Electrode-Skin Impedance Changes due to an Externally Applied Force

Anas Albulbul, Adrian D. C. Chan
Department of Systems and Computer Engineering
Carleton University
Ottawa, Canada
albulbul@sce.carleton.ca

Abstract— **The objective of this research is to analyze the effect of an externally applied force on surface biopotential electrodes. Electrode-skin impedance is an important factor in biopotential measurements. Lower electrode-skin interface impedance is desired because it improves the measurement of biological signals and helps mitigate noise/artifacts. Electrode-skin interface impedance was measured from two subjects (from 1 Hz to 1 MHz) while applying different magnitudes of force (0 N, 8.8 N, and 22.3 N) on Ag/AgCl electrodes that were placed on the ventral side of the forearm. When 8.8 N of force was applied, the impedance at 10 Hz decreased compared to when there was no externally applied force. Increasing the applied force to 22.3 N produced inconsistent results between the two subjects, with one exhibiting an increase in impedance, while the other a decrease. When all applied forces were removed from the electrodes, there was a sustained decrease in impedance, as compared to the initial impedance with no externally applied force. An externally applied force can reduce the electrode-skin impedance, which is maintained even after the force was removed.**

Keywords-biopotential; electrode; force; impedance; skin

I. INTRODUCTION

Various biopotential signals, such as electrocardiograms, electromyograms, and electroencephalograms, can be monitored noninvasively using electrodes placed on the surface of the skin. The electrode-skin interface is an important factor in determining the quality of biopotential measurements [1]-[5]. Lower electrode-skin impedance is desired, as well as electrode impedance balance (note that lower electrode-skin impedance helps mitigate the electrode impedance imbalance). The electrode-skin impedance is affected by a number of factors, including electrode type, electrode size, and skin preparation [2][5]. An external force, applied to a biopotential electrode, can also change the electrode-skin impedance [6]-[9].

In [6], they found a general decrease in electrode-skin impedance when using light to moderate applied forces; changes were in the order of hundreds to thousands of ohms. As their primary interest was in the application area of impedance plethysomography, they reported only average impedance values at 5 kHz.

Decreases in electrode-skin impedance, associated with an applied force were also observed in [7]; however, while [6] observed impedance changes around 300% with dry tissue and 20% with wet tissue, [7] only observed impedance changes in the order of 7% and 5%, respectively. Differences were attributed to the application of the electrodes [7]. It was also noted in [7], that initial application of an applied force to an electrode caused irreversible changes in the impedance, implying a hysteresis effect. Successive applications of an applied force caused smaller changes that eventually became reversible.

In [8] and [9], the electrode-skin interface was modeled using an RC electrical circuit that yielded a double time constant. Circuit model parameters were estimated by a least-mean-squares curve fitting of the time domain, step response. The authors associated the first time constant with the electrode-electrolyte (or electrode-sweat) interface, and the second time constant with the electrolyte-skin interface. It is expected that the electrode-electrolyte impedance would dominate over the electrode-skin interface. While two time constants were observed, it may be better to associate each time constant with a separate electrode-electrolyte interface; measurements in [8] and [9] were performed using two electrodes, each with its own electrode-electrolyte interface, which are unlikely equal. Thus, each electrode could be associated with one time constant. Regardless, the results in [8] and [9] also show a change in impedance due to applied force. While there was a general decrease in impedance with increasing applied force, the trend was not always consistent across subjects and electrodes.

In this work, we examine the effects of a larger range of applied forces, in which the electrode-skin impedance is measured over a large range of frequencies. We also examine hysteresis effects (i.e., force loading/unloading) and its impact over time.

II. METHODOLOGY

A. Measurement Setup

Pregelled Ag/AgCl surface electrodes (MVAP II, MVAP Medical Supplies Inc., Newbury Park, CA, USA) were used in this experiment. These electrodes have a diameter of 1 cm. A pair of electrodes was placed on the ventral side of the forearm, spaced 7 cm apart, with the distal electrode approximately 11 cm from the wrist (Fig. 1a). No skin preparation was performed. A snap electrode lead was used to interface the electrodes to an impedance measurement system, which

