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RESEARCH PAPER

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Bioelectrical Impedance Spectroscopy (BIS) for Ratiometric Identification

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ABSTRACT

This research explores the potential use of Electrical Impedance Spectroscopy (EIS) and ratiometric methods to improve security and reproducibility in bioelectrical impedance-based biometric authentication systems. Traditional biometric technologies such as fingerprints are susceptible to forgery and less effective in handling external variations, making bioelectric signal-based approaches a promising alternative. By using Analog Discovery 2 to measure the impedance of ten pairs of fingers in the frequency range of 20 kHz to 500 kHz, with a 1 mA sinusoidal current injected into the subject's fingers, real-time data collection can be performed with the precision required for biometric applications. The measurement results show that the impedance value for each finger differs among subjects, making it a useful parameter for biometric authentication. The application of the ratiometric method successfully reduces day-to-day measurement variations, especially at high frequencies above 100 kHz, resulting in more stable and consistent data. This research shows that bioelectrical impedance methods have the potential to improve security compared to traditional methods such as fingerprinting, as they are more difficult to replicate. This approach offers a promising solution for a more secure and highly reproducible biometric authentication system, with potential applications in various security systems and wearable technologies.

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1. INTRODUCTION

Biometric technology has become one of the fastest-growing areas of technological development. It utilizes individual identifiers such as fingerprints, hands, palm lines, face, voice, iris, retina, and gait [1][2][3] as biometric authentication, which plays an important role in maintaining personal, national, and global security. The integration of biometric technology into everyday life offers convenience and simplicity, making it increasingly popular among the public [4]. Despite its many advantages, biometric technology also has certain disadvantages, as the system can be easily spoofed. For example, iris recognition systems can be faked by using printed irises [5], photographs [6], or colored contact lenses [7], and artificial fingerprints can be created by using gelatin prints [8]. In addition, biometric systems are vulnerable to various external attacks that can disrupt system operations, as outlined in ISO/IEC 30107-1 [9][10]. The vulnerability of this technology to counterfeiting causes an imbalance between usability and susceptibility to misuse, thus limiting its implementation in everyday life.

New alternatives have been explored to improve security. Various new features and approaches, including the use of bioelectric impedance, have been investigated. However, bioelectric impedance or bioimpedance has not provided satisfactory results for practical applications due to several reasons, such as limited accuracy, long recognition time, and sensitivity to movement, stimuli, and emotions [11][12].

In contrast, the application of bioelectrical impedance as a non-invasive measurement and monitoring authentication method has been successfully used to diagnose physiological conditions and identify individual characteristics. Besides being less sensitive to emotional states, bioelectrical impedance provides different analyses for each tissue and individual. This is because the electrical response of body tissues depends on the frequency of the applied alternating current signal. Despite the advantages offered by bioelectrical impedance when applied to biometric technology, bioelectrical impedance still has relatively low reproducibility and requires further research to improve security and performance in the application of biometric technology in society [13].

Electrical Impedance Spectroscopy (EIS) is one of the techniques used to obtain ratiometric features as a ratiometric method [11][14]. This technique belongs to in vivo research, the application in humans involves measuring physiological states using electrodes placed in

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locations that provide information about bioelectric impedance. The frequency obtained serves as an identifier of individual characteristics and biometric ratios by maintaining a constant record over a period. However, variations caused due to external factors and normal physiological changes may affect the ability to accurately identify individuals. The application of this method aims to improve convenience and accuracy by allowing measurements in various parts of the body [15].

The Analog Discovery 2 is a multifunctional instrument that can measure, visualize, generate, record, and control a mixed signal circuit in a single device [4]. Analog Discovery 2 can measure bioimpedance with its portable form factor, fast measurements, high-accuracy low-frequency measurements, and electronic circuit prototypes through a variety of integrated devices, such as oscilloscopes, logic analyzers, signal generators, and voltmeters [16][17].

Noh et al (2019) proposed a novel approach using the ratiometric method to address the low reproducibility of impedance-based biometric technology. The ratio method assumes that changes in the electrical properties of the finger occur proportionally in all components [7]. However, bioelectrical impedance-based authentication is still inaccurate for commercialization. Noh et al., (2021) conducted a follow-up study using different device configurations, which included an Atmega328p-based MCU from Microchip Technology, an AD9833 generator from Analog Device, and VCCS. However, a decline in device performance is observed with increased usage over time [8]. In addition, in 2012, LC Ward used electrical impedance spectroscopy to measure hand volume [18]. In 2021, MH Jung used electrical impedance spectroscopy to analyze the composition of the human body [11]. In 2023, Al-Ali used Analog Discovery 2 to detect wideband signals with electrical impedance spectroscopy [16].

