Comparing Wet and Dry Contact Biopotential Electrodes

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Abstract- **Electrodes are an important concept when considering bioimpedance and are commonly used when measuring biopotentials. In this paper, we will be analyzing the non-invasive approach of measuring EMG, also called surface EMG or sEMG. As the name suggests, sEMG are measured on the surface of the skin and can be classified as either dry-contact or wet-contact. We chose to compare the effects of two electrodes, AgCl and Platinum, using both the dry-contact and wet-contact approaches to determine which electrode would be best in measuring biopotentials. Considering that most useful biosignal frequencies range between 50Hz- 150Hz, all 4 methods would provide viable signal amplification in that range. However, we concluded that the wet-contact Platinum electrode is the best in measuring biopotentials since it had the lowest total impedance seen across the circuit. This would contribute to the least amount of noise and better preserve signal stability. For future directions, we could consider more materials- such as gold, nickel, or carbon based electrodes. There is also discussion about semi-wet-contact electrodes which use saline solutions rather than the traditional conductive gel solution used in wet-contact electrodes. The saline solution acts as an intermediate solution to wet and dry electrodes, offering the potential benefits from both designs while eliminating some of the drawbacks posed by each method.**

I. INTRODUCTION (*HEADING 1*)

Surface Electromyography (SEMG) is the recording and analysis of electrical activity produced by muscles through static or dynamic stretching, by utilizing electrodes at designated positions to capture electric fields produced by ionic diffusions within the muscles. The overall purpose of this instrument is to determine activity of a muscle during a particular action. These include whether the muscle is active or inactive, analysis of activity presented during a selected period of time and describing relationships between muscles studied. The data collected from EMGs can then be utilized for analysis of movement and gait through determining position, speed and acceleration parameters and analysis of fatigue in observing changes in behavior of EMG traces over time. These factors are then utilized to evaluate the frequencies of muscle activity for diagnostic and therapeutic purposes and aid in measuring activity for sport performance. Although EMGs provide the amount of muscular effort made from different motions based on the placement of the device, electrodes do not provide force parameters. They create the detection volume, the volume that is able to be detected from either a surface or intramuscular electrode. Surface electrodes are placed on the surface of the skin whereas intramuscular electrodes are placed deeper within the skin to attach to the muscle in study. The placement of these electrodes affect what is known as the conduction volume, the volume of tissue that the electrical signal travels to the electrode. The location plays a role in how the electrical signals are displayed, due to the fact that the deeper the electrode, the lesser the amount of energy that will reach the electrode, resulting in clearer EMG traces. Before any of the data can be collected, a reference node must be placed on an electrically neutral tissue, usually close to a bone plane. A limitation involved with SEMGs is due to the muscle continuously moving, the displacement and change in volume is able to be displayed. This can affect the results by the intensity of the signal changing throughout testing due to the altering configuration of the muscle and may alter the position of these electrodes.

Wet gel electrodes typically consist of Ag/AgCl and utilize an electrolytic gel. This gel material acts as a conductor between the skin and electrode and reduces impedance between the two by creating a conductive path for the electrical signal [8]. These wet electrodes are clinically utilized as the standard within the medical industry but have many disadvantages, one being the cost being high due to an extra material of the gel being implemented. Wet electrodes are also time consuming to use due to the preparation of the skin being an extra step in testing, as well the required time to wait for the impedance to decrease before testing. If the analysis were to be used for an extended period of time, the gel may dehydrate and a possibility of irritation of the patient's skin requires reapplication and interruption of signal monitoring. Although they do have these disadvantages, the noise received from these electrodes are measured at a lower frequency than those of dry electrodes, which is the main reason why they are utilized in EMGs [8].

