Hindawi
Mathematical Problems in Engineering
Volume 2024, Article ID 1024006, 10 pages
https://doi.org/10.1155/2024/1024006

Research Article

Implementation of Bioelectrical Impedance Measuring Instrument Based on Embedded System

Charu Pawar,[1] **Munna Khan**,[2] **Jai Prakash Saini**,[3] **Dev Singh**,[4] **Manish Bhardwaj**,[5] **and Yu-Chen Hu**[6]

[1]*Department of Electronics and Communications Engineering, Netaji Subhash University of Technology, Delhi, India*
[2]*Electrical Department, Jamia Milia Islamia, New Delhi, India*
[3]*Netaji Subhash University of Technology, Delhi, India*
[4]*Department of Applied Mathematics, Allenhouse Institute of Technology, Kanpur, India*
[5]*Department of Computer Science and Engineering, KIET Group of Institutions, Delhi-NCR, Ghaziabad, India*
[6]*Department of Computer Science, Tunghai University, Taichung City, Taiwan*

Correspondence should be addressed to Yu-Chen Hu; ychu@thu.edu.tw

Received 16 January 2023; Revised 5 February 2024; Accepted 21 March 2024; Published 25 April 2024

Academic Editor: Qibin Lin

The present research aims to measure the segmental bioelectrical impedance (BI) of the human body at multifrequency, using a server user interface-based prototype, which provides subjects with measured data online anywhere accessed by their unique identifications. The present research measures the BI of the human leg and arm at a multifrequency range of 50–400 kHz with a developed and standard device. Recorded data can be transferred to the subject using Wi-Fi technology with their unique identifications and password. The system uses Wi-Fi interfacing for real-time data measurement and online data storage. The prototype can be used commercially. The compact size of the prototype becomes the demand of the common population. The pocket carry size makes it easy to carry anywhere for regular monitoring of the human body to prevent critical disease. The resultant data show that the mean and standard deviation of the left and right leg are 282.2 ± 14.29 and $274.80 \pm 13.91\,\Omega$, respectively. Similarly, in the case of the left arm and right arm, the mean and standard deviation are 325.41 ± 16.54 and $320.73 \pm 16.07\,\Omega$, respectively. The relative error between developed and standard devices is 3.53%. Results show that the left leg and arm impedance is always greater. However, the right leg and arm muscles are stronger than the left one, with less impedance at all frequencies.

1. Introduction

The human body's bioelectrical impedance (BI) shows body cells' embodied condition. The existing literature helps us understand the different methodologies and standards for BI measurement [1]. In rural areas, 10% of villages and 27%–28% of district people suffer from joint problems because of being overweight and sometimes underweight in case of imbalanced body growth. The surveys clearly said India suffers from common diseases in both cases, first due to obesity and second due to inadequate implementation. The population going through these types of situations stands at the deadline of joint diseases [2]. Most people suffering from joint disease face different body disasters, such as immobility of some body segments, morning stiffness, joint pain, swelling, and ruggedness. They become dependent on others. The regular monitoring of the body in the form of regular measurement of the impedance of the human body or joint is proof-like support to prevent these diseases. Overweight and obese is the main reason for common problems because a heavy body puts pressure on other joints, especially the lower body joint, so it becomes necessary to diagnose the problem early so treatment can start on time. The present prototype is more helpful for the early detection and analysis of upcoming diseases due to obesity. In other words, regular measurement of the BI of the human body makes an ordered series to know about their recovery and healing from these diseases [3]. Some research suggests that if a 5 kg weight is reduced from a standard range of body mass index (BMI) in obese and overweight people, it makes considerable support to avoid 24% of surgical cases in knee osteoarthritis (OA).

Early detection of arthritis also prevents surgery [4]. There are two methods for measuring bioimpedance: bipolar and tetra-polar. In bipolar current drive and voltage, sensing uses the same electrode; besides the tetra polar, voltage and sense circuits are separate. The three-electrode systems do exist but are for very specialized purposes. The eight-electrode method, for example, for stand-on impedance devices, adopts the tetrapolar method and cycles through pairs of electrodes to measure body regions sequentially. The tetra-polar method is the most popular method because its accuracy increases [5]. The BMI is related to joint problems as early as 20 years in men and 11 years in women.

The researchers suggest that a high BMI is risky for adults. To prevent leg problems, weight control is primarily necessary [6]. OA is a hazardous factor due to a high BMI for a long time. The mass index can be controlled with the help of regular body monitoring [7]. Single-frequency and multifrequency are used to measure the human body's segmental or whole-body BI. The literature shows that a single frequency is not suitable to provide accurate internal fluid conditions of the body. Multifrequency is used because of this deficiency of single frequency. A single low frequency cannot determine the internal position of body cells due to low frequency as it can flow only outside the cell. Inversely, high frequency can easily flow inside the cells to know the internal position. Multifrequency is used instead of single frequency to measure body composition parameters [8].

The analysis of measured values of total body water (TBW) and fat-free mass (FFM) shows that predicted values at 50, 100, and 200 kHz are nearly equal to measured values. This is because, at low frequencies, current cannot cross the cell membrane and flow only in extracellular fluids. However, high frequencies strike the cell membrane and are conducted through intracellular and extracellular fluids [9]. Multifrequency measures body composition parameters like FFM and TBW, so the 50–300 kHz range is normally used to diagnose body tissues [10].

On the other hand, segmental BI is better than whole-body impedance, as analysis of a specific body segment is possible with segmental impedance [11]. The segmental impedance gives detailed information about a particular body part or joint of the human body, which can become supportable for correct treatment and solution. There are various techniques for the measurement of body composition and bioimpedance of the human body, such as bioelectrical impedance analysis (BIA), dual-energy X-ray absorptiometry, magnetic resonance imaging, or computed tomography [12]. A significant fat mass (FM) measurement with BIA can reduce clinical injuries [13].

