Evaluating Dry Electrodes and Bioinstrumentation for Wearable Arm ECG Acquisition

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Abstract- **Arm-based electrocardiogram (ECG) offers a more comfortable and user-friendly alternative to traditional chest ECG for wearable cardiac monitoring in daily health applications. However, arm ECG faces challenges such as capturing extremely low-amplitude signals in the microvolt range and significant electromyogram (EMG) noise contamination. The aim of this study was to evaluate the performance of dry electrodes for arm and chest ECG monitoring using gold standard BIOPAC and proposed mDAQ systems. This study consisted of two phases. In Phase 1, we evaluated different dry electrode materials, including silver knit fabric and gold-plated electrodes, with six healthy adult participants (N = 3 males and N = 3 females) having upper arm circumference ranging from 27 to 42 cm. We used a BIOPAC system as a gold standard to collect arm ECG, upper arm EMG, and reference chest ECG during standardized movement tasks. Results showed that silver knit electrodes demonstrated superior QRS energy (0.705 ± 0.151), surpassing chest gel floating ECG QRS energy (0.328 ± 0.026), with lower EMG interference across movement conditions. In Phase 2, we developed a bioinstrumentation system (mDAQ) optimized for dry electrodes, demonstrating reliable ECG acquisition in both chest Lead I and arm configurations. -We validated our bioinstrumentation with sixteen healthy adult participants (N = 8 male and N = female). The mDAQ system maintained high signal consistency with a skewness effect size of 0.963 and showed a mean heart rate bias of only -1.842 bpm compared to the BIOPAC system, confirming its viability for wearable ECG monitoring applications.**

Keywords—Bioinstrumentation, gold plated electrodes, biopotential electrode, BIOPAC, arm ECG, Silver knit electrodes, Adjustable armband.

I. Introduction

Electrocardiogram (ECG) is a primary method for cardiac monitoring, traditionally performed using dry electrodes placed on chest measurements due to its proximity to the heart [1]. However, chest-based ECG wearables can be cumbersome and require gender-specific designs, often scoring low in usability compared to alternatives [2]. Recent studies indicate that the upper left arm, below the shoulder deltoid (triangular-shaped muscle covering the shoulder joint), yields high R-wave amplitudes among non-conventional locations [3, 4]. Since the mid-upper arm circumference is smaller than the chest, electrode orientation must be adjusted evenly across the arm to minimize noise and muscle artifacts [5]. Employing a standard three-electrode configuration around the upper arm, aligned with the heart's dipole, can minimize common mode noise and mitigate powerline-based disturbances [6]. Past studies have developed custom-fit armbands tailored to individual arm anatomy to ensure proper electrode orientation and contact pressure [7]. However, arm ECG faces challenges such as capturing low-amplitude signals in the microvolt range and significant electromyogram (EMG) noise contamination [8]. This influences dry electrodes particularly since the lack of gel results in higher skin-electrode impedance and more motion artifacts, requiring appropriate bioinstrumentation system design [9].

Compared to chest ECG, datasets on arm ECG are limited, and only a few studies have investigated the influence of noise during different movements using dry electrodes [5]. Furthermore, research on electrode materials and orientations is scarce due to the difficulty of prototyping armband electrode positions tailored to participants' arm circumferences.

To address these issues, we present a two-phase research project with a systematic evaluation of both electrode materials and bioinstrumentation. In Phase 1, we evaluate different dry electrode materials for arm ECG acquisition and characterize EMG interference patterns during standardized movement tasks. We compare silver -knit fabric and gold-plated electrodes using a research-grade BIOPAC system to establish baseline performance metrics. Phase 2 focuses on validating our custom-designed bioinstrumentation system (mDAQ) optimized for dry electrode characteristics, primarily through Lead I ECG measurements while also including preliminary feasibility testing of arm ECG acquisition.

Our key contributions scientific in this work include:

- Development and customization of wearable armband with dry ECG electrodes: In this study, we developed an adjustable, fabric-based armband integrated with dry electrodes and bioinstrumentation for capturing arm ECG data. The armband utilizes silver knit and flexible gold-plated electrodes, which were tested for optimal placement and performance on various upper arm sizes.
- Human study: We performed a two-phase study to evaluate ECG signal quality from different dry electrodes and bioinstrumentation systems.
- Signal quality analysis: For phase one, we performed a time-frequency domain analysis of synchronized EMG and multichannel ECG signals to assess the impact of movement noise and muscle artifacts on the quality of upper-arm ECG signals. In phase two, we compare the

