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Design and Development of a Body Fat Percentage Measurement System Using the Bioelectrical Impedance Analysis (BIA) Foot-to-Foot Method

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Abstract – *A person's nutritional status is ideally determined based on a body composition assessment, which differentiates the fat mass and fat-free mass in a human body. Fat and fat-free mass can be calculated using a non-invasive method called bioelectrical impedance analysis (BIA). In this research, a body fat measurement system was designed using the BIA foot-to-foot method, which is also equipped with the automatic body mass and height measurements system using a load cell sensor and a ToF VL53L1X sensor. The BIA method is designed to flow a 0.4mA current with a frequency of 50kHz into the body using four electrodes through the object's feet. Other parameters required in this system, such as age and gender, will be entered using the keypad. The computing and data processing process uses an Arduino Nano microcontroller and is displayed on the LCD. The system that has been designed is then compared with a similar measuring instrument, Mi Scale Body Composition 2. The results obtained in this study are: the average error value for measuring body weight is 0.43kg; the average error for measuring height is 1.13cm; the average error in measuring BMI is 0.32 kg/m*^{2}*; and the average error in measuring body fat percentage is 3.25%.*

Keywords – *body composition assessment; bioelectrical impedance analysis; BIA foot-to-foot; load cell sensor; Arduino Nano.*

I. Introduction

HEALTH is a crucial aspect for every individual and is of global concern. Ideally, a person's health should be monitored from the womb, through infancy, adolescence, and into adulthood. One of the health parameters that can be observed to determine an individual's health status is their nutritional status. Nutrition is a key determinant of human resource quality, where adequate nutritional intake leads to proper growth and serves as a preventive measure against diseases [1]. Fathonah and Sarwi (2020) categorize five types of nutrients: carbohydrates, fats, proteins, minerals, and vitamins. The balance between the intake of nutrients from food and the body's nutritional needs must be maintained. Each individual has different nutritional needs depending on age, gender, daily physical activity, body weight, and other factors [2]. An imbalance between the intake of nutrients from outside and the nutritional needs of the body can lead to nutritional problems. In Indonesia, several common nutritional problems are encountered in the environment, such as protein-energy malnutrition (PEM), anemia, iodine deficiency disorders (IDD), vitamin A deficiency (VAD), undernutrition, and obesity.

Based on data reported by the Global Nutrition Report, the global percentage of obesity has continuously increased from 2000 to 2019. This increase occurs among children and adolescents aged 5–19 years, as well as adults over 18 years old. The report indicates that in 2019, approximately 1.2 billion adults were obese [3]. Meanwhile, a report from the World Health Organization shows that 462 million people were underweight [4]. For domestic data, according to the Basic Health Research (Riskesdas) 2018, the obesity rate among adults over 18 years old in Indonesia reached 21.8 percent of the population that year.

Obesity is a condition where there is an excess accumulation of fat beyond the amount required for normal body functions. This condition is generally caused by nutrient intake from food that far exceeds

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the body's nutritional needs [5]. According to Rachmawati (2014), obesity in adolescents has the potential to increase in adulthood, leading to an increased risk of death and being a factor in degenerative diseases such as type II diabetes, cardiovascular diseases, and cancer [6]. Obesity does not occur quickly; it requires a lengthy process for an individual to reach this condition. Therefore, many people ignore it because there are no clear signs or symptoms felt or shown in the body. Some people do not realize they are obese because their body size is not too large. However, body size cannot be used as a benchmark to determine whether the body's fat levels are appropriate or excessive or insufficient.

Until now, the classification of underweight, overweight, and obesity has often been based on the calculation of the Body Mass Index (BMI). BMI is obtained by dividing body mass in kilograms (kg) by the square of height in meters. Thus, the ideal body classification still depends on the relationship between body mass and height. Even obesity classification is still conducted using waist circumference measurement. This type of measurement is considered less accurate for determining whether an individual is obese because it cannot differentiate between fat mass, fat-free mass, and the distribution of adipose tissue in each individual's body [7]. Given the shortcomings of the previously mentioned methods, it would be better to observe an individual's fat levels to determine the correct nutritional status.