Dry contact electrodes are different from wet electrodes as they transfer bioelectrical signals between the electrode and skin without any added electrolytes. Dry electrodes typically consist of a small disk or piece of metal which is placed on the skin, and adheres naturally through sweat production[2]. Some advantages to dry electrodes are that they are much more comfortable for the patient, and are longer lasting than conventional gel electrodes[1]. There is also newer technology in dry electrodes in which the metal is surrounded by elastic material for increased flexibility, which can be useful when performing EMG on muscles with more curvature, such as the forearm[3]. One limitation to dry electrodes is that there is an increased likelihood of motion artifacts during recording[2]. Additionally, dry electrodes are not currently a standard in the medical industry, and are typically used for more limited applications[1]

II. METHODS

A. Assumptions

For ease of calculations, we assumed that polarizable and nonpolarizable materials share the same circuit model.

This was useful because while AgCl is a non-polarizable material, Platinum is polarizable but with our assumption, they can be analyzed similarly with their circuit models. We also made the assumptions that resistance from sweat and hair follicles (R_s) and capacitance from stratum corneum (C_s) are the same for silver and platinum electrodes. We also assumed that the electrodes are the same size. When analyzing the behavior of the AgCl and Platinum circuit models, we assumed steady state conditions at the electrode-electrolyte interface.

B. Models

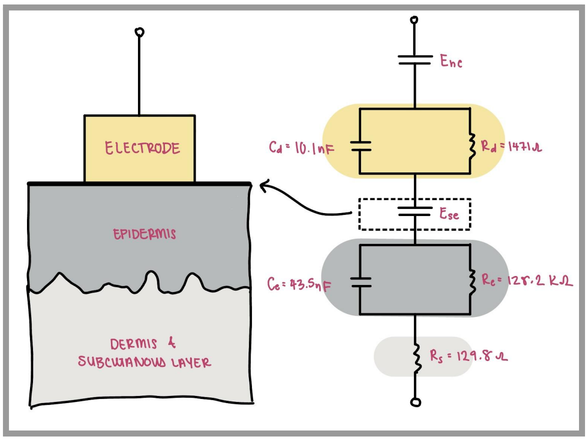

Figure 1: Equivalent circuit model for dry-contact AgCl

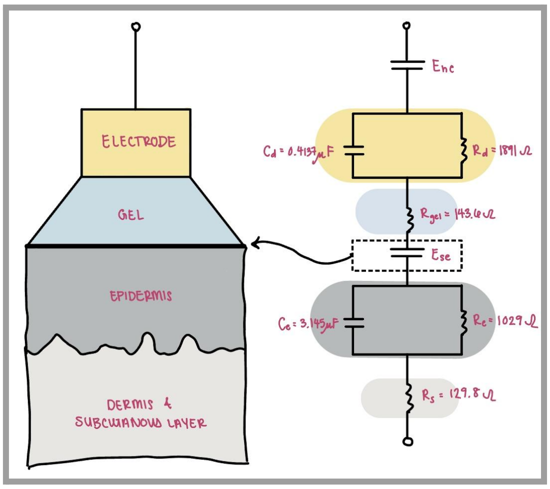

Figure 2: Equivalent circuit model for wet-contact AgCl

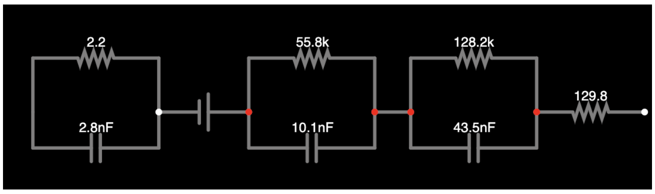

Figure 3: Equivalent circuit for dry-contact Platinum

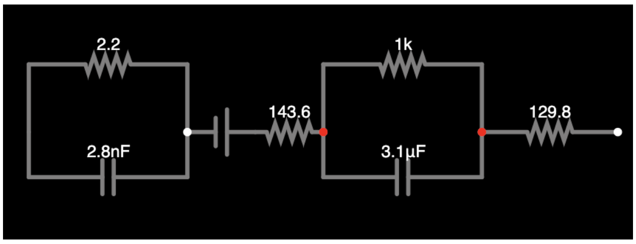

Figure 4: Equivalent circuit for wet-contact Platinum

We analyzed both the dry contact and wet contact circuit models for AgCl and Platinum electrodes. In the wet-contact circuit model, there is an added series resistance from the gel. This resistance acts as a conductive path between the skin and the electrode, to reduce the impedance between the electrode and the skin. Ultimately, this increases the overall impedance of the system which allows for weaker signals to be transmitted easier. The wet circuit model is advantageous for those considering the quality of the signal

Considering the dry-contact model which does not have the addition of the series resistance seen by the gel, this reduces the overall system impedance which can better preserve signal stability compared to the wet-contact circuit model.