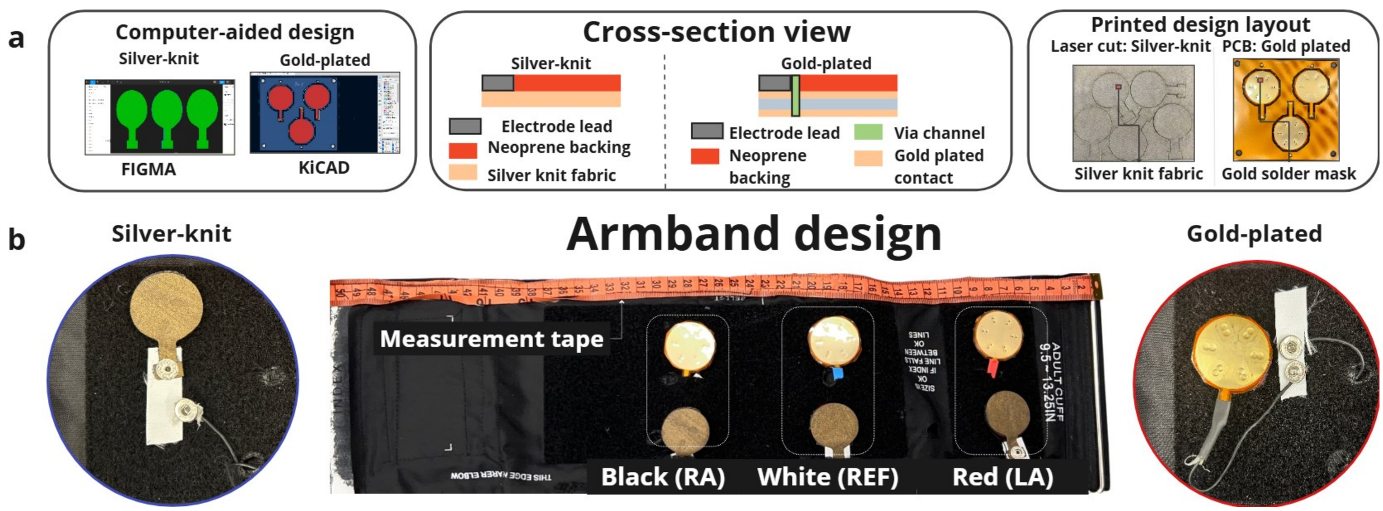


Figure 1: a) Development process of armband with dry electrodes. b) Layout of armband with adjustable dry electrodes

different bioinstrumentation system based on ECG signal quality and heart rate measures.

These findings advance the development of comfortable, reliable wearable ECG monitoring systems while providing crucial insights into the challenges and solutions for arm-based measurements. The results support the potential of textile-based dry electrodes for long-term ECG monitoring when paired with appropriate bioinstrumentation design.

II. Materials

A. Dry Electrode Fabrication

The development of flexible and biocompatible electrodes with both lower impedance and better conductivity is crucial for wearable biosensing applications of arm ECG [9]. Previous research in our lab has found that silver knit dry electrodes can maintain lower impedance even with varying sweat levels and are comparable to standard gel electrodes for ECG [10]. In this study, we have employed rapid prototyping of silver knit electrodes along with flexible printed circuit board (flex-PCB) based gold-plated electrodes seen in Fig. 1 (a).

For the silver knit electrodes, we used Shieldex Siltex silver knit fabric [11]. The fabric was precisely cut into 30mm disk shapes with a stalk using a 40W CO_2 laser cutter (GlowForge), guided by 2D patterns designed in Figma graphic editing software [12]. To enhance contact pressure with the skin and secure electrode wires, we added neoprene backing and snaps as shown in Fig. 1 (a). The electrodes were then connected using stretchable multicore copper conductive wires to ensure durability and flexibility.

For the gold-plated electrodes, we designed 30mm Flex PCB circuits in KiCAD PCB layout software. These electrodes featured conductive copper and stiffener layers with an exposed solder mask serving as the conductive patch as shown in Fig. 1 (a). Contact pads of electrodes were integrated with wires and snaps, allowing seamless attachment to base armbands.

B. Textile Armband Design

The armband used in this study was adapted from a standard 50 cm adult blood pressure cuff, with the inflation bladder removed [13]. A measuring tape was stitched along its length to facilitate precise electrode placement. The original soft Velcro for securing the blood pressure cuff was repurposed to attach the electrodes to the armband. Adjustable channels were designed, allowing each electrode to move horizontally up to 8 cm, providing a ±4 cm range for repositioning. Each electrode was equipped with flexible wires and snap interfaces, enabling quick and secure attachment to the armband and easy adjustment of electrode locations as needed. When donned, the left arm electrode was fixed on the outer side of the upper arm, with the metal ring of armband aligning in front. The reference electrode was positioned in the center, and the right arm electrode was placed near the axilla. The integration and configuration of the silver-knit and gold-plated electrodes on the armband are illustrated in Fig. 1 (b). Each electrode wires are terminated into Molex connector to directly connect with BIOPAC analog modules for measurement.