Currently, technology has been developed to measure body fat levels based on body composition assessment. Body composition assessment is a method to accurately analyze an individual's body status to obtain the values of fat mass and fat-free mass that compose the body. One of the methods used in body composition assessment is Bioelectrical Impedance Analysis (BIA). Bioelectrical Impedance Analysis (BIA) is a widely used, non-invasive method for assessing body composition, particularly fat mass and fat-free mass [8, 9]. It involves passing a low-amplitude electrical current through the body and measuring resistance and reactance [10, 11]. BIA is relatively inexpensive, portable, and easy to use, making it suitable for both clinical and research settings [12, 13]. While it provides reliable estimates of total body water and fat-free mass in healthy individuals and those with certain chronic conditions, its accuracy can be affected by various factors such as hydration status, body position, and recent food consumption [14,15]. Despite some limitations, BIA remains a valuable tool for monitoring body composition changes, assessing nutritional status, and evaluating disease progression in various populations [8, 9]. This method involves passing an alternating current (AC) through the body at a certain frequency, then measuring and calculating the voltage and impedance values produced. The body's impedance value is used to determine an individual's body fat level [16]. BIA has been widely used because the results can be obtained quickly, non-invasively, accurately [17], and can be easily used independently. In theory, BIA is used to measure body hydration levels, such as intracellular and extracellular water content. However, fat-free mass (FFM) and body cell mass (BCM) can also be measured using BIA by assuming both are in a constant state of hydration [18].

There are several methods of measurement using BIA, including hand-to-hand using two electrodes, hand-to-hand using four electrodes, foot-to-foot, and whole body methods. These various measurement methods differ in the number of electrodes used and the placement of the electrodes on the human body. All four methods have been conducted in previous research using a body fat percentage measuring instrument with an automatic switch based on ATmega32 [19].

In this study, body fat percentage measurement will be conducted using the foot-to-foot measurement method because it is considered relatively easy to perform. This method requires four electrodes, with two electrodes placed on the front part of the feet and two electrodes placed on the back part of the feet. The electrodes on the front part of the feet act as outer electrodes, which deliver current at a certain frequency, and the electrodes on the back part of the feet serve as inner electrodes, which measure the body's potential difference. The measurement method, which involves stepping on a scale (load cell), is also considered familiar to many people because it follows the same concept as weighing body weight.

The BIA system designed in this study uses an Arduino Nano microcontroller equipped with a load cell sensor for body mass measurement and a ToF VL53L1X sensor for height measurement. Arduino Nano is a development board that uses the IC ATMega32P as its base. The Arduino Nano shown in the image has relatively small dimensions, with a length of 45 mm, a width of 18 mm, and a weight of 7 grams. Meanwhile, the load cell sensor consists of several components such as conductors, strain gauges, and Wheatstone bridges [20], where these components play a role in two measurement stages: the mechanical structure reading stage and the conversion of resistance changes [21]. Strain gauge load cells come in various shapes and sizes, with load cells commonly used for measuring human body mass having a maximum mass specification of 50 kg.

The use of a load cell sensor is complemented by the HX711 signal amplifier. HX711 is an amplifier designed for digital scale sensors, where this device works by converting resistance values into voltage [22]. The time-of-flight (ToF) sensor is a distance sensor that works by continuously emitting light waves and returning them when reflected by an object. The distance value can then be determined by measuring the time it takes for the light waves to be emitted and received back by the sensor [23].

II. Research Methods

i. Materials and Research Equipment

This research requires materials, hardware, and software that play important roles in the research process, which are described as follows: The hardware used in this research is shown in Table 1.

Table 1: List of hardware used in the research

No	Hardware
1	12V/2A Adapter
2	50kg Load cell
3	Load cell amplifier HX711
4	Time-of-Flight proximity sensor VL53L1X
5	3x4 Keypad matrix
6	20x4 LCD
7	Measurement device frame
8	Electrodes
9	Mi Scale Body Composition 2

The software used in this research includes KiCAD, which is used to design electronic schematics and printed circuit board (PCB) layouts, and Arduino IDE, which is used to program the microcontroller.