The second electrode we chose to consider was platinum. Because of the assumption we made earlier that polarized and non-polarized materials share the same circuit model, the platinum circuit model is the same as silver chloride for simpler calculations.

C. Equations

In order to evaluate the performance of different electrodes' material and the effect of wet/dry electrode models, we need to find out the total impedance of each electrode system. With the total impedance, we can generate a bode plot and investigate the performance of each electrode model.

Using the Tafel equation, the general relationship between the potential and the current is

$$i = i_0 [\frac{C_0}{C_0^{\cdot}} e^{(\frac{\alpha n F \eta}{RT})} - \frac{C_R}{C_R^{\cdot}} e^{\frac{-(1-\alpha) n F \eta}{RT}} \qquad (1)$$

In this equation, i_0 is the exchange-current density, C_0 and C_R are the concentrations of oxidants/reductants at the electrode surface, $C_0^{\cdot}$ and $C_R^{\cdot}$ are the concentrations of oxidants/reductants at the electrolyte, F is the Faraday's constant, T is the temperature in kelvin, R is the gas constant, is the reaction order, n is the number of electrons involved, and α is the overpotential that represents the degree of polarization.

When we assume the concentration in the electrolyte s the same as the electrode surface, $\frac{C_0}{C_0^{\cdot}} = \frac{C_R}{C_R^{\cdot}} = 1$, which simplifies the equation to

$$i = i_0\left[e^{\left(\frac{\alpha n F \eta}{RT}\right)} - e^{\frac{-(1-\alpha) n F \eta}{RT}}\right] \quad (2)$$

Assuming the electrochemical system is at equilibrium and the overpotential is very small, we have the expression for the charge-transfer resistance:

$$R_{ct} = \frac{RT}{nFi_0} \quad (3)$$

Since R(gas constant), T(temperature), and F (Faraday's constant) are constants, the Charge-transfer resistance R_{ct} can be calculated when n(electrons involved in reactions) and exchange-current density i_0 are known.

In our project, we are looking at two different electrochemical reactions, one with Ag/AgCl electrodes and the other with Platinum.

Ag/AgCl Platinum in NaCl electrolyte

$Ag + Cl^- \rightleftharpoons AgCl + e^-$ (4) $Pt + 4Cl^- \rightleftharpoons [PtCl_4]^{2-} + 2e^-$(5)

,which means n = 1 for Ag/AgCl and n = 2 for Platinum.

The exchange current density is defined as the current flow at the surface of the electrode at equilibrium potential. To find the exchange-current density, we use the Nernest equation to find the equilibrium potential of our models first.

Referring to textbook 5.6, Nernest equation

$$E = E^0 + \frac{RT}{nF} \ln a_{C^{n+}} \quad (6)$$

,where E^0 is the standard half-cell potential, n is the valence of electrode material, $a_{C^{n+}}$ is the activity of cation Cn+.

