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Understanding the effect of carbon in carbon/salt/adhesive electrodes for surface electromyography measurements

Hugo F. Posada-Quintero [a], Ryan Rood [a], Ken Burnham [b], John Pennace [b], Ki H. Chon [a,*]

[a] University of Connecticut, Storrs, CT 06269 USA
[b] FLEXcon, Spencer, MA 01562 USA

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ABSTRACT

Dry electrodes that do not require silver and hydrogel might provide the advantages of having very long shelf life and lower cost, compared to the gold standard Ag/AgCl hydrogel electrodes. Recently, we compared novel carbon/salt/adhesive (CSA) electrodes with Ag/AgCl electrodes for surface electromyography (sEMG) signal collection. We found no significant differences in amplitude, but CSA electrodes outperformed Ag/AgCl in response to noise and motion artifacts. However, the carbon component may be redundant, and the salt/adhesive (SA) mixture might be as effective as CSA for such a task. In the SA electrodes, the salt concentration is the only tunable factor. To determine if carbon contribution is necessary for effective sEMG measuring capabilities, we varied the salt concentration in the SA electrodes to 10%, 15%, and 25% and their performance was compared to the functional capabilities of CSA electrodes. Twenty subjects were recruited to collect simultaneous recordings of sEMG signals using CSA and SA electrodes, side-by-side on triceps brachii, tibial anterior muscles, biceps brachii and quadriceps femoris. SA 15% and SA 25% electrodes detected higher amplitude values during contraction in biceps, tibials and quadriceps, compared to CSA. All SA electrodes exhibited high mean correlation with CSA electrodes, on the linear envelopes ($\geq$ 0.887), RMS envelope ($\geq$ 0.87) and power spectrum density ($\geq$ 0.94). SA 15% and SA 25% electrodes performed better in response to noise and were more sensitive to myoelectric activity than CSA electrodes, but CSA electrodes exhibited better response to motion artifacts than SA electrodes. SA 10% electrodes presented high electrode-skin impedance, producing some lower values in sEMG signals during contraction, worse motion corruption and spectral deformation compared to CSA. Results suggest that carbon improves capability to manage motion, but at the expense of more susceptibility to noise corruption. Higher salt concentration reduced motion artifacts and spectral deformation, but reduced the sensitivity to myoelectric signals. In conclusion, SA electrodes, specifically the mixture with 15% salt, provided a better response to myoelectric activity and seem to be the most suitable alternative for sEMG data collection.

1. Introduction

Novel dry electrodes designed by combining carbon black powder with a quaternary salt and visco-elastic polymeric adhesive [1] (termed carbon/salt/adhesive or CSA electrodes) were recently compared for their functional performance to the standard Ag/AgCl electrode when acquiring surface electrocardiographic (sEMG) signals [2]. It was found that CSA electrodes outperformed Ag/AgCl electrodes for sEMG data collection. Hence, any new electrode design for sEMG applications should be benchmarked against CSA electrodes.

CSA electrodes consist of three components: the conductive layer, the adhesive layer and the bridge [3]. The adhesive layer contains the carbon/salt/adhesive mixture. To reduce the impedance, carbon particles of this layer are aligned in the Z direction through the activation (electrophoresis) process. The third component, the bridge, is needed in order to connect the isolated Z direction conductive pathways.

Although CSA electrodes have been shown to be a suitable surrogate for Ag/AgCl electrodes for sEMG, further investigation needs to be performed to better understand the contribution of carbon as a conductive material for sEMG data collection. If carbon is found to be unnecessary, the activation process and the bridge are also unnecessary, making the fabrication process easier, leading to potentially less expensive electrodes. The precursor to CSA electrodes is a signal receptive material that did not contain carbon for its fabrication (a mixture of salt and adhesive, SA). This type of

* Corresponding author.
E-mail address: kchon@engr.uconn.edu (K.H. Chon).

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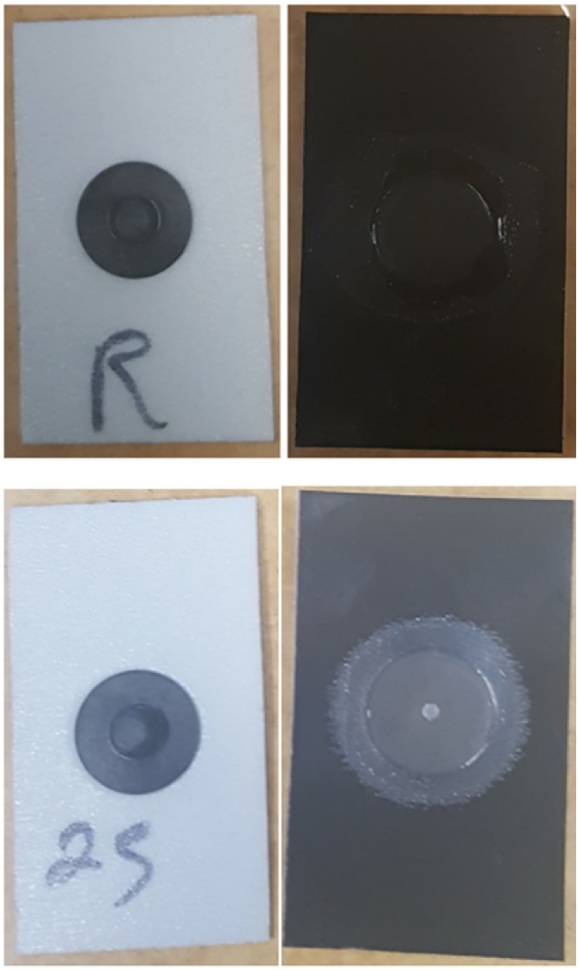

