Development of a Bioelectrical Impedance Analyzer Prototype for Body Fat Mass Assessment

Umiatin[1*], *Azzahra* Khairunisa[1], *Taryudi*[2], *Bedy* Purnama[3], *Rista Putri Nur* Ifa[4], *Muhammad* Abidin[4], *Zendi* Iklima[5,6], and *Riandini* [7]

[1]Physics Study Programme, Faculty of Mathematics and Natural Science, Jakarta State University, Jakarta, Indonesia, 13220
[2]Electrical Engineering Department, Universitas Negeri Jakarta, Jakarta State University, Jakarta, Indonesia, 13220
[3]Center of Excellence Artificial Intelligence for Learning and Optimization, Telkom University, Bandung, Indonesia, 40252
[4]Frenmed Inovasi Bangsa, Depok, West Java, Indonesia, 16414
[5]Electrical and Electronics Engineering Department, Faculty of Engineering, Universiti Teknologi PETRONAS
[6]Electrical Engineering Department, Faculty of Engineering, Universitas Mercu Buana
[7]Electrical Engineering Department, Politeknik Negeri Jakarta (PNJ)

Abstract. Obesity is a medical disorder considered by the excessive accumulation of body fat tissue. It is a risk factor for various diseases, including stroke, cardiovascular disorders, cancer, and diabetes, which contribute to high mortality rates. Measurement of body fat mass is critical in assessing individual health risks. The Bioelectrical Resistance Analysis (BIA) is a widely used method for estimating body fat mass (FM), fat-free mass (FFM), and body fat percentage (BF) by transmitting a low alternating electrical current at a specific frequency through the body and measuring the resulting current to determine body impedance. This impedance value is subsequently used to analyze body fat composition. The present study aims to develop a Bioelectrical Impedance Analyzer (BIA) prototype using the AD5933 module and an Arduino microcontroller. Frequency optimization (25 kHz, 50 kHz, and 100 kHz) as well as measurement method optimization (hand-to-hand, foot-to-foot, and hand-to-foot) were performed. The findings indicate that body fat percentage capacities using the hand-to-hand, foot-to-foot, and hand-to-foot methods at 50 kHz demonstrated greater stability compared to those obtained at 25 kHz and 100 kHz. Furthermore, at 50 kHz, the hand-to-hand method achieved an accuracy of 96.40%, the foot-to-foot method 97.71%, and the hand-to-foot method 97.96%. In conclusion, the development of a BIA prototype demonstrated that the hand-to-foot method at 50 kHz provided most optimal performance for body fat percentage measurement.

* Corresponding author: umiatin@unj.ac.id

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1 Introduction

Indonesia is currently facing a triple burden of disease, including catching diseases, developing infectious diseases, and non-communicable diseases (NCDs). Globally, NCDs account for 71% of all deaths, with cardiovascular diseases being the leading cause (44%) [1–3]. Indonesia ranks fifth in the world for the highest mortality rate due to cardiovascular diseases [1–4]. Giving to the American Heart Association, the main contributing factors to cardiac diseases contain hypertension and obesity.

According to Indonesia's Basic Health Research (Riskesdas), the prevalence of obesity among adults nearly doubled from 10.5% in 2007 to 21.8% in 2018, with the highest rates reported in Java and Bali. This increasing trend highlights the need for effective screening and management strategies [5, 6]. Among the methods optional by the World Health Organization (WHO), body mass index (BMI) is widely used due to its simplicity, low cost, and non-invasive nature. But, BMI does not offer information on body fat mass, body fat percentage, or fat distribution, which are important indicators of cardiovascular disease risk [7]. Therefore, body composition analysis has become an important tool for assessing health status and is widely used in nutrition, hydration, and recovery monitoring [9, 10].

The gold standard for clinical body configuration quantity is dual-energy X-ray absorptiometry (DXA), which provides high accuracy but is costly and limited to modern healthcare facilities. A simpler and more affordable alternative for body composition measurement is Bioelectrical Impedance Analysis (BIA). This method has several compensations: it is non-invasive, non-radiative, portable, relatively fast, and efficient [11,12]. BIA works by applying a small alternating current at a specific frequency through the body via electrodes, and then measuring the voltage to determine the impedance value [13].

BIA conceptualizes the human body as an electrical circuit, which is influenced by the frequency of the applied current [14]. Pawar et al. developed a BIA device using a frequency range of 50–400 kHz and compared impedance values between the left side (left arm and leg) and the right side of the body, obtaining an error of 3.53% [15]. BIA is particularly valuable for obesity screening and general health monitoring. However, variations exist among commercial BIA devices, resulting in inconsistencies across instruments. Therefore, this study focuses on developing a BIA prototype with optimization of both measurement methods and frequency variations to achieve the most accurate results with high repeatability.