For AgCl it is

$$E = E^0_{Ag} + \frac{RT}{nF} \ln K_s - \frac{RT}{nF} \ln a_{Cl^-} \quad (7)$$

For Platinum it is

$$E = E^0_{Pt} + \frac{RT}{nF} \ln K_s - \frac{RT}{nF} \ln a_{Cl^-} \quad (8)$$

Looking up for the standard half-cell potential in previous researches, we have

Metal/Ion Equilibrium Potentials	
Metal/Metal Ion	Vo [volt]
Pt/Pt^{2+}	~1.2
Ag/Ag^{+}	0.80

Table 1. The Equilibrium(standard) Potentials for platinum and silver ions [3]

Referring to the relationship between potential and exchange-current density in figure 5, for an equilibrium potential of Ag/AgCl electrode around 0.8 volt, the exchange-current density is about 1×10^{-5} to $1.3 \times 10^{-5} A/cm^2$; for an equilibrium potential of Platinum electrode around 1.2 volt, the exchange-current density is about $8 \times 10^{-4} A/cm^2$. [5]

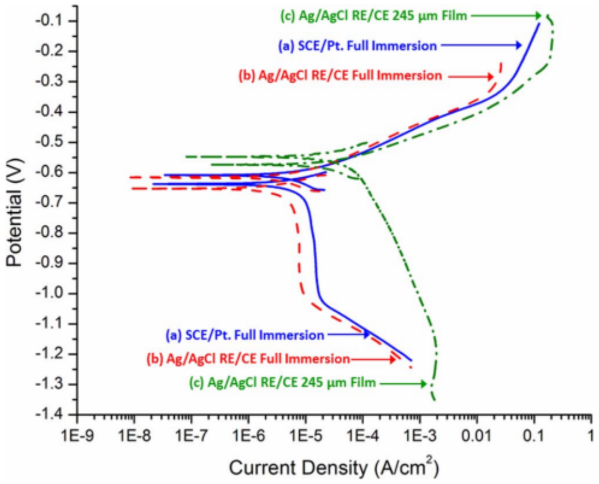

Figure 5: Polarization curves for steel (in 0.6 M NaCl) using (a) a conventional SCE and Pt. mesh in full immersion, (b) a sintered Ag/AgCl as combined RE and CE in full immersion, and (c) a sintered Ag/AgCl as combined RE and CE in thin electrolyte film of 245 microns. [5]

Plug in the values we have into the equation (3)

For Ag/AgCl electrode,

$$R_{ct} = \frac{RT}{nFi_0} = \frac{8.314 J/mol\cdot K \times 298.15\, K}{1 \times 96485\, C/mol \times 1.3{*}10^{-5} A/cm^2}$$

$$= 1968.9\, \Omega/cm^2$$

For Platinum electrode,

$$R_{ct} = \frac{RT}{nFi_0} = \frac{8.314 J/mol\cdot K \times 298.15\, K}{2 \times 96485\, C/mol \times 8{*}10^{-4}\, A/cm^2}$$

$$= 16.0\, \Omega/cm^2$$

Referring to previous research from our literature review, we confirmed that our theoretical values are similar to experimentally measured values. For Ag/AgCl electrode, the previous measurements is 1471 Ω/cm2 in the dry electrode model and 1891 Ω/cm2 in the wet electrode model. [6] For Platinum electrodes, the previous experiment states the charge-transfer resistance to be around 30 Ω/cm2.

Using the double layer capacitance, we can calculate the total impedance and evaluate between the wet/dry electrode model and the Ag/AgCl, platinum material difference.

	Dry electrode	Wet/Semi-dry Electrode
C_d (Ag/AgCl)	10 nF	0.4157 μF
C_d (Platinum)	2.8 nF	2.8 nF

Table 2. The double layer capacitance of the dry electrode and wet/semi-dry electrode. [7]

The transfer function equations were found by combining the impedances of each of the circuit diagrams, and then numeric values were substituted in. MATLAB was utilized to combine fractions and convert the equations into their correct form. The bode plots were also obtained from MATLAB using the ‘tf’ and ‘bode’ functions.