C. Wearable bioinstrumentation – mDAQ

Dry electrodes for ECG bioinstrumentation introduce challenges like higher skin-electrode impedance and signal instability, leading to increased noise and artifacts [9]. This impedance mismatch between electrodes and the absence of conductive gel worsens baseline and motion artifacts. This requires the bioinstrumentation hardware that have a high input impedance and suitable filters.

We propose a data acquisition system, namely mDAQ, that utilizes the MAX30001G analog front-end in conjunction with Raspberry Pico W dual-core microcontroller for 16-bit ECG measurements. The MAX30001G biopotential amplifier features a single biopotential channel providing electrocardiogram (ECG) waveforms and heart rate detection [14]. It was selected for its ability to handle impedance mismatch between dry electrodes through configurable filter passbands, making it ideal for ECG and heart rate monitoring in free-living conditions. The system architecture of the proposed wearable bioinstrumentation system including all peripherals within the system is shown in Fig. 2

The biopotential amplifier interfaces over SPI bus with the Raspberry Pico W microcontroller that can configure and acquire 16-bit ECG signals with a gain of 160V/V and passband of 0.5Hz to 45Hz at 128Hz sampling rate. The dimensions of the proposed mDAQ acquisition hardware with the 3D printed enclosure are 90 x 52 x 17mm and weighs 63g. The system is powered by a rechargeable 3.7V lithium-ion battery with a rated capacity of 400mAH. The other sensors and peripherals present within the mDAQ are connected to the microcontroller over the I2C port. Additionally, the system also uses the RV8803 real-time clock to maintain system timestamps. During operation, the ECG data is logged at 128Hz to the SD card upon receiving a start trigger from the TSOP38238 infrared receiver. To ensure consistent sampling despite SD logging, the operations are split between the dual cores of the Pico W microcontroller. The sensor data payloads are formatted as character tab-separated values by the sampling core and passed onto the datalogging core through Semaphore synchronization [15]. The sensor data is logged to a new file within the SD card every 2-minutes. The filenames were assigned based on the unix-timestamp epochs from the RTC.

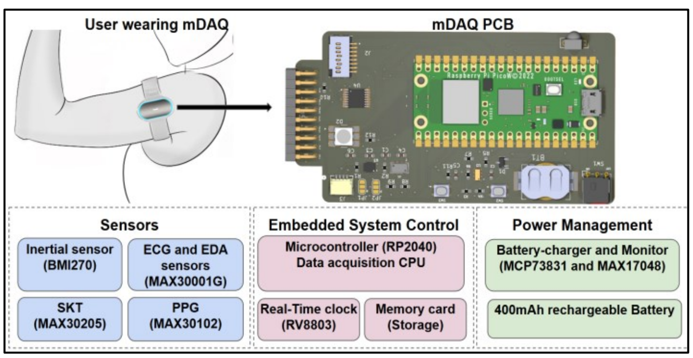


Figure 2: Embedded system architecture for bioinstrumentation.

III. Methods

A. Phase 1-Study Setup

The Phase 1 was aimed to evaluate different dry electrodes for acquiring arm ECG. We used MP160 BIOPAC system, known for its research-grade biopotential modules for collecting biosignals. We employed the BioNomadix 2-Channel ECG and EMG amplifiers [16] for simultaneous data collection. We recruited six healthy adult (above 18 years) participants (three males and three females) who signed consent before data collection. The participant's upper arm circumference varied between 27 cm and 42 cm, prompting adjustments to the orientation of the dry electrodes on the armband before wearing. The setup included two types of electrodes for upper arm ECG—silver-knit and gold-plated electrodes—randomized in top and bottom of the band. Additionally, two gel EMG electrodes were placed at the center of the muscle belly below the deltoid, with a reference electrode on the elbow's bony area. Reference gel electrodes were also attached to the right and left upper chest regions. All ECG and EMG modules were secured using Velcro, with the chest ECG module attached at the waist. The core aim of phase 1 is to understand how the signal quality of different dry electrodes vary during different upper body movements.