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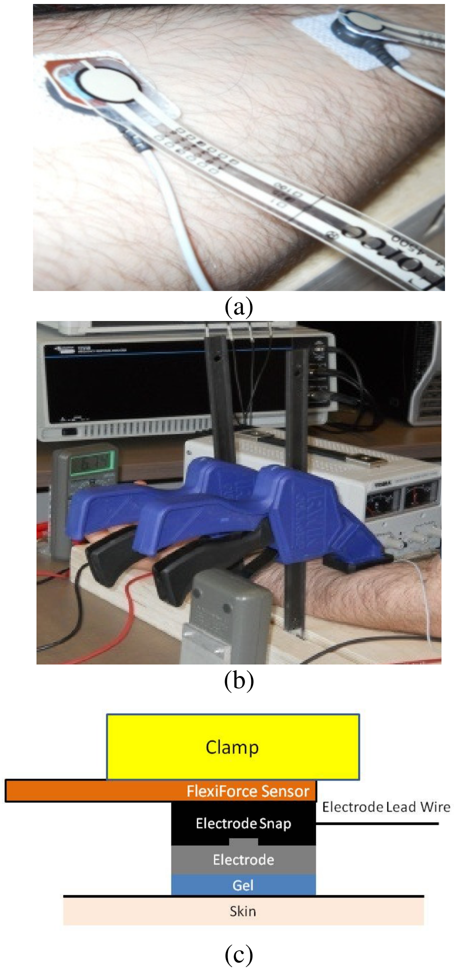

Figure 1. (a) Pair of Ag/AgCl electrodes placed on the ventral side of the forearm, with snap leads, and FlexiForce sensors. (b) Custom clamp device used to provide externally applied forces. (c) Schematic of the measurement setup.

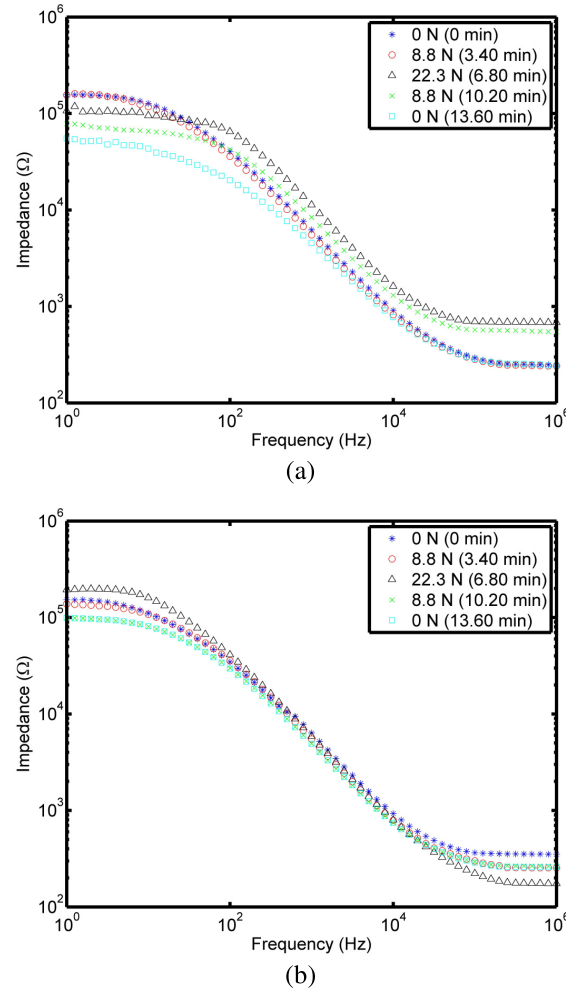

Figure 2. Electrode-skin impedance frequency response with externally applied forces for (a) subject 1 and (b) subject 2. Times in parentheses indicate the start time of the impedance measurement.

consisted of a frequency response analyzer (model 1255A, Solartron Analytical, Farnborough, UK) and an impedance interface (model 1294A, Solartron Analytical, Farnborough, UK).

A custom device was constructed to provide an externally applied force (Fig. 1b). The device consisted of two clamps (SL300 Quick-Grip, Irwin Tools), integrated into a fixed wooden base, which was used to provide a downward vertical force. Force sensors (FlexiForce A201, 25 lb range, Tekscan, Boston, MA, USA) were used to measure the applied force. A schematic of the measurement setup is shown in Fig. 1c.