To address the challenges and problems mentioned above, this research focuses on applying the ratiometric method and hardware configuration using Analogue Discovery 2 to improve the accuracy and reliability of bioimpedance-based authentication. Specifically, this research aims to:

1. Evaluate the feasibility of bioimpedance as a biometric authentication method by examining the stability and consistency of impedance parameters under various physiological conditions as well as external factors that may affect the measurement results.
2. Improving the security system of biometric technology by utilising rasiometric analysis to reduce data variability and increase resistance to forgery and signal manipulation-based attacks.
3. Assess the performance and reliability of the Analogue Discovery 2 in bioimpedance measurement, including its ability to measure impedance with high precision, low frequency accuracy, and ease of use in portable biometric applications.

Develop the basis for the application of rasiometric methods in future biometric authentication, by exploring the potential integration of bioimpedance into broader security systems, both for individual identification and access verification in high-security environments. Thus, this research is expected to make a significant contribution to the development of bioimpedance-based authentication technology, as well as open up opportunities for the application of this method in biometric systems that are more secure, efficient, and practical for everyday use.

2. MATERIALS AND METHOD

A. Dataset

This study aims to evaluate finger impedance as a biometric characteristic using a dataset obtained from biometric impedance measurements on five fingers of the left hand (thumb, index, middle, ring, and little fingers), coded A, B, C, D, and E, respectively. The measurements were performed on 10 subjects with non-sweaty hands, sitting upright, and in a calm state. Each finger pair was tested with sequential combinations to generate 10 different finger pair combinations. The finger pair combinations tested include A-B, A-C, A-D, A-E, B-C, B-D, B-E, C-D, C-E, and D-E. The measurement frequency used ranged from 20 kHz to 500 kHz, with a sinusoidal current of 1 mA. The dataset includes measurement results obtained over three consecutive days, with three subjects tested each day. Each subject generated a total of 30 data points based on the combination of finger pairs tested. Table 1 contains anthropometric data of subjects.

Table 1. Data anthropometry

Variable	Average	
	Male (n=3)	Female (n=7)
Age	40.00	37.29
Weight (kg)	65.33	52.14
Height (cm)	166.33	149.71
BMI (kg/m2)	23.70	23.18

B. Data Collection

Data collection was conducted using a system consisting of Analog Discovery 2 hardware, an Impedance Analyzer, electrodes, and WaveForms software. These hardware components were connected to regulate the injection current and measure the voltage across selected finger pairs. Data was recorded with a consistent current distribution, where an electric current with specific frequency variations was applied to the finger pairs. The

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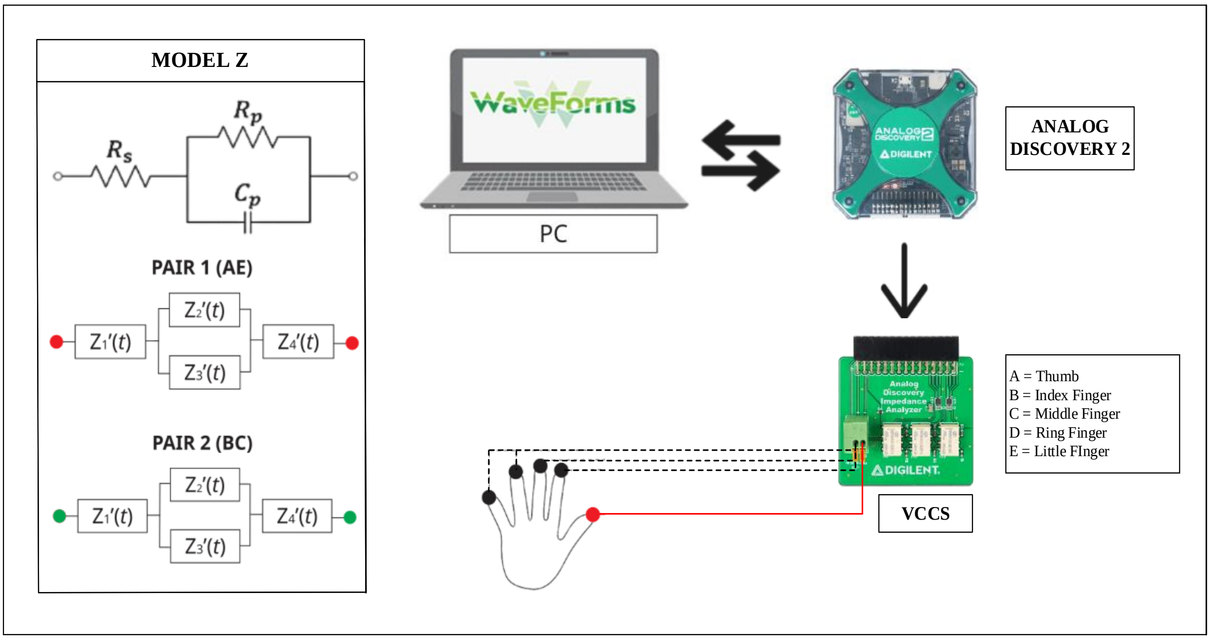

Fig. 1. Block diagram and workflow for Biometric Impedance Measurement

electrodes were placed on the fingertips, directly on the skin where fingerprints are present. The electrodes used had a diameter of 25.4 mm.

