Measuring Body Composition via Body Impedance

Karthik Raj[1], Nitesh Sunku[1], Jason Tsujimoto[1]

***Abstract*— Body composition is a measure detailing the proportion of fat and non-fat mass in one's body, and is useful in determining someone's current health levels. Using electrical circuitry and bioinstrumentation analysis, we can determine the impedance of someone's body based on the voltage inputs and outputs, in which the amount of impedance correlates to the proportion of these two values. For this analysis, we simulated 500 Ohm, 1000 Ohm, and 1500 Ohm impedances to represent equivalent bioimpedance samples within a range of normal body impedances at 50 MHz with a 0.707 A AC Current Source. With an op amp gain of 8 V/V we were able to obtain our desired sensitivity of 4 mV/Ohm. Using the output signals of these simulations, we were able to calculate the measured impedance values and compare them to our actual impedance values. The results and graphs showed that the calculated and real values were very close, and equivalent within a small error bound of less than 1% error. These promising results lead us to conclude that the circuit we designed can adequately measure impedance and has the potential to function well as a component of a body composition measurement device, following additional testing on real human bodies.**

I. Introduction

A. Motivation

With the lack of physical exercise, continued high consumption of food, and degradation of people's mental health during the COVID-19 Pandemic, many have experienced unprecedented levels of weight gain, dramatically increasing their risk for diabetes, high cholesterol, hypertension, heart disease, etc. As a result, many people will be heavily invested in their nutrition and exercise when life returns to some sense of normalcy, with the hope of improving their body composition to their previous form, if not better. When it comes to improving one's body composition, too many people focus on the number of pounds or kilograms that comes off the scale, as opposed to the weight of fat. The issue with this is that if people are exercising and eating healthy, they will be burning their gained fat while simultaneously gaining some muscle, and because muscle is more dense, the increased muscle mass will contribute to a plateau if not increase in weight gain.. This could be demotivating for some as although they are making themselves physically healthier, their state of mind will tell them that they are working hard to get worse results. If people properly monitored their health goals with their body composition instead of the amount of weight loss they incurred, and monitored these values over time, many people would be able to properly achieve their fat loss and body composition goals. [6]

The science behind fitness and health has advanced drastically in the past several decades. Now, instead of just measuring weight and BMI, obtaining body composition measurements has become easily accessible. With the introduction of commercial smart scales, individuals are now able to keep track of their body fat and muscle mass percentages in addition to the standard weight measurement. This is beneficial for most individuals since the typical BMI scale used to track healthy weight can provide skewed measurements for those at the extreme ends of the spectrum. BMI exclusively uses weight and height to provide a single measurement value. As a result, someone that is extremely muscular can be labeled as obese, and someone trying to lose weight may be losing important muscle mass under the assumption they are becoming healthier. By tracking fat mass instead of overall weight, individuals can better assess the rate and direction of their progress, and these smart scales can help monitor it.

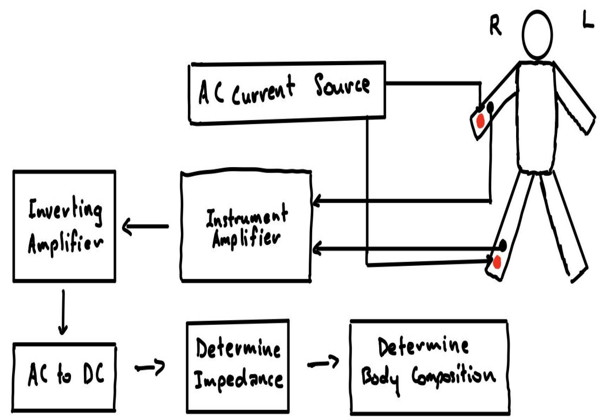

Fig. 1. Diagram of the system used to measure body composition through impedance analysis. An AC current is passed through the body and the resulting voltage difference is measured by the instrumentation amplifier. This voltage signal is amplified and used to determine body impedance. Using bio-impedance equations, the body impedance can be used to estimate body fat percentage.

