Testing the Need for Carbon in Salt/Adhesive Electrodes for Surface Electromyography Measurements: Preliminary Results

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***Abstract*— We compared previously carbon/salt/adhesive (CSA) electrodes with Ag/AgCl electrodes for surface electromyography (sEMG) signals collection. We found no differences in amplitude, but CSA electrodes exhibited a significantly better response to noise and motion artifacts. However, the carbon component may not be needed, and the salt/adhesive (SA) mixture might be as good as CSA for such a task. Either CSA or SA mixtures have the potential to provide the unique advantages of having longer (theoretically infinite) shelf life and potentially lower cost, compared to the gold standard Ag/AgCl hydrogel electrodes. In order to determine if carbon contribution is necessary for effective sEMG measuring capabilities the mixture, the functionality of SA electrodes utilizing different levels of salt concentration were compared to the capabilities of CSA electrodes. The levels consisted of 10%, 15%, and 25% salt concentration. Six subjects have been recruited so far 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. For all three levels of salt concentration in the SA electrodes, high correlation was found to the CSA electrodes on the estimated linear envelopes, RMS envelope and power spectrum density. Furthermore, no significant differences in amplitude, compared to CSA electrodes, were found for the three concentrations. Based on signal-to-noise and signal-to-motion measures on the preliminary data set, it seems like adding carbon to the mixture improves the response to motion, but impairs the noise corruption of the sEMG signals.**

I. Introduction

Novel dry electrodes designed combining carbon black powder with a quaternary salt and visco-elastic polymeric adhesive [1] (termed carbon/salt/adhesive or CSA electrodes) were recently compared based on performance to the standard Ag/AgCl electrodes' when acquiring surface electrocardiographic (sEMG) signals [2]. In that study, we found no significant differences between our dry CSA electrodes and gold standard Ag/AgCl electrodes, in the amplitude and activation times of sEMG signals. In addition, CSA electrodes were more resistant to noise and motion artifacts and delivered signals with lower spectral distortion, compared to Ag/AgCl. This is of relevant importance because of the two salient disadvantages of Ag/AgCl electrodes that are not a problem for CSA: dehydration with storage or prolonged use, and higher cost. In general, CSA electrodes outperformed Ag/AgCl electrodes for sEMG signals collection.

CSA electrodes consist of three components: the conductive layer, the adhesive layer and the bridge. The adhesive layer contains the carbon/salt/adhesive mixture. 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. To reduce the impedance, carbon particles of this layer are aligned in 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 showed to be a suitable surrogate of Ag/AgCl for sEMG, further investigation needs to be deployed to better understand the contribution of carbon to the mixture. The precursor to CSA electrodes is a signal receptive material that did not need carbon for its fabrication (a mixture of salt and adhesive –SA-). Furthermore, SA electrodes need neither the activation process nor the bridge component, making the fabrication process much simpler. CSA and SA electrodes are shown in Fig. 1.

In order to determine if carbon contribution is necessary for effective sEMG measuring capabilities of CSA electrodes, the functionality of SA electrodes utilizing different levels of salt concentration was compared to the capabilities of CSA electrodes. These levels will consist of 10%, 15%, and 25% salt concentration.

The reader might think that we should have compared SA electrodes to CSA and gold standard Ag/AgCl electrodes. However, three reasons lead us to compare SA vs. CSA only. First, given the impossibility of placing three pairs of electrodes on subjects' middle- (e.g. tibials anterior) or small-

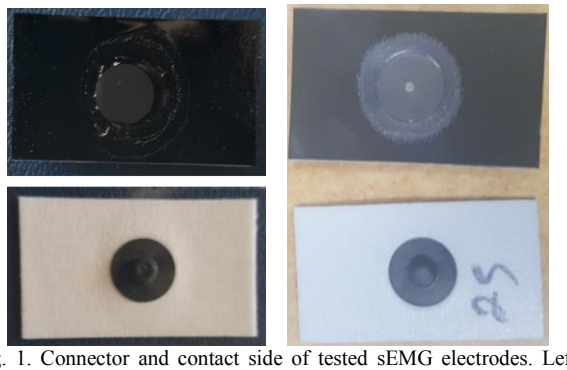

Fig. 1. Connector and contact side of tested sEMG electrodes. Left: CSA electrodes; right: SA electrodes (25 % salt). Dimensions are the same for both.