For each finger pair, data collection was automatically repeated 20 times. Each finger pair was tested for three consecutive days on three different subjects, ensuring optimal data variation. Data collection was conducted under controlled conditions to minimize interference or external noise, ensuring measurement accuracy. Figure 1 illustrates the block diagram of data collection and processing in bioelectrical impedance spectroscopy (BIS) for ratiometric identification.

C. Device Validation

The Analog Discovery Signal Generator can consistently produce a root mean square (RMS) voltage of 0.7 volts within a frequency range of 1 kHz to 1 MHz, as shown in Figure 2.

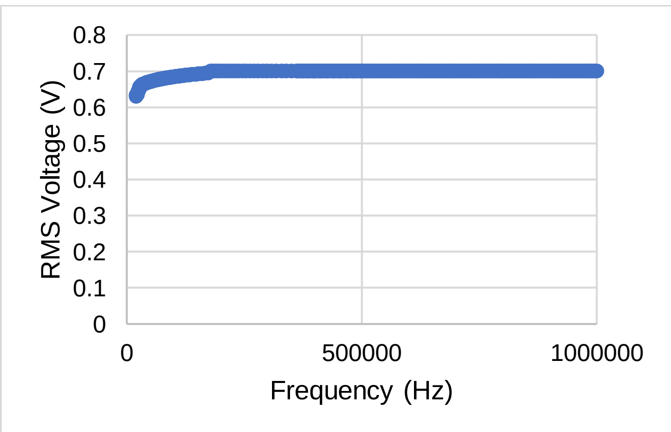

Fig. 2. Analog Generator Discovery Test Result Graph

This experiment was conducted using a load ranging from 1 kΩ to 7 kΩ. The Voltage-Controlled Current Source (VCCS) is capable of generating a stable current across a load of 1 kΩ to 7 kΩ within a frequency range of 10 kHz to 500 kHz, as illustrated in Figure 3. The fluctuation of the injected current remains within safe limits for the human body, as it stays below 1 mA.

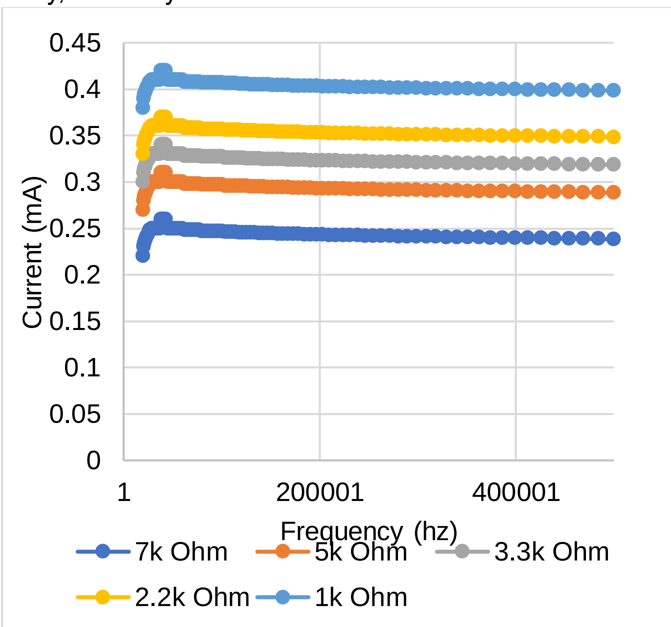

Fig. 3. VCCS Circuit Test Result Graph

D. Data Processing

The data obtained from the measurement process consists of Nyquist plots and impedance values for each pair of fingers at various frequencies. Once the data is collected, the ratio-metric method proposed by Noh et al. (2019) is applied to calculate the impedance ratio. In this method, each finger pair is used only once as the numerator and denominator in the ratio calculation. This

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process generates 10 ratio values from 10 combinations of finger pairs. Next, normalization is ready to be used for to be used for further evaluation processes or as input in the development of classification systems.

