Wearable Bioimpedance Device

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***Abstract*—Obesity and severe obesity of adults in the US is a demanding issue that has negatively impacted the health of many and has continued to grow over 20 years. Obesity can result in the emergence of serious health complications and is brought on by bad diets, physical inactivity, and hereditary predispositions. The overarching health issue that our wearable Bioelectrical impedance analysis (BIA) device seeks to address is obesity. Bioelectrical impedance analysis is a method that determines a subject's fat-free mass (FFM) and total body water (TBW). In this paper, we designed a circuit that finds voltage drop across the body to deduce body composition which is done by running a small current through the body and measuring the voltage drop. Our device can be worn on the hands of individuals, where with the press of a button, users will receive a detailed breakdown of their body composition. Regarding the circuit's design, preliminary unwanted signals are filtered. The attenuated signal runs through the body which generates a small voltage and an infinitesimal current. The voltage differential across the body is magnified and quantified using an instrumentation amplifier. The isolated signal along with the measured current is used to find the unknown body impedance which then is translated into fat-free mass.**

I. Introduction

A. Motivation

With the advent of globalization, the increasing availability of ingredients and cuisine continues to engender more Americans to consume higher amounts of food. A survey conducted by the United States Department of Agriculture (USDA) found that Americans currently consume more food than what is federally recommended. This has been an observed trend since the 1970s into the 21st century, where food consumption has steadily increased past current dietary standards [1]. The need to flatten the curve of food consumption is imperative to American health, for it is one of the direct causes of America's obesity epidemic. Since the turn of the century, there was more than an 11.9% increase in obesity and a 4.5% increase in severe obesity among adults in the United States [2]. Obesity leads to stroke, type II diabetes, heart disease, and some cancers, and is one of the leading causes of early death. While national levels of obesity cannot be decreased overnight, individually one could take care of their own body. Taking the time to exercise and prioritizing a healthy diet are two aspects that are within one's control in maintaining a healthy body weight; but in doing so, there comes a need to track this progress, ideally in the form of body fat.

Current measurement techniques are diverse in terms of accessibility and accuracy. The first of its kind is hydrostatic underwater weighing [3]. This technique works by determining the ratio of body fat to lean mass by measuring a person's water displacement in a body of water, thus acquiring their body density and body fat percentage. While this method is highly accurate, it is not readily available, cumbersome, and expensive. A quicker method is the skin caliper test [4]. This involves pinching the skin with a caliper to find its length, where it is plugged into a population-specific equation derived from measuring a large population of people through underwater weighing. The constitutive equations predict body fat percentage within a 3-5% range and are dependent on many factors such as age, gender, training, and culture in the compared population. This method is fast and simple, but often inaccurate and unreliable given the number of required parameters. To date, the most accurate way to measure body fat percentage is a dual-energy X-ray absorptiometry (DEXA) scan [5]. It involves emitting a low-dose X-ray to measure bone density, which can be used to derive body fat percentage at specific body parts. While it is fast and known to be the gold standard for determining body composition, it is not available for public use as it is primarily used in clinical practice and research.

B. Bioelectrical Impedance Analysis

To facilitate the promotion of a healthy lifestyle, it becomes important for people to have ways to track their body composition that are both readily available and within the average consumer's reach. The benefit of knowing one's body composition is that it will engender the user to either make lifestyle changes in their diet or fitness or confirm their progress towards the results they desire. BIA is a method that determines a subject's fat-free mass (FFM) provided the subject is under normal physiological conditions, while not suffering from substantial fluid and electrolyte fluctuations [6]. It functions by passing a small alternating current between an electrode on the wrist and an electrode on the foot, where the supplied current creates a voltage drop that determines the impedance. This is possible because fat mass has a greater impedance than lean mass, meaning current travels slower in fat mass as compared to FFM [7]. Since muscle, fat, and bone all have different electrical conductivities, we can deduce the fat mass based on the speed of the current, where its numerical value can be approximated by first determining FFM from a standardized population-controlled constitutive equation, then subtracting the subject's total mass from FFM to determine their fat mass.