III. Results

A. *Transfer Functions/ Bode Plots*

The transfer functions and Bode plots of the wet and dry sweat-exposed electrodes for Platinum and Silver were obtained. Due to the additional impedance of the skin, the transfer function of the dry electrodes were both of a higher order than the gel (3rd vs 2nd)(Fig.3,5). Similarly, the main differences in the Bode plots were between the wet vs.dry electrode, and only were altered slightly between the two different types of metal. All of the bode plots obtained had equal number of poles as zeros, which simplified the plot.

$$\frac{3.19 * 10^{-7}s^3 + .086s^2 + 217.7s + 135360}{2.46 * 10^{-9}s^3 + 7.96 * 10^{-6}s^2 + .0069s + 1}$$

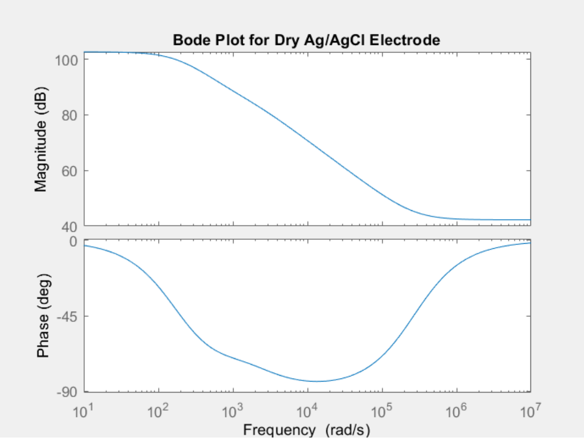

Fig. 6: This figure displays the transfer function(above) and the bode plot of the dry Ag electrode.

In both silver electrodes, the first cutoff frequency was approximately 100 rad/s, and the second differed only by a magnitude of one. The phase margin was also very similar for both the wet and dry silver electrodes.

$$\frac{3.25 * 10^{-4}s^2 + 7.37s + 3.05 * 10^3}{2.5 * 10^{-6}s^2 + .004s + 1}$$

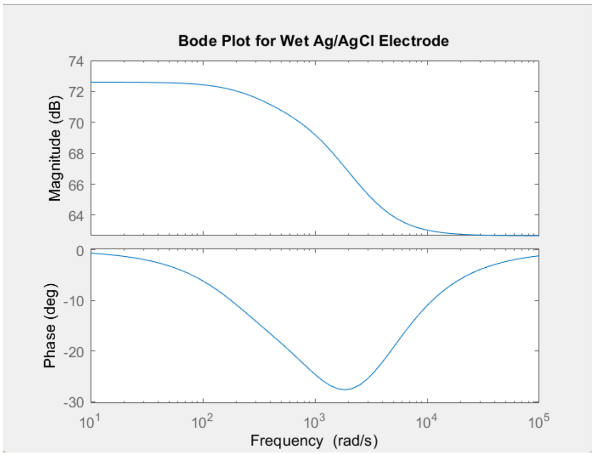

Fig. 7: This figure displays the transfer function(above) and the bode plot of the wet Ag electrode.

$$\frac{1.26 * 10^{-8}s^3 + 2.08s^2 + 4.04 * 10^3 s + 641660}{9.69 * 10^{-11}s^3 + .0157s^2 + 27.89s + 5}$$

The platinum electrodes displayed more drastic differences between the wet and dry than the silver electrodes. The main difference was that for the dry electrode, the initial cutoff frequency was at about 0.1 rad/s, but for the wet platinum electrode, the first cutoff frequency was at 10^8 rad/s. Thus, there is a very large difference between the operating frequencies of the wet vs. dry Pt electrodes, unlike the Ag. Also, as seen from Fig.6, the bandwidth of the wet Pt electrode was only one order of magnitude, which is significantly less than the rest of the electrodes, which were 2-3.