B. Smart Scales

These smart scales function by passing a small electrical current through the body and calculating the body impedance. This current is usually passed from the right arm to the right leg or the right leg to the left leg. The current passing through the body generates a voltage drop across the body that is used to calculate body impedance. Since fat mass and muscle mass have different impedances due to their individual compositions (muscle mass having lower impedance due to increased water content), the net body impedance can be used to determine the relative composition of fat mass and fat-free mass. The general system for a body composition measuring device consists of an AC current function generator, a voltmeter, a series of signal amplifiers, an AC to DC converter, and a computer that converts output voltage to impedance and body composition. [1]

C. Equations

A study conducted by E. Mylott determined that the approximate body impedance to body composition relationship is as follows:

$$FFM = 0.36(H^2/Z) + 0.162H + 0.289W - 0.134A + 4.83G - 6.83 \quad (1)$$

Where Z is impedance in Ohms, H is height in centimeters, W is weight in kilograms, A is age in years, and G is gender (with 1 being male and 0 being female).

$$FM = W - FFM \quad (2)$$

Where FM is Fat Mass in kg, W is weight in kg, and FFM is Fat Free Mass in kg.

$$BF = FM/W * 100 \quad (3)$$

Where BF is body fat percentage. [5]

These equations were derived from the trend that women and the elderly tend to have lower muscle mass and higher body fat percentages (scalar corrections for the equation), while height and weight are more directly linked to the calculation of fat-free mass. The dependence of body fat percentage on impedance, height, weight, age, and gender was experimentally determined and is not going to be accurate for everyone, but it does provide a means of tracking change in body composition. [5]

D. Aim of the Study

Our goal was to model a circuit for the body fat measurement device using the arm-leg orientation. To accomplish this goal, we needed to design a circuit that could measure the voltage across the body between the two current supplying electrodes. This voltage measurement could then be used to calculate body impedance which could be plugged into our body impedance to fat mass equations.

II. Methods

A. BIA Circuit Design

The overall goal of our design was to calculate the voltage difference across the user's body impedance and amplify this difference to a scale allowing for easy interpretability of changes in the patient's body impedance, which implies changes in body composition. Another specification as mentioned initially above was established such that the user is not harmed in the process of determining the body composition. This requirement was that the solution draws no more than 0.8 mA of current from the body. This was achieved via the AD622 Instrumentation Amplifier whose high input impedance ensures that no more than 0.8 mA of current was drawn from the body. Our design solution is designed for an impedance range of 250 ohms to 1750 ohms which encompasses the normal range of body impedances of 500 ohms to 1300 ohms as established through our research. The extra range was used to allow for our solution to account for people with abnormally low or high body impedances. The sensitivity or slope of the relationship between the output of the amplified voltage and the input of the user's body impedance was chosen to be 4 mV/ohm because it allows the final output voltage to be displayed on a scale that allows for easy acknowledgment of differences within body impedances. [3] [4]

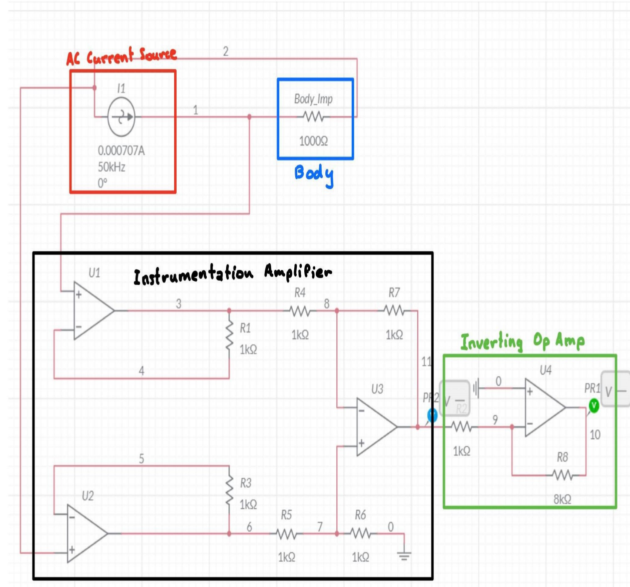

Fig. 2. Circuit Design implemented via instrumentation amplifier and inverting amplifier. This circuit measures the output voltage of the body and amplifies it by a gain of 8. This gain increases the sensitivity (mV/Ohm) of our device.