The overall BIA system design is conducted primarily in two stages: AC-input through electrodes that pass through the body that runs through a first-order high pass filter, and an instrumentation amplifier, shown in **Figure 1.**

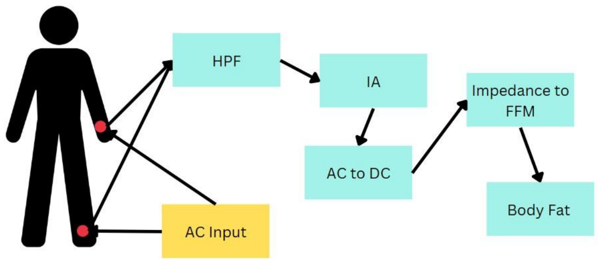


Figure 1 Bioimpedance Analysis Block Diagram

A small AC current passes through the body. The natural impedance of the body generates a voltage difference. This differential is measured, filtered, and amplified. It is then translated back into finding the body's impedance.

C. Goals

In this paper, we propose an alternative method to bioimpedance analysis: a wearable bioimpedance device. Our solution is derived from designing wearable electrodes that perform bioelectrical impedance analysis (BIA). We hope to design a device that will allow anyone to have a basic understanding of their body composition to inspire users to take action and implement a lifestyle with more exercise and a healthier choice in diet.

One advantage we hope to have over traditional body composition analysis is the combination of portability, accessibility, and accuracy. Methods like DEXA and MRI are accurate but extremely hard to find outside of a doctor's office and most people would not bother with scheduling an appointment solely to learn their body composition. Methods like skin calipers and tape measuring can have large degrees of error due to issues with individual body composition differing from the average values established by prior research [4]. Our device hopes to provide the best of both worlds by using a more standardized but accessible system by making the device as small and cheap as possible.

II. Methods

A. Circuit Parameters

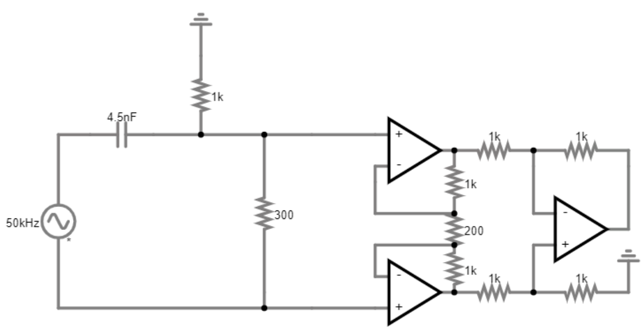


Figure 2: BIA Circuit Design

A 50kHz 0.035 V AC source feeds into a high-pass filter to cut out signals higher than 50kHz. The body is hooked up to electrodes that generate a voltage differential. Lastly, the instrumentation amplifier amplifies the voltage differential across the body by a gain of 11.

The first circuit element to discuss is the power source. Our circuit is powered by one 50kHz alternating 0.035 V power source. This power source was chosen specifically for safety concerns. Currents that are as small as 100 mA can cause respiratory and cardiac arrest, heart fibrillation, and electrical burns. Because of this, we hope to induce a tiny current. Assuming a minimum body impedance of 300 Ω with our voltage source of 0.035 V gives us a maximum possible current through the body of 0.1 mA, well within the boundaries of a safe current through the body. The reason we chose 50kHz as the frequency was due to the fact that the literature we referenced showed that as a safe threshold for usages for body analyses of any kind [6].

The second parameter is our high-pass filter. The goal with this circuit element was to attenuate the AC signal to ensure that our source is behaving as close to ideal. This was a concern as our circuit depends on a number of gain and theoretical relationships that would not be applicable if special care was not taken to make our input signal as close to ideal as we could. We hoped to cut out any portion of our signal that resulted in about 70% of the frequency of our 50 kHz goal. By using a resistor with a value of 1 kΩ and a capacitor of 4.5 nF., we achieved a cutoff frequency of 35367.765 Hz. We feel that this produces a circuit that removes any unwanted noise and produces a signal very close to an ideal current source.

The next circuit element in the BIA circuit is the user's body. The body can be approximated to a resistor. Our main goal with this circuit is to find body impedance therefore finding the resistance of the body resistor is of paramount importance. At this point, we use two electrodes for the current to enter and leave the body. A probe was attached to the input electrode to find the current flowing into the body. This will be useful later on when we want to quantify our voltage differential. The voltage differential is generated when set or body impedance is in parallel with our instrumentation amplifier.