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Fig. 2. Time frame for movements while recording sEMG signal.

size (e.g. triceps) muscles, comparison needed to be made to only one kind of electrodes. Second, in our previous study CSA electrodes outperformed Ag/AgCl electrodes [2]; for that reason we chose to compare SA electrodes to the best available alternative. Third, if we want to analyze the need for carbon in the mixture, we should compare electrodes with and without carbon.

II. Methods

A. Details on electrodes fabrication

CSA sEMG electrodes' fabrication process has been described before [2]. Basically, to create CSA 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 & a quaternary ammonium salt. The adhesive layer of CSA electrodes require an activation process through electrophoresis. As mentioned, the bridge is a conductivity enhancing feature 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.

Fabrication of SA electrodes require only the conductive layer and the adhesive. In this case, the adhesive is loaded only with quaternary ammonium salt. Again, SA electrodes neither require carbon in the adhesive layer, nor the activation process nor the bridge feature.

B. Protocol

The protocol is similar to the used in a previous study [2]. This paper includes preliminary results for the first six subjects enrolled to take part in this test. The procedure described below was repeated three times on each subject taking part of the experiment, since we want to try three levels of salt concentration on 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 the SA electrodes were assigned a lateral position (left or right on the same muscle) that alternated from subject to subject, to eliminate any benefit from being on either side.

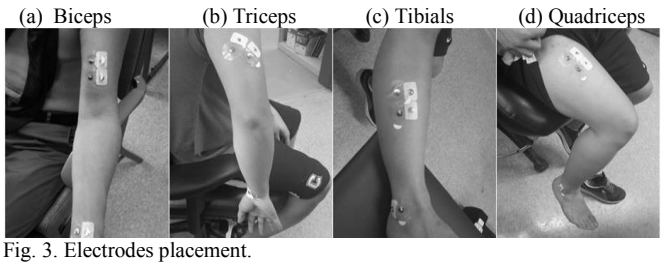

Fig. 3. Electrodes placement.

EMG signals were acquired using a Dual Bio Amp (ADInstruments) and digitized at 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 same time frame was followed for EMG signal recording on every muscle (Fig. 2). Subjects was let to practice the maneuvers prior to every test until they felt comfortable with the procedure.

We had subjects lift a weight of 3 lb. (1.36 kg) for testing on triceps brachii and tibialis anterior muscles. For biceps brachii and quadriceps femoris, they used a weight of 6 lb. (2.72 kg). Fig. 3 shows the areas where the electrodes were placed on each muscle. The electrodes were placed with the subjects in resting condition. sEMG measurements of the biceps brachii, triceps brachii (long head), tibialis anterior, and quadriceps femoris (rectus femoris) were recorded while subjects performed four muscle contraction maneuvers during the experiment, one for each muscle. These specific muscles were chosen based on their variance in size. It has been observed that muscles of varying sizes will produce sEMG signals of varying amplitudes.

Before performing every test, it was assured that the locations where the electrodes were placed was hairless and had been wiped with alcohol and allowed to dry. As we were taking three recordings (one for each salt level), we removed SA electrodes, prepared the site of the skin they were placed, let dry, and placed the next salt level SA electrodes. CSA electrodes remained for the three data recordings. Fig. 3 shows the areas where the electrodes were placed.