The BIA shows a compatible correlation between both sexes in estimating FM and FFM [14]. It is found that the percentage of body fat is underestimated for normal BMI. Body fat percentage is overestimated for obese BMIs and overweight mass index. Segmental bioelectrical is useful for knowing how any segment of the body affects any diseases and is also helpful in diagnosing changes in different types of body composition parameters like mass of particular segments mass and fat [15]. The BIA foot-to-foot method accurately predicts different fat levels in healthy Asian individuals. In obese people, BIA also calculates FFM. Existing research shows that the obesity parameter scale affects the accuracy of BIA in individuals [12]. According to the measurement of BIA, the FM for the arm and leg is considered underestimated, and the lean mass for the arm and trunk is overestimated [16]. Some studies reported that resistance and reactance of different body segments directly correlated to body fat percentage. At the same time, BMI is highly correlated with the percentage of body fat [17].

The assessment of BI of the leg and arm is more valuable than the trunk, as analysis of FFM in obese and nonobese women is accurate. The literature said that BIA and the underwater weight of a woman are almost the same in predicting the FFM of women who follow the diet or combine it with exercise [18]. The variables of BI are inversely proportional to BMI. BI variables are R_0, known as resistance at zero frequency; $R\infty$ at infinite frequency; and Ri, intracellular resistance. The BMI and BI are significantly correlated [19]. The routine measurement of impedance becomes helpful in informing about the healing progress of fractured or healthy bone. The impedance of a fractured bone is more than that of a healthy bone. Regular checkup marks the healing of diseases [6]. The improvement in the healing and recovery of a group suffering from diseases also depends on the body's BMI. If a body's BMI decreases, then fast improvement occurs in pain, but healing takes time at increments in BMI [20].

2. Materials and Methods

This section shows different modes for BI measurements.

2.1. Basic Principle of Segmental BI Measuring. The use of Ohm's Law theory reveals that, concerning the human body, the source known as voltage (used to insert current into the human body) is produced between the different points in body fluids. Apart from this term, the sink is known as current, which flows between two electrodes (used to detect the current response [21]).

Figure 1(a) shows an electrical circuit of the body cell. As shown, the cell membrane consists of intracellular fluid (ICF) and extracellular fluid (ECF), which are considered the body's resistance, with the same platform cell membrane, also considered a capacitor. A human body with respect to biological tissues is known as having three components: RC-circuit, in which C_M is the capacitance of cell membrane, R_{ICF} is the resistance of intracellular fluid, and R_{ECF} is the resistance of the ECF. The capacitor C_M is connected in a parallel series of R_{ICF} and R_{ECF}.

The equivalent circuit of human body cells is shown in Figure 1(b). The connection shows how sensing electrodes connect with body cells. Low and high-frequency effects prove that biological tissues of the human body have different impedance properties with the multifrequency current; the electrode system Z_X, composed of the electrode and