The BIA circuit design begins with a 50 MHz current source with a peak current value of 0.707 mA to generate the voltage difference across the body impedance. 50 MHz was used because it was the frequency primarily used by other smart-scale or bioimpedance analysis devices. 0.707 mA was used to stay in line with the design specification of 0.8 mA drawn or supplied to the human body and more importantly, to stay well below the threshold of maximum current that the human body can safely handle. The primary reason why we use an AC current source rather than a DC current source is because the body has both resistive and capacitive properties. At constant frequencies, however, the net impedance measured remains constant and can be measured similar to a single resistor. For this reason, we removed the capacitor out of our body circuit to make it easier to compare our actual impedance to the measured impedance. No extra calculations were necessary to determine the actual impedance. [5]

The BIA circuit encompasses two distinct phases: measurement of the voltage difference across the user's body impedance and amplification of this voltage difference to a scale allowing for easy interpretability of differences within the user's body impedances. Although the AD622 instrumentation amplifier can also be used for amplification purposes, in this design, the AD622 was primarily used as a means of calculating the voltage difference by not using a gain resistor in conjunction with the AD622. The sensitivity is ensured through the LM741 operational amplifier being used as an inverting amplifier with a gain of 8 established through the operational amplifier's ratio of impedances being 8. The final output voltage was not filtered because the noise primarily due to 60 Hz is ineffective to the final output voltage signal.

B. Calculations of the Body Impedance

In order to determine whether the circuit is functioning properly, an equation was derived which calculates the initial body impedance by taking into account the input current, output voltage, and the gain of 8 achieved through the LM741 operational amplifier being used as an inverting amplifier.

$$Z_{body} = V_{rms}/(8 * I_{rms}) \tag{4}$$

Then, the calculated body impedance can be compared to the actual body impedance to verify if the circuit design is functioning as expected. The current RMS was determined by taking the peak of the input current signal and dividing it by the square root of 2.

$$I_{rms} = I_{peak}/\sqrt{2} \tag{5}$$

The voltage RMS was determined by taking the peak of the output voltage signal and dividing it by the square root of 2.

$$V_{rms} = V_{peak}/\sqrt{2} \tag{6}$$

III. Results

In order to test our circuit, we conducted several simulations using MultiSim to determine if our circuit output could be used to accurately back-calculate the input impedance. Our simulation plotted the output voltage signal for several different impedances (500 Ohms, 1000 Ohms, and 1500 Ohms). Using the equations we derived earlier, we computed the measured impedance value and compared it to the actual body impedance we tested with. This test allowed us to determine how well our circuit and equations can accurately measure a body impedance. Having high accuracy for body impedance is of high importance because it is the primary independent variable used to calculate fat free mass, fat mass, and body fat percentage (Equations 1-3). Figures 3-5 shows the plots of these output signals with the body output voltage shown in blue and the amplified circuit output voltage shown in green. Table 1 displays the calculated impedances from these signals.

