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A Feasibility Study on Textile Electrodes for Transcutaneous Electrical Nerve Stimulation

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Abstract*—Over recent decades, wearable electronics have introduced successful bio-medical products to the commercial market, including real-time monitoring, symptom diagnosis, stimulation therapy, and rehabilitation. Hydrogel electrodes are commonly used in such devices, for data acquisition or electrical intervention. However, they are not a comfortable option for long-term applications and can trigger allergic reactions. Therefore, low-cost textile electrodes are actively being researched as an alternative to hydrogel standards. In this work, we study the efficacy of different electrolyte layers (water, water-in-oil (W/O) cream, and oil-in-water (O/W) cream), placed between the skin and textile-based electrodes, on contact impedance during transcutaneous electrical nerve stimulation (TENS). Both electrode-tissue impedance (ETI) and normalized cross-correlation (NCC) analyses were used to evaluate and compare the performance of textile electrodes with electrolyte to hydrogel electrodes. The study revealed that textile-based electrodes with O/W cream present a viable, effective alternative to hydrogel standards for short-term use, whereas W/O cream presents a possible solution for some longer-term applications.

***Keywords*—Textile electrodes, transcutaneous electrical nerve stimulation, electrode-tissue impedance, EMG.**

I. Introduction

Over the course of the last twenty years the use of wearable biomedical solutions has exploded [1]. Conductive hydrogel electrodes play a vital role in a number of such biomedical devices ranging from neurophysiological diagnostics to electrical therapy [2]. Despite their widespread uptake, however, they suffer from a key set of limitations. Though they are clinically standard, it is well-known that as the electrodes dry out, their performance suffers, with signal quality reducing noticeably with time [3]. Furthermore, the adhesive nature of the electrode is known to cause allergic reactions and irritation when applied for a long time [4], and cause discomfort or pain when removed [5], [6].

To this end, a promising alternative is seen in conductive textile-based electrodes. While the specific designs vary, these instruments are constructed from a conductive fabric layer, medically safe metal connectors, and a soft inner filling to produce an electrically conductive surface able to be applied comfortably to the skin [7]. In addition, a second conducting layer of electrolyte may be needed between the conductive fabric and skin. This is particularly important in applications where moderate amount of electrical current is injected to the body, as in transcutaneous electrical nerve stimulation (TENS) [8] – [11].

Throughout the literature, both pure water and sodium chloride solution are commonly used as electrolytes alongside textile electrodes during electrical stimulation [12], [13]. To this end, both the volume and concentration of sodium chloride required for textile electrode function have been previously established [14]. Furthermore, it has been demonstrated that most water-based electrolytes, such as pure water, saline and conductive gel, gradually evaporate, resulting in signal degradation for long-term use [10]. However, there is not sufficient evidence investigating viable alternative electrolytes for electrical stimulation involving human subject participation and controlled measurement. The aim of this work is to determine the possibility of TENS using textile electrodes and optimal composition/volume of electrolyte to ensure stable performance over both short and long-term timescales. This was achieved by simultaneous ETI and EMG measurements to validate the efficacy of our electrode setup. Fig. 1 denotes some popular placements of wearable TENS devices with proposed textile-based electrodes for different medical purposes, including pain relief, motor impairment rehabilitation and bladder management.

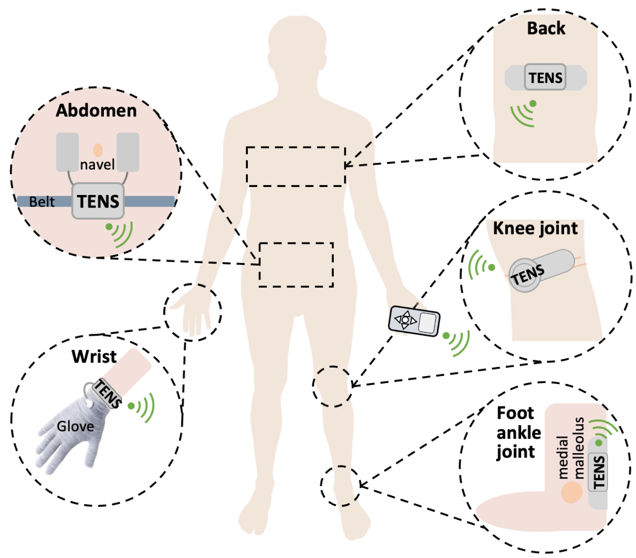

Fig. 1. Examples of various ambulatory TENS devices used for medical applications.