2 Material and methods

2.1 Hardware Design Block Diagram

The block diagram of the BIA analyzer prototype is revealed in Figure 1.

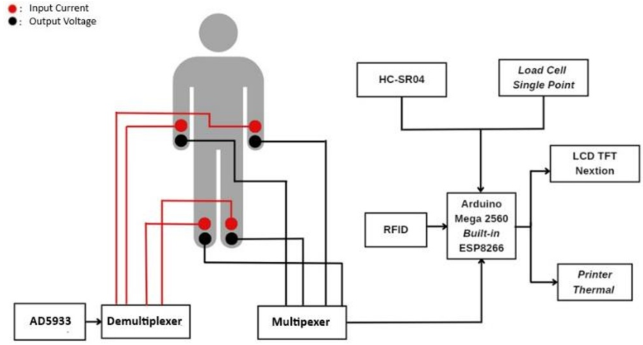


Fig. 1. Block Diagram of the BIA Prototype.

The prototype utilizes an AD5933 module as an impedance converter, connected to the CD74HC4067 as multiplexer and demultiplexer to determine which electrode is activated, electrode pads is used for delivering a weak alternating current to the body, Arduino Mega 2560 with built-in ESP8266 as the microcontroller unit, RFID, HC-SR04 ultrasonic sensor is used for height size, single-point load cell sensor is used for body weight measurement, thermal printer, and Nextion TFT LCD. The measurement frequencies used were 25 kHz, 50 kHz, and 100 kHz. The BIA prototype, dimension 352 mm × 418 mm × 1804 mm, was constructed using PLA+, acrylic, iron, stainless steel, rubber, and aluminum.

2.2 Determination of Body Fat Percentage

Body fat percentage was determined in calculating fat-free mass (FFM) using the equation developed by Elliot Mylott et al (19):

$$\text{FFM} = 0{,}360\left(\frac{height^2}{z}\right)0{,}162(height) + 0{,}289(weight) - 0{,}134(age) + 4{,}83(G) - 6{,}83 \quad (1)$$

With: FFM (Fat Free Mass (kg)); Height (cm); z (impedance (ohm)); Weight (kg); Age (years); G (gender, male = 1, female=0); BF (Body fat (%)). Fat mass (FM) and body fat percentage (BF) were calculated as equation 2 and 3.

$$\text{FM} = \text{Weight} - \text{FFM} \quad (2)$$

$$\text{BF} = \frac{\text{FM}}{\text{Weight}} \text{x } 100\% \quad (3)$$

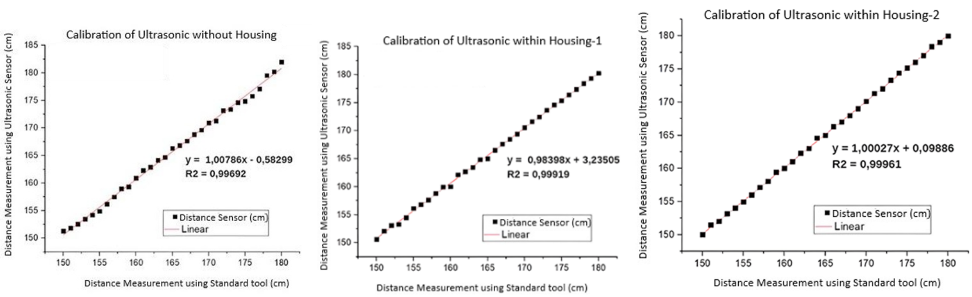
2.3 Data Collection

The prototype was tested on 20 subjects (aged 21–23 years), gender (male 9, female 11) who provided informed consent. Each subject underwent three repeated measurements using the prototype and three commercial BIA devices: Finlon BF 306, Onemed EF-872, and Omron HBF 375. Measurements were performed using hand-to-hand, foot-to-foot, and hand-to-foot methods by frequency variations of 25 kHz, 50 kHz, and 100 kHza.

3 Result and discussion

3.1 Callibration of the HC-SR04 Ultrasonic Sensor

Calibration of the HC-SR04 ultrasonic sensor was performed by comparing the sensor output with standard measurements using a tape measure. To improve accuracy, three sensor casing variations were tested: without housing, housing type-1 (5.1 × 2.5 × 3.1 cm), and housing type-2 (5.1 × 2.5 × 5.7 cm), all made of PLA+. Calibration was carried out at 31 points within the range of 150–180 cm at 1 cm increments, with five repetitions. The results are shown in Figure 2. Based on Figure 2, the sensor with housing type-2 demonstrated higher stability, following the regression line closely, with a correlation coefficient (R^2) of 0.99961 and sensitivity of 1.00027.