B. Phase 2 – Study Setup

Phase 2 was aimed to validate mDAQ bioinstrumentation system. We have compared mDAQ bioinstrumentation system with BIOPAC 2-channel ECG. We have first compared lead one ECG configuration for BIOPAC and mDAQ using silver knit electrodes (We have used silver-knit electrodes since they had comparable results with chest-gel electrodes in phase one). The Lead 1 ECG study was conducted with a total of 16 healthy adult (above 18 years old) participants, consisting of an almost equal number of male and female who provided informed consent. In addition to that, we have performed upper arm ECG feasibility testing with mDAQ and silver knit electrodes on one participant. To synchronize our bioinstrumentation with the BIOPAC system, we utilized an external trigger feature of BIOPAC software. The external trigger in BIOPAC was configured to detect a positive edge cycle to begin data acquisition for two minutes. The trigger signal was provided to

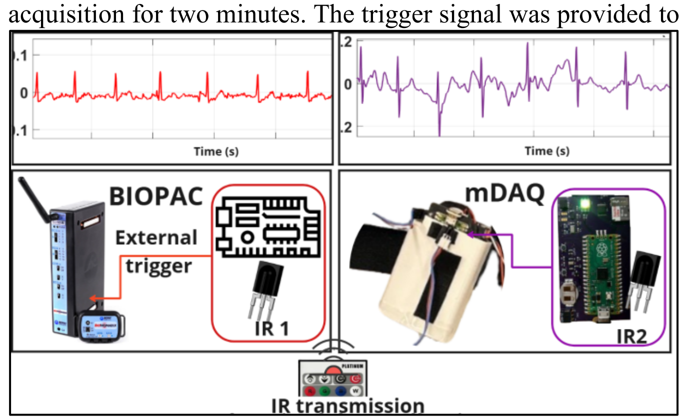


Figure 3: Synchronized data collection setup

BIOPAC using a relay module connected to an Arduino Uno through an infrared receiver (TSOP38238). The same infrared receiver present within our mDAQ system enables synchronized data logging with the BIOPAC system as shown in Fig. 3. This study received approval from the University of Rhode Island Institutional Review Board (IRB No# 2125810).

C. Experimental Procedure

In Phase 1, participants performed tasks based on visual and auditory cues from a TV screen. Participants were first asked to wear and rate the comfort of the armband on a scale of 0-10 before performing all tasks. The protocol consisted of four sets of movement tasks. The first task involved sitting still for 2 minutes. The second and third tasks required arm flexion-extension and arm up – down movement. For these tasks, participants rested for 20 seconds, then performed the movement for 5 seconds, followed by another 20-second rest, and repeated this sequence until 120 seconds had elapsed.

Lastly, for walking, participants were asked to sit for starting 10 seconds, then walk normally for next 50 seconds and then sit back for one minute as listed in Table 1.

Table 1: Experimental tasks with activity breakdown

Exercise	Duration	Activity breakdown
Sitting	120s	Sitting in chair with armrest
Arm Flexion-Extension	120s	20s rest → 5s move (repeated)
Arm up-down	120s	20s rest → 5s move (repeated)
Walking	120s	10s sit → 50s walk → 60s sit

Phase 1 study setup with all activities are showed in Fig. 4. All signals were recorded at a sampling rate of 125 Hz. While EMG spans a wide frequency band, our focus is specifically on EMG noise within the ECG frequency band. All the electrodes along with armband were cleaned using UV-treatment prior to data collection.

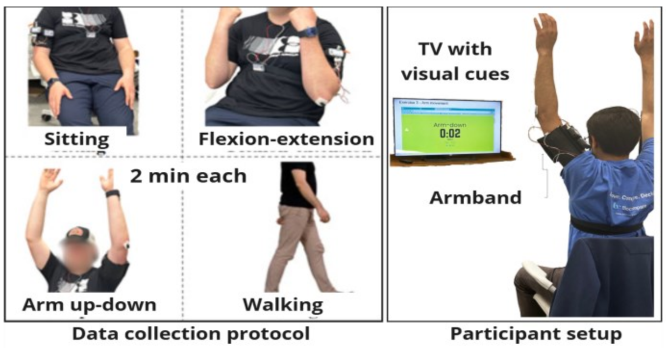


Figure 4: Phase -1 Experimental study setup

Based on Phase 1 results, we chose silver knit electrodes with mDAQ bioinstrumentation board for Phase 2 of the study. For Lead 1 configuration, two pairs of dry electrodes were attached to each participant's hands, with one pair connected to the BIOPAC system and the other to the mDAQ system. Hydrogel medical tape was used for attaching dry electrodes, which was gentle on the skin compared to gel electrodes. Additionally, we focused on the upper left arm region above the bicep, where R-wave peak intensities in ECG are higher [4]. To avoid common mode noise, we used 3-electrode configuration for arm ECG. In our experiment, we integrated dry electrodes with hook-loop patches on the back of a neoprene and attached to a stretchable band. The upper arm circumference of the participant was measured to ensure the six dry electrodes were evenly distributed on the hook-loop strap. The armband was securely wrapped around the arm to guarantee proper skin contact. Three electrodes were connected to the BIOPAC system, and the remaining three to the mDAQ system in a single-arm configuration as illustrated in Fig. 5. Additionally, a set of gel electrodes was connected to another channel of the BIOPAC system in Lead 1 configuration to serve as a reference.