This paper is organized as follows. Section II presents the methodological approaches, section III presents the results and implications, and finally section IV states the conclusions with future work.

II. METHODS

A. Textile Electrode Prototypes

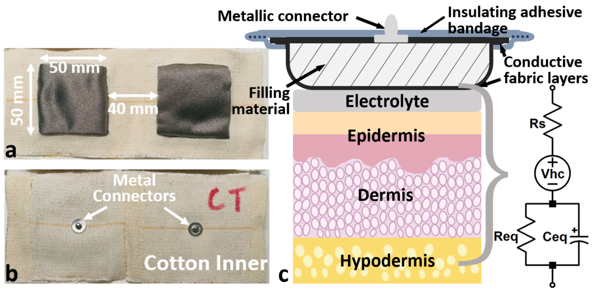

Fig. 2. A manufactured prototype embedded with a pair of textile electrodes in-house. (a) A top view of the electrode prototype. (b) A bottom view. (c) A cross-sectional view of the textile electrode with electrolyte in close contact with the skin surface and an equivalent electrical model of the electrode-tissue interface (adapted from [15]).

The electrode prototypes used in the study comprised a knit conductive fabric, a soft insulating filling, an underlying layer of insulating fabric, and a pair of metal connectors (see Fig. 2a and 2b). During the design process, three different types of insulating filling were considered: polyurethane (PU) sponge, polyester sponge, and natural cotton, respectively. Based on volunteers' feedback, natural cotton was selected due to its soft and comfortable skin contact. In addition, two conductive fabrics of differing resistance were considered in the initial design phase for electrode conducting surface. The first material was comprised of 63% cotton, 35% silver yarn and 2% spandex, while the second one was comprised of predominantly nylon (87%), with a smaller proportion of silver yarn (17%). The former was considered as a better-suited material due to its lower resistance, less than 1 Ω per foot. The equivalent model associated with contact impedance is shown in Fig. 2c. All the textile electrode prototypes used in this study have identical dimensions of 50 mm × 50 mm to match the size of typical CE-certified hydrogel electrodes.

B. Estimation of Main Frequency of Stimulation Pulses

A number (N = 48) of electrical current stimulation pulses (2 Hz frequency, 200 µs pulse width (PW)) generated from a TENS device (DS7A, Digitimer Ltd, UK), were converted to voltage pulses across a 1-Ω resistor for post-processing. We adjusted the intensity of stimulation pulses from 5 to 20 mA with an interval of 5 mA during measurement and analyzed 48 converted stimulation pulses at four different intensity levels (5, 10, 15 and 20 mA) by the fast Fourier transform (FFT) algorithm. Each median frequency composition out of each power spectrum was estimated by using a MATLAB® function called *medfreq*. The averaged result of four estimations was 10 kHz, which was considered to be a significant composition for ongoing experiments related to ETI measurement in the time domain.

C. Measurement of Electrode-Tissue Impedance

The electrode tissue impedance (ETI) of the fabricated textile-electrodes and standard medical hydrogel electrodes was used as the standard measure of quality [16]. This was done using an R&S® HM8118 programmable LCR bridge set to produce a 1-V sinusoidal input in the frequency range of 20 Hz to 200 kHz (total 42 increments).

Four healthy volunteers – one female (25 years old), and three males (28, 32, and 35 years old) – participated in the first experiment. All experimental protocols were approved by the Informatics Research Ethics Committee for the Edinburgh Neuroprosthetics Laboratory, University of Edinburgh, and all participants gave written informed consent before the start of the trial. During the experiment, participants were asked to sit in a comfortable chair with their right leg placed on a height-adjustable table. Before recording, the surface of the skin over: the gastrocnemius and soleus (calf) muscles, the bottom, and side of the tested foot, and the entire ankle joint, were cleaned with 75% isopropyl alcohol wipes before electrodes (either hydrogel or textile) were mounted. Electrodes were placed 10 mm behind the posterior malleolus, and 40 mm above [17]. As participants possessed slight physiological differences, e.g., foot size and body mass index (BMI), the correctness of electrode location was confirmed by observation of a twisting motion of the big toe during TENS at a certain level of current injected (motor threshold, or MotTh).

