Sensors and Materials, Vol. 36, No. 3 (2024) 1231–1241
MYU Tokyo

S & M 3594

Bioelectromagnetic-response-based Input Interface for Mobile Devices —Finger Identification Using Bioimpedance Characteristics—

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(Received December 31, 2023; accepted March 21, 2024)

Keywords: mobile device, input interface, finger identification, bioelectromagnetic response, bioimpedance

In this study, we realize a next-generation extended input interface that can identify the fingers used for operating mobile devices through bioelectromagnetic response sensing. First, the impedance characteristics of the five fingers were elucidated through an experiment involving different subjects. Furthermore, we discussed the possibilities of finger identification and subsequently focused on the differentiation between the thumb and the index finger. Next, we evaluated the differences between the bioimpedance characteristics of each finger for several subjects and clarified that the bioimpedance scale relation between fingers is the same for a particular subject. Moreover, the bioimpedance of a single subject was measured by letting the subject change the manner by which they hold a case or touch an electrode, and the results demonstrated that the bioimpedance characteristics of the thumb and index finger can be clearly distinguished even in discontinuous measurements. Finally, we implemented an identification algorithm in which the bioimpedance of the index finger from previous measurements was taken as the reference and performed evaluations to verify if a highly accurate differentiation of the thumb and index finger is possible. The results demonstrated that the proposed interface can be used in practical applications. Additionally, these findings highlight the potential of various applications utilizing bioelectromagnetic response sensing.

1. Introduction

Mobile devices such as smartphones and tablets continue to become smaller, and even wearable devices including smartwatches have appeared in the market, highlighting the ongoing improvements in the portability of information and communication devices. Moreover, the operability of touch panels became more limited owing to the increasing miniaturization of these devices, causing a trade-off between portability and operability. A touch panel is an interface that uses changes in capacitance caused by fingers touching its screen to obtain information that is limited to the coordinates of the area being touched. An approach where

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https://doi.org/10.18494/SAM4864

ISSN 0914-4935

distinguishing fingers that operate a device and assigning different functions (text selection, copy, paste, starting specific applications, etc.) to each finger is gaining attention for solving operability problems and improving the input function of mobile devices.[1,2] For instance, an interface in which microfiber optics are used to project images and identify fingerprints simultaneously and extend operation according to each fingerprint[3] or finger identification based on the capacitance image of the finger in contact with the touch panel[4,5] has been proposed. Previously reported methods for identifying fingers using attached sensors include the attachment of an IR proximity sensor to the finger pulp to detect the distance between the finger and the touch panel,[6] the incorporation of a ring that contains a built-in magnet and a magnetic sensor to the touch panel,[7] and the attachment of a vibration sensor to each finger to detect vibrations when the finger touches the touch panel.[8] In the case of the human body communication technology,[9–11] a system where finger identification is performed using a high-frequency signal transmitter worn on a wrist, which measures, for example, signal attenuation, propagation delay, and phase difference, is being examined.[12] Furthermore, for personal computer operation, the identification of fingers operating a keyboard based on images captured by cameras is being conducted.[13] In addition to finger identification, a technology for identifying which among the four sections of a finger—the fingertip, finger pulp, nail, and finger joint—touched the panel has been proposed. Here, this identification is realized by analyzing the sound produced when fingers contact the touch panel, which is recorded by a microphone.[14]

Thus, over the years, many technologies have been researched and developed to improve the information input function of mobile devices. However, these approaches either involve operating large installed devices[3,12] or require wearing additional devices.[6–8] Furthermore, in existing systems that can achieve finger identification using only mobile devices, there are issues such as low identification accuracy due to the necessity for user training[4] and operational delays stemming from complex identification algorithms.[5] Therefore, these approaches must be improved so that they can be incorporated to mobile devices and also to ensure high identification rates with simple algorithms. Hence, we propose the following three conditions for devising new extended input interfaces: (1) an intuitive interface that does not require users to make special preparations or undergo training for its operation, (2) an appropriate interface scale that allows interface installation in small mobile devices (sensing techniques, measurement parameters, and frequency band), and (3) an interface that does not require any additional devices other than the operating mobile device. As a technology that can satisfy these three conditions, we are aiming to realize a next-generation extended input interface that identifies the fingers used for operating a touch panel through the finger's bioelectromagnetic response, thereby markedly improving the information input function. In this study, we propose and evaluate the feasibility of an interface in which a high-frequency current of a few MHz is applied to a user operating a mobile device, and the user's bioimpedance is measured to identify the fingers used for operating the device based on their characteristics through an experiment involving subjects.