The following is the equation used in data processing:

1. **Bioelectric impedance (Z)**
Bioelectric impedance (Z) is a measure of tissue resistance to the flow of alternating electric current (AC). This impedance consists of two components: resistance (R) and reactance (X). Mathematically, impedance can be expressed as:
$$Z = R + jX \qquad (1)$$
where :
Z is the complex impedance
R is the resistance (real component)
X is reactance (imaginary component)
j is the imaginary unit (j $-\sqrt{-1}$)

2. **Ratiometric Method**
The ratiometric method is used to reduce measurement variation by comparing the impedance between two pairs of fingers. If Z_1 and Z_2 are the impedances of two different pairs of fingers, then the impedance ratio (R_{ratio}) can be calculated as:
$$R_{ratio} = \frac{Z_1}{Z_2} \qquad (2)$$
this ratio is then normalised to reduce unwanted variations:
$$R_{normalized} = \frac{R_{ratio} - \mu}{\sigma} \qquad (3)$$
where :
σ is the average value of R_{ratio}
μ is the standard deviation of R_{ratio}

Study Period and Location This research was conducted at the Modern Physics Laboratory of Universitas Airlangga over three consecutive days from July 15 to July 17, 2024.

3. RESULTS

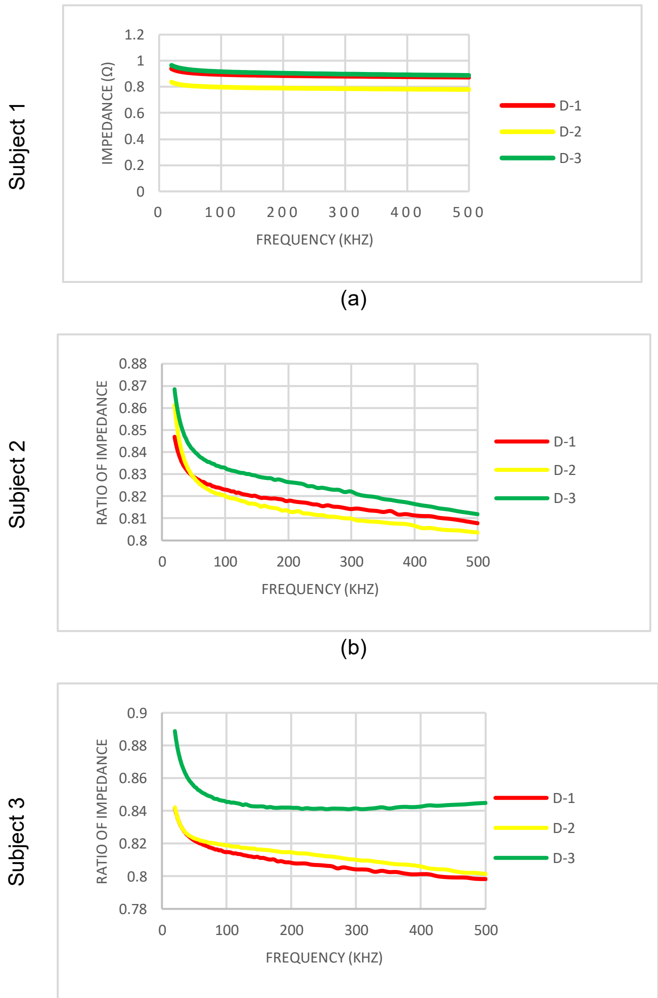
A. Biological Impedance Variation by Undesirable Factors

The low reproducibility of human body impedance measurements is due to significant variations influenced by various unwanted factors. Based on this, we investigated the factors that affect impedance-based identity recognition. These factors can be categorized into two groups: (i) changes in external environmental conditions (e.g., temperature, humidity) and (ii) inherent physiological variations. To examine the impact of external environmental factors, we studied the effect of body temperature on impedance across the fingers. An external temperature chamber was used to regulate hand temperature between 29°C and 37°C for three healthy adults.

Additionally, other biological factors also influence impedance. To analyze their effects, we conducted daily impedance measurements over three consecutive days.

Fig.4 shows that while hand temperature was kept constant, the impedance values of both subjects varied depending on the measurement date. This indicates that impedance can be affected by other unwanted factors, even when temperature is strictly controlled.

Pair [AB/BC]



(c)

Fig. 4. Data variations in 3 subjects with measurements over 3 days: (a-c) ratiometric feature data

B. Accuracy

In this study, Analog Discovery 2 was used as the main device to measure the impedance of the correspondents' fingers. The measurement results show that each finger of each subject has a different impedance value, suggesting that the difference can be utilized as a parameter for biometric identification. To eliminate the influence of unwanted factors and obtain consistent data, the raw impedance data is converted into ratio properties using a basic bio-impedance electrical model with a Z model, as shown in Figure.1. Next, the bio-impedance data was measured using an Analog Discovery 2. The use of this device allows for accurate, efficient, precise, and

