Bioimpedance Monitoring

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Bioimpedance Monitoring in Residual Limbs

***Abstract* - This project study focuses on creating an adaptable prosthetic design through bioimpedance monitoring sensors. This set-up primarily covers diurnal volumetric changes in below-knee residual limbs. The design encompasses different measurements between the frequency altered voltage inputs sent through the body and the resulting output voltage. Extracellular fluid resistance is quantified and applied to determine the extracellular fluid volume of the limb. The resulting changes are sent to actuators in a prosthetic socket to adjust the internal socket volume. Using our design we measured a 12.5cm limb segment to have an extracellular fluid volume of $5.74*10^{-4}$ cm^3.**

I. INTRODUCTION

Poor circulation or peripheral artery disease (PAD) is the most common reason for amputation: affecting around 150,000 amputees on an annual basis. PAD often results in amputation due to the restriction of flow via a dangerous hardening of the arteries [1]. Those with such amputations often look to prosthetics to improve daily life. A prosthetic consists of a prosthetic socket that provides a crucial foundation for the prosthesis to attach [2]. Contemporary socket-fitting practices primarily take into account how much body-weight is being applied to the socket region. This practice, however, lacks necessary adjustment for the natural diurnal volume fluctuations. Volume is consistently changing depending on factors such as environment, daily movement, activity, and health. These changes can lead to the pistoning effect, the undesired movement of the amputated segment within an ill-fitting socket that acts as a crucial point of attachment between an amputated limb and a prosthetic device. Apart from pistoning, prostheses which cannot account for volume fluctuations, may cause excessive sweating, irritation and ill-fit [4]. Hence, these diurnal volume changes are important considerations in lower limb prosthetics. As a result, this paper proposes the addition of an auto-adjustable socket that will adjust according to diurnal volume changes.

In this study, bioimpedance analysis (BIA) was used to determine the limbic volume, V, for use in prosthesis applications. BIA provides information about the extracellular fluid levels as it measures the effective impedance of a cell by injecting a low amplitude and high frequency current into the body through surface electrodes. The cellular model [Fig. 1] represents the bioimpedance produced by the limb. This model is approximated as the resistance of the extracellular fluid (Re) in parallel with the series combination of the resistance inside the cell (Ri) and the capacitance of the membrane (Cm).

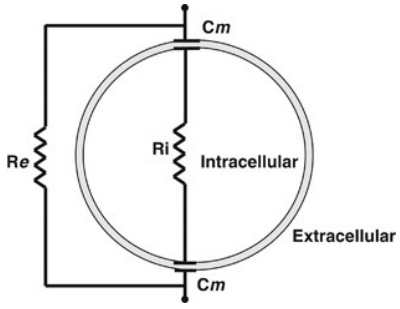

Figure 1. Impedance model of a cell.

Using the measured impedance, volume can be calculated and programmed to be adjusted in real-time. These real-time calculations may then inform the automated mechanical adjustment of the prosthetic socket's dimensions.

II. METHODS

The overall aim of our design is to create a prosthetic socket that can detect and adjust for daily volumetric changes. The system model utilizes closed loop feedback where a known voltage controlled current is injected into a section of a residual limb, the voltage across a limb segment analyzed. As shown in [Fig.2], the inputted current and outputted voltage is used to determine the impedance of the limb segment. This impedance is then used to determine the volume of the segment which is sent to the prosthetic socket to be adjusted to ensure total socket-limb contact. Bioimpedance components are separated and analyzed to show proof of concept for future socket designs.

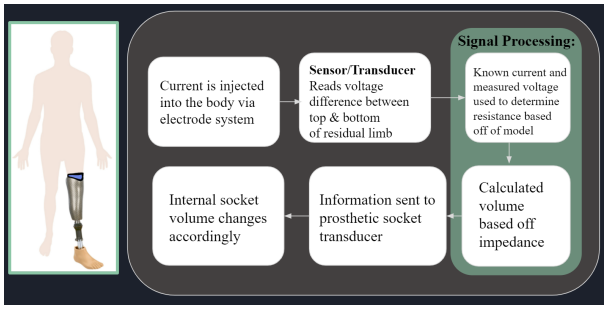

Figure 2. Bioimpedance block diagram.

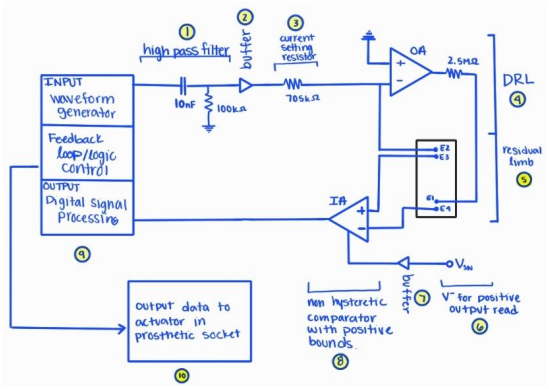

Figure 3. Circuitry of bioimpedance sensor with output to prosthetic socket.