Lastly, we have the instrumentation amplifier. This is the element that allows us to amplify and isolate our voltage differential. This is because the equation for the gain of the instrumentation amplifier includes the difference between our two input voltages as a parameter in the gain function (see figure 4).

$$Gain = \frac{V_{out}}{V_2 - V_1} = 1 + \frac{2R}{R_G} \tag{1}$$

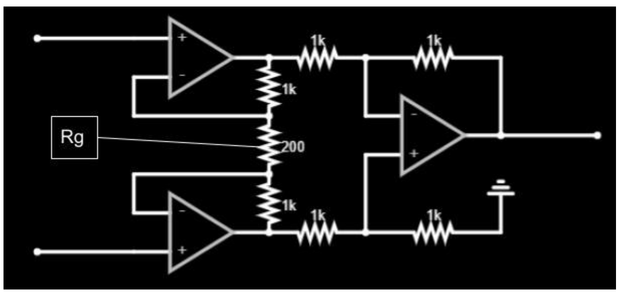


Figure 3: Instrumentation Amplifier

$$Gain = \frac{V_{out}}{V_2 - V_1} = 1 + \frac{2R}{R_G}$$

$$R_G = 200\Omega,\ R = 1000\,\Omega \gg Gain = 11$$

By measuring the circuit's output voltage we can solve for voltage differential by plugging it into the gain equation.

B. Equations

An experiment conducted by U.G. Kyle led to an equation that relates body impedance to body composition. The fat-free mass equation is as follows:

$$FFM = -4.104 + (0.518 \cdot \frac{2 \cdot Height}{Resistance}) + (0.231 \cdot weight) + (0.13 \cdot reactance) + (4.229 \cdot Gender: Male - 1, Female = 0). \quad (2)$$

Where height, is the height of the subject in centimeters, resistance is the body resistance of the subject in Ohms, in our case we used 300Ω, weight is the weight of the subject in kilograms, reactance is the non-resistive component of impedance in Ohms which based off our resistance comes out to 35.1Ω, and finally we must factor in whether our subject is a male or female (1 for male and 0 for female). This is vital as females tend to hold more fat than muscle and the equation must account for that.

After calculating the fat-free mass through equation 2 we can then use that to calculate the body fat percentage by using the following equation:

$$BF = \frac{(W - FFM)}{W} \cdot 100 \quad (3)$$

Where W is the weight of the subject and FFM is the fat-free mass calculated from equation 2. This equation then gives us a body fat percentage.

III. Results

A. High Pass Filter

To understand the theoretical electrical behavior of the HPF the equations for $H(j\omega)_{HP}$ was calculated. This mathematical model enables us to analyze the circuit output for each possible input.

$$H(j\omega)_{HP} = \frac{1}{(sR_bC+1)(\frac{R}{R_b+R})} \quad (4)$$

Using this equation and the values for each respective circuit component we create a bode plot to observe its behavior in our circuit design.

Figure 4: Plot generated using MATLAB, displaying the high pass filter magnitude bode plot with cutoff frequency at around 30000 Hz.

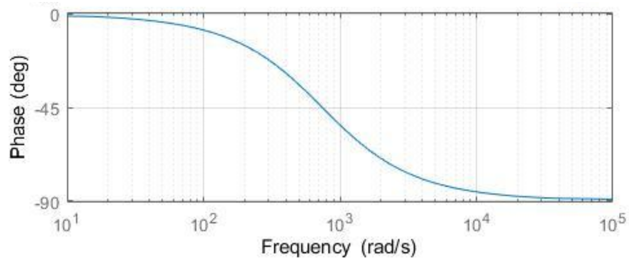


Figure 5: Plot generated using MATLAB, displaying the high pass filter phase bode plot with 90 degrees as frequency increases.

Here the cutoff frequency is where the magnitude response drops by 3dB, approximately 1187 Hz. Also, the phase plot shows that the signal approaches -90 degrees as frequency increases above the cutoff frequency.