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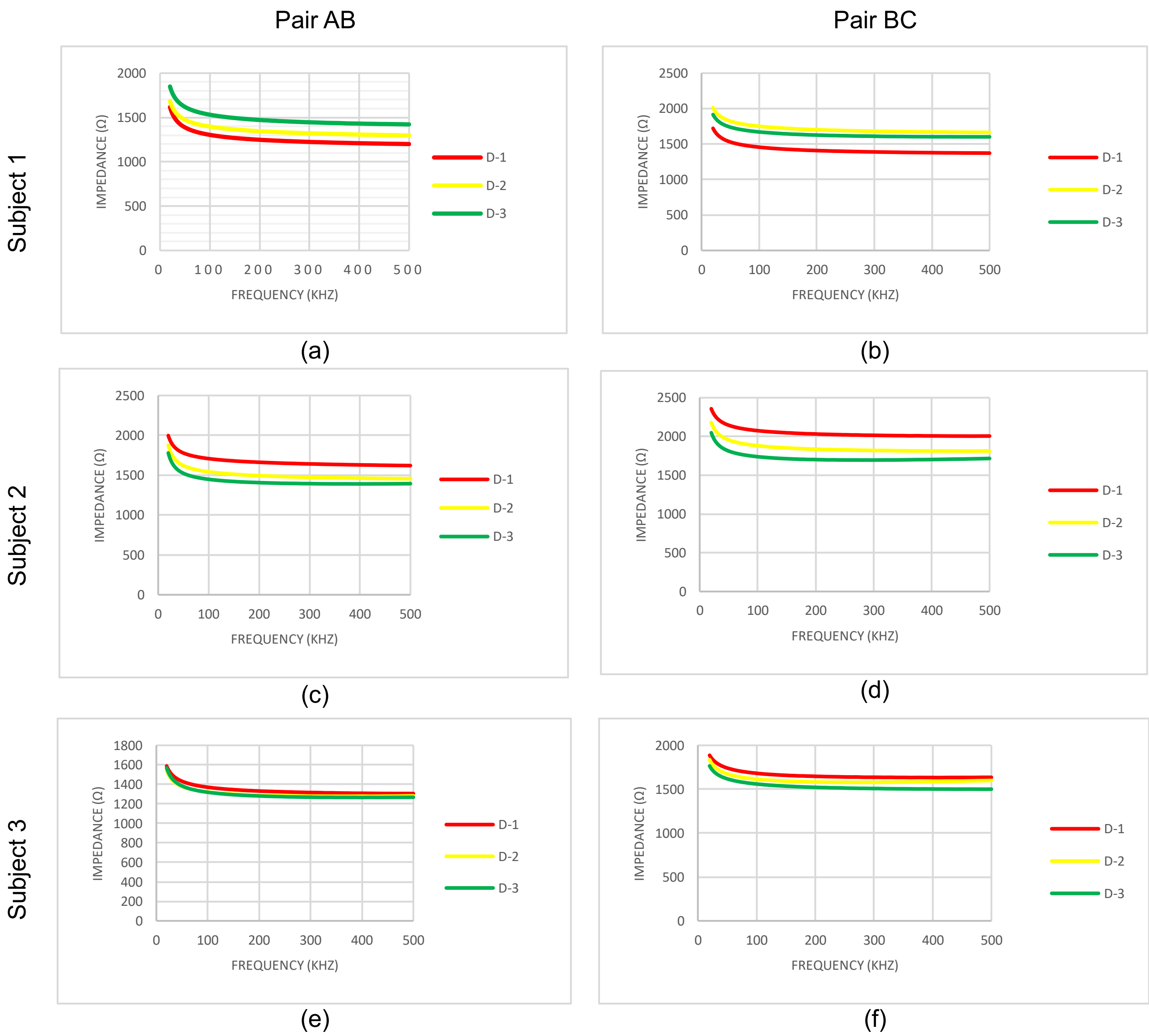

Fig. 4. Data variations in 3 subjects with measurements over 3 days: (a-f) impedance data

consistent data collection.

The measurement results were further analyzed, and the visualization is shown in Figure 4 (a-i). The impedance measurements taken at different times (day 1, day 2, day 3) showed variations in the impedance curves of the finger pairs for three subjects over 20 repetitions.