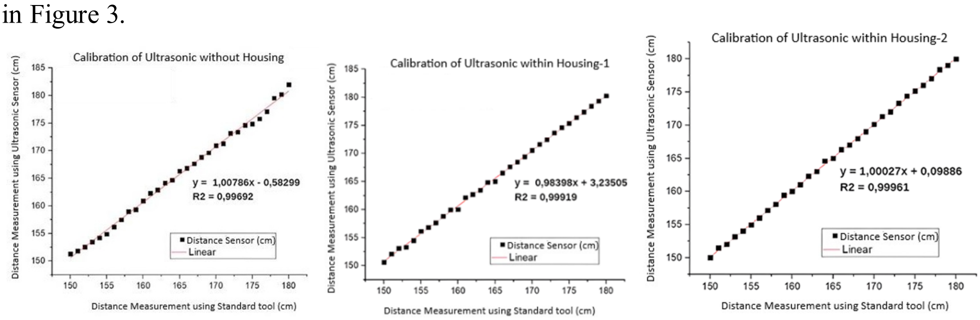


(a) (b) (c)

Fig. 2. Calibration graphs of the HC-SR04 ultrasonic sensor: (a) without housing, (b) housing-1, (c) housing-2.

3.2 Callibration of the Single Point Loadcell

Calibration of the single-point load cell was conducted by comparing the sensor output with standard mass measurements. Data collection was performed at 31 points within the range of 45,000 g to 75,000 g, with 1,000 g increments, repeated five times. The results are presented in Figure 3.



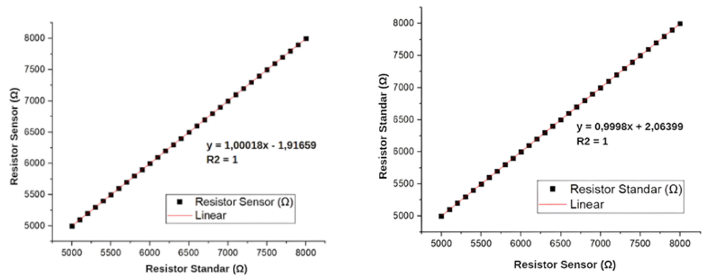
(a) (b) (c)

Fig. 3. Calibration graphs of the single-point load cell: (a) transfer function, (b) inverse function.

The calibration results yielded an R^2 value of 0.99963 and a sensitivity of 0.99799, confirming that the load cell exhibits excellent accuracy in mass measurement.

3.3 Callibration of the AD5933

The AD5933, a 12-bit impedance converter manufactured by Analog Devices, operates within a frequency range of 10 Hz to 100 kHz. Calibration was performed by comparing output resistor values from the AD5933 with standard resistor values (20). Data were collected at 31 points within the range of 5,000 Ω to 8,000 Ω, with 100 Ω increments and five repetitions. Results are shown in Figure 4:



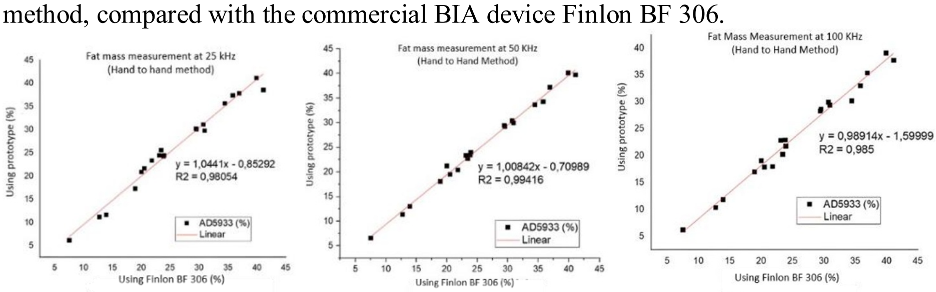
(a) (b)

Fig. 4. Calibration graphs of the AD5933: (a) transfer function, (b) inverse function.

The calibration achieved a correlation coefficient (R^2) of 1, a sensitivity of 1.00018, and an average relative error of 0.0121%, confirming high precision.

3.4 Hand-to-hand Method Testing

Figure 5 presents the measurement results of body fat percentage using the hand-to-hand method, compared with the commercial BIA device Finlon BF 306.