Fig. 1. Connector and contact side of tested sEMG electrodes. Top: CSA electrodes (the label R in the plot means "Reference"); bottom: SA electrodes (25% salt). Dimensions are 1 1/2" x 7/8" (3.81 cm x 2.22 cm) for both.

electrode was not tested for collection of sEMG signals. CSA and SA electrodes look similar because the conductive layer is still carbon for both, and the bridge layer coincides with the bottom part of the snap connector (Fig. 1).

As salt is conductive, the elimination of carbon can be compensated for by increasing the salt concentration of the adhesive layer. To determine the optimal salt concentration, the SA electrodes were tested with three different levels (10%, 15%, and 25%) and they were each compared to the CSA electrodes. These different concentrations will determine whether the carbon contribution is a necessary ingredient for effective sEMG measuring capabilities of CSA electrodes, and if salt alone (at the optimal concentration) can provide similar functional performance to that of CSA electrodes.

2. Materials and methods

2.1. Electrode fabrication

The CSA sEMG electrodes' fabrication process has been described before [2–4]. Succinctly, to create CSA-based sEMG electrodes, the conductive base layer, the adhesive, and the bridge are prepared beforehand. The conductive layer is made with a polyethylene foam carrier coated with an electrically conductive material consisting of a polymeric binder loaded with conductive fillers. The adhesive layer is a releasable carrier coated with a doped adhesive such as an acrylic pressure sensitive type loaded with conductive carbon filler and a quaternary ammonium salt. The salt in the mixture does not have any significant disassociation. It does not separate into ions as would be the case for NaCl in water, for example. The adhesive layer of CSA electrodes used in this study contain 15% salt. The adhesive layer of CSA electrodes requires an activation process through electrophoresis. The bridge is a conductivity-enhancing conduit made of low impedance electrically conductive material that produces a lower electrode ohm value by connecting in parallel multiple isolated Z direction (out of plane) conductive pathways in the adhesive layer.

Fabrication of SA electrodes requires only the conductive layer and the adhesive. In this case, the adhesive is loaded only with quaternary ammonium salt. Thus, SA electrodes require neither carbon in the adhesive layer, nor the activation process nor the bridge feature. CSA and SA electrodes' dimensions are 1 1/2" x 7/8" (3.81 cm x 2.22 cm).

2.2. Electrode-skin contact impedance measurements

Electrode-skin impedance measurements were carried out using CSA and SA electrodes. The skin of the test subject was cleaned before each measurement by wiping with a 2%-alcohol impregnated cotton pad, which was allowed to evaporate before applying the electrodes. Two identical (CSA or SA) electrodes were mounted on the left forearm, one on the palm side of the wrist, and the second 5 cm apart from the first but situated towards the elbow. These electrodes were connected to a Hioki IM3570 impedance analyzer, and each measurement was the result of averaging 20 measurements. The signal voltage amplitude was set to 1 V and the frequency range varied from 4 to 2 KHz. N = 8 electrodes of each type of electrode were used (CSA, SA 10%, SA 15%, SA 25%). To keep skin properties as constant as possible, all measurements were performed in a single day.

2.3. Protocol for sEMG signal collection

The protocol was similar to that used in a previous study [2]. The procedure described below was repeated three times on each subject taking part in the experiment, since we wanted to try three levels of salt concentration in the SA electrodes (10%, 15%, and 25% salt concentration). To ensure accurate comparison between the electrodes, simultaneous measurements were recorded. To do this, SA and CSA electrodes were placed side-by-side. CSA and SA electrodes were placed on a lateral position (left or right on the same muscle) that alternated from subject to subject, to eliminate any bias from being only on one side.

sEMG signals were acquired using a Dual Bio Amp (ADInstruments) and digitized at a sampling frequency of 2 kHz. sEMG measurements of the biceps brachii, triceps brachii (long head), tibialis anterior, and quadriceps femoris (rectus femoris) were recorded in four separate parts of the experiment. The sampling frequency was selected to meet the requirements set in previous studies on sEMG that involved the muscles tested in this work [5–7]. The required sampling frequency is especially high for the biceps brachii and the tibials anterior. The same time frame was followed for sEMG signal recording on every muscle (Fig. 2). Subjects practiced the maneuvers prior to every test until they felt comfortable with the procedure.

We had subjects lift a weight of 3 lbs. (1.36 kg) for testing electrodes on triceps brachii and tibialis anterior muscles. For biceps brachii and quadriceps femoris, subjects used a weight of 6 lbs. (2.72 kg). Fig. 3 shows the areas where the electrodes were placed on each muscle [8]. The electrodes were placed with the subjects in the resting condition. sEMG measurements of the four muscles were recorded while subjects performed four muscle contraction maneuvers during the experiment, one for each muscle. These spe-