The HPF in this circuit design plays an essential role to maintain unwanted frequencies coming from the voltage source and entering the body of the user. As a result, we maintain the output of the body accurately to continue through the amplification amplifier. To verify that the signal was stable before entering the body a waveform generator was utilized to administer an AC sine of identical 50kHz. Using the simulation we determine the relevance of the HPF as it enters the body

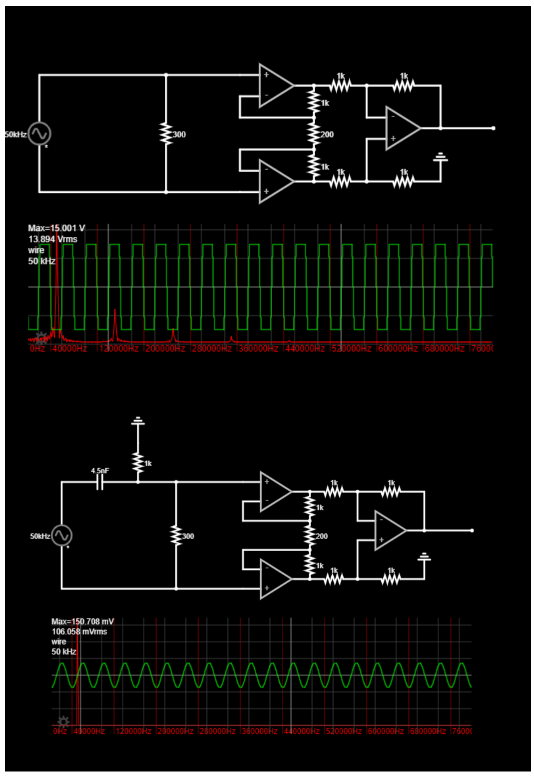


Figure 6: FALSTAD simulation illustrating the behavior of noise (red spikes) in a circuit without HPF (top) and with attenuation of HPF (bottom). The low frequencies are essentially eliminated.

The simulation analysis showed a significant reduction of noise produced by the voltage source which served to confirm the relevance of the HPF.

B. Instrumentation Amplifier

The instrumentation amplifier provides high-precision amplification of low-level signal coming from the electrodes placed on the skin which is essential for BIA readings. The purpose of integrating it is to accurately measure the electrical impedance of biological tissue, which will help to determine the overall hydration levels. Additionally, it also serves as a noise filtering component coming from the user's movement (common-mode rejection); this is useful for making it portable since it allows the user to perform their daily activities without compromising the accuracy of measurements.

To understand the theoretical electrical behavior of the instrumentation amplifier, the equations for $H(j\omega)_{IA}$ was calculated. This mathematical model enables us to analyze the overall output for each possible input.

$$H(j\omega)_{IA} = \frac{(\frac{R_3}{R_G})(1+SR_2)}{\frac{(sR_1+1)}{(sR_5+1)(sR_6+1)}} \qquad (5)$$

Using this equation and the values for each respective circuit component we create a bode plot to observe its behavior in our circuit design.

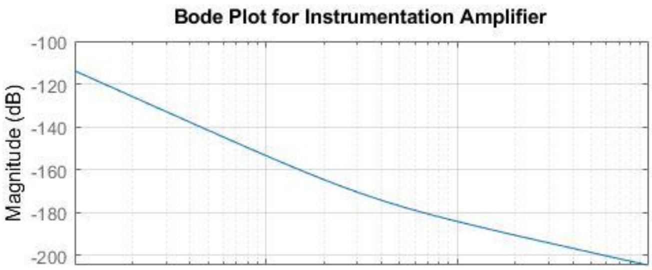


Figure 7: Plot generated using MATLAB, displaying the instrumentation amplifier that shows a gain decreased as frequency increases

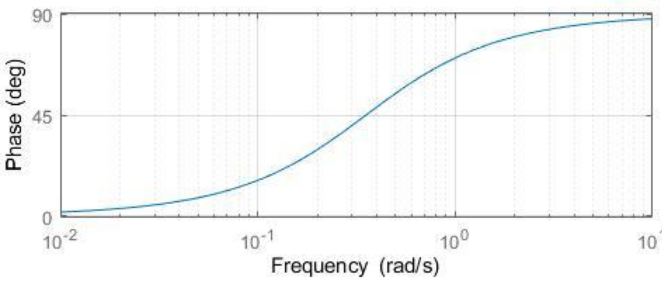


Figure 8: Plot generated using MATLAB, displaying the instrumentation amplifier that shows phase shift occurring at -45 degrees at the cutoff frequency