Note that this measurement setup measured the electrode-skin impedance as well as the subcutaneous impedance (i.e., tissue underneath and between the electrodes); however, it is assumed that the subcutaneous impedance (typically less than 500 Ω) is negligible compared to the electrode-skin impedance [3][10].

B. Data Collection

This research was reviewed and approved by the Carleton University Research Ethics Committee. Measurements were conducted on two male subjects. Impedance measurements were performed using three force levels: 0 N (no externally applied force), 8.8 N and 22.3 N (equivalent to applying a weight of 0 lb, 2 lb, and 5 lb). Impedance was measured from 1 Hz to 1 MHz (10 points per decade), averaging 20 cycles per frequency, using an AC supply current (100 µA root mean square). Each impedance measurement took approximately 4.5 min to complete. The room temperature and humidity were measured as 22°C and 31%, respectively.

An electrode pair was placed on the right forearm, with impedance measured while varying the applied force. Impedance was measured in succession using the following forces: 0 N, 8.8 N, 22.3 N, 8.8 N, and 0 N. Another electrode pair was then placed on the left forearm and the impedance measured at 0 N. Impedance was then measured alternately from the right and left forearm for the next 30 min at 0 N.

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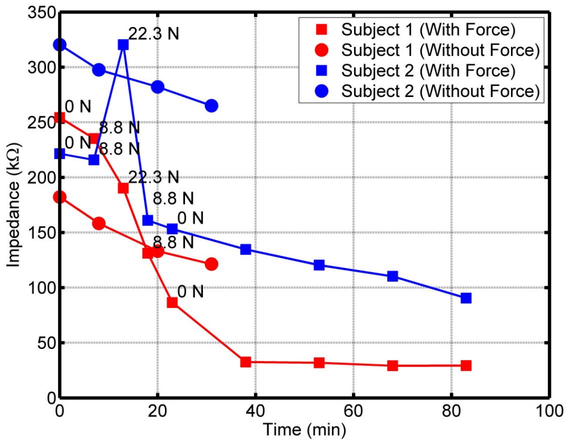

Figure 3. Electrode-skin impedance at 10 Hz as a function of time. Applied forces are indicated during load/unloading phase of the experiments (unlabeled data points have no applied force; i.e. 0 N).

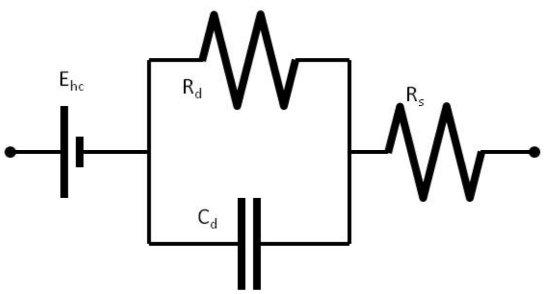

Figure 4. Equivalent circuit model for the electrode-skin interface.

III. Results

Fig. 2 is a plot of the electrode-skin impedance frequency response for both subjects while the applied force was varied. For both subjects, when the 8.8 N force was first applied, the impedance decreased; most notably for the lower frequencies. For subject 1, when the applied force was increased to 22.3 N, the impedance decreased for lower frequencies and increased for higher frequencies. For subject 2, the impedance had the opposite behavior, increasing for lower frequencies and decreasing for higher frequencies. For both subjects, the impedance was lower when the force level was returned back to 0 N, compared to the initial impedance at 0 N (i.e., before any force was applied); particularly for lower frequencies.

Fig. 3 is a plot of the electrode-skin impedance at 10 Hz as a function of time (time $t = 0$ min is associated with the time at which the electrode pair was first applied). The impedance before and after force loading/unloading was decreased by 73% and 36% for subject 1 and 2, respectively. For subject 1, the impedance after the force loading/unloading, remained relatively stable (32 kΩ at time $t = 31$ min and 100 kΩ at time $t = 83$ min). For subject 2, the impedance after the force loading/unloading continued to decrease (135 kΩ at time $t = 31$ min and 100 kΩ at time $t = 83$ min). The impedance for the electrode pair that did not undergo any force loading/unloading decreased by 30% and 17% for subject 1 and 2, respectively.

Table I. Percentage decrease in electrode-skin impedance in the first 30 min at 10 Hz.

Subject	With Force	Without Force
1	73 %	30 %
2	36 %	17 %

Table II. Equivalent circuit model parameters for the electrode-skin interface before and after force loading/unloading.