Figure 4(a) displays the raw impedance data of the three subjects. Each curve in Figure 4(a) shows a consistent decrease in impedance values across days 1, 2, and 3. At high frequencies, the curves for days 1, 2, and 3 approach more stable values. This stability becomes more apparent at frequencies above 100 kHz, where the differences between days become smaller. On the other hand, at frequencies below 100 kHz, each subject showed variations in impedance. Figures 4 (g), (h), and (i) show the measurement curves obtained by applying the ratio method to the fingers of subjects 1, 2, and 3. For subject 1, the impedance ratio shows a steady decrease as the frequency increases on days 1, 2, and 3. Although the pattern of decrease seemed consistent, there were differences in the ratio values between days. Day 1 had a lower ratio compared to day 3, indicating better ratio stability on the latter day. For subject 2, the impedance ratio also consistently decreased as the frequency increased. Day 3 tended to show higher stability compared to days 1 and 2. In addition, the variation from day to day was smaller, indicating more consistent results over time. In contrast, for subject 3, the ratio decreased as the frequency increased, but the variation from day to day was more pronounced compared to the other two subjects, especially at lower frequencies. Day 1 had a lower ratio, while day 3 tended to show higher ratio values across the frequency range.

Next, in Figure 5(a) presents the measured raw impedance data of the finger pairs, while Figure 5(b) displays the ratio feature data for subjects 1, 2, and 3

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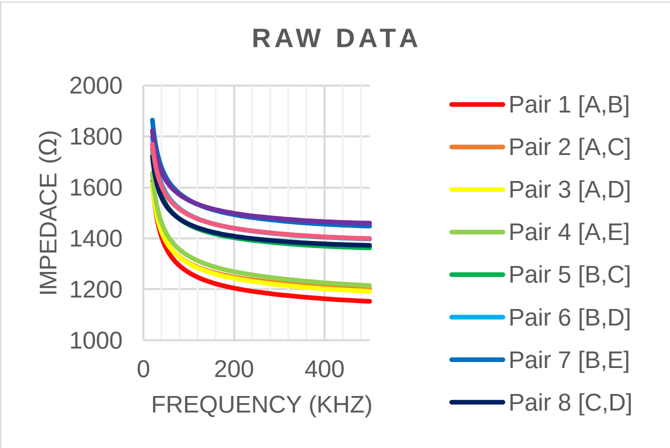
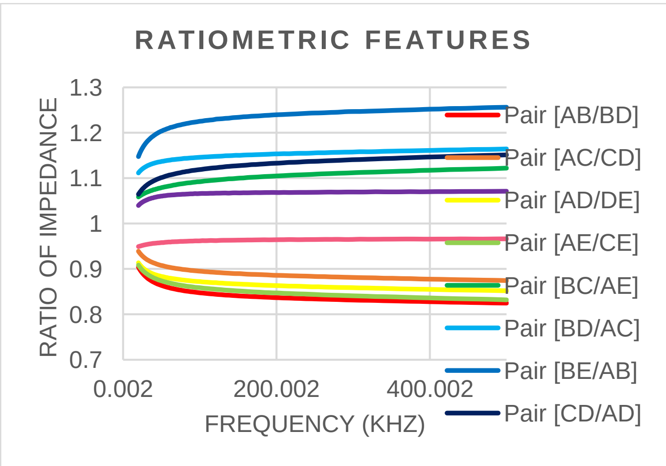
obtained by transforming the raw impedance of the finger pairs. The two curves clearly illustrate the difference in impedance values at each frequency for the raw data and the ratiometric features. The ratio features for each subject show variations in pattern, slope, and impedance value. Figure 6 shows the finger pairs used to obtain accurate ratio features.

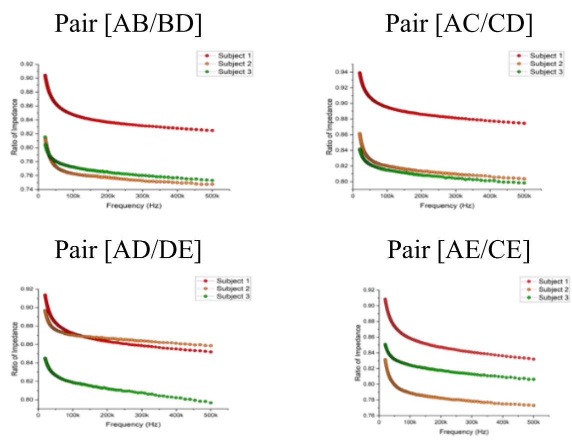


(a)



(b)

Fig. 5. (a) Raw data of the impedance measured from the finger pairs. (b) Ratiometric features obtained by transforming the raw impedance from the finger pairs.