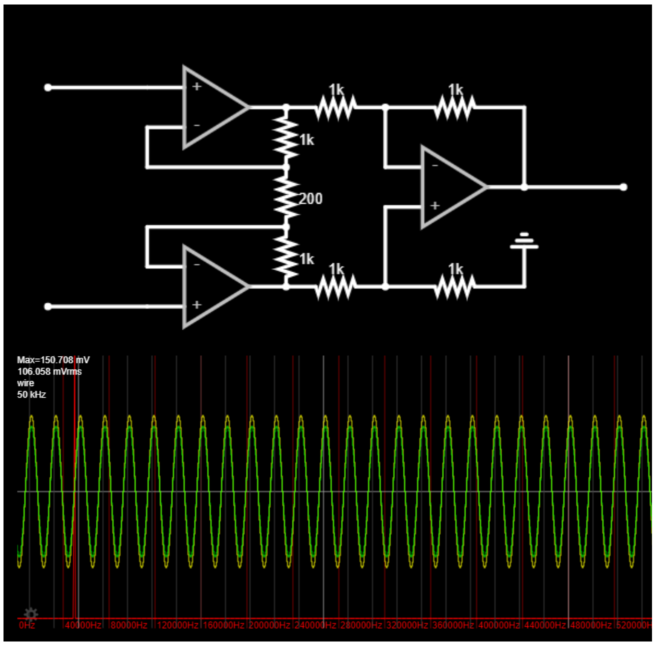


Figure 9 FALSTAD simulation illustrating the behavior of the instrumentation amplifier to compare the theoretical outputs (gain=11, output=150mV) with the actual values computed by the simulation.

The theoretical value for the voltage output gives 150.722mV, however, the simulation showed an output of slightly less. This shows that the overall error of calculations is relatively low making the device reliable and accurate.

C. Analysis

Given that the tested frequency at 50kHz yields normal oscillations, it can be safe to assume that the filter frequency and the instrumentation amplifier allow frequencies to stay stable at 50kHz. This is ideal for a portable device because the user will be able to perform daily activities without inaccuracies in measurements. The voltage across the highpass filter

Actual Impedance	300 Ω	500 Ω	1500 Ω
Measured Impedance	294.75 Ω	499.93 Ω	1499.79 Ω
Percent Error	1.75%	0.0139%	0.0141%

Figure 10: Error Analysis Table

As seen from the error values above, our circuit struggles to maintain a very low percent error when evaluating body impedances on the lower end. However, our error is smaller than that of the skin caliper method (error = 3-5%).

IV. Discussion

A. Advantages

The main advantage of our BIA design is that it saves users the time and money that would have otherwise been spent on a DEXA scan. Similarly, it is convenient in the sense that it is a light device that can be worn on the wrist of an individual. Our design features a combination of affordability and convenience which gives it the potential to be a gadget used widely amongst the general population in the near future.

Another advantage would be that noise is minimized in the frequency filter and instrumentation amplifier which allows the device to be worn at any time.

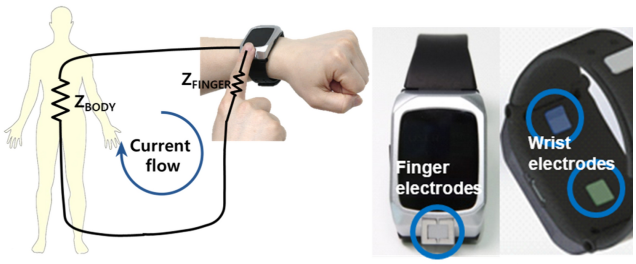
B. Limitations

While our BIA device has advantages, it also has its limitations. One limitation is the fact that it only measures the body composition of approximately $\frac{1}{2}$ the body since our design has 2 electrodes. This means that the other half would essentially be estimated which could potentially cause some errors. We say this because it has been proven that some are susceptible to having extra fat on the left or right side of their body which means that if our design only measures one side of their body, overall results would yield a higher error.

Another limitation is the absence of a user interface. There is no screen/user-friendly interface that the user can navigate through. The BIA device, as of now, needs to be plugged into an oscilloscope in order to find variables to plug into our fat-free mass equation.

C. Future Implications

Looking into the future of our wearable bioImpedance analysis device, the sky's the limit. We aim to integrate a microcontroller that would do the calculations for the FFM in a short amount of time, thus reducing the hassle of plugging it into an oscilloscope and calculating it manually. Consequently, we aim to create a user interface screen that displays their fat and lean body percentages.



(a) (b)

Figure 11 Depiction of how the BIA device sends a small current through the body through the utilization of finger electrodes and wrist electrodes

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