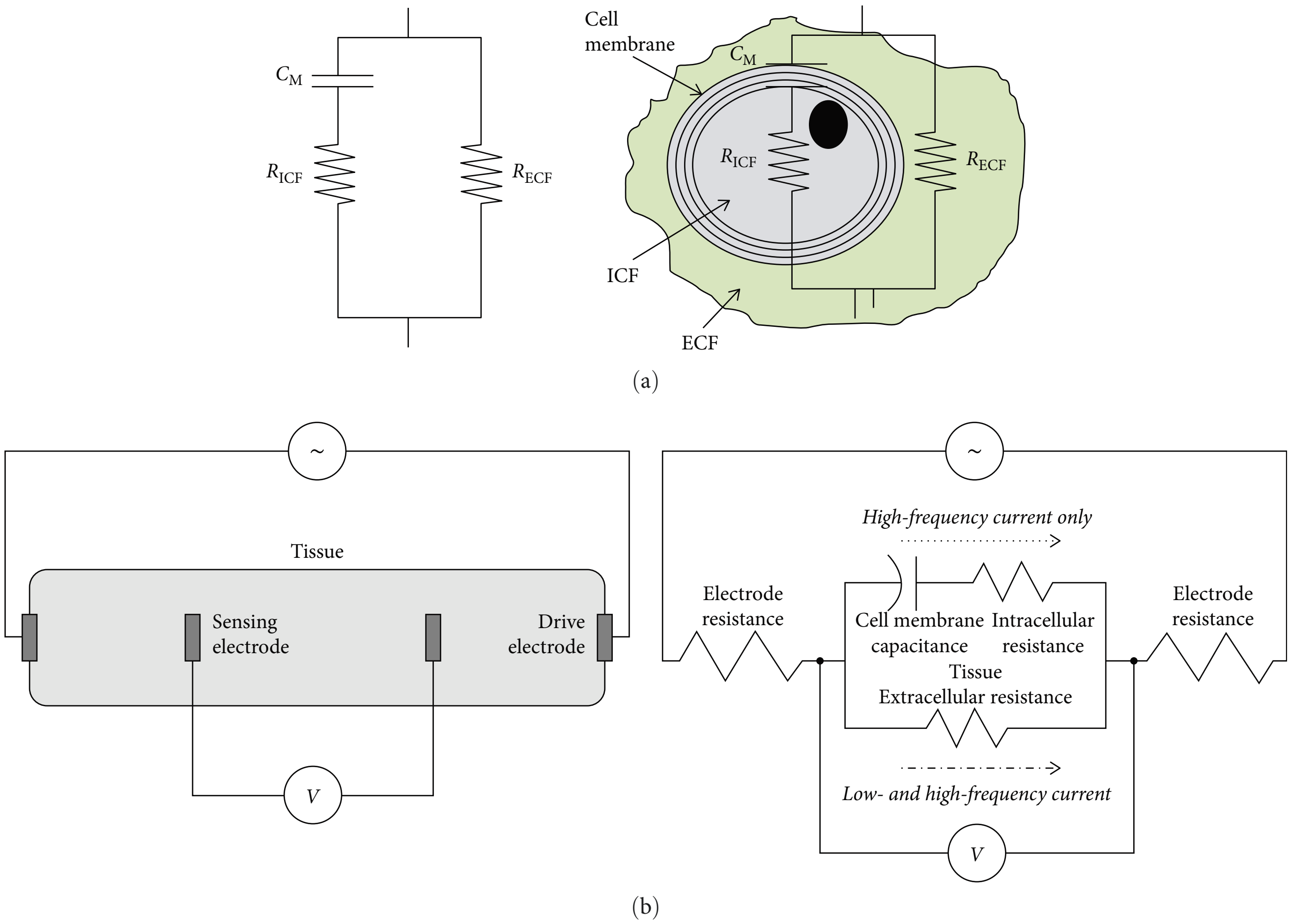

FIGURE 1: Electrical circuits of the body cell: (a) bioelectrical impedance measurement model with ICF and ECF; (b) model of body cell's equivalent circuit.

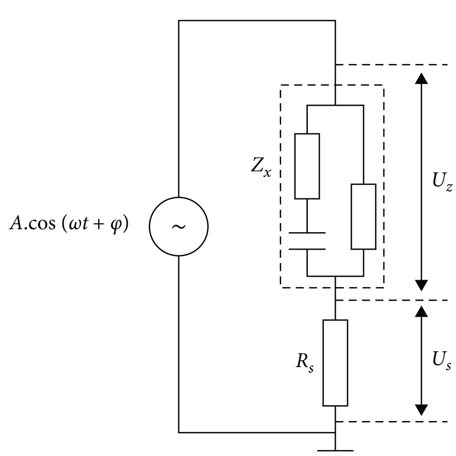

FIGURE 2: Model of bioelectrical impedance measurement.

human tissues, connects with a standard resistor R_S in series [22]. The model for the bioelectrical measurement is shown in Figure 2. The voltage across Z_X and R_S becomes U_Z and U_S after signal processing when there is an excitation current in the circuit. The current through Z_X and R_S are I, and the relationship between U_Z and U_S is as follows:

$$\frac{U_Z}{U_S} = \frac{I.Z_X}{I.R_S} = \frac{Z_X}{R_S}. \quad (1)$$

Using Equation (1), it is concluded that,

$$Z_X = R_S \frac{U_Z}{U_S} = R_S \frac{|U_Z| \angle \varphi_1}{|U_S| \angle \varphi_2} = R_S \frac{|U_Z|}{|U_S|} \angle \theta. \quad (2)$$

Here, $\angle\theta$ is the phase difference of U_Z and U_S.

The BI of body tissues diversifies with the different frequency ranges of current implemented to them. The frequency and impedance are inversely proportional to each other. An increment in the frequency decreases the corresponding value of the impedance of biological tissues [23]. The relation between X_c (capacitive reactance) and f (frequency) is also inversely proportional; X_c reduces rapidly up to zero at a high or infinite frequency. Similarly, X_c acts as an open circuit at zero frequency and increases up to infinity.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}, \quad (3)$$

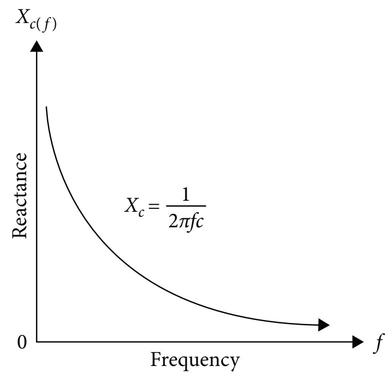

Figure 3: Capacitive reactance against frequency.

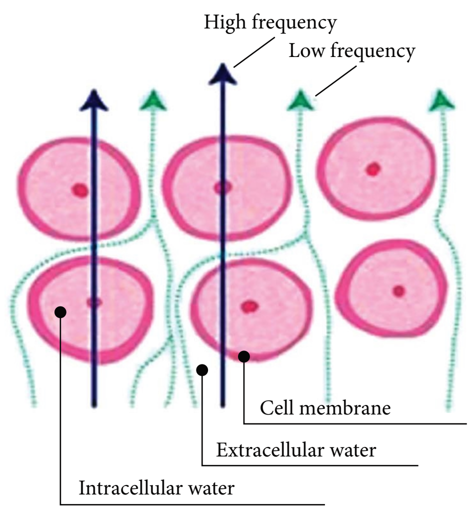

Figure 4: Biological current flow of low and high frequency in the cell membrane of the human body.

where X_C is the capacitive reactance, C is the capacitance in farads, and f is the frequency in Hertz.

Figure 3 shows a nonlinear curve between capacitive reactance and frequency. The graph's nonlinearity follows that a capacitor's reactance value is high at low frequency but decreases quickly as frequency increases. The relation between frequency and impedance is nonlinear or inversely proportional, as impedance will be reduced with a frequency increment.

2.2. Multifrequency and Segmental BI Measurement. The research uses a multifrequency measurement technique because single- or low-frequency currents cannot punch body tissues and can only calculate the extracellular fluid value of human body cells. A high and low range of frequencies is required to estimate both ECF and ICF. The impedance of the human body can be calculated at a different frequency, and measured values of ICF and ECF become helpful in computing the value of TBW. The single frequency can not find the situation of ICF, so it becomes difficult to get satisfactory results [24]. Figure 4 represents the biological current flow of low and high frequency in the cell membrane of the human body.