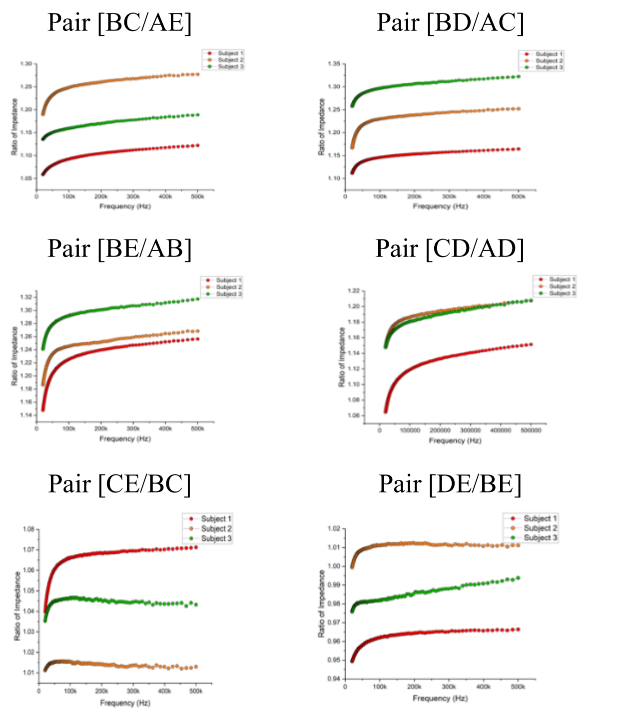
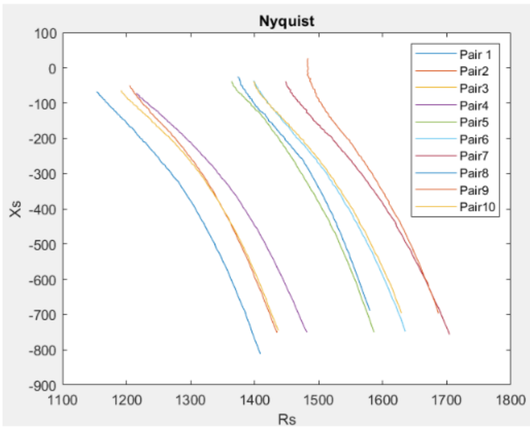
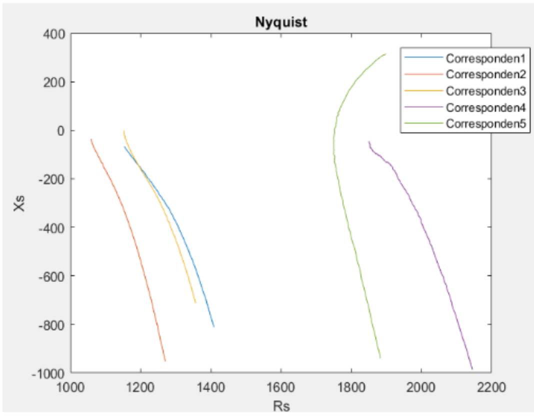


Fig. 6. Ten pairs of ratiometric feature combinations from 3 subjects with measurements over 3 days



(a)



(b)

Fig. 7. Nyiquist graph (a) 10 finger pair on 1 subject (b) pair AB on 5 subject

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Figure 7(a) shows the Nyquist plot of 10 finger pairs on one subject. Each line in the graph represents one pair of fingers tested, labeled from Pair 1 to Pair 10. From this graph, it can be seen that each pair of fingers has different impedance characteristics, with variations in the values of Rs (resistance) and Xs (reactance). Although the curve patterns are similar, the trend seen is a decrease in Xs as Rs increases, which is a common characteristic in impedance analysis.

Meanwhile, Figure 7(b) displays the Nyquist plot of one particular finger pair (Pair AB) measured on five different subjects. Each line represents the measurement results from a different individual, labeled Correspondent1 to Correspondent5. Additional subjects were added to find out more about the differences in the characteristics of each individual. From this graph, it can be seen that there are differences in impedance characteristics between individuals even though the same pair of fingers were tested. Some curves show similarities, while others have considerable differences in Rs and Xs.

4. DISCUSSION

A. 3 Days Analysis

This trial was conducted with the aim of seeing how the pattern of impedance on each subject for three consecutive days. The impedance of the subject's finger pair was measured 20 times and the average was taken for 3 consecutive days. Based on Figure 2, Each subject showed variations in impedance at specific frequencies. This shows that although there are variations between days, similar trends are observed for all subjects.

At high frequencies, the curves for days 1, 2, and 3 approach more stable values. This stability becomes more apparent at frequencies above 100 kHz, where the differences between days become smaller. This stability is very important in the ratiometric method, as smaller day-to-day variations at high frequencies help to produce more consistent ratios. Stability occurs at frequencies above 100 kHz because according to Kim *et* al (2019), the best performance for identifying characteristcs is obtained at frequencies above 100 kHz [26]. On the other hand, at frequencies below 100 kHz, each subject showed variations in impedance. This indicates that each subject has different bioimpedance characteristics, which can also be distinguished visually. This is in accordance with research conducted by Pawar (2024) [27][28] that impedance is more stable at high frequencies.

B. The Ratio Features

In accordance with Figure 4, ratio features are needed. The ratio features for each subject show variations in pattern, slope, and impedance value. These features aim to ease subject identification and improve biometric performance.