Seeing as the percent errors are all the same and that each measured value is only slightly below the actual value, we assume that this offset is likely due to an error in computer rounding (perhaps the peak measured is not the actual peak) but there is still a possibility that our circuit does not in fact amplify the body output by exactly a gain of 8. All of these percent errors are sufficiently small, however, so we are able

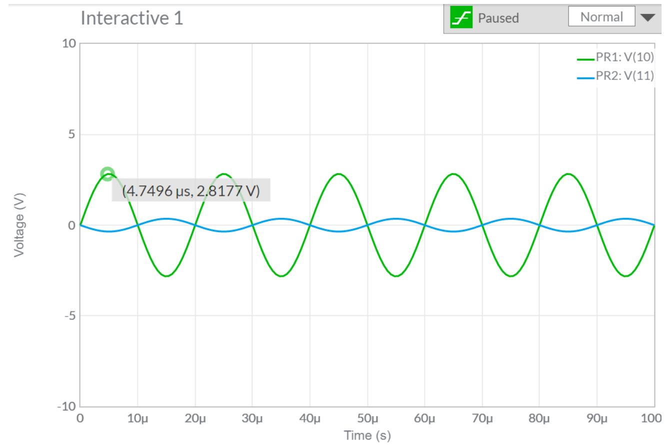

Fig. 3. Plotted results when changing the body impedance of the circuit diagram to 500 ohms.

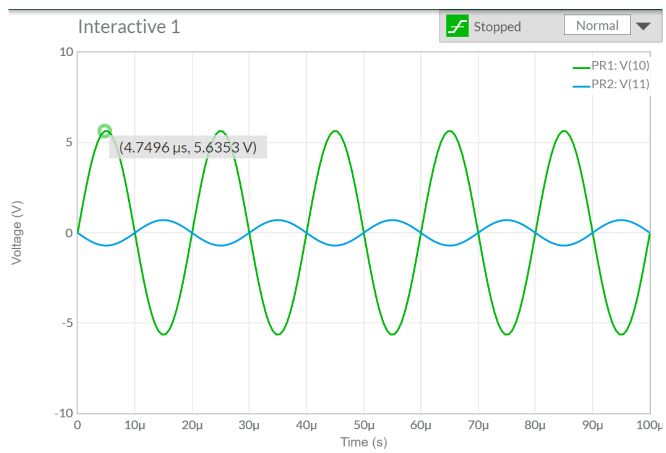

Fig. 4. Plotted results when changing the body impedance of the circuit diagram to 1000 ohms.

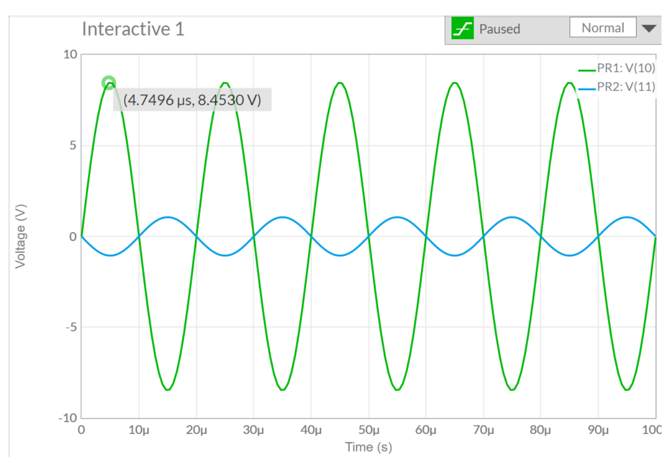

Fig. 5. Plotted results when changing the body impedance of the circuit diagram to 1500 ohms.

Actual Impedance	Measured Impedance	Percent error
500 Ohms	498.1 Ohms	-0.38 %
1000 Ohms	996.2 Ohms	-0.38 %
1500 Ohms	1494.3 Ohms	-0.38 %

TABLE I
MEASURED VALUES FOR IMPEDANCE ARE CALCULATED USING EQUATION 4 AND SIMULATION VOLTAGE SIGNALS.

to conclude that our circuit adequately performs its function of measuring body impedance. This error will only propagate slightly when inserted into Equation 1, so the error in our body fat percentage calculations will be minimal.

However, this testing is only theoretical as it was conducted via simulation rather than on an actual body. Further testing is required before conclusions can be made on its effectiveness as a component of a real body composition measurement device.