D. Signal Analysis

The phase one time-synchronized biosignal data analyzed were gel chest ECG, dry arm ECG (Silver-knit and Gold-plated) and gel arm EMG. Significant ECG QRS peaks were observed within EMG data, and arm ECG signals were notably affected by EMG artifacts during arm movements. Fig. 6 shows time-frequency data from thirty seconds extension-flexion extension-flexion data. Consistent power scales across signals ensures accurate comparisons. Our analysis indicates that EMG interference intensifies during active muscle movements. Identifying exact sources of noise is crucial for effectively separating ECG from EMG, required for wearable development and signal processing. To analyze the cross-contamination of signals within the QRS frequency range further, we processed the chest ECG along with the upper arm ECG and EMG signals. We implemented the basic signal processing and analysis pipeline in Python, utilizing functions from the SciPy library package [17]. The BIOPAC acquisition ". mat" files were imported by the Python script sequentially for each participant and exercise type. The ECG signals are band-pass filtered using a 5^{th}-order Butterworth filter between the frequency band of 0.5 to 45 Hz before further analysis.

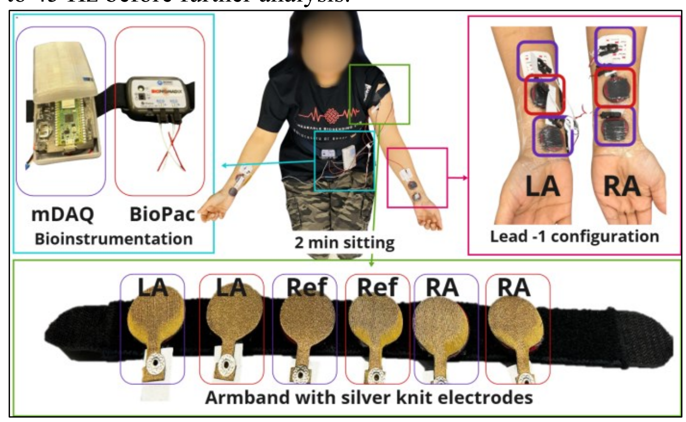


Figure 5: Phase - 2 Experimental study setup

The power spectral density (PSD) of arm, chest ECG, and EMG signals are then extracted using Welch's method that divides data into overlapping segments to compute periodograms that are averaged. Following this, the mean-squared error between the different arm ECG PSD and the chest ECG PSD is computed to understand how the frequency characteristics vary between the exercises for the different dry electrodes. In addition to this, we also compute the cross-spectral density (CSD) between the different upper arm ECG and the EMG signals. CSD is a measure of the spectral density of the cross-spectrum between two signals, and it provides information about the frequency-dependent correlation between different signals [18]. The sum of CSD is utilized to understand EMG interference.

The phase two time-synchronized ECG signals were analyzed for the BIOPAC and mDAQ bioinstrumentation systems for Lead 1 and arm ECG. First, the mDAQ and BIOPAC recordings were loaded sequentially for different participants for the experimental runs. Both the systems had different frequency ranges where mDAQ was sampled in 128 Hz while BIOPAC was sampled for 125 Hz. We have non-linearly interpolated and downsampled mDAQ data to 125 Hz. The ECG signals acquired from mDAQ had a passband of 0.5 to

