) of the textile electrodes is assessed based on tensile strength and elongation. The knitted conductive fabric demonstrated a tensile strength of 85.229 N/mm² and a high elongation of 139%, indicating excellent flexibility and decent strength. This balance is ideal for wearable applications that require conformity to body movements without material failure. In contrast, the woven conductive fabric(figure 8) exhibited a significantly higher tensile strength of 759.794 N/mm² but a much lower elongation of 29.83%, suggesting it is structurally strong but relatively stiff and less suitable for dynamic anatomical regions.

The graphene thin sheet, based on standard technical data, displayed a tensile strength of approximately 30 MPa. Although lower in strength compared to the woven fabric, its intrinsic flexibility and exceptional electrical conductivity make it a valuable component for enhancing electrode performance. Overall, the knitted fabric provides high elasticity, the woven fabric offers mechanical robustness, and graphene contributes flexibility with superior conductivity—making the hybrid integration of all three materials beneficial for durable and wearable ECG electrodes.

Impedance Analysis

The impedance characteristics of the developed textile electrodes were evaluated under both dry and phosphate-buffered saline (PBS)-

Table 2: Elemental composition of conductive fabrics

Material	Element	Weight %	Atomic %
Knitted Type	C K	46.28	62.60
	O K	33.89	34.41
	Ag L	19.82	2.99
Woven Type	C K	7.36	27.11
	O K	3.02	8.35
	Ni K	36.79	27.73
	Cu K	52.84	36.81

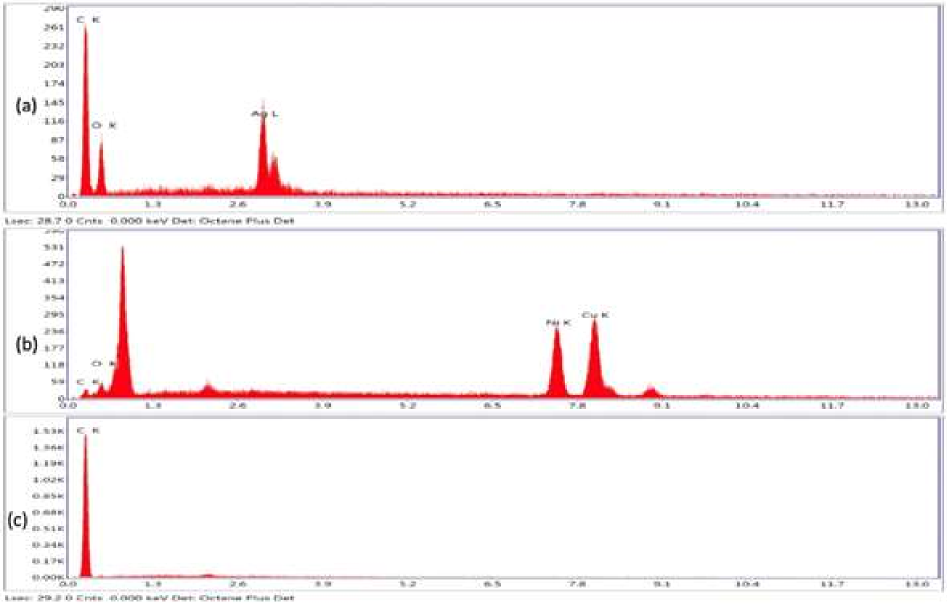

Figure 6: (a) EDS data of knitted conductive fabric (b) EDS data of woven conductive fabric(c) EDS data of graphene thin sheet

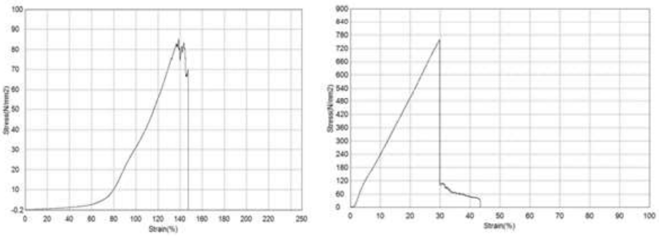

Figure 7: (a) Stress–strain curve of knitted conductive fabric (b) Stress–strain curve of woven conductive fabric

Table 3: Impedance values of textile electrodes in dry and PBS-wet conditions

Material	Impedance Range (Dry, Ω)	Impedance Range (PBS-Wet, Ω)
Woven	0.21427 – 0.21561	0.17116 – 0.17469
Knitted	5.3487 – 5.59714	6.1564 – 6.7106
Graphene	22.345 – 30.290	6.0860 – 6.3019