For the purposes of our analysis we use our waveform generator to sweep from frequencies of 50kHz to 50.5kHz. This allows us to remain in the optimal range of frequencies for a bioimpedance sensor while also providing a large enough range to test and evaluate the measured impedance from the body without harm [6]. All components are supplied by a +/-5V voltage source unless otherwise stated. A four electrode model is utilized as it is ideal for the frequency range chosen, providing the separation of current and voltage input/output to avoid unwanted impedances being generated from the electrodes and to maintain accurate impedance measurements [7].

A. Input and Current Injection

The input from the waveform generator is a two volt peak-to-peak and two volt DC offset voltage with a frequency sweeping from 50k to 50.5k Hz. Before current can be processed and injected into the body, the input must be zero-centered, therefore a high pass filter with a low cutoff frequency is used. The capacitor was chosen to be 10nF and a resistor of 100kΩ was chosen to minimize power consumption. This created a cutoff frequency of 1.6kHz which allows the signal to be centered and noise to be removed without distorting the input voltage. Using the known relationship that $V_{out}=0.707*V_{in}$ at the -3dB cutoff frequency the output voltage is 1.41V. To ensure that the highpass output voltage is not affected by the rest of the circuit a buffer is used. When creating a bioimpedance sensor the amount of current going into the body needs to be minimized. We decided to ensure the current injected is far below the threshold for perception, 1 and 10 mA [8], and choose the injected current value to be 2µA. Using ohm's law and the known output voltage of 1.41V, the resistor that ensures the current injected is 2µA is found to be 705kΩ.

In order to further protect the body, we want to use an active grounding component that would limit the CMRR degradation due to impedance mismatch of the electrodes so we can reduce the common mode voltage directly [9]. This component is the driven right leg (DRL), which allows maximum current to be determined based upon the known relationship:

$$i_{outMAX} = \frac{V+}{R_3} \qquad (1)$$

where V+ is the 5V supplied to the op-amp, i_{max} is 2µA, and R_3 is the protective resistor. Using these equations and values, the protective resistor, R_3, is found to be 2.5MΩ.

These components ensure the amount of injected current into the body through electrodes E1 and E2 is within a safe range with the supplied voltage and frequency.

B. Voltage detection

To compare the unknown voltages across the section of interest a non hysteretic comparator is used. This

was chosen as the reading is given quickly and the high fluctuations in the voltage graph will not impact our reading. For this component the output voltage is equal to the positive or negative supply voltage depending on the relationship of the input voltage. As our microcontroller is only able to read positive voltages we are going to replace the negative voltage supply with a +2.5V input. This value was chosen as it was positive and different from the positive voltage supply of 5V. To ensure the output from the voltage supply is not affected by the rest of the circuit a buffer is used.These components allow for the voltage across the limb segment to be detected and sent for analysis from electrodes E3 and E4.

C. Microcontroller

The microcontroller is a key component in calculating the bioimpedance and consists of 4 main components: a waveform generator, digital signal processing, a feedback loop, and output. The waveform generator changes the frequency of the sine wave that is input into the circuit from 50k to 50.5k Hz. The digital signal processing portion of the microcontroller receives the voltage and calculates the difference in magnitude and phase angle between the input and output at the given frequency. The feedback loop tells the waveform generator that the signal has been received, processed, allowing the waveform generator to run again at a different frequency incrementally through the range. Once the designated range of frequencies have been run through the average impedance is found. This impedance is used to calculate the volume of the limb segment, approximated as a homogenous cylindrical conductor, based off the following equation:

$$V_{ECF} = \left(\frac{1}{1000}\right)\left(\frac{\rho_{ECF} C}{R_{ECF}}\right)^{2/3} \frac{L^{5/3}}{(4\pi)^{1/3}} \quad (2)$$

Where V_{ECF} is the volume of the extracellular fluid, ρ_{ECF} is the specific resistivity of the biofluid is 47 Ωcm, R_{ECF} is the resistance of the extracellular fluid, C is the average circumference of the limb segment, and L is the length of the limb segment [10]. If the volume of the extracellular fluid is found to be different than the previous measurement, the information is sent to an actuator on the prosthetic socket that would either increase or decrease the internal socket volume.

III. RESULTS

Using the theoretical circuit design outlined in Fig. 3 a real circuit model [Fig. 4] was built to find the bioimpedance of a limb segment. The input and output voltages were mapped to an oscilloscope to provide proof of concept and knowledge as to what the microcontroller is registering [Fig.5]. The electrodes used were placed 12.5 cm apart, with an average arm circumference of 19 cm, and resitivity of ECF is 47 Ω·cm.