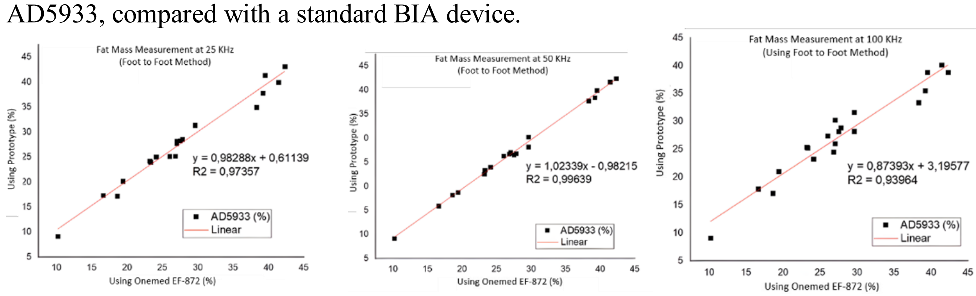
(a) (b) (c)

Fig. 5. Body fat percentage measurement with hand-to-hand method at (a) 25 kHz, (b) 50 kHz, and (c) 100 kHz.

Comparison of average errors in body fat measurements at various frequencies (25 kHz, 50 kHz, and 100 kHz) were 6.0859%, 3.5965%, and 8.0424% at 25 kHz, 50 kHz, and 100 kHz, respectively. The lowest average error was observed at 50 kHz, indicating the highest measurement accuracy for the hand-to-hand method.

3.5 Foot to foot Method Testing

Figure 6 shows body fat percentage measurements using the foot-to-foot method with the AD5933, compared with a standard BIA device.



(a) (b) (c)

Fig. 6. Body fat percetage measurement with foot-to-foot method at (a) 25Khz, (b) 50 Khz, and (c) 100 Khz.

A comparison of the normal error levels in fat mass measurements at occurrences of 25, 50, and 100 kHz using the foot-to-foot method were 4.3615%, 3.1978%, and 7.9481% at 25 kHz, 50 kHz, and 100 kHz, correspondingly. The measurements at 50 kHz were more stable, indicating the highest measurement accuracy and yielding a correlation coefficient (R^2) of 0.99639.

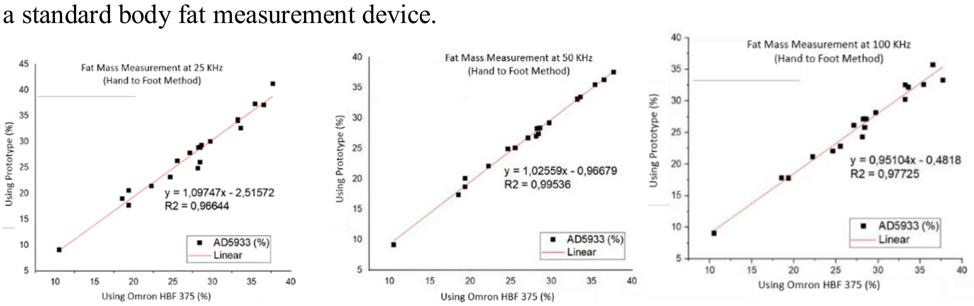
3.6 Foot to foot Method Testing

Body fat percentage measurements using the hand-to-foot method were conducted at rates of 25 kHz, 50 kHz, and 100 kHz on a sample of 20 participants as shown in Figure 7. These three frequency variations were tested to determine the most effective frequency for this method.

(a) (b)

Fig. 7. Body fat composition measurement a) using Omron HBF 375, b) using prototype.

Figure 8 presents the body fat percentage results obtained with the AD5933 compared to a standard body fat measurement device.



(a) (b) (c)

Fig. 8. Graphs of body fat percentage using the hand-to-foot method: (a) 25 Khz, (b) 50 Khz, (c) 100 Khz.

The average errors in fat mass measurements obtained using the hand-to-foot method were 7.3010%, 3.0176%, and 9.5496% at 25 kHz, 50 kHz, and 100 kHz, respectively. The lowest average error was observed at 50 kHz, indicating the highest measurement accuracy among the tested frequencies. Measurements at 50 kHz were also more stable, yielding a correlation coefficient (R^2) of 0.99536.

4 Conclusion

The developed MF-BIA prototype demonstrated that the hand-to-hand, foot-to-foot, and hand-to-foot methods at 50 kHz provided more stable measurement results compared to 25 kHz and 100 kHz. At 50 kHz, the hand-to-hand method achieved an accuracy of 96.40%, the foot-to-foot method 97.71%, and the hand-to-foot method 97.96%.

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