Table 4: AC conductivity of various electrodes at low frequency

Material	Conductivity (S/m)
Knitted conductive fabric	0.35
Woven conductive fabric	15.00
Graphene thin sheet	1.50
Ag/AgCl adhesive electrode	0.0117

wet conditions to assess their electrical performance in physiological environments. The results are summarized in table 3. In the dry state, the woven conductive fabric exhibited the lowest impedance range (0.214–0.216 Ω), attributed to its high metal content (Cu and Ni) and tightly interlaced structure that minimizes contact resistance. The knitted fabric presented moderate impedance values (5.35–5.60 Ω), which can be ascribed to its looped and porous architecture. In contrast, the graphene electrode exhibited the highest impedance (22.35–30.29 Ω), likely due to its planar sheet structure and poor interfacial contact in the dry state. Upon PBS wetting, a significant impedance reduction is observed for the graphene electrode (6.09–6.30 Ω), indicating improved ionic conductivity and interface hydration. The woven fabric's impedance also decreased slightly (0.171–0.175 Ω), while the knitted fabric showed a slight increase (6.16–6.71 Ω), possibly due to moisture retention altering the contact surface.

Impedance spectra across varying frequencies revealed a typical frequency-dependent decrease, consistent with capacitive coupling effects. This trend is more pronounced in PBS-wet conditions, affirming enhanced charge transport in hydrated environments.

The contact resistance analysis indicated that the woven structure, due to its metallic integration, exhibited minimal interfacial resistance. Conversely, the knitted fabric demonstrated higher contact resistance due to loose fiber connections and air gaps. The graphene sheet, although initially resistive in dry conditions, showed considerable improvement in contact conductivity under PBS treatment, confirming its suitability for biopotential monitoring when hydrated.

Electrical performance

The electrical performance of the textile-based electrodes, including knitted, woven, and graphene thin sheet types, has been comprehensively examined. Key parameters include AC conductivity, signal transmission quality across frequencies, and intrinsic electrical properties such as resistance, capacitance, inductance, and phase angle. These characteristics play a crucial role in determining the electrodes' suitability for real-time biopotential acquisition in wearable healthcare systems.

AC conductivity comparison

Table 4 presents the measured AC conductivity at low frequency, which is particularly relevant for bio signal applications such as electrocardiography (ECG). Among all samples, the woven conductive fabric demonstrated the highest conductivity (15 S/m), attributed to its dense metallic fiber content (Cu/Ni) and well-structured geometry. The graphene thin sheet recorded moderate conductivity (1.5 S/m), benefiting from the inherent electronic properties of graphene, while the knitted fabric yielded 0.35 S/m due to its looped and elastic structure. Notably, all samples outperformed the commercial Ag/AgCl adhesive electrode, which showed the lowest conductivity (0.0117 S/m).

Voltage-frequency characteristic response

From table 5, Signal transmission efficiency is further evaluated at 100 Hz using an input signal of 20 mV. The graphene thin sheet achieved the highest detected voltage (19.890 mV) and signal-to-noise ratio (SNR = 45.14 dB), indicating superior electrical sensitivity and minimal signal degradation. The woven electrode also displayed robust signal performance (SNR = 37.96 dB), followed by the knitted electrode (SNR = 36.32 dB). In contrast, the Ag/AgCl electrode registered the lowest SNR (31.78 dB), reinforcing the benefits of novel gel-less alternatives.

Four-probe electrical characterization

From table 6, four-probe measurements below 100 Hz frequency provide critical insight into the resistive-capacitive-inductive characteristics of the electrodes. The woven electrode displayed the lowest resistance (0.27 Ω), supporting its excellent signal conductivity and charge storage capacity. The knitted fabric showed moderate resistance (5.35 Ω) and a near-zero phase angle, indicating a balanced resistive-capacitive interface with minor inductive influence. The graphene thin sheet exhibited the highest resistance (22.8 Ω) with a moderate parallel capacitance (30μF), suggesting stable behaviour and consistent signal conduction across the interface.

Performance comparison with Ag/AgCl electrodes

This section evaluates the developed textile-integrated and graphene-based electrodes against conventional Ag/AgCl gel electrodes in terms of signal quality, comfort and wearability, and long-term monitoring potential.

From table 7, the knitted, woven, and graphene electrodes exhibited comparable or superior signal quality to Ag/AgCl electrodes when tested under identical conditions (100 Hz, 20 mV input). The

Table 5: Voltage-frequency characteristics at 100 Hz

Electrode Type	Input Voltage (mV)	Detected Voltage (mV)	SNR (dB)
Woven	20	19.750	37.96
Knitted	20	19.695	36.32
Graphene	20	19.890	45.14
Ag/AgCl	20	19.498	31.78

Table 6: Four-probe electrical properties below 100 Hz

Electrode Type	Frequency	Resistance (Ω)	Cp (µF) [Parallel capacitance]	Ls (mH) [Series Inductance]	Phase Angle (°)
Knitted	<100 Hz	5.35	11.31	0.0003	0
Woven	<100 Hz	0.27	128.39	0.0002	0.21
Graphene	<100 Hz	22.8	30	0	0

detected voltages for textile and graphene electrodes were close to the input signal, indicating minimal signal attenuation. The graphene-based electrode delivered the highest signal-to-noise ratio (SNR), reflecting exceptional signal fidelity and low electrical noise. Textile electrodes (knitted and woven) also demonstrated good signal stability, making them viable alternatives to gel-based electrodes.