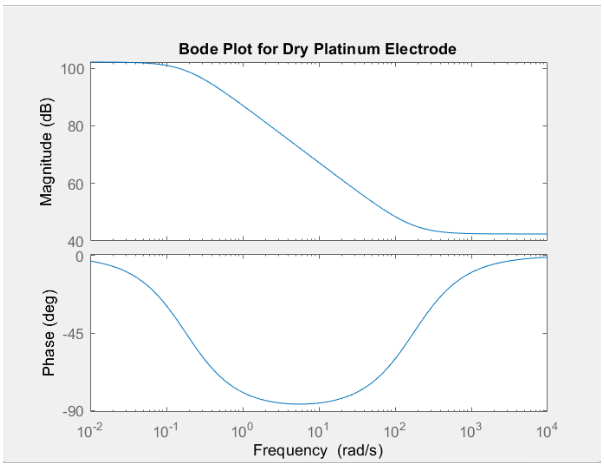

Fig. 8: This figure displays the transfer function(above) and the bode plot of the dry Pt electrode.

$$\frac{1.24 * 10^{-8}s^2 + 5.11s + 1704}{9.5 * 10^{-11}s^2 + .016s + 5}$$

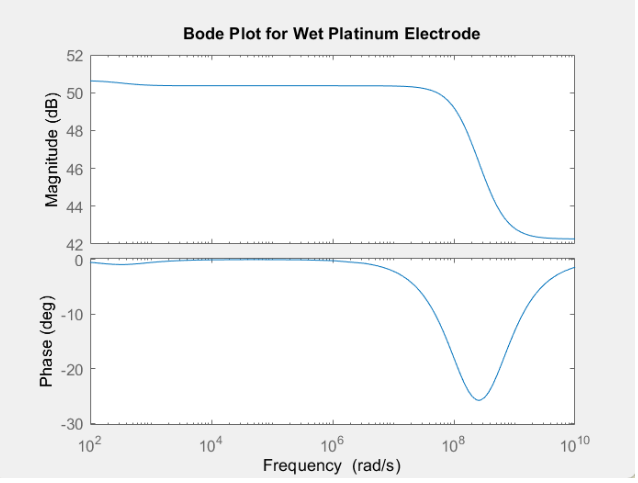

Fig. 9: This figure displays the transfer function(above) and the bode plot of the wet Pt electrode.

B. *Total Impedance*

The total impedances for the dry electrodes were on average much higher than for the gel electrodes, even with sweat, which contradicted our initial predictions. The dry silver electrode had the highest total impedance, while the wet platinum electrode had the lowest. Overall, both platinum electrodes displayed a lower total impedance in comparison to silver for both the wet and dry electrodes.

Total Impedances		
Material	***Dry***	***Wet***
Silver	$1.85 * 10^{5}\Omega$	$3.19 * 10^{3}\Omega$
Platinum	$7.54 * 10^{4}\Omega$	$1.27 * 10^{3}\Omega$

Table 3: This table displays the total impedance for wet and dry electrodes of both silver and platinum. It should be noted that in each scenario, sweat is accounted for in the calculation.

IV. Discussion/Conclusion

The most useful biosignal frequencies fall within the range of 50-150 Hz, with most physiological measurements being below 1kHz[4]. From the bode plots, all 4 electrode designs provide high signal magnitude in that range, meaning all 4 designs provide viable signal amplification.

From the previous circuits, we were able to find the overall impedance values for each condition. In the table we can see that for the silver chloride electrode, the wet electrode had a lower impedance than the dry electrode. This is preferred because we have read that electrodes should ideally have impedances under 5kΩ. The dry electrode has a much higher impedance and may result in higher amounts of noise in the signal. Similarly, in the Platinum electrode the wet electrode performs much better than the dry electrode. Interestingly we see a lower impedance value for the wet platinum electrode. So we conclude that the best electrode is the wet platinum electrode.

Future Directions

Future directions we could explore would include expanding our analysis to more materials. Other possible electrode materials could be gold, nickel or even carbon based electrodes. In addition, there have been publications about new electrode types other than dry and wet electrodes. One such electrode is the “semi-wet electrode” which utilizes saline solutions instead of a conductive gel. These act as an intermediate solution to wet and dry electrodes, offering the potential benefits from both designs while eliminating some of the drawbacks of each. We can also research the effectiveness of dry elastomer electrodes, where thin film metal is embedded in elastomer. These provide great electrical conductivity and more flexibility than the standard metal disks used in dry electrodes.

Acknowledgments

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