Improvement in the ability to distinguish finger pairs can be achieved through the ratio-metric feature. Since each finger has a different anatomical configuration, the impedance between finger pairs also varies. In contrast, the ratio-metric features have different patterns and slopes for each finger pair (Figure 5), making them easier to distinguish visually compared to the raw data. The data from each subject also shows small differences in pattern and magnitude for each pair of fingers [7]. It can be expected that more finger pairs will improve the discrimination accuracy. In this context, the experimental results show that the ratio-metric features are robust to the influence of environmental factors, thereby improving the discrimination ability based on reliable properties.

This study has the same statement as Muramatsu (2024) [19] and Soria (2008) [29] that bioimpedance can be used as an identification of a person's characteristics and can be used as the development of biometric systems to improve defense systems.

C. The Nyquist Plot

The Nyquist Plot displays the real (Rs) and imaginary (Xs) parts of the impedance (or system response) that will change as the frequency changes. This graph simply shows how the real and imaginary parts of the impedance relate in the complex plane without explicitly displaying an axis representing frequency [20][21].

The results displayed in Figure 5(a) show that the impedance of each pair of fingers within an individual has a unique trend. This can be caused by anatomical differences between fingers, such as tissue thickness or body fluid distribution, which affect their electrical impedance values [22]. Biological tissues consist of cells with membranes that serve as non-conductive dielectrics, while intracellular (ICF) and extracellular (ECF) fluids act as electrolytes. Low-frequency currents pass through the extracellular fluid due to the cell membrane barrier, while high-frequency currents can penetrate the cell membrane. The impedance of complex biological tissues can be measured to determine their electrical properties, which helps to study the characteristics of cells and tissues [23]. This finding indicates that impedance can be used to distinguish pairs of fingers based on their electrical characteristics within a single individual [24] in line with research conducted by Yang et al (2014) [30].

In contrast, the results in Figure 5(b) show that even though the same pair of fingers are tested, the impedance values are different in each individual. This variation is most likely due to biological factors such as skin thickness, moisture content in the tissue, or physiological differences between individuals. These results suggest that electrical impedance can be used to distinguish individuals based on their body's electrical characteristics, which could potentially be applied in impedance-based identification systems. This is in line with the fact that cells and tissues from different individuals have different time constants and responses to different frequencies. Therefore, the resistivity and frequency characteristics of each individual can be a distinctive feature that distinguishes one individual from another [23].

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From both graphs, it can be concluded that finger impedance is affected by two main factors, namely the finger pairs tested (intra-individual) and biological differences between individuals (inter-individual). The implication of this study is that using more finger pairs in the analysis can improve the classification accuracy of individuals based on their electrical impedance. These results also open up opportunities for further applications in biomechanics, individual identification, and muscle and nerve health analysis. [25].

Through the three discussions that have been discussed, this research has shown potential in overcoming the limitations in the application of bioimpedance as a biometric method such as increasing the security of biometric systems that are quite vulnerable to counterfeiting, where this system is of interest used among the public. However, the limitations of this research still need to be considered. One of them is the limited number of samples which still amounts to 10 subjects, the more the number of samples studied increases the accuracy of the impedance measurement results. In addition, the use of electrodes that can provide measurement inaccuracies due to movement or friction on the finger is one that needs to be considered, including system security vulnerabilities. Given these limitations, future research needs to increase the number and diversity of subjects, application of electrodes, and validation with commercial devices to develop autonomous systems.

5. CONCLUSION

Based on this research, it can be concluded that Bioimpedance Spectroscopy (BIS) using the ratiometric method has the potential for identification and enhancing the security and reproducibility against falsification of biometric technology. By applying this approach, the variation of bioimpedance obtained from the subject's fingers can accurately reflect individual characteristics, even during long-term use, still resulting in stable bioimpedance. The use of the Analog Discovery 2 device provides sufficient flexibility and accuracy in measuring bioelectrical impedance over a range of frequencies. The research findings show that at high frequencies (above 100 kHz), the impedance curve tends to be more stable, and the difference between measurement days or sessions becomes smaller, indicating improved data reproducibility, which is crucial for biometric authentication. Compared to traditional biometric methods such as fingerprinting, this approach offers a higher level of security due to the difficulty of faking the subject's anatomical and bioelectrical characteristics. Moreover, BIS for fingerprinting does not involve the acquisition of any visual features, making it easy to integrate without requiring significant changes. Overall, this research has the potential to become a future biometric authentication solution with better reproducibility and higher security, especially when combined with other biometric technologies.

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APPENDIX

This research dataset can be accessed at the following link :

https://drive.google.com/drive/folders/17rdqs4KQ8MmxlU8d3KKjOgZuRU4pGVys?usp=drive_link

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