Textile electrodes may be used in dry or wet conditions [18], therefore, we compared the efficacy of three different types of electrolytes for hydrating the textile electrodes: tap water, general-purpose cream (NIVEA, Beiersdorf AG, Germany), and soft cream (NIVEA, Beiersdorf AG, Germany). In this case, general-purpose cream refers to a type of water-in-oil (W/O) emulsion, which contains a large concentration of water droplets suspended in oil. The soft cream refers to an oil-in-water (O/W) emulsion, where oil is dispersed in a continuous water phase, giving it a less viscous consistency. The experiment was repeated on each participant for several electrode/electrolyte combinations, the order of which was determined randomly.

D. Recording of Evoked EMG

The same volunteers participated in the second experiment, which followed the exact procedure explained in the previous section. The second experiment was conducted to evaluate the cotton-filled textile electrode (with electrolyte) to trigger EMG signals via TENS.

An EMG recording machine (Blackrock Microsystems, Blackrock Neurotech, USA) can immediately begin recording by receiving triggers from the TENS device when it was sending out stimulation current pulses. A custom pulse generator was designed (2 Hz frequency, 5.2 ms pulse width (PW)) to synchronize the TENS device with the Blackrock system. The stimulation was applied to each participant for 30 seconds with a total number of 60 pulses at one fixed current intensity which varied from 1 mA to 50 mA or maximum injected current individual could tolerate (maximum threshold or MaxTh) depending on different subjects. This was repeated for different PW, including 200 µs, 100 µs and 50 µs for all participants.

Both hydrated-textile and hydrogel electrodes were placed in identical positions to those in experiment one. Furthermore, three small hydrogel electrodes for EMG recording were placed on foot and ankle bone, respectively, as shown in Fig. 3(a), (b). EMG electrodes were covered with medical adhesive to ensure constant skin-surface contact during recording. All data recoded by EMG machine was saved in Neuro Stream Four (NS4) file format with a sampling frequency of 10 kHz.

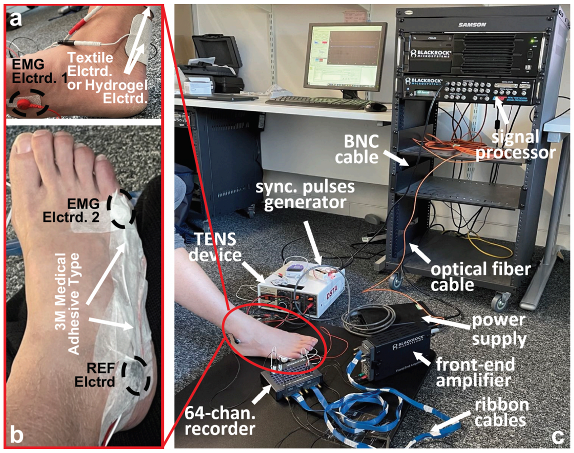

Fig. 3. Experimental setup for recording of EMG during TENS. (a) Placement of one of EMG electrodes. (b) Location of the other EMG electrode and a reference electrode. (c) Overview of cable connections between relevant devices.

E. *Normalized Cross-Correlation for Data Comparison*

To compare the EMG traces produced by the second experiment, a normalized cross-correlation (NCC) was performed. In brief, this technique determines the similarity between two sets of time series data (X_i and Y_i, where $0 \leq i \leq N - 1$ and $N = 850$) by normalizing any differences in amplitude (scaling) and correlating the two traces [19]. This process is repeated for every possible alignment of the curves in time, by shifting one forward or backward relative to the other (the "time lag") [20], producing a curve depicting the strength of the correlation between traces (the NCC coefficient or *R*-value, where $-1 \leq R \leq 1$) as a function of time lag.

Therefore, this technique provides two key pieces of information: 1. the magnitude of the correlation between the curves at the point of recording (e.g., the correlation where time lag is zero), and 2. the time lag required to maximize the alignment of the curves (e.g., where the largest correlation is observed) [21]. This NCC was only performed on the average raw EMG traces obtained from each participant at an average MotTh.

III. Results and Discussion

A. *Optimization of Electrolyte Volume*

Fig. 4. Different volumes of the W/O cream dipped on the finger.

We used modest volume of electrolyte (Fig. 4) that the user can easily put on around the area of textile electrodes sometime before the TENS device is powered ON. In order to create a controlled environment, we carefully applied the different volumes of electrolyte (both types of cream and water) using a 2 mL syringe on the same surface area the electrodes were placed, but that was not essential for real-life usage.