Ag/AgCl electrodes, while clinically reliable, often present limitations such as skin irritation, drying of the conductive gel, and reduced adhesion during prolonged use. In contrast, knitted and woven electrodes, which are soft, flexible, and seamlessly integrated into fabrics, offer enhanced comfort, better skin conformity, and non-irritating contact surfaces. Although the graphene thin sheet is slightly stiffer, it provides lightweight coverage and, when properly laminated onto fabric, offers acceptable wearability suitable for continuous monitoring applications.

Ag/AgCl electrodes are prone to degradation over time due to gel drying, making them unsuitable for continuous or long-term monitoring, particularly in wearable healthcare applications. In contrast, textile electrodes demonstrate strong structural and electrical stability over extended periods, with the added benefits of being washable, reusable, and capable of delivering consistent signal performance in both dry and PBS-wet conditions. Additionally, the graphene electrode, characterized by its high purity and chemical stability, exhibits minimal degradation, positioning it as a promising candidate for chronic and long-term physiological monitoring.

Knitted, woven, and graphene electrodes outperform Ag/AgCl electrodes in terms of comfort and longevity, with graphene showing the best electrical performance. These alternatives demonstrate strong potential for next-generation, long-term wearable ECG monitoring systems.

Discussion

The performance of the proposed electrode design is analyzed in relation to existing textile- and graphene-based methods, highlighting key differences in structural configuration, electrical characteristics, and long-term monitoring performance.

The proposed method integrates conductive fabric elements/graphene layers within a biocompatible silicone substrate, combining flexibility, mechanical strength, and high conductivity. The knitted electrodes exhibited impedance ranges of 5.35–5.60 Ω (dry) and 6.16–6.71 Ω (PBS-wet), while the woven electrodes showed 0.214–0.216 Ω (dry) and 0.171–0.175 Ω (PBS-wet). The graphene-integrated electrode achieved 6.09–6.30 Ω (PBS-wet). In terms of signal quality, the proposed graphene configuration recorded a signal-to-noise ratio (SNR) of 45.14 dB, which is significantly higher than knitted (36.32 dB), woven (37.96 dB), and conventional Ag/AgCl (31.78 dB) electrodes. These results demonstrate the method's strong electrical stability and superior signal fidelity. Earlier textile-based studies typically reported impedance values above 10 Ω under dry conditions and SNR values ranging between 28–35 dB during long-term monitoring [18-21], often affected by unstable skin–electrode contact and motion artifacts. Similarly, graphene-based electrodes in previous works achieved impedance levels of 8–12 Ω under wet or sweat-simulated conditions with SNR values typically between 38–42 dB [24, 25].

Table 7: Voltage detection and signal-to-noise ratio (SNR)

Electrode	Detected Voltage (mV)	SNR (dB)
Woven	19.750	37.96
Knitted	19.695	36.32
Graphene	19.890	45.14
Ag/AgCl	19.498	31.78

Simulation-focused studies [31,32] emphasized optimizing current distribution to minimize resistive losses and improve signal stability. The present experimental findings support these observations, showing low intrinsic resistance and stable voltage–frequency responses across the physiological range.

Conclusion

This study reports the design, development, and performance comparison of capacitive electrodes for gel-free ECG monitoring. The electrodes were fabricated on a biocompatible silicone flap substrate, developed using Liquid Silicone Rubber (LSR) to ensure skin safety and mechanical adaptability for wearable applications. Morphological analysis using SEM and EDS confirmed successful integration of conductive materials, while mechanical tests highlighted the flexibility of knitted fabrics and the strength of woven types. Electrical characterization under dry and PBS-wet conditions demonstrated excellent conductivity, low impedance, and high signal-to-noise ratios, particularly for graphene-enhanced variants. Compared with conventional Ag/AgCl gel electrodes, the proposed electrodes offered improved comfort, long-term usability, and stable performance without the limitations of conductive gels. The graphene electrodes with high SNR remained effective over prolonged durations and were suited for dynamic environments due to their flexibility. Future developments will explore enhanced hybrid structures through advanced graphene integration directly onto textile substrates, enabling even better conductivity and form-factor adaptability. These improvements aim to optimize real-time, continuous health monitoring systems in wearable biomedical applications.

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