

A controlled evaluation of dry textile EEG electrodes using simulated P300 and SSVEP recordings with a gelatin-based skin phantom

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ABSTRACT: Dry textile electrodes offer reduced setup time and improved user comfort, making them attractive for everyday electroencephalography (EEG) recordings. However, dry electrodes typically exhibit higher electrode-skin impedance, so their signal quality must be carefully evaluated for brain-computer interface (BCI) applications. In this study, dry textile EEG electrodes were evaluated using a gelatin-based skin phantom. Simulated EEG recordings during P300 and steady-state visual evoked potential (SSVEP) tasks were delivered through electrodes embedded in the phantom model. Signals recorded from textile electrodes placed on the surface of the phantom show strong agreement with those from Ag-AgCl electrodes. P300 components were clearly observable in the event-related potentials, and distinct spectral peaks were detected at the stimulation frequencies in the SSVEP recordings. These results suggest that dry textile electrodes provide signal quality comparable to conventional Ag-AgCl electrodes under controlled conditions, warranting further investigation into their feasibility for BCI applications.

INTRODUCTION

Electroencephalography (EEG) is widely used in brain-computer interface (BCI) systems due to its non-invasive nature, relatively low cost, and high temporal resolution [1-3]. In conventional BCI systems, EEG signals are acquired using silver/silver-chloride (Ag-AgCl) electrodes together with a conductive gel or electrolyte to reduce electrode-skin impedance. While these electrodes provide high-quality recordings, their use requires skin preparation and gel application, which increases setup time and limits their suitability for long-term or continuous BCI use [4-6].

Dry electrodes have emerged as a promising alternative because they do not require an electrolytic medium and thus reduce setup time [7,8]. Textile-based electrodes offer flexibility and integration with wearable garments, making them well suited for everyday continuous recordings [9-11]. However, dry textile electrodes are often reported to exhibit higher electrode-skin impedance and suffer from reduced signal quality compared to gel-based electrodes [12]. As such, careful evaluation of the signal quality of dry textile electrodes is necessary for long term BCI systems.

While previous studies have demonstrated the

feasibility of textile sensors, validation often relied on human trials where physiological noise and contact variability make it difficult to isolate the intrinsic electrical performance of the textile-to-skin interface and [7,13]. Specifically, physiological variability in scalp anatomy, hair density, and user mental states can obscure subtle differences in sensor impedance and frequency response [13-15]. To address this, gelatin-based skin phantoms have been proposed for high-fidelity, repeatable benchtop testing of EEG electrodes since they exhibit electrical properties similar to those of human skin [16]. While various head models exist, gelatin-based phantoms offer an adjustable level of conductivity that closely mimics human skin [16]. In this study, we utilize a gelatin-based skin phantom to provide a controlled environment for quantitative characterization of dry textile electrodes. While this approach does not account for ecological factors like hair or motion artifacts, it provides a necessary baseline validation of signal quality between dry textile electrodes and Ag-AgCl electrodes.

MATERIALS AND METHODS

Textile electrode fabrication: Textile electrodes were fabricated by knitting a 1 cm by 1 cm patch of conductive threads (carbon-impregnated yarns and silver-plated fibers) into an elastic nylon-Lycra substrate (Fig. 1). The electrodes were connected to snap button connectors via conductive traces.

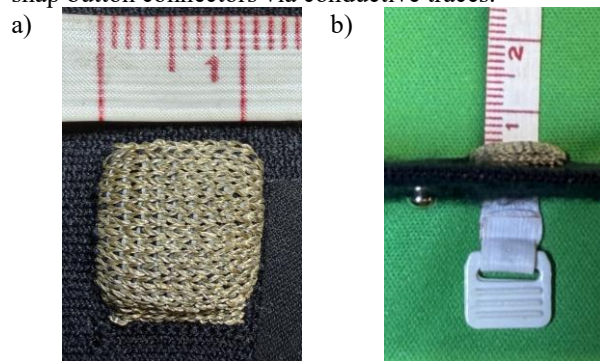


Figure 1: a) Top and b) side view of textile electrode fabricated through Myant proprietary Textile Computing™ (linear mass density of 100-200 Denier, linear resistance <100 Ω /m)

Skin phantom: A skin phantom was prepared according to Owda et al. [16] by mixing 9 g of sodium chloride and 200 g of gelatin powder in 1000 g of deionized water. The mixture was heated in a microwave for 2 minutes and stirred to eliminate clumping. Subsequently, 1 mL of dimethicone and 3 mL of Germall Plus were added as an antifoaming and antimicrobial agent, respectively. The solution was poured into a 1 L plastic food container (21 cm x 15 cm x 7 cm) with two embedded electrodes (3.5 mm gold-plated audio jacks) fixated 10 cm apart at the base of container (Fig. 2). The phantom was cooled at 3°C for 48 hours to allow for complete solidification.