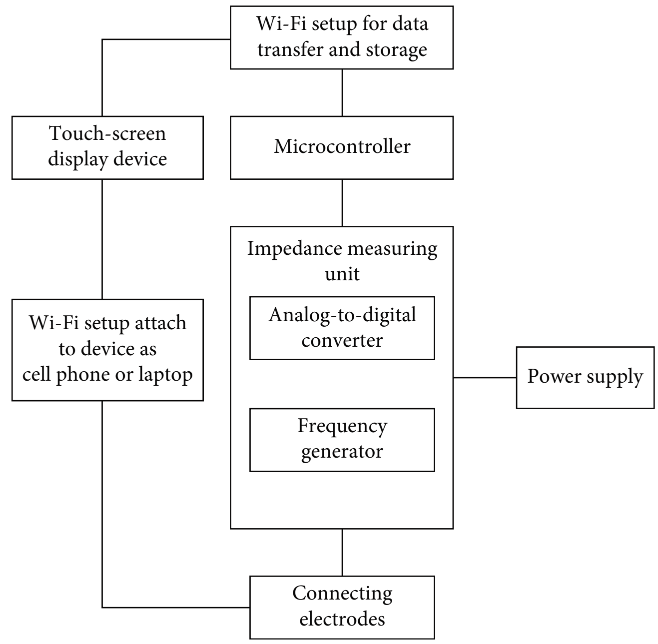

Figure 5: Block diagram of the proposed system.

The multifrequency is usable for measuring parameters related to body composition, such as TBW, FFM, ICW, and ECW, at different frequencies. So, multifrequency is used in this research [25].

2.3. System Architecture. The basic block diagram of the BI analyzer is shown in Figure 5. It consists of an Arduino microcontroller to control the necessary action for data performance and storage, a subminiature version-A (SMA) to alligator cable for electrode connections, an impedance analyzer circuit for impedance measurement, and thin film transistor (TFT) LCD to display the measured as results. Figure 6 shows an experimental setup for the measurement of the BI of the human body. The present prototype is more affordable and reliable than the other BIA devices already available in the market because available devices with all features presented in the prototype are bulky and out of reach for a common population to regularly monitor diseases. The present prototype is compact and pocket-carrying, so it can be easy to carry anywhere and do monitoring anytime.

2.4. Arduino Microcontroller. To make the present prototype compact, an Arduino Mega (ATmegha2560) is used [3]. The length and width of ATmegha2560 are 4 and 2.1 inches, respectively. It has a total of 54 input and output ports, with a combination of 14 pulse-width modulation outputs and 16 analog inputs.

2.5. TFT LCD Display Screen. The measured results are shown on the 2.4-inch TFT LCD-colored screen. The hardware of this microcontroller consists of a resistive touch screen, an SD card slot, an Arduino shield, and a reset button. Arduino also required preinstalling the TFT library, in which Arduino uses the SPI interface to use this shield.

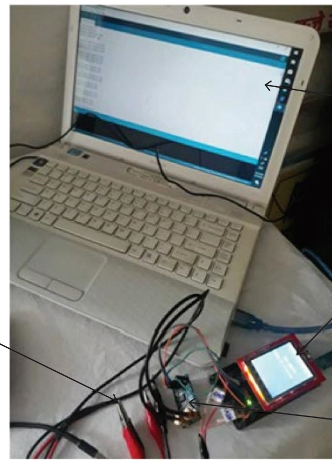

Figure 6: Experimental setup for the impedance measurement system.

Figure 7: The required components: (a) impedance analyzer; (b) Arduino microcontroller; (c) SMA to alligator coaxial cable; (d) TFT LCD screen.

2.6. Impedance Analyzer Circuit. The impedance analyzer used in the present research consists of an onboard frequency generator AD5933 and an analog-to-digital converter (ADC) with a 12-bit impedance converter. The main feature of this analyzer is the measurement of the known impedance of the human body at a known frequency with the help of ADC. The output of AD5933 depends on the excitation amplitude. The range of measured impedance is affected by the AD5933 chip regarding linearity and calibration process [26]. The required components for designing the impedance analyzer are shown in Figure 7.

2.7. Electronics Connections. The skin electrode is suitable for measuring the lower leg's BI [27]. Because of the different types of apparatus and methodology, the prediction of BIA varies by 10% of body weight. The different estimated equations with their variables are developed based on the method used as a reference [28]. The device used in [29] has multilead or multielectrodes for accurate measurement. It is also used for the measurement of volume at different segments of the body. About 200-Ω unchanging impedance can be provided by spherical electrodes in full range frequency. These types of electrodes show zero phases with resistive behavior. Additionally, quadrate electrodes show complex and high impedance at low frequencies [30]. The bioimpedance analyzer's manufacturers used an electrode that minimizes the error in equipment at the right side of the human body at 50 kHz frequency, but at high frequency, when measured impedance becomes low, the error may increase. To prevent these problems, low-impedance electrodes are mostly suitable to be used [31, 32]. Design requirements can be used to connect the structural elements in a permanent and nonpermanent manner [33]. There are different types of treatment for the affected body, and choosing the correct treatment method depends on the patient's tolerance and health [34].

2.8. System for Storage and Data Transfer. The main aim of the present research is to make the system digital in the form of data storage and the transaction to the subjects whose measurements will be done. As a developed prototype used to measure the BI of the human body at multifrequency, it is necessary to send measured data to the subjects and examiner for future use or research the data academically or commercially [35–40]. The research uses an in-build device with a Wi-Fi chip to send the data to the server.