The necessary materials include electronic components to be used in the PCB for the bioelectrical impedance analysis (BIA) subsystem, power subsystem, and microcontroller subsystem. These include passive components, amplifying components, voltage regulator circuits, sine wave generator components, and other supplementary components. This research is conducted sequentially based on the procedural stages or research flow shown by the flowchart in Figure 1.

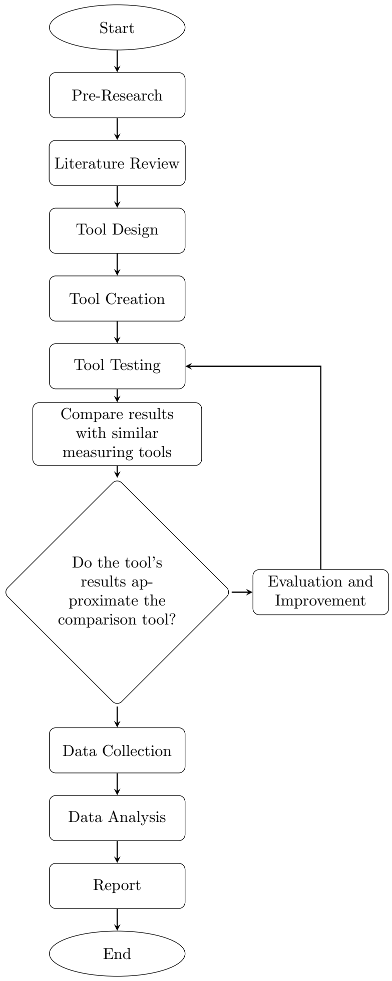

Figure 1: Research flowchart

ii. System Design

In general, the hardware system design for the body fat percentage measuring device using the Bioelectrical Impedance Analysis method is shown in Figure 2. In this research, the body fat percentage measuring system consists of three parts, or subsystems: the power subsystem, the microcontroller subsystem, and the BIA subsystem.

The power subsystem consists of a 12V/2A DC adapter, an MP1584 module for generating +12 volt and -12 volt outputs, and an LM2596 module for stepping down the voltage to 5 volts. The BIA subsystem consists of a sine wave generator circuit, a voltage-controlled current source (VCCS), a differential amplifier, a Twin T active notch filter, and a rectifier. The next subsystem is the microcontroller subsystem, which consists of an Arduino Nano for processing data from the BIA subsystem, load cell, flight sensor, and other integer data inputs from the keypad, which will then be displayed on the 20×4 LCD.

The BIA subsystem includes four electrodes: two electrodes as outer electrodes and two electrodes as inner electrodes. The electrode configuration in this system is shown in Figure 3.

In addition to hardware design, software design is also carried out where all programs to be used in the system are created using Arduino IDE. The overall system workflow on the microcontroller is shown by the flowchart in Figure 4.

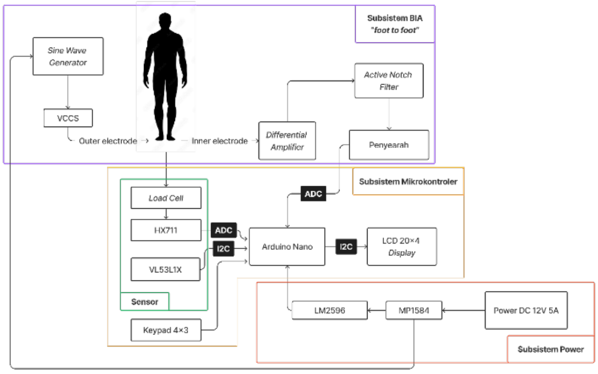

Figure 2: System flow of the body fat percentage measuring device using the BIA method

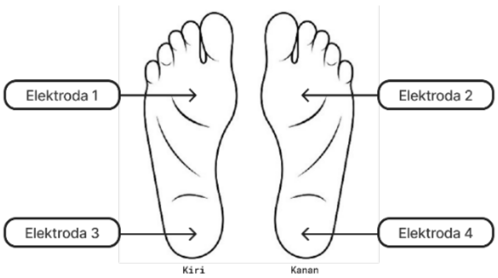

Figure 3: Electrode configuration on the feet of the tested object

III. Results and Discussion

Several stages were involved in the testing and data collection process in this study. These stages include functional testing of the electronic design in the power subsystem and the Bioelectrical Impedance Analysis (BIA) subsystem, testing the load cell and VL53L1X sensors, and overall device testing, which includes collecting height, weight, body fat percentage, and Body Mass Index (BMI) data.