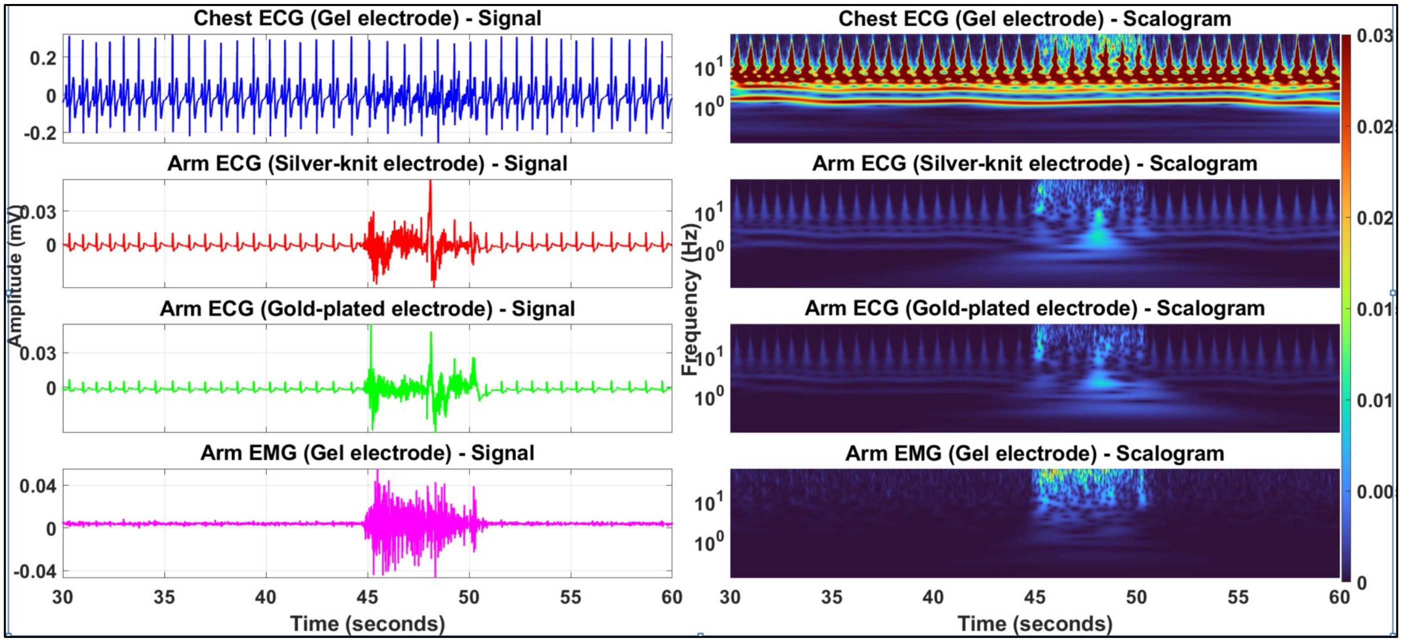


Figure 6:Extension-flexion 30 second signal and frequency distribution

45Hz while BIOPAC system had a passband of 0.05 to 150Hz. The R-peaks of the ECG signals were detected using the Pan Tompkin's algorithm which is used widely and is even implemented on-board the MAX30001G chip. In the MATLAB code, heart rate was computed every 30 seconds for comparison. Individuals ECG beats that are 1.2 seconds long were segmented from the original signal recordings 0.2 second before R-peak and 1 second after the R-peak. Following this, different Signal Quality Index (SQI) measures were extracted from the ECG beats in the experimental datasets. The statistical SQI measures identified for this study were Standard Deviation, Skewness, Kurtosis. In addition to those measures, the energy at specific frequency bands about the QRS component (5-15Hz) and power line spectrum (60Hz) were obtained from the ECG beats.

IV. Results and Discussion

A. *Phase 1: EMG- Arm ECG Interference Analysis for flexible PCB & Silver knit Dry Electrodes on*

Fig. 7 visualizes the mean-square error (MSE) between the PSD of the gel-chest ECG signal compared to the upper arm ECG signals acquired from the silver-knit and gold-plated electrodes. In our analysis of MSE-PSD from ECG recordings during different exercises, we observed that physical activity significantly influences signal quality. The walking exercise had the highest MSE values for both gold-plated and silver-knit electrodes, due to movement artifacts. Sitting, with minimal upper body movements, showed the lowest MSE, suggesting that under resting conditions arm ECG offers similar data quality to chest ECG. The dynamic movements in arm up down and extension-flexion exercises resulted in intermediate MSE values, highlighting a moderate impact of localized arm movements on signal quality. The type of electrodes also played a crucial role in the level of MSE observed; silver-knit electrodes generally produced lower MSE across all activities, suggesting their better adaptability to body movements and potential for reducing noise. In contrast, gold-plated electrodes, being more rigid, were more susceptible to higher MSE, particularly in exercises involving extensive movement like walking.

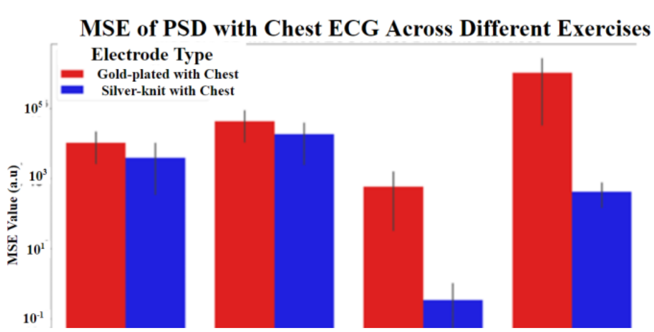
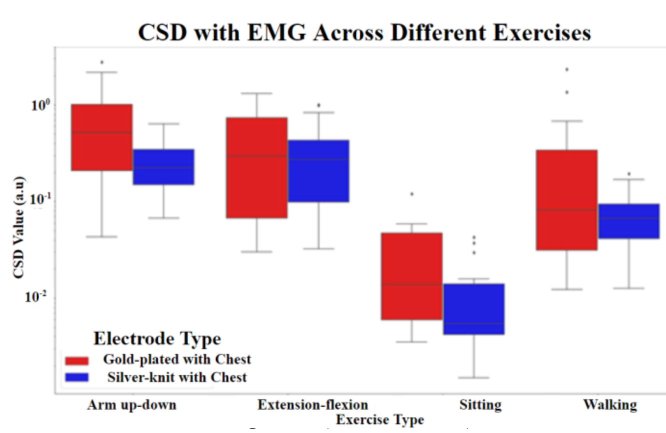


Figure 7: PSD-MSE comparison of arm ECG with dry electrodes to chest ECG with gel electrodes in log-scale (lower is better).