Subjects were asked to perform these maneuvers: 1) to contract their biceps, bringing the elbow to a 90 degree angle, with the forearm in supination; 2) to contract their triceps and extend their elbow joint so that the weight was suspended backwards; 3) to contract their tibialis anterior muscle and lift the weight off the floor without extension of the great toe; and 4) to lift their leg up (extend their knee) to procure contraction of the quadriceps. The protocol was approved by the Institutional Review Board of the University of Connecticut.

B. Signal processing

We processed sEMG signals offline to quantify their quality and to compare the performance of SA electrodes (the three salt levels) to the CSA electrodes. Several time- and frequency-domain indices of sEMG signals' quality were computed. In the time domain, we computed the linear envelope, the RMS envelope and the amplitude of sEMG signals. The linear envelope of each sEMG signal was computed using rectification and a low pass filter (7th-order Chebyshev, cut-off frequency = 16.66 Hz). RMS envelope was computed from the windowed (25ms) signals before rectification [3].

The mean value of the linear envelope was computed as an amplitude estimation of sEMG signals. For frequency domain analysis, the power spectral density (PSD) of each sEMG signal was calculated using Welch's periodogram method with 50% data overlap. A Blackman window (length

TABLE I. RESULTS FOR AMPLITUDE, ENVELOPE CORRELATION AND PSD CORRELATION

	Biceps		Triceps		Tibials		Quadriceps	
	Relaxation	**Contraction**	**Relaxation**	**Contraction**	**Relaxation**	**Contraction**	**Relaxation**	**Contraction**
Amplitude CSA	0.05 ± 0.04	0.08 ± 0.02	0.07 ± 0.03	0.11 ± 0.03	0.04 ± 0.07	0.06 ± 0.05	0.01 ± 0.01	0.1 ± 0.06
Amplitude SA 10%	0.11 ± 0.06	0.08 ± 0.01	0.09 ± 0.07	0.1 ± 0.03	0.08 ± 0.05	0.06 ± 0.03	0.16 ± 0.08	0.09 ± 0.04
Amplitude SA 15%	0.03 ± 0.03	0.08 ± 0.01	0.07 ± 0.03	0.11 ± 0.04	0.03 ± 0.03*	0.07 ± 0.04	0.02 ± 0.01*	0.08 ± 0.06
Amplitude SA 25%	0.05 ± 0.04	0.09 ± 0.01	0.08 ± 0.05	0.11 ± 0.04	0.06 ± 0.1	0.07 ± 0.05	0.02 ± 0.01*	0.1 ± 0.05
Correlation of linear envelope SA vs. CSA electrodes								
SA 10%	0.87 ± 0.07		0.86 ± 0.05		0.88 ± 0.05		0.87 ± 0.09	
SA 15%	0.87 ± 0.07		0.85 ± 0.03		0.89 ± 0.04		0.91 ± 0.01	
SA 25%	0.85 ± 0.11		0.87 ± 0.04		0.89 ± 0.04		0.89 ± 0.02	
Correlation of RMS envelope SA vs. CSA electrodes								
SA 10%	0.89 ± 0.07		0.89 ± 0.04		0.92 ± 0.04		0.92 ± 0.05	
SA 15%	0.9 ± 0.06		0.894 ± 0.02		0.93 ± 0.02		0.94 ± 0.01	
SA 25%	0.88 ± 0.1		0.907 ± 0.03		0.92 ± 0.03		0.93 ± 0.01	
Correlation of PSD SA vs. CSA electrodes								
SA 10%	0.99 ± 0.01		0.97 ± 0.02		0.98 ± 0.01		0.91 ± 0.11	
SA 15%	0.99 ± 0.01		0.95 ± 0.06		0.98 ± 0.01		0.96 ± 0.03	
SA 25%	0.99 ± 0.01		0.95 ± 0.06		0.99 ± 0.01		0.95 ± 0.03	

Values are expressed as mean ± standard deviation.
CSA: carbon/salt/adhesive; SA: salt/adhesive; RMS: root mean square; PSD: power spectral density

of 256 data points) was applied to each segment and the fast Fourier transform (FFT) was calculated for each windowed segment. Finally, the power spectra of the segments were averaged. An FFT segment size of 1024 data points was used.