Subject	Model Parameter	Before	After
1	Cd	28 pF	35 pF
	Rd	157 kΩ	40 kΩ
	Rs	288 Ω	294 Ω
2	Cd	29 pF	34 pF
	Rd	118 kΩ	81 kΩ
	Rs	295 Ω	391 Ω

IV. Discussion

The electrode-skin impedance can be lowered through the application of a light to moderate force (8.8 N). This force may be increasing the effective electrode-skin contact area, thereby decreasing the impedance [7]. With a higher applied force (22.3 N), the results between the two subjects are inconsistent. Inter-subject differences may be accounted for in the manner by which the electrolyte redistributes itself at high applied forces. In [7], an increase in electrode-skin impedance with increasing applied force was noted for recessed electrodes. They hypothesized that the increased force caused the electrolytic paste to escape from the electrode cup, thereby increasing the electrode-skin impedance. A similar effect could account for increases in impedance here. A large applied force may cause the electrolyte to be squeezed out from underneath the electrode, resulting in an increase in impedance.

The shape of the frequency response (Fig. 2) is expected and often modeled using the equivalent circuit model for an electrode, shown in Fig. 4 [11]. E_{hc} is the half-cell potential, R_d and C_d are the impedance associated with the electrode-skin interface and polarization effects, and R_s is the series resistance associated with the interface effects. As the frequency increases, the impedance associated with C_d approaches zero and the electrode impedance approaches R_s. At low frequencies, the impedance associated with C_d increases to infinity and the electrode impedance approaches $R_s + R_d$. Table II shows how the circuit model parameters change as a result of the force loading/unloading procedure (parameters were estimated using a least-squares curve fitting method). The force loading/unloading caused a decrease in electrode-skin impedance for both subjects with a larger change observed for the lower frequencies (primarily associated with R_d). The irreversible decrease in electrode-skin impedance is consistent

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with the observations made by [7]. The decrease in impedance is associated with an increase in the effective electrode-skin contact area, across which the impedance is measured [7]. In addition, the force may have enabled the electrolyte to penetrate the outer dry layers of the skin (stratum corneum).

For the electrode pair that did not undergo any force loading/unloading, the electrode impedance also decreased. This temporal dependence of electrode-skin impedance is consistent with previous research [5][7][9][12][13]. The electrode settling is due to changes in the electrode-skin interface, such as sweat gland activity or the electrolytic gel moisturizing the interface.

A larger decrease in impedance was obtained in the electrode pair that underwent force loading/unloading compared to the electrode pair that experienced no externally applied force (Table I). This suggests that when using surface electrodes, the application of a temporary external force can serve to reduce the electrode-skin impedance and electrode settling time.

V. CONCLUSIONS

An externally applied force can have a large effect on the electrode-skin impedance. While a light to moderate applied force can decrease the electrode-skin impedance, a large force may result in an increase in the impedance. This increase may be attributable to a redistribution of the electrolyte used with nonpolarizable electrodes; however, further investigation is required to confirm this.

A hystersis effect was observed, where the application and subsequent removal of an applied force resulted in a sustained decrease in electrode-skin impedance. Some of the decrease in impedance can be attributed to electrode settling; however, the electrodes that underwent force loading/unloading exhibited a decrease that was more than double than the electrodes that had no force applied to them.

The effect of external forces on the electrode-skin impedance is important in applications such as wearable physiological monitoring systems (e.g., electrocardiography, electromyography, electroencephalography). In wearable systems, electrodes are often integrated into a compliant fabric. The size and compliancy of the fabric will impact the force applied to the electrode. As seen from this work, the applied force affects the electrode-skin impedance, which in turn can impact the quality of the biopotential measurement [1]-[5]. The applied force may also be dynamic, as the size and shape of a person's anatomy can change (e.g., the diameter of muscle can increase during flexion). Dynamic changes in electrode-skin impedance can result in artifacts within the measurement (e.g., motion artifact [14]). Better understanding of the effect of an applied force on the electrode-skin impedance can help ensure better biopotential measurements.

Continued research will involve a larger data set to provide more conclusive results. Analysis based on the electrode circuit model will help to explain the observed behaviors. Investigations concerning repeated force load/unloading and polarizable electrodes (i.e., dry electrodes that do not require the use of an electrolytic gel) will also be conducted.

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