i. Sine Wave Generator Circuit Testing

The purpose of testing the sine wave generator circuit is to determine whether the frequency produced by the ICL8038 circuit meets the system requirement of 50kHz. The circuit testing was performed using a digital oscilloscope to measure the output frequency of the sine wave generator and the frequency at the electrodes to be connected to the human body. This test used a 1000 Ohm resistor as a substitute for human body resistance. Figure 5 shows the sinusoidal signal produced by the ICL8038, which has a measured frequency of 47.08kHz and a measured voltage on a digital multimeter of 0.1 Volt.

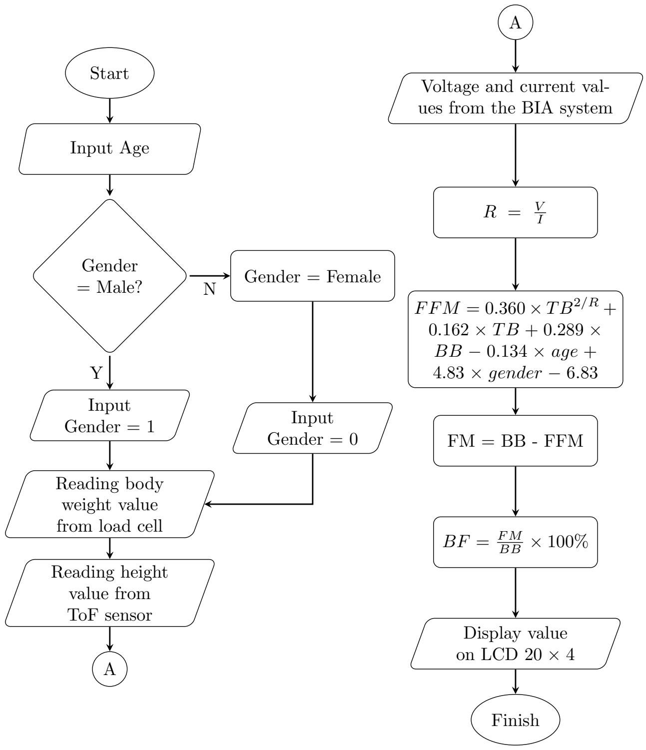

Figure 4: Microcontroller system flowchart

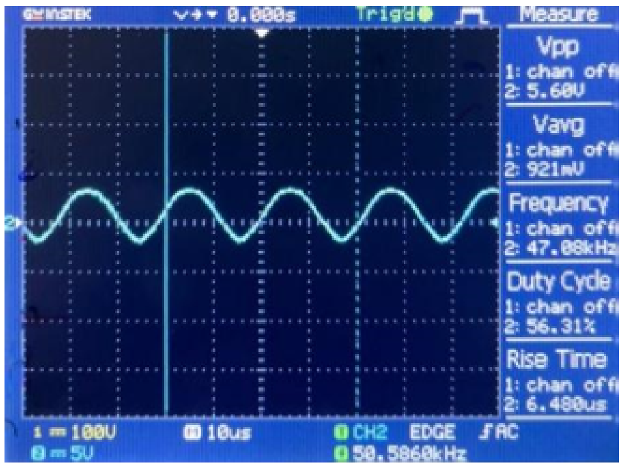

Figure 5: Frequency testing results at the ICL8038 output pin

ii. Voltage Controlled Current Source (VCCS) Circuit Testing

The VCCS circuit test aims to determine the current that will be supplied to the human body. A multimeter was used to measure the VCCS input voltage from the ICL8038, yielding a voltage of 0.1 Volt. To achieve a current of 0.2mA – 0.8mA, the required resistance value can be theoretically obtained using Ohm's Law, as shown in Equation 1. The calculation resulted in a resistance value of 333 Ohm.

$$R = \frac{V}{I} \tag{1}$$

After determining the required resistance value, the circuit was tested to measure the current produced by the VCCS circuit. The measured current using a multimeter at the VCCS circuit output was consistently 0.4 mA, indicating that the circuit can be used in the body fat percentage measuring device.

iii. Linearity Testing of the BIA Subsystem

The linearity testing of the BIA subsystem was conducted after the overall functional testing of the electronic design in the BIA subsystem. This test aims to determine the microcontroller's response to the tested impedance values. Table 2 shows the test results using nine resistor variations, where V_x is the voltage between electrode 3 and electrode 4 measured using a digital multimeter, and V_y is the voltage read by the microcontroller.