3. Interfacing Software/Flowchart

The developed prototype works with inbuilt software with embedded C language. This inbuilt software developed

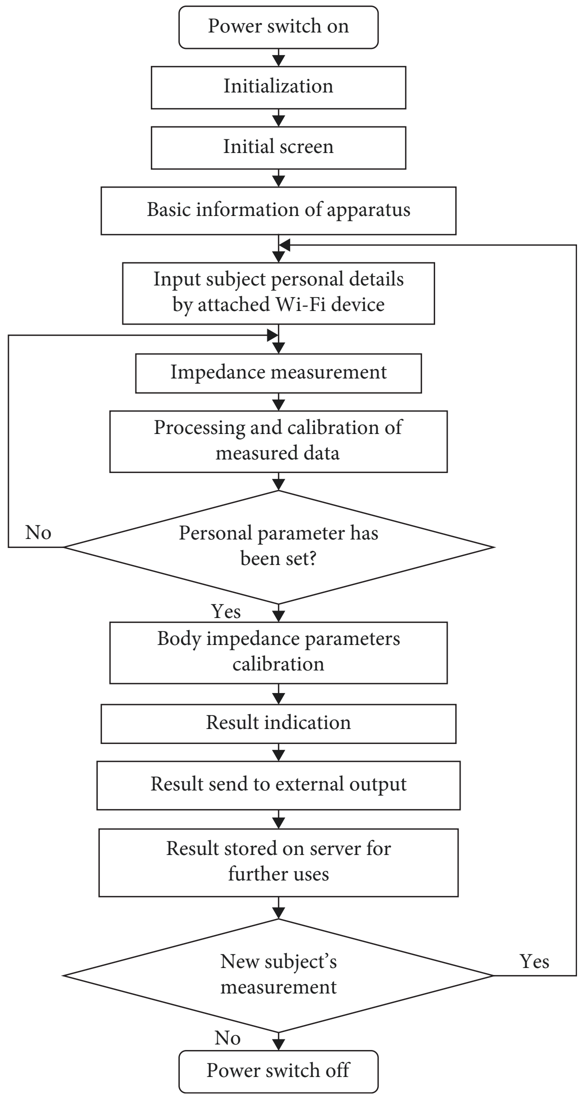

Figure 8: Flowchart of the impedance measurement algorithm.

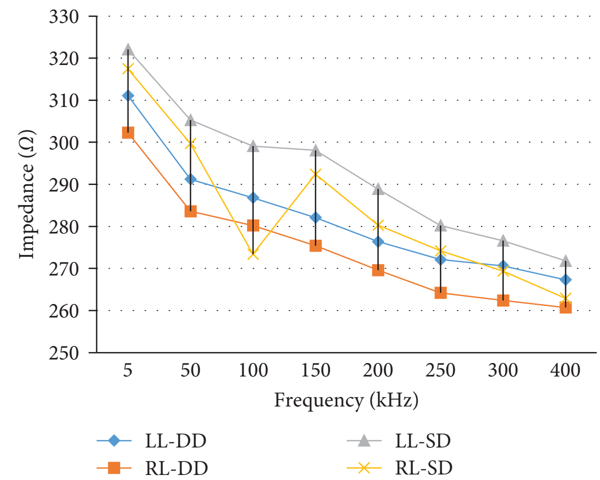

Figure 9: Graph for the comparative analysis of developed and standard devices for human legs.

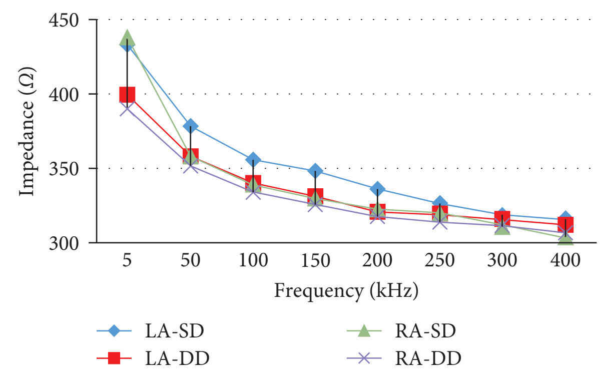

Figure 10: Comparative analysis of developed and standard devices for the human arms.

embedded C language controls all the action functionality. The flow chart in Figure 8 shows the basic algorithm of the impedance-measuring prototype.

4. Results and Discussion

4.1. Measurement of BI of Upper and Lower Limbs of the Human Body. The prototype used in this research measures the BI of the human body's legs (left and right) and both arms (left and right) at multifrequency. Observing the measured data indicates that the impedance of the left leg is always more than that of the right leg. Similarly, the right arm's impedance is less than the left arm's, although the right arm's muscles are stronger than the left one's. The measurement of both legs and arms is made at the same frequency. The computation of intracellular and extracellular resistance is done with multifrequency help. Figures 9 and 10 list the comparative analysis of developed and standard devices for the human legs and arms, respectively. The position of the electrode placement for the upper and lower limbs is shown in Figure 11, respectively.

Tables 1 and 2 show the results of the measurement of the BI of the human left and right leg at the frequency range of 5–400 kHz for the developed and standard device (standard device already available in the lab model: microprocessor-based four-channel auto mode T.E.N.S unit), respectively. Results vary from 311.1 to 267.3 Ω for the left leg and 302.3 to 260.7 Ω for the right leg with different frequencies in the developed devices and from 322.1 to 271.8 Ω for the left leg and 317.5 to 262.9 Ω for the right leg with varying values of frequency in the standard device. It can be noticed from the table that the impudence of the human leg increases at the lowest frequency and decreases at the highest frequency. Measured impedance is inversely proportional to the frequency applied during measurement.

Table 3 represents the comparative analysis between data recorded through the developed and standard devices at the same frequency for the left and right leg of the human body. According to the resultant data, the difference error varies from 1.66% to 5.37% between the developed and standard devices for the left leg and from 0.84% to 5.81% Ω for the right leg. The phase of the device can vary according to the different frequencies at which measurements are taken.