In frequency domain, we computed signal-to-noise ratio (SN ratio) and signal-to-motion ratio (SM ratio). SN ratio is defined as any signal of unrecognizable source present in the high-frequency range of the PSD [6]. For the SN ratio calculation we assumed that noise had a constant power density over the frequency region of interest in sEMG recordings and that no muscular activity-related power was present above 800 Hz (upper 20% of the frequency range). The power for the frequency range above 800 Hz was computed. The predicted total power of the noise is this power projected over the whole frequency range. The SN ratio was then calculated as the ratio of the total sEMG power to the total power of the noise.

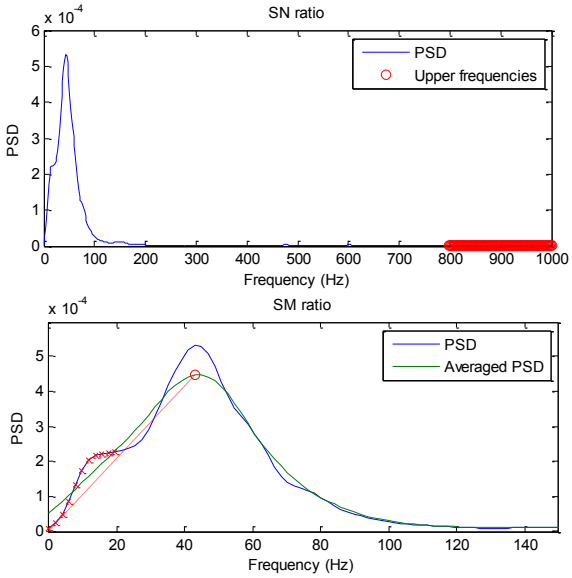

Fig. 4. Illustration of SN ratio (top) and SM ratio (bottom) estimation.

For computing the SM ratio, motion artifacts are defined as low-frequency fluctuations of the signal induced by mechanical alteration of the electrode-skin interface. Use of the SM ratio is based mainly on two assumptions: 1) the frequency of motion-induced artifacts of the signal stays well below 20 Hz, and 2) the shape of the non-contaminated sEMG power spectrum is fairly linear between 0 and 20 Hz [7]. As a consequence, the motion artifacts' spectral power will be mixed in with the true signal dynamics at frequencies between 0 to 20 Hz (area between the red dotted line and the blue line with red "x" in Fig. 4). The highest mean power density (the red dot in the averaged spectral plot of Fig. 4) was defined as the largest mean spectral value within a window length of 25.4 Hz starting from 35 Hz to 500 Hz. Finally, the sum of the area under the PSD for all frequencies divided by motion artifact power was computed to obtain the SM ratio.

Correlation between CSA and SA electrodes was computed in time domain and frequency domain to test interchangeability between the two media, for the task of sEMG signals collection.

III. RESULTS

Fig. 5 shows representative sEMG signals acquired with CSA and SA electrodes. The results for amplitude, linear envelope, RMS envelope and PSD correlation are shown in Table I. For all muscles, sEMG signals acquired using CSA, SA 15% and SA 25% were higher in average during the contraction period. SA 10% sEMG signals were usually higher during the relaxation period, with the exception of Triceps.