IV. CONCLUSION

This study designed a circuit for a simple body composition measurement device. We developed this circuit based off of previously determined system schematics and design requirements from the limitations of the body. Testing of our circuit determined that it can accurately compute impedance of the body through simulation of an AC current source and voltage differentials. This impedance measurement can be used to estimate body composition and serve as means of tracking change in body composition. While our circuit design functioned sufficiently well under our simulation, further testing would need to be conducted in order to include it as a component of a functioning body composition measurement device. The circuit functions theoretically but testing on an actual body with real components and electrodes is necessary to determine its effectiveness for a body composition measurement device. This testing would require the use of volunteers as well as a second device (to measure a real body impedance and composition). The accuracy of the circuit in our device could then be tested against a baseline device using a diverse range of volunteers to gain insight to its overall effectiveness as a portable body composition measurement device.

If further testing shows that this circuit can adequately measure impedance, this circuit has the potential of serving as an affordable, at-home body composition measurement device (used in conjunction with an AC current source and a computer) to aid individuals in maintaining a healthy body composition. Using the impedance to body fat percentage equations, change in body fat can be accurately tracked over time. However, although these portable body composition scales can provide an idea of one's composition, the amount of changing variables can lead to inaccurate readings when used as single use cases. Body composition will vary due to hydration levels, as muscles contain water and will therefore increase or decrease one's body fat percentage, depending on whether someone is dehydrated or hydrated, respectively. Furthermore, the accuracy of these measurements will also be dependent on one's biological gender, as body composition varies drastically between fully developed individuals of the opposite sex Additionally, age is also a limiting factor as bone density decreases with age and contributes to one's overall body composition, but cannot be obtained with direct measurement. On the other side of the spectrum, young children experience rapid changes in their body composition as they are developing, meaning that these scales will not be accurate or very useful in monitoring single use body fat measurements or trends in body fat measurements. Because of all these variations, correcting factors are used as accommodation, but these are not applicable to every type of person, leading to error in the ultimate body composition reading displayed. While portable devices such as this will be limited in single use accuracy, the trend over time can be a useful metric for individuals to use in conjunction with their weight to track fat loss progress. [2]

REFERENCES

[1] Ain, K., Soelistiono, S., Wibowo, R. A., Muniroh, L., Anggono2, T., Sari1, W. W. (2018, November 01). IOPscience. Retrieved from https://iopscience.iop.org/article/10.1088/1742-6596/1120/1/012043

[2] Buchholz, A. C., Bartok, C., Schoeller, D. A. (2004, October 01). The Validity of Bioelectrical Impedance Models in Clinical Populations. Retrieved from https://aspenjournals.onlinelibrary.wiley.com/doi/abs/10.1177/011542 6504019005433

[3] Kyle, U. G., Bosaeus, I., Lorenzo, A. D., Deurenberg, P., Elia, M., Gómez, J. M., . . . Pichard, C. (2004, August 10). Bioelectrical impedance analysis-part I: Review of principles and methods. Retrieved from https://www.sciencedirect.com/science/article/pii/S0261561404000937?

[4] Kyle, U. G., Bosaeus, I., Lorenzo, A. D., Deurenberg, P., Elia, M., Gómez, J. M., . . . Pichard, C. (2004, November 18). Bioelectrical impedance analysis-part II: Utilization in clinical practice. Retrieved from https://www.sciencedirect.com/science/article/pii/S0261561404001633 ?casa-token=l9I0upPcpWIAAAAA:ZZycf1cD4j-gphpOWipvs0xIci-FZq11D2DdBeIGTW6ZUC60aGM-Zqi48JsdfWUa7KacowEL9g

[5] Mylott, E., Kutschera, E., Widenhorn, R. (1970, January 01). Bioelectrical impedance analysis as a laboratory activity: At the interface of physics and the body. Retrieved from https://aapt.scitation.org/doi/10.1119/1.4866276

[6] Swift, D. L., Johannsen, N. M., Lavie, C. J., Earnest, C. P., Church, T. S. (2014). The role of exercise and physical activity in weight loss and maintenance. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3925973/