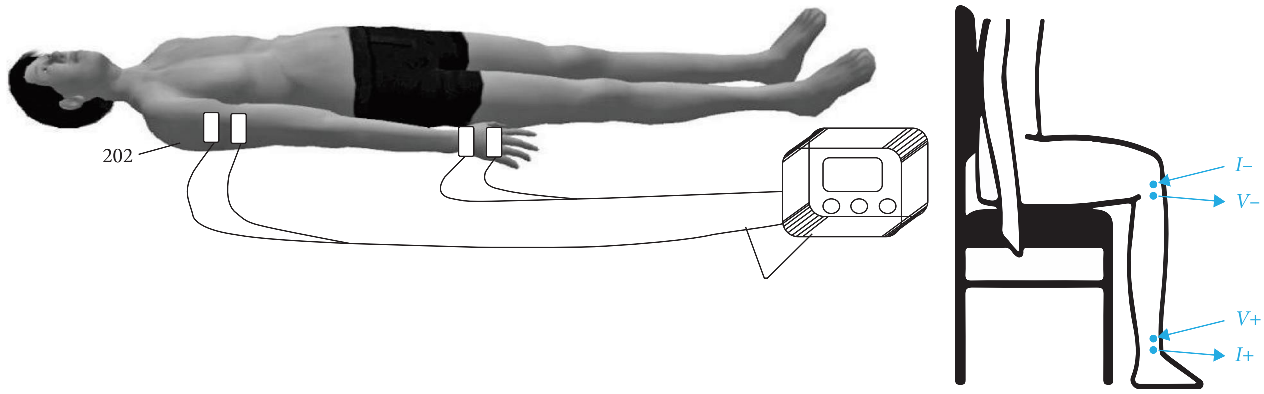

Figure 11: Position of electrodes for the measurement of limbs: (a) position of electrodes for the measurement of upper limb; (b) position of electrodes for the measurement of lower limb.

Table 1: Bioelectrical impedance of human left and right legs at multiple frequencies using the developed prototype.

Frequency (kHz)	Left leg (Ω)	Right leg (Ω)
5	311.1	302.3
50	291.2	283.6
100	286.8	280.2
150	282.1	275.4
200	276.4	269.6
250	272.1	264.2
300	270.6	262.4
400	267.3	260.7

Table 2: Bioelectrical impedance of human left and right legs at multiple frequencies using the standard device.

Frequency (kHz)	Left leg (Ω)	Right leg (Ω)
5	322.1	317.5
50	305.3	299.7
100	299.1	273.4
150	298.1	292.4
200	288.9	280.3
250	280.2	274.2
300	276.6	269.4
400	271.8	262.9

Table 3: Difference error between the bioelectrical impedance of human left and right legs at multi frequencies using the developed and standard device.

	Impedance (Ω) Mean value					
Frequency (kHz)	Left leg			Right leg		
	Standard device	BIA instrument	Diff./error (%)	Standard device	BIA instrument	Diff./error (%)
5	322.1	311.1	3.42	317.5	302.3	4.79
50	305.3	291.2	4.62	299.7	283.6	5.37
100	299.1	286.8	4.11	273.4	280.2	2.49
150	298.1	282.1	5.37	292.4	275.4	5.81
200	288.9	276.4	4.33	280.3	269.6	3.82
250	280.2	272.1	2.89	274.2	264.2	3.65
300	276.6	270.6	2.17	269.4	262.4	2.60
400	271.8	267.3	1.66	262.9	260.7	0.84

Table 4: Bioelectrical impedance of human left and right arms at multi frequencies using the developed device.

Frequency (kHz)	Left arm (Ω)	Right arm (Ω)
5	399.3	390.4
50	357.6	351.7
100	339.6	334.3
150	330.8	326.2
200	321.4	317.5
250	318.7	314.3
300	315.2	311.6
400	312.1	307.4
500	307.9	302.8

Table 5: Bioelectrical impedance of human left and right arms at multiple frequencies using the standard device.

Frequency (kHz)	Left arm (Ω)	Right arm (Ω)
5	433.2	437.2
50	378.6	358.3
100	356.3	339.2
150	348.8	330.2
200	336.4	323.4
250	326.5	320.7
300	319.2	311.4
400	316.1	304.4
500	312.5	298.8

Table 6: Difference error between the bioelectrical impedance of human left and right arm at multiple frequencies using the developed and standard devices.

Frequency (kHz)	Impedance (Ω) Mean value					
	Left arm			Right arm		
	Standard device	BIA instrument	Diff./error (%)	Standard device	BIA instrument	Diff./error (%)
5	433.2	399.3	7.83	437.2	390.4	10.70
50	378.6	357.6	5.55	358.3	351.7	1.84
100	356.3	339.6	4.69	339.2	334.3	1.44
150	348.8	330.8	5.16	330.2	326.2	1.21
200	336.4	321.4	4.46	323.4	317.5	1.82
250	326.5	318.7	2.39	320.7	314.3	2.00
300	319.2	315.2	1.25	311.4	311.6	0.06
400	316.1	312.1	1.27	304.4	307.4	0.99

Tables 3 and 4 show the results of measuring the BI of the human left and right arm at the frequency range of 5–400 kHz for developed and standard devices, respectively. Results vary from 399.3 to 307.9 Ω for the left arm and 390.4 to 302.8 Ω for the right leg for different frequencies in the developed devices, and from 322.1 to 271.8 Ω for the left leg and 317.5 to 262.9 Ω for right leg with different values of frequency in the standard device. It can be noticed from the table that the impudence of the human arm increases at the lowest frequency and decreases at the highest frequency. Measured impedance is inversely proportional to the frequency applied during measurement.

Table 5 lists the results of the BI of human left and right arms at multiple frequencies using the standard device. Results vary from 433.2 to 312.5 Ω for the left arm and 437.2 to 298.8 Ω for the right leg for different frequencies in the developed devices. Table 6 represents the difference error between data recorded through the developed and standard devices at the same frequency for the left and right arm of the human body. According to the resultant data, the difference error varies from 1.25% to 7.83% between the developed and standard devices for the left arm and from 0.06% to 10.70% Ω for the right arm.

The advantages of the developed prototype are as follows:

(1) Cost-effective: The device proposed in this research detects estimated risks at a low cost.
(2) Pocket size: The proposed device is small, like a cell phone.
(3) Early detection: The device is useful for detecting body diseases early with daily monitoring.
(4) Fitness scale: To identify limits of physical workout according to their capability.
(5) Acceptance: The proposed device can be easily accepted by everyone in the medical field, including clinical and laboratory, sports, nutrition, and psychology.
(6) Fast response: The proposed device is very fast as it is a real-time monitoring device.
(7) Quick and reliable: The prototype gives a quick and reliable additional assessment.