Figure 2: a) Top and b) side view of gelatin-based skin phantom with embedded electrodes

Simulated EEG recordings: To validate the signal quality of the textile electrodes, raw unfiltered EEG recordings were extracted from a public dataset by Lee et al. [17]. These recordings comprise of EEG signals collected during a visual P300 task and a steady-state visually evoked potential (SSVEP) task. In the P300 task, participants selected a target amongst 36 symbols over a total of 1980 trials (330 target, 1650 non-target). In the SSVEP task, participants were instructed to attend one of four target frequencies (5.45 Hz, 6.67 Hz, 8.57 Hz, 12.0 Hz). A total of 100 trials (25 trials per target frequency) were completed. Data from participant 6 in session 2 was selected due to high classification performances reported during this session [17]. The Oz channel was specifically selected for simulation as it is the primary site for recording visual evoked potentials and typically exhibits the highest signal-to-noise ratio (SNR) for these paradigms.

The simulated EEG signals were generated using the 3.3V audio output of a Lenovo Legion Pro 5 laptop. To translate the digital signal into the microvolt range suitable for EEG amplification, a scaling factor was applied. A total gain of 36 was chosen to compensate for signal attenuation through the gelatin medium. This ensured the potential difference at the phantom surface

remained within the typical physiological range (100 μ V), preventing amplifier saturation while maintaining a signal magnitude comparable to real-world recordings. The signals were delivered between two embedded electrodes (output and ground) at the base of the phantom. Signals were recorded simultaneously from textile electrodes and flat snap Ag-AgCl electrodes (OpenBCI) placed on the surface of the gel. Recording electrodes were positioned around the output embedding electrode, while reference and ground electrodes were centered around the ground embedding electrode. A 100 g load was applied to all surface electrodes to ensure uniform pressure application. All signals were collected at a sampling rate of 500 Hz using a wireless EEG amplifier (Liveamp Brain Products, Germany) with an analogue differential DC amplifier (BIP2AUX adapters, Brain Products, Germany). All recordings were made at an ambient temperature of 21°C and a relative humidity of 32%.

Signal analysis: Signals recorded from surface textile and Ag-AgCl electrodes were filtered between 0.3 to 40 Hz. A notch filter was applied at 60 Hz to remove electrical line noise.

For the P300 recording, epochs were extracted from -200 to 1000 ms relative to the visual cue onset. Baseline correction was applied by subtracting the mean of the pre-stimulus interval for each channel. Trial-level agreement was quantified using the root mean-squared error (RMSE) and the Pearson correlation between textile and Ag-AgCl signals.

For the SSVEP task, 4-second epochs were extracted and baseline-corrected using the mean of the entire trial duration for each channel. Power spectral density (PSD) was estimated using the Welch method. The SNR for each target frequency, f_{target} , was computed according to Equation 1. The signal power was defined as the PSD within the 1 Hz band centered around the stimulus frequency, while the noise power was defined as the broadband power between 0.5 Hz and 15 Hz (excluding the signal band).

$$SNR_{f_{target}} = 10 \log \frac{\overline{P_{signal}}}{\overline{P_{noise}}} \quad (1)$$

To facilitate comparison between textile and Ag-AgCl signals, we compute the relative SNR (rSNR) by normalizing the SNR of the textile signals by the SNR of the Ag-AgCl signals (Equation 2).

$$rSNR = \frac{SNR_{textile}}{SNR_{Ag-AgCl}} \quad (2)$$

RESULTS

P300 recordings: Fig. 3 plots the event-related potential (ERP) response from the textile and Ag-AgCl recording during the P300 task. A distinct P300 component can be observed in both ERP signals. The ERP waveform of the textile electrode showed a strong correspondence to that of the Ag-AgCl electrode.

Textile and Ag-AgCl signals had a trial-wise RMSE of $1.10 \pm 0.61 \mu\text{V}$ (mean $\pm$ std dev) and a mean Pearson correlation of 0.9999 ($p < 0.001$), suggesting a high degree of agreement.

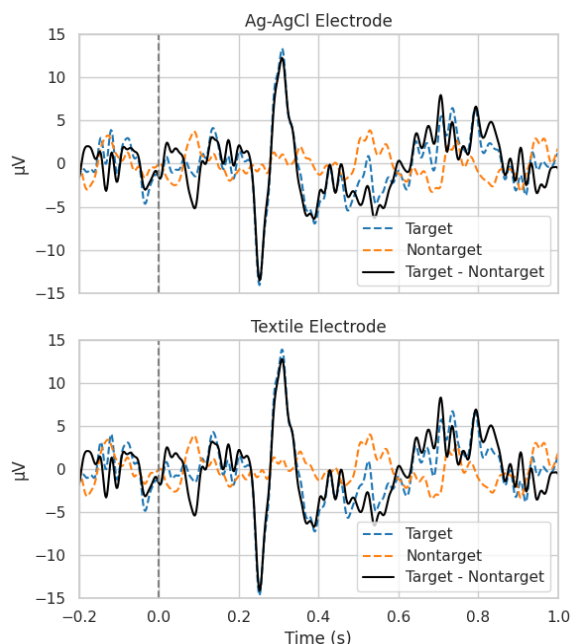


Figure 3: Event related potential response for Ag-AgCl and textile electrodes during simulated P300 recordings