The analysis of Cross Spectral Density (CSD) between upper arm ECG and EMG signals seen in Fig. 8 across different exercises highlights how physical activity impacts ECG signal integrity.

Dynamic exercises, such as arm up-down and extension-flexion, correlate with increased CSD values, suggesting more pronounced interference from upper arm muscle activity. Conversely, the sitting exercise, which involves minimal movement, shows the lowest CSD values, indicating reduced signal disturbance. Walking, involving more complex body movements, also showed higher CSD values with EMG than walking though considerably lower than other movement types.

Regarding electrode performance, the data suggest that silver-knit electrodes tend to exhibit lower CSD values across various exercises compared to gold-plated electrodes, likely due to their better contact with the body during movements improving signal quality. The QRS band energy values across different exercises seen in Table 2 reveal how physical activities impact the ECG signals recorded from the arm, particularly when compared to the more stable chest readings (using gel electrodes).

Table 2: Comparison of ECG QRS band energy with different exercise types.

Exercise	Chest QRS energy	Arm QRS energy (Gold-plated)	Arm QRS energy (Silver-knit)
Arm up-down	0.317 ± 0.101	0.208 ± 0.143	0.205 ± 0.134
Extension-flexion	0.345 ± 0.098	0.172 ± 0.094	0.204 ± 0.243
Sitting	0.358 ± 0.081	0.316 ± 0.138	0.705 ± 0.151
Walking	0.290 ± 0.087	0.233 ± 0.160	0.275 ± 0.174

In general, arm ECG signals (both gold-plated and silver-knit) exhibit lower QRS energy than the chest across most exercises, suggesting greater variability and possibly reduced signal clarity due to movement. Notably, during the sitting, the silver-knit electrode shows a significant increase in QRS energy within 5-15 Hz band (0.705 ± 0.151), surpassing even the chest ECG measurements. This might be due to its measurement with 3-electrode configuration compared to the 2-electrode configuration of chest ECG. Conversely, in more dynamic exercises like arm up-down and extension-flexion, both types of arm electrodes tend to capture less energy compared to the chest, with the gold-plated electrode showing particularly lower energy in extension-flexion. Altogether, silver-knit electrode shows better performance due to conformability and adaptation to skin. Participants also claimed that silver-knit electrode side in armband is more comfortable than gold-plated electrodes due to soft and flexible nature of textile.

B. Phase 2 –mDAQ and BIOPAC Performance Comparison

Analyzing the Gardner-Altman plots in Fig. 9, the mDAQ exhibits a higher skewness with an effect size of 0.963 and a less peaked kurtosis (effect size: -0.373), reflecting differences in signal morphology captured in the two systems. Despite a more pronounced variability, the QRS power spectral density (PSD) shows a lower band energy in mDAQ (effect size: -1.334), suggesting a smoother signal in the 5-15Hz band. The lower energy at the 60Hz band for mDAQ (effect size: -0.558) could imply better rejection of power line interference compared to BIOPAC system potentially due to differences in the filter pass band in both systems.

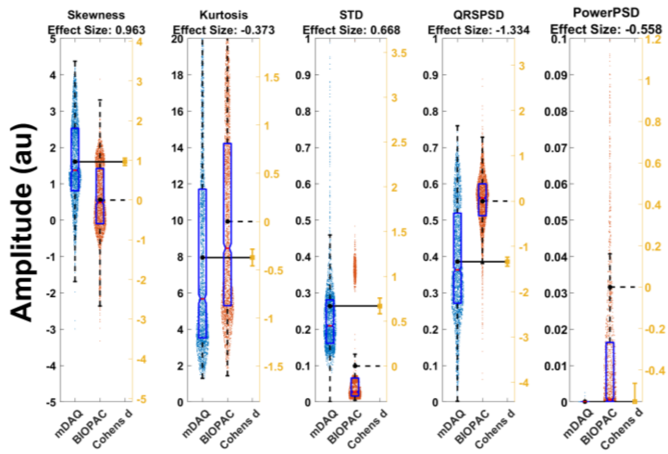


Figure 9: Consolidated Gardener-Altman plot of ECG statistical and power spectral density measures (Blue- mDAQ, Red- BIOPAC)

The Bland-Altman plot comparing heart rate measurements between mDAQ and the reference BIOPAC system can be seen in Fig.10. The plot shows a mean bias of -1.842 bpm, with a confidence interval (CI) of -4.498 to -0.8141 bpm, indicating that mDAQ tends to slightly underestimate heart rate. The limits of agreement are relatively narrow, ranging from -24.63 to 20.94 bpm with CIs of -29.23 to -20.02 bpm and 16.34 to 25.54 bpm, respectively.