5. Conclusions

The summary of the overall study and development of the present prototype defines the BIA technique as the simplest method to measure the BI of human body segments using this device. The device includes segmental measurements with impedance analysis of the upper and lower limbs. The measurement's time duration shows the developed device's fast measurement response. For the examination of the body, a small amount of current passes into the body using two pairs of electrodes, and the corresponding response is recorded in the form of impedance. The instrument developed for measuring the segmental body is used to measure segmental BIA parameters. IOT technology was used to make the instrument capable of making quick decisions at the critical stage of diseases. This instrument measures basic BIA parameters such as multifrequency resistance, reactance, and impedance. The developed prototype in this research will be more demandable because of its compact size and low weight. The BIA technique is more prevalent in a normal population's medical, academic research, and daily routine life to protect them from different types of diseases. The present device can also add more features to measure other related parameters.

Data Availability

The data that were utilized to support the conclusions of this research may be obtained from the corresponding author upon written request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the participants of this study. The authors would like to acknowledge Dr. Dev Singh for his valuable assistance in research. We would also like to thank the Head of the Medicine Department of GSVM, Kanpur; Dr. Richa Giri, for their assistance in the data collection procedure.

References

[1] X. Gao and J. Tang, "Human bioelectrical impedance measuring method based on principle of multi-frequency and multi-segment," *Procedia Engineering*, vol. 24, pp. 459–463, 2011.

[2] G. P. Khan, M. Khan, and S. Mehfooz, "Generalized sex and age specific body composition prediction equations for Indian subjects," *International Journal of Computational Engineering Research*, vol. 3, no. 12, pp. 1–15, 2013.

[3] M. Khan, S. P. S. M. A. Sirdeshmukh, and K. Javed, "Evaluation of bone fracture in animal model using bio-electrical impedance analysis," *Perspectives in Science*, vol. 8, pp. 567–569, 2016.

[4] D. Coggon, I. Reading, P. Croft, M. McLaren, D. Barrett, and C. Cooper, "Knee osteoarthritis and obesity," *International Journal of Obesity*, vol. 25, no. 5, pp. 622–627, 2001.

[5] S. W. Baik, Y. J. Kim, J. H. Kim et al., "Implementation of bioelectric impedance measurement system using multi-frequency applying method and two-electrode method," in *International Conference on Chemistry, Biomedical and Environment Engineering (ICCBEE'14)*, pp. 10–15, International Academy of Arts, Science & Technology, 2014.

[6] A. K. Wills, S. Black, R. Cooper et al., "Life course body mass index and risk of knee osteoarthritis at the age of 53 years: evidence from the 1946 British birth cohort study," *Annals of the Rheumatic Diseases*, vol. 71, no. 5, pp. 655–660, 2012.

[7] D. M. Pacca, G. C. de-Campos, A. R. Zorzi, E. A. Chaim, and J. B. de-Miranda, "Prevalence of joint pain and osteoarthritis in obese Brazilian population," *ABCD. Arquivos Brasileiros de Cirurgia Digestiva*, vol. 31, no. 1, 2018.

[8] K. Chinen, I. Kinjo, A. Zamami et al., "New equivalent-electrical circuit model and a practical measurement method for human body impedance," *Bio-Medical Materials and Engineering*, vol. 26, no. s1, pp. S779–S786, 2015.

[9] M. Khan, S. Mehfuz, and G. P. Khan, "Bioelectrical impedance analysis (BIA) for assessing Tbw and Ffm of Indian females," *International Journal of Computational Engineering Research*, vol. 1, 2014.

[10] D. K. Kamat and P. M. Patil, "Multi-frequency and multi-segment bio-impedance measurement using tetra-polar electrode setup," in *2nd International Conference on Control Science and Systems Engineering (ICCSSE)*, IEEE, 2016.

[11] B. Chen, X. Zhang, and N. Liu, "Research and design of human impedance measuring instrument based on the method of multi-frequency and multi-segment," in *2nd International Conference on Biomedical Engineering and Informatics*, pp. 1–4, IEEE, 2009.

[12] B. C. Wingo, V. G. Barry, A. C. Ellis, and B. A. Gower, "Comparison of segmental body composition estimated by bioelectrical impedance analysis and dual-energy X-ray absorptiometry," *Clinical Nutrition ESPEN*, vol. 28, pp. 141–147, 2018.

[13] C. H. Y. Ling, A. J. M. de Craen, P. E. Slagboom et al., "Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population," *Clinical Nutrition*, vol. 30, no. 5, pp. 610–615, 2011.

[14] J. A. C. de Castro, T. R. de Lima, and D. A. S. Silva, "Body composition estimation in children and adolescents by bioelectrical impedance analysis: a systematic review," *Journal of Bodywork and Movement Therapies*, vol. 22, no. 1, pp. 134–146, 2018.

[15] T. Cannon and J. H. Choi, "Development of a segmental bioelectrical impedance spectroscopy device for body composition measurement," *Sensors*, vol. 19, no. 22, Article ID 4825, 2019.

[16] C.-S. Wu, Y.-Y. Chen, C.-L. Chuang et al., "Predicting body composition using foot-to-foot bioelectrical impedance analysis in healthy Asian individuals," *Nutrition Journal*, vol. 14, no. 1, Article ID 52, 2015.

[17] B. Ragini, S. R. Aishwarya, M. Tamil Selvan, A. Pillai, and M. Anburajan, "Prediction of body fat using segmental body composition by bioelectrical impedance in the evaluation of obesity," *Journal of Engineering and Applied Sciences*, vol. 10, no. 8, pp. 3627–3634, 2018.