Table 2: Linearity testing results of the BIA subsystem

Z (Ohm)	V_x (Volt)	V_y (Volt)
189	0.059	2.401
285	0.089	2.413
371	0.112	2.459
409	0.137	2.468
527	0.167	2.471
646	0.212	2.472
780	0.307	2.500
876	0.394	2.535
944	0.486	2.544

The table is visualized in the form of a graph showing the relationship between V_x and V_y as represented by Equation 2.

$$V_y = 0.335V_x + 2.382 \tag{2}$$

Thus, the resistance value can be obtained through Ohm's Law in Equation 1, and the impedance equation for the system is shown in Equation 3.

$$Z(\Omega) = \frac{2.986V_y - 7.111}{I} \tag{3}$$

iv. Load Cell Sensor Testing

The load cell calibration process was performed on one test object, Object 1, with a body mass of 78.40 kg (measured using the Mi Scale 2). The calibration process was then conducted on three test objects with three repetitions each to test the load cell sensor's reliability. The results are shown in Table 3.

Table 3: Load cell sensor calibration results

Object No.	Weight Value on Mi Scale (kg)	Measurement Value (kg)		
		1st	2nd	3rd
1	78.50	78.75	78.95	78.94
2	62.75	62.57	63.94	63.69
3	62.78	62.79	61.04	62.78

Next, body mass data collection using the load cell sensor was performed on 10 individuals with varying body masses. Table 4 shows the comparison of body mass values for 10 test objects measured using the load cell sensor and the Mi Scale Body Composition 2.

Table 4: Load cell sensor data acquisition results

Object	Weight (kg)	Mi Scale (kg)	Error (kg)
1	78.50	78.40	0.10
2	62.75	62.30	0.45
3	55.80	55.45	0.35
4	62.78	62.80	0.02
5	56.70	56.65	0.05
6	63.04	62.45	0.59
7	88.15	87.70	0.45
8	58.69	58.55	0.14
9	54.40	54.20	0.20
10	61.64	61.95	0.31

The average error between body weight measurements using the load cell and Mi Scale was 0.199 kg, with an average relative error of 0.42%. The error value in body weight measurement using the load cell is relatively small compared to the Mi Scale, indicating good performance in body weight measurement using the load cell.

v. ToF VL53L1X Sensor Testing

Height data collection using the ToF VL53L1X sensor was performed on 10 individuals with varying heights. Table 5 shows the comparison of height values for 10 test objects measured using the VL53L1X sensor and a measuring tape.

The average difference between height measurements using the ToF VL53L1X and the measuring tape was 0.81 cm, with an average relative error of 0.49%. The error value in height measurement using the ToF VL53L1X is relatively small compared to the measuring tape, indicating good performance in height measurement using the ToF VL53L1X.

Table 5: ToF VL53L1X sensor data acquisition results

Object	Height (cm)	Height Tape (cm)	Error (cm)
1	161.93	161.00	0.43
2	179.57	180.00	0.12
3	155.12	155.00	0.93
4	180.23	180.00	0.23
5	167.64	169.00	1.36
6	155.44	156.00	0.56
7	168.99	172.00	3.01
8	153.81	153.00	0.81
9	149.43	150.00	0.57
10	160.89	161.00	0.11

vi. Overall System Testing

The overall system testing phase was conducted to test the entire system at one time, where user body data to be measured includes body weight, height, BMI value, and body fat percentage.