The experiment revealed a noticeable effect of electrolyte type on textile ETI. Specifically, both W/O cream and water displayed a greater ETI when compared to the standard hydrogel electrode (Fig. 5). However, the same could not be said for O/W cream, which was found to possess a lower ETI than the standard hydrogel electrode under all applied volumes. Additionally, larger volumes of applied O/W cream were found to be proportional to the decrease in ETI. This was likely driven by the greater concentration of water found within this compound, resulting in an improved conductivity of the contact interface.

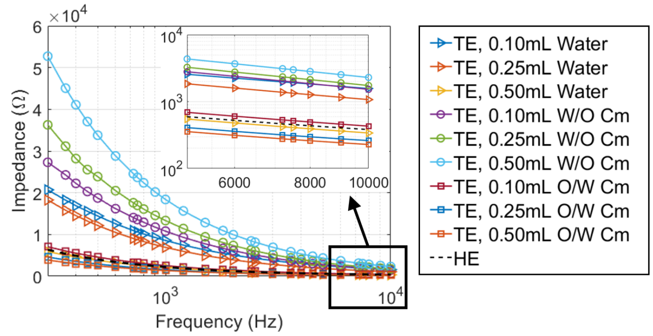

Fig. 5. ETI of textile electrodes with three different types of electrolytes (water, cream, and soft cream) compared with standard hydrogel electrodes. (Abbrev.: TE, textile electrodes; HE, hydrogel electrodes)

Further examination of the change in impedance measured at 10 kHz over time under each electrolyte condition revealed an interesting pattern. In every case, the ETI of the textile electrode increased gradually. The greatest rate of drift was seen in the water condition, and the smallest in the W/O cream condition. However, the baseline ETI was greatest in the W/O cream condition, and the smallest in the O/W cream condition (Fig. 6). These findings are likely explained by the greater oil-related content in the W/O cream electrolyte, which would both reduce the conductance of the compound, and decrease its rate of absorption or evaporation.

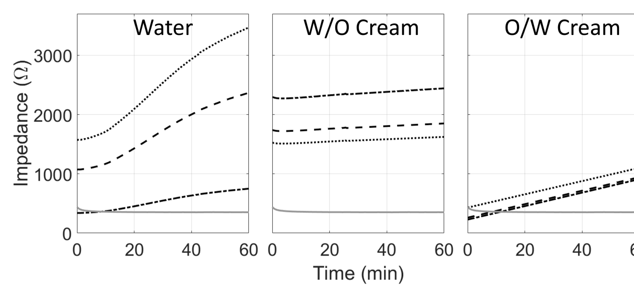

Fig. 6. Optimization of volume of different electrolytes (where dotted lines: 0.1 mL, dashed lines: 0.25 mL, dash-dotted lines: 0.5 mL) for textile electrodes compared with hydrogel electrodes (solid lines).

Taken together, these results suggest that for short-term use (i.e., less than one hour) larger volumes of O/W cream are the favorable option. However, for longer-term solutions, smaller volumes of W/O cream (0.1 mL) are preferable, as despite its increased baseline ETI, the slower rate of change allows it to maintain this level of efficacy for longer.

B. *Performance of Textile Electrodes with Electrolyte*

Due to noise arising from voluntary muscle contraction and TENS artifacts, the raw EMG data was pre-processed before further analysis. This helped eliminate some of the general interference present within the data, including movement artifacts (1 – 10 Hz), and electromagnetic noise (50 Hz and higher harmonics). After examining the datasets, the average MotTh was 20 ± 2 mA, while MaxTh was 40 ± 10 mA across all participants. Additionally, the raw EMG traces obtained from textile electrodes (with 1 mL W/O cream) and hydrogel electrodes at MotTh (200 µs PW) displayed a remarkable similarity (Fig. 7(a)). Likewise, the area under the curve (AUC) of rectified M-Waves (Fig. 7(b)) recorded from this participant reflect the efficacy of W/O cream-hydrated textile electrodes, suggesting that they are close to that of hydrogel electrodes for different PW conditions.