This paper is organized as follows. The detailed principle of the proposed interface is outlined in Sect. 2. In Sect. 3, the measurement system and conditions used in the experiment involving subjects are explained. In Sect. 4, the bioimpedance characteristics of the five fingers of a subject are measured, the differences in characteristics between the fingers are estimated, and the finger types to be identified are determined. Moreover, the effects of the individual characteristics of a user, such as their body type or hydration situation, on the bioimpedance characteristics are described in this section. Additionally, an identification algorithm is proposed on the basis of the obtained results, and its identification accuracy is evaluated. Finally, in Sect. 5, we present the conclusion.

2. Principle of Proposed Finger Identification

As shown in Fig. 1, in the proposed finger identification system, electrodes are placed on one side of a mobile device and at the back of its operating unit (capacitive touch panel) to apply a high-frequency current of approximately a few MHz to the human body. The system then identifies the finger operating the device on the basis of the scale relation and frequency characteristics of the obtained bioimpedance. A user holding a mobile device in their left hand will touch the side electrode with the ball of their thumb (i.e., the soft part at the base of the thumb) and the operation surface electrode (front electrode) using the fingers on their right hand simultaneously. Moreover, the current flows in the following order: side electrode → left thumb ball → left arm → trunk → right arm → right fingers → front electrode. When the impedance of this circuit is expressed as left thumb ball: Z_{tb}, left arm: Z_{la}, trunk: Z_{body}, right arm: Z_{ra}, and right fingers: Z_{fin}, the bioimpedance Z is the sum of all these impedances, as shown in Fig. 2. Here, regardless of the right finger used for touching the front electrode, the bioimpedance Z_{fix} does not change because the current circuit from the side electrode to the right hand remains unchanged. Thus, as only the changes in the bioimpedance of each right finger Z_{fin} appear as changes in Z, one can infer that finger identification is possible.

3. Experimental Setup

The bioimpedance characteristics of each finger were elucidated using the measurement system shown in Fig. 3 to identify fingers operating a mobile device. A 10 × 10 mm^2 electrode

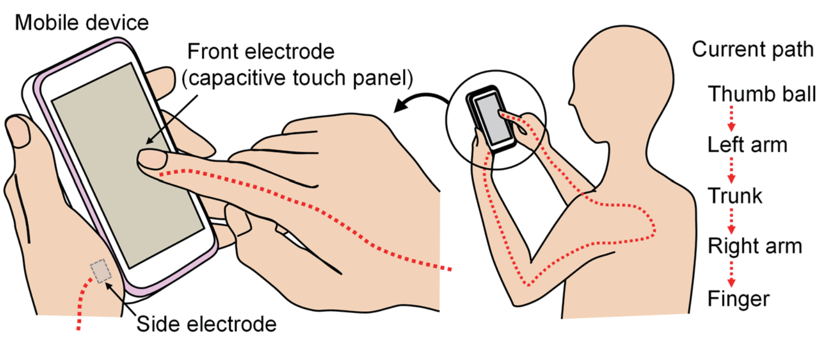

Fig. 1. (Color online) Finger identification system for mobile devices based on bioelectromagnetic response.

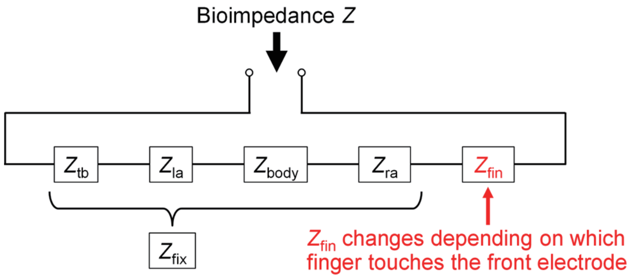

Fig. 2. (Color online) Measurement circuit for estimating bioimpedance.

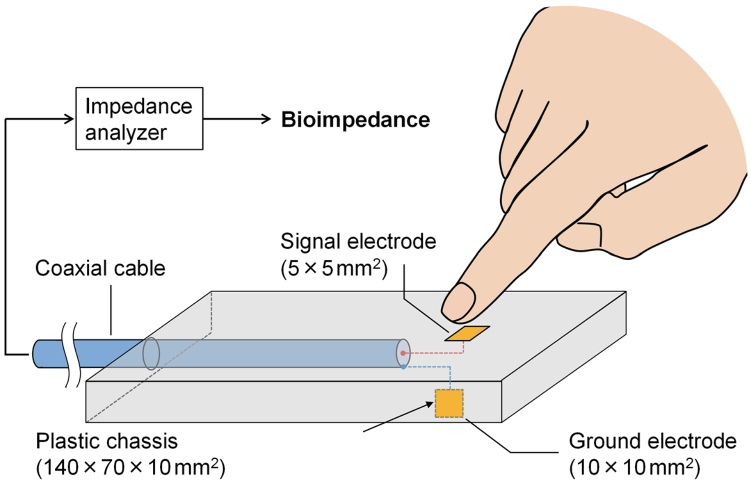

Fig. 3. (Color online) Bioimpedance measurement system.