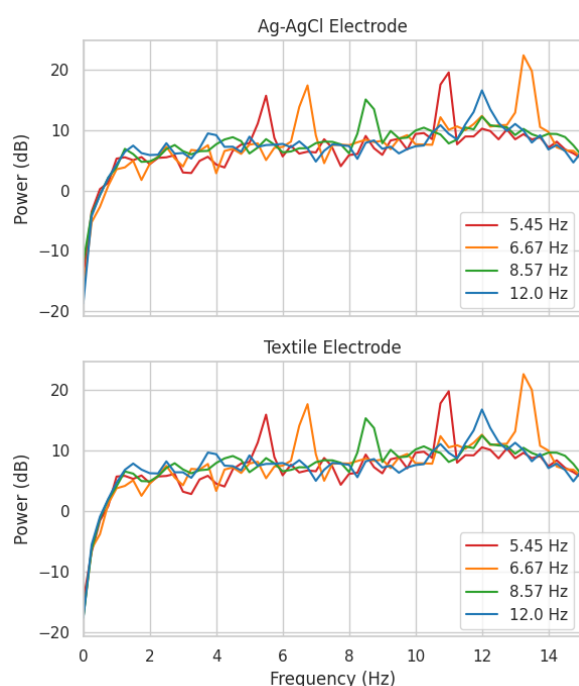


Figure 4: Power spectral density of Ag-AgCl and textile signals during simulated SSVEP recordings

SSVEP recordings: PSDs for each target stimulation frequency during the SSVEP task are plotted in Fig. 4. An increase in spectral energy was observed at the target frequencies in both textile and Ag-AgCl electrodes. Tab. 1 summarizes the SNR from each electrode and the rSNR across all stimulation

frequencies. The mean rSNR remained close to unity across all conditions, indicating strong correspondence between textile and Ag-AgCl recordings during steady-state visual stimulation.

Table 1: Signal-to-noise ratio (mean $\pm$ std dev) of Ag-AgCl and textile electrode during the SSVEP recording

Target Frequency (Hz)	Ag-AgCl Electrode SNR (dB)	Textile Electrode SNR (dB)	rSNR
5.45	7.12 (4.17)	7.08 (4.17)	0.995 (0.014)
6.67	8.79 (4.11)	8.77 (4.10)	0.997 (0.015)
8.57	5.81 (5.28)	5.86 (5.30)	1.021 (0.093)
12.00	9.10 (8.50)	9.05 (8.67)	0.996 (0.022)

DISCUSSION

Signal quality during simulated EEG: Textile signals closely matched Ag-AgCl signals across both simulated P300 and SSVEP recordings. In the P300 task, low RMSE values indicate strong trial-level correspondence between textile and Ag-AgCl recordings, and averaged ERP waveforms revealed clear P300 components in both electrode types, suggesting that dry textile electrodes can capture task-relevant physiological features to facilitate BCI classification.

For the SSVEP task, both textile and Ag-AgCl electrodes exhibited distinct spectral peaks at the target stimulation frequencies and their harmonics. rSNR values remained near unity, suggesting that textile electrodes are comparable in performance to Ag-AgCl electrodes, and can reliably neural responses in the frequency domain. The clear separation between target frequencies further supports the feasibility of using dry textile electrodes for SSVEP-based decoding.

Limitations and future directions: The results demonstrate that dry textile electrodes can replicate both the temporal and spectral characteristics of benchmark Ag-AgCl electrodes under controlled conditions. These findings support the potential of textile electrodes as viable alternatives for EEG recording, particularly in use cases where comfort, wearability, and long-term use are important.

While the present study focused on comparing the signal quality of dry textile electrodes against gold-standard Ag-AgCl electrodes in a controlled phantom environment, further validation is needed to evaluate their performance under realistic recording conditions. Future studies should assess performance in human subjects, where factors such as hair coverage, perspiration, and motion-related artifacts may influence electrode contact and signal stability. Such evaluations will be important for determining the reliability of textile electrodes in practical BCI applications and for guiding the design of wearable EEG systems intended for everyday use.

CONCLUSION

This study presented a systematic characterization of

dry textile EEG electrodes using a gelatin-based skin phantom. By using a controlled phantom setup, we isolated the intrinsic electrical performance of the textile electrode from the biological variability inherent in human trials. Across simulated P300 and SSVEP paradigms, textile signals demonstrated strong correspondence with signals from Ag-AgCl electrodes, supported by high correlation coefficients and consistent spectral power densities at target frequencies. These results suggest that dry textile electrodes are capable of delivering signal quality comparable to conventional sensors in controlled environments, representing a key step toward their integration into wearable, long-term BCI applications.

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