No significant differences in amplitude were found between CSA and SA (10%, 15% and 25% salt) sEMG signals during contraction for any muscle. During relaxation time, we found significant lower values in Tibials using SA

TABLE II. INDICES OF NOISE AND MOTION ARTIFACTS

	Biceps	Triceps	Tibials	Quadriceps
		SN Ratio		
CSA	39.6 ± 3.98	46.7 ± 6.23	35.1 ± 9.37	44.6 ± 8.16
SA 10%	40.7031 ± 4.57	44.9222 ± 5.86	36.3166 ± 10.4	45.1266 ± 6.49
SA 15%	40.8047 ± 4.85	46.9209 ± 5.99	39.0201 ± 10.2	43.292 ± 8.17
SA 25%	41.5294 ± 3.24	47.9609 ± 6.86	36.875 ± 9.06	45.5879 ± 5.76
		SM Ratio		
CSA	26.2 ± 8.71	36.6 ± 5.25	40.9 ± 24.6	42.9 ± 7.45
SA 10%	34.3 ± 22.7	31.1 ± 7.58*	25 ± 12.8	43.5 ± 20.4
SA 15%	28.8 ± 8.79	34.1 ± 6.58	38.4 ± 21.2	42.8 ± 14.8
SA 25%	39.6 ± 28.2	35.3 ± 8.87	35.9 ± 26.2	46.5 ± 20.2

Values are expressed as mean ± standard deviation.
CSA: Carbon/Salt/Adhesive; SA: Salt/Adhesive; SN Ratio: signal-to-noise ratio; SM Ratio: signal-to-motion ratio.

15%, compared to CSA. In the Quadriceps we found significantly higher values in SA 15% and SA 25%, compared to CSA. Table 2 includes the frequency-domain indices for quality assessment of sEMG signals. SN ratio was very close between CSA and SA electrodes (all three concentrations). In the SM ratio, SA 10% exhibited a significantly lower value in the triceps.

IV. DISCUSSION

As observed in Table I, we found few significant differences between CSA and SA electrodes, in the preliminary data. Correlation was high between the two media, both in time- and frequency-domain measures. A remarkable observation of amplitude measurements is that SA 10% electrodes showed higher amplitude during relaxation period, compared to contraction period. The same SA 10% electrodes exhibited significantly lower SM ratio in the triceps sEMG measures. This results suggests that SA 10% are not suitable for sEMG data collection.

Values of SN ratio were usually slightly higher in average for SA 15% and SA 25% compared to CSA (Table II). SA electrodes seem to have a better response to noise, compared to CSA electrodes. Nevertheless, mean SM ratio of CSA electrodes was higher in triceps and tibials, and lower for biceps and quadriceps, compared to any concentration of SA electrodes. We expect a better response of CSA electrodes to motion artifacts, because their main advantage is that the bridge connects parallel multiple isolated Z direction conductive pathways in the adhesive, reducing the effects of movement in other directions.

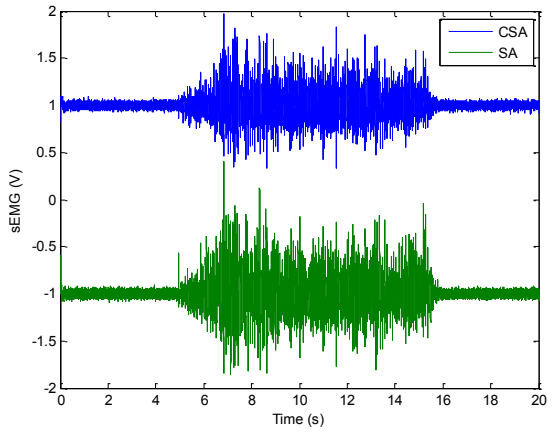

Fig. 5. Sample sEMG measures using CSA (top) and CSA electrodes (bottom) on a given subject's Biceps. Offset (+1 for CSA, -1 for SA) added for fashion purposes.

V. CONCLUSION

CSA electrodes showed a slightly better response to motion in the overall. SA 15% and SA 25% electrodes exhibited a better response to noise in the average. It seems that carbon (and subsequent activation and bridge) provides a better capability to manage motion, but is more sensitive to noise. If no differences are found between SA 15% and SA 25% concentrations, SA 15% should be chosen to avoid possible skin irritation produced by salt. More data need to be collected to properly conclude on this matter.

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