The testing phase begins with inputting age and gender data into the system using the keypad and LCD, as shown in Figure 6. To start the measurement, the subject stands on the device in an upright position facing forward, with both feet barefoot and in contact with the electrodes as per the specified configuration. The final stage is adjusting the plate above the subject's head to touch the head for height measurement. The data collection process on the device is shown in Figure 7.

Figure 6: Input age and gender data

The overall data collection process was performed on 10 test subjects with varying body shapes and sizes. The obtained values were then compared with those obtained using the Mi Scale Body Composition 2, accompanied by the Zepp Life application. Table 6 shows the results of data collection on the entire device.

Figure 7: Overall system testing

The average error between body fat percentage measurements using the measuring device and the Mi Scale was 3.25%, with an average relative error of 14.95%. The overall system data collection results showed a minimum error in body fat percentage measurement of 1.02% on Object 1 and a maximum error of 6.66% on Object 4. The maximum error is likely due to the subject's foot size, which is 29 cm long, while the distance between electrodes on the device is 18 cm. This caused improper electrode placement on the subject's foot, resulting in inaccurate measurements.

According to the study conducted by Macias [19], the error values obtained in the overall system testing can be attributed to certain health conditions of the subjects, such as diabetes, heart disease, and pregnancy, which were not accounted for in this study [19]. Additionally, some clinical characteristics that affect measurements using the bioelectrical impedance analysis method include the subject's body position, activities performed before measurement, food intake, skin temperature, and changes in body fluid distribution.

IV. Conclusion

Through the testing and analysis process conducted on the body fat percentage measuring device using the bioelectrical impedance analysis method, it was found that the body fat percentage can be measured

Table 6: Overall device data collection results

Object	Age and Gender (years)	Parameter	Measured Value	Comparison Value
1	22 (F)	Height (cm)	162.37	161.00
		Weight (kg)	77.37	78.15
		Fat Percentage (%)	40.82	39.80
		BMI (kg/m^2)	29.35	29.40
2	24 (M)	Height (cm)	180.68	180.00
		Weight (kg)	63.94	62.30
		Fat Percentage (%)	12.15	10.60
		BMI (kg/m^2)	19.59	19.20
3	23 (F)	Height (cm)	155.98	154.00
		Weight (kg)	54.38	54.20
		Fat Percentage (%)	21.72	17.70
		BMI (kg/m^2)	22.35	22.60
4	22 (M)	Height (cm)	180.22	180.00
		Weight (kg)	62.79	62.80
		Fat Percentage (%)	18.16	11.50
		BMI (kg/m^2)	19.33	19.40
5	22 (M)	Height (cm)	167.58	169.00
		Weight (kg)	56.71	56.65
		Fat Percentage (%)	10.20	12.60
		BMI (kg/m^2)	20.19	19.80
6	22 (F)	Height (cm)	155.43	154.00
		Weight (kg)	62.40	62.45
		Fat Percentage (%)	25.33	22.30
		BMI (kg/m^2)	25.82	25.70
7	23 (M)	Height (cm)	169.37	172.00
		Weight (kg)	88.32	87.70
		Fat Percentage (%)	33.32	29.20
		BMI (kg/m^2)	30.79	29.60
8	22 (F)	Height (cm)	153.81	153.00
		Weight (kg)	58.69	58.55
		Fat Percentage (%)	26.04	22.00
		BMI (kg/m^2)	24.81	25.00
9	22 (F)	Height (cm)	149.51	150.00
		Weight (kg)	54.35	54.30
		Fat Percentage (%)	16.51	19.00
		BMI (kg/m^2)	24.31	24.10
10	23 (F)	Height (cm)	161.31	161.00
		Weight (kg)	61.20	61.95
		Fat Percentage (%)	22.59	19.40
		BMI (kg/m^2)	23.58	23.90

using the bioelectrical impedance analysis foot-to-foot method, which measures body impedance through electrode placement on both feet. The body fat percentage measuring device with the BIA method can be combined with a load cell sensor and a ToF VL53L1X sensor to automatically input body weight and height values. The results of the overall system testing showed that the average error in body weight measurement is 0.43kg, the average error in height measurement is 1.13cm, the average error in BMI measurement is 0.32 kg/m^2, and the average error in body fat percentage measurement is 3.25%.

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