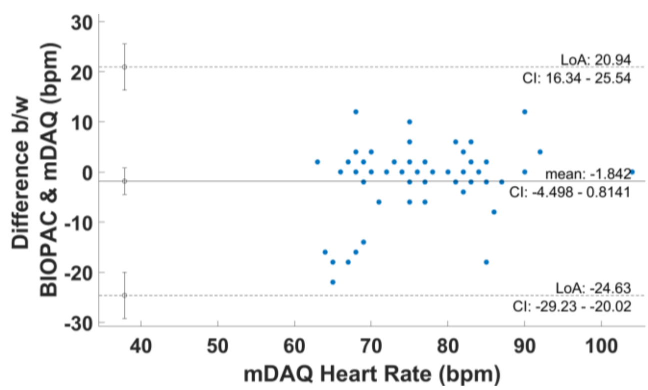


Figure 10: Bland-Altman plot of mean HR between mDAQ and BIOPAC system for 30-second ECG windows

This suggests that while there is some variability between mDAQ and BIOPAC, the measurements are in agreement, indicating the viability of mDAQ for HR monitoring. Fig. 11 shows the simultaneous ECG signals acquired in arm by both mDAQ and BIOPAC using proposed dry electrodes. A standard gel electrode Lead 1 ECG was also acquired for reference. Arm ECG dry electrode amplitudes are smaller as compared to standard Lead 1 gel electrodes due to the smaller biopotential dipole. Despite smaller ECG amplitude both systems can acquire heart beats in arm.

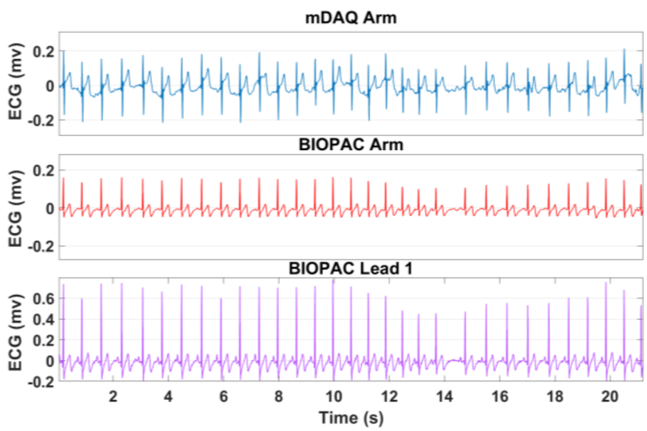


Figure 11: Arm & Lead 1 ECG comparison between BIOPAC and mDAQ system

V. Conclusion and Future Works

This study presents a comprehensive evaluation of both dry electrode materials and bioinstrumentation requirements for reliable arm ECG monitoring. By repurposing an adult blood pressure cuff into an adjustable armband, we developed a platform that accommodates various arm sizes while enabling optimal electrode positioning. Our systematic investigation of electrode materials revealed that silver-knit electrodes, with their flexibility and conformability, consistently outperformed gold-plated alternatives across different movement conditions. This was evidenced by lower MSE and CSD values during dynamic exercises and superior QRS energy during static conditions, suggesting their potential for long-term wearable applications.

The custom mDAQ bioinstrumentation system, optimized for dry electrode characteristics, demonstrated comparable performance to the research-grade BIOPAC system. The close agreement in heart rate measurements, with a mean bias of only -1.842 bpm and narrow confidence intervals, validates its potential for practical applications. While dynamic exercises, especially walking and arm movements, introduced notable signal degradation, the system maintained reliable performance during controlled movements, particularly with silver-knit electrodes. The higher QRS amplitudes observed with mDAQ, attributed to its optimized front-end design for dry electrodes, suggests its suitability for both chest and arm ECG monitoring applications.

Future research will focus on enhancing signal accuracy through multiple approaches. We plan to integrate additional EMG channels for triceps and biceps within a compact, integrated armband to comprehensively assess muscle noise patterns. This will be complemented by developing a robust dataset of simultaneous ECG and EMG recordings, enabling the application of machine learning techniques for effective noise isolation. Additionally, we will evaluate various R-peak detection algorithms and implement advanced noise reduction strategies, including adaptive filters and deep learning algorithms, to ensure reliable heart rate detection during diverse physical activities. These efforts will contribute to refining wearable ECG systems for effective real-time heart monitoring across different user conditions while maintaining signal quality comparable to traditional gel-based systems.

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