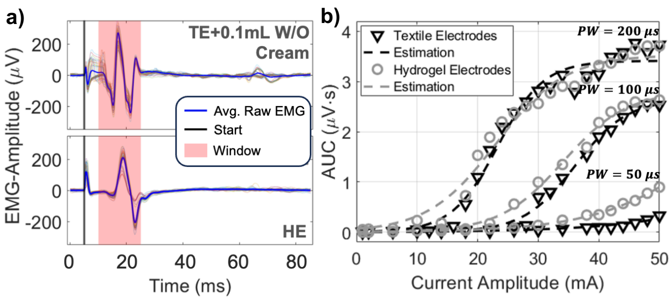

Fig. 7. (a) Raw EMG response at MotTh of 22 mA for textile and hydrogel electrodes. (b) AUC of rectified M-wave with respect to different pulse widths. (Abbrev.: TE, textile electrodes; HE, hydrogel electrodes)

Further evidence supporting the similarity in performance between textile electrodes (with electrolyte) and hydrogel electrodes may be seen in the results of the NCC analysis. Across all participants, a significant correlation at zero lag time between textile and hydrogel electrode traces (R_{1700} = 0.28, 0.92, 0.91, 0.78, where R_{1700} denotes the NCC coefficient of 1700 data points (the first 850 points were extracted from the raw EMG trace, and the other 850 points were extracted from the same trace shifted to a negative period starting from –850 ms); $p < 0.05$ in all cases) was observed (Fig. 8, right traces). However, the maximum correlation between the two signals was found several milliseconds before, or after, zero. This was especially apparent in the data obtained from participant one (Fig. 8(a)) where the greatest correlation was seen at a lag time of –12 ms (R_{1700} = 0.74). These results suggest that the textile electrodes have a similar ability to generate M-waves as hydrogel standards. However, they may differ slightly in response time (i.e., the speed at which the electrodes produce M-waves after stimulation), as indicated by the variation in peak correlation time.

Despite this, the small magnitude of this variability across participants 2 to 4, along with the lack of consistent timing of the peaks, suggests that the observed differences in response time may simply be due to physiological differences. Nevertheless, this does not explain the shorter response time seen in participant one. It is possible that this divergence was driven by variation in the placement of electrodes, leading to a change in EMG trace timing.

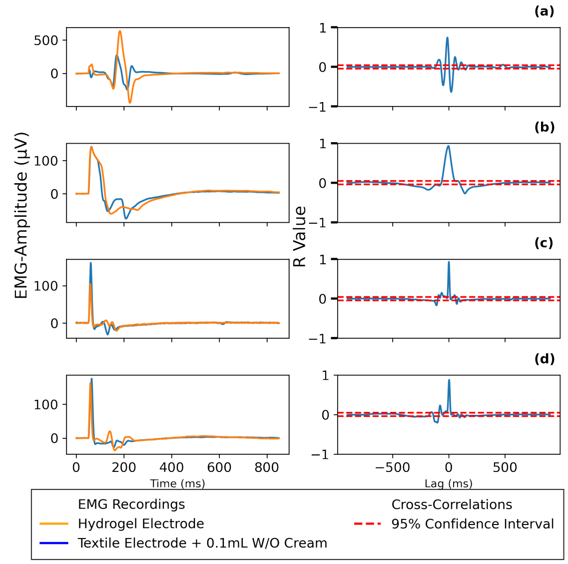

Fig. 8. Average surface-EMG traces (left), and cross-correlation analyses (right) obtained from participants 1 (a), 2 (b), 3 (c), and 4 (d). *R* values above or below the confidence intervals (red dashed lines) were considered significant ($p < 0.05$).

IV. Conclusions

This work confirms that in terms of performance during TENS, textile-based electrodes with electrolytes are similar, and in some cases superior to, standard hydrogel equivalents. Specifically, the findings indicate that cotton-filled textile electrodes knitted with silver-coated conductive yarns are a preferable wearable design, able to fully contact the skin without excessive compression. Additionally, in the presence of a water-based electrolyte (O/W cream), the ETI of textile electrodes was found to be lower than that of the hydrogel standard. Coupled with the similar AUC and EMG performance, and the correlation between EMG traces, it is likely that textile-electrodes (with oil-based electrolyte), may serve as an effective replacement to hydrogel electrodes in TENS-related interventions. While TENS-based devices are widely used in clinical practice, their use in ambulatory applications is limited due to the need for a long-lasting, reusable electrode. Hence, our results demonstrate the possibility of creating comfortable, home-based, wearable nerve stimulators that may be useful for a number of medical applications. We expect that putting on a small amount of oil-based moisturizer can be considered an acceptable practice, even for older people.

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