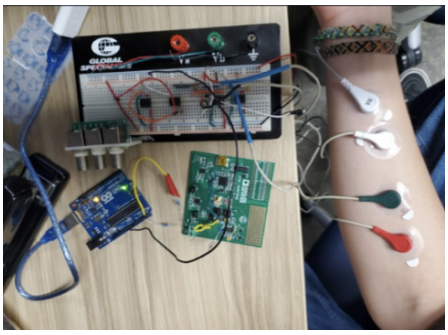

Figure 4. Practical Bioimpedance Circuit

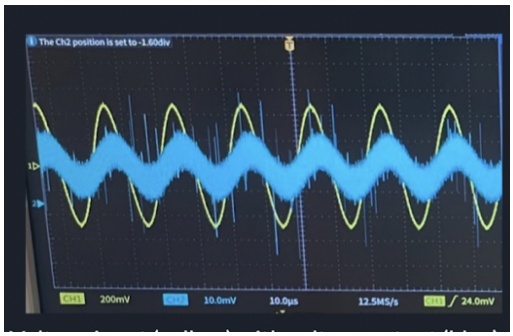

Figure 5 Input (yellow) and output (blue) voltage obtained from bioimpedance circuit analysis

The difference between the input and the output magnitude and phase shift are sent to the microcontroller and processed through a range of frequencies between 50k-50.5k. This allows the total impedance as well as the individual components of the cell model to be found. The stabilized magnitude of the frequency is approximately 20350 Ω [Fig.6]. Using the aforementioned measurements, we found that our subject's volume of extracellular fluid was $5.74*10^{-4}$ cm^3.

This practical model serves as the basis for which we can monitor the bioimpedance of residual limbs in real-time to improve the fit and comfort of prosthetics.

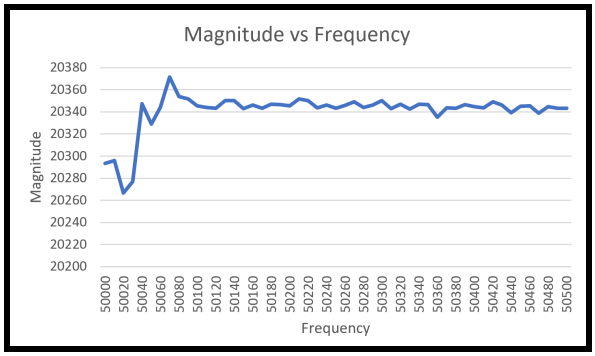

Figure 6. Magnitude of Impedance for ECF in response to varying frequencies

IV. CONCLUSIONS AND DISCUSSION

Limitations

In its current state, the model has several limitations, the addressal of which can lead to improved impedance-based volume approximations for socket fit. Referencing [Fig. 5], the output signal contains significantly more noise than the input signal likely due to the following sources of error: poor skin-to-electrode contact, high frequency noise from nearby electronics and subject movement. These sources of error could be reduced by the implementation of a bandpass filter (cutoff frequencies are <40kHz and >60Khz), tighter controls on a high pass filter, or with actively filtering electrodes that can perform all functions of traditional electrodes before noise can be added. Noise due to poor skin-to-electrode contact can also be exacerbated from consistent wear as shown in this study's prosthetic application. Adhesive electrodes as those used here may face wear and tear from sweat among other factors.

Apart from practical limitations of the model, BIA itself possesses limitations in body composition assessment via impedance monitoring. BIA assumes that hydration factors are constant across people with varying fat concentrations. But fat's water content is higher than that of muscle, deeming the model used inconsistent for obese amputees. It also estimates limbs as perfect cylinders rather than estimating their organic spatial volumes which may cause inconsistencies in socket adjustment if not accounted for.

Advantages

Considering the limitations previously mentioned, the advantages evidently outweigh the disadvantages. Our proposed model offers a non-invasive and inexpensive solution for monitoring the extracellular fluid changes in real time. Similarly, the model proposes a better fit environment for the prosthetics that takes into account any disease-related volume changes. This alternative may revolutionize the precautionary care for amputees with diabetes, as restriction of circulation often leads to initial or further amputation.

Future Steps

The proposed solution uncovers a variety of areas for improvements. As a result, integrating the designed circuit into a feedback system that controls and optimizes the prosthetic adjustments is the primordial step to improve the design. The feedback system is crucial to prevail effective employment of the model, as it will prevent erroneous measurements that may lead to unintentional adjustment of the socket. Next, it is important to consider the volume changes while sitting, standing, and walking. The volume of the residual limb changes throughout the day, and as a result of these varying activities, volume reduction makes a loose fit socket while volume expansion increases the tissue pressure in the residual limb. Finally, it is important to make the system register the spatial volume of the residual limb rather than the global volume. This is crucial as two limbs might have the same volume, yet they are shaped differently. By having a model that considers spatial volume, the auto-adjustable limb socket will prove to be a universal tool for prosthetic analysis that promotes well-being for any patient with a residual limb.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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