[18] A. C. Utter, D. C. Nieman, A. N. Ward, and D. E. Butterworth, "Use of the leg-to-leg bioelectrical impedance method in assessing body-composition change in obese women," *The American Journal of Clinical Nutrition*, vol. 69, no. 4, pp. 603–607, 1999.

[19] T. L. Grisbrook, P. Kenworthy, M. Phillips, P. M. Gittings, F. M. Wood, and D. W. Edgar, "Alternate electrode placement for whole body and segmental bioimpedance spectroscopy," *Physiological Measurement*, vol. 36, no. 10, pp. 2189–2201, 2015.

[20] R. L. Alvarenga and M. N. Souza, "Assessment of knee osteoarthritis by bioelectrical impedance," in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, vol. 4, pp. 3118–3121, IEEE, 2003.

[21] S. Z. Yanovski, V. S. Hubbard, S. B. Heymsfield, and H. C. Lukaski, "Bioelectrical impedance analysis in body composition measurement: national institutes of health technology assessment conference statement," *The American Journal of Clinical Nutrition*, vol. 64, no. 3, pp. 524S–532S, 1996.

[22] L. Hui and L. W. Ding, "Low-power and portable design of bioelectrical impedance measurement system," in *2010 WASE International Conference on Information Engineering*, vol. 3, pp. 38–41, IEEE, 2010.

[23] B. H. Cornish, B. J. Thomas, and L. C. Ward, "Improved prediction of extracellular and total body water using impedance loci generated by multiple frequency bioelectrical impedance analysis," *Physics in Medicine and Biology*, vol. 38, no. 3, pp. 337–346, 1993.

[24] W. J. Hannan, S. J. Cowen, K. C. H. Fearon, C. E. Plester, J. S. Falconer, and R. A. Richardson, "Evaluation of multi-frequency bio-impedance analysis for the assessment of extracellular and total body water in surgical patients," *Clinical Science*, vol. 86, no. 4, pp. 479–485, 1994.

[25] https://www.robotshop.com/media/files/pdf/arduinomega2560datasheet.pdf.

[26] A. Al-Ali, A. S. Elwakil, A. Ahmad, and B. Maundy, "Design of a portable low-cost impedance analyzer," in *International Conference on Biomedical Electronics and Devices*, vol 2, pp. 104–109, SciTePress, Porto, Portugal, 2017.

[27] K. S. Kim, D. Y. Yoon, Y. K. Yang, J. H. Seo, K.-S. Kim, and C. G. Song, "A new bio-impedance sensor technique for leg movement analysis," in *Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference*, IEEE, Melbourne, VIC, Australia, 2004.

[28] J. Joshi, R. Ms Shruti, and U. R. Bagal, "Development of bioelectrical impedance analyzer for body composition analysis," *IOSR Journal of Electrical and Electronics Engineering*, vol. 9, no. 5, pp. 53–62, 2014.

[29] D. K. Kamat, V. Shende, and P. M. Patil, "Measurement system for bio-impedance signal analysis using impedance analyzer," *International Journal of Engineering Research & Technology*, vol. 4, no. 7, 2015.
[30] S. Corbellini and A. Vallan, "Arduino-based portable system for bioelectrical impedance measurement," in *2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, pp. 1–5, IEEE, 2014.
[31] P. Bogónez-Franco, L. Nescolarde, E. McAdams, and J. Rosell-Ferrer, "Multifrequency right-side, localized and segmental BIA obtained with different bioimpedance analysers," *Physiological Measurement*, vol. 36, no. 1, pp. 85–106, 2015.
[32] M. S. Mialich, J. F. Sicchieri, and A. J. Junior, "Analysis of body composition: a critical review of the use of bioelectrical impedance analysis," *International Journal of Clinical Nutrition*, vol. 2, no. 1, pp. 1–10, 2014.
[33] D. Rozumek, R. Brighenti, Z. Marciniak, and M. Smaga, "Mechanics, fatigue, and fracture of structural joints," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 8707038, 2 pages, 2019.
[34] F. Zhang, F.-Q. Pei, Q.-W. Shao, Y. Deng, P.-J. Dai, and D.-Z. Yang, "Coronal movement during flexion and extension of knee joints," *Evidence-Based Complementary and Alternative Medicine Article*, vol. 2022, Article ID 4237558, 7 pages, 2022.
[35] J. Wu, S. A. Haider, M. Bhardwaj, A. Sharma, and P. Singhal, "Blockchain-based data audit mechanism for integrity over big data environments," *Security and Communication Networks Article*, vol. 2022, Article ID 8165653, 9 pages, 2022.
[36] L. He, G. Jin, and S.-B. Tsai, "Design and implementation of embedded real-time english speech recognition system based on big data analysis," *Mathematical Problems in Engineering*, vol. 2021, Article ID 6561730, 12 pages, 2021.
[37] H. Zheng, S. Yu, and X. Xu, "A systematic methodology for multi-images encryption and decryption based on single chaotic system and FPGA embedded implementation," *Mathematical Problems in Engineering Article*, vol. 2014, Article ID 698608, 15 pages, 2014.
[38] W.-M. Niu, F. Li-qing, Z.-Y. Qi, and D.-Q. Guo, "Small displacement measuring system based on MEMS accelerometer," *Mathematical Problems in Engineering*, vol. 2019, Article ID 3470604, 7 pages, 2019.
[39] Z. Bogicevic, S. Bjelić, P. Spalević, and M. Mišić, "Graph-analytical method of determining impedance in electrical transformers," *Mathematical Problems in Engineering*, vol. 2015, Article ID 745629, 11 pages, 2015.
[40] H. Zhang, M. Qiu, X. Yu, Y. Wu, and Y. Ma, "Application of boiler optimization monitoring system based on embedded internet of things," *Mathematical Problems in Engineering*, vol. 2022, Article ID 9974393, 12 pages, 2022.