(side electrode) was placed on the side of a 140 × 70 × 10 mm^3 plastic chassis, which corresponds to the dimensions of a common smartphone, and a 5 × 5 mm^2 electrode (front electrode) was placed at the front of the chassis. Moreover, we ensured that the front electrode had a sufficiently small surface area in relation to finger pulps to guarantee that the contact surface between a finger and an electrode remains constant. Each electrode was connected to the internal and external conductors of a coaxial cable, which was in turn connected to an impedance analyzer (Keysight 4294A). Thus, this bioimpedance measurement system can measure the bioimpedance $Z = Z_{fix} + Z_{fin}$ of a subject when they insert their finger between the side and front electrodes.

The subjects participating in the experiment were five males in their twenties (#1–#5). They held the case and touched the side electrode with their left hand and used each finger of their right hand to touch the front electrode. Subsequently, their bioimpedance Z was measured at 4–10 MHz. Considering the possibility that the contact condition between the electrode and the skin could change in a very short time because the contact condition depends on how the chassis was held or the type of grip exerted by the fingers on the electrode, we used the average bioimpedance from 16 consecutive measurements for evaluation. The participation of human subjects was approved by the Research Ethics Committee of The University of Tokyo, and written informed consent was obtained from each participant prior to starting the experiment.

4. Experiment Results and Discussion

In this section, the bioimpedance characteristics of five fingers obtained from the experiment using the bioimpedance measurement system were evaluated and a quantitative estimation was performed to verify whether finger identification is possible. Moreover, considering the possibility that the bioimpedance characteristics of each user obtained using this system could be different, the impedance characteristics of several subjects are compared. In addition, fluctuations in the bioimpedance characteristics caused by a user changing the manner by which they hold a mobile device are ascertained. Lastly, the finger identification accuracy of the proposed algorithm is evaluated.

4.1 Bioimpedance characteristics of each finger

Figure 4 shows the frequency characteristics of the bioimpedance $|Z|$ obtained when a subject touches the front electrode with each of the five right fingers. The thumb exhibited a smaller $|Z|$ than the other fingers over the entire measured frequency bandwidth. Additionally, the $|Z|$ values exhibited by the four fingers other than the thumb decreased in the following order: index finger > middle and ring fingers > little finger. However, at frequencies higher than 7 MHz, the characteristics of the index and middle fingers were almost identical. This is attributed to the fact that except for the thumb, which is thicker and shorter than the other fingers, the others do not exhibit a clear difference between their thickness and length. For instance, at 4 MHz, the $|Z|$

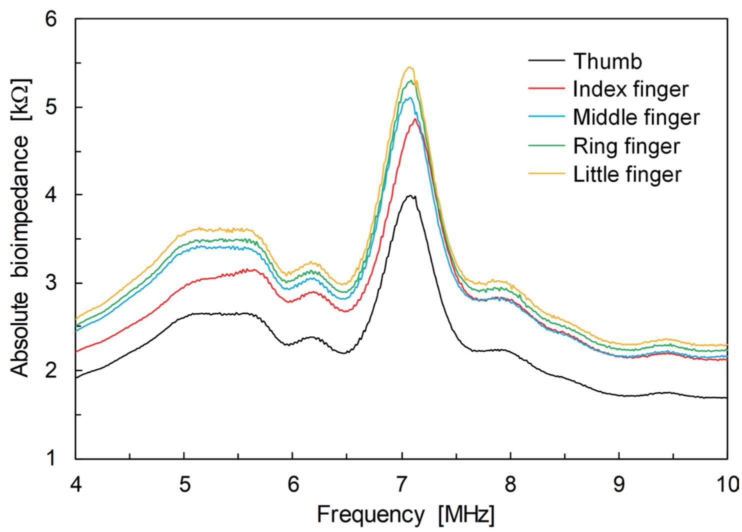

Fig. 4. (Color online) Bioimpedance characteristics of each finger as a function of frequency.

of the thumb was determined to be 270 and 570 Ω smaller than those of the index and little fingers, respectively. Thus, when reproducible differences of few hundred Ω occur, one can infer that finger identification is possible using values from only a single frequency. Moreover, the maximum $|Z|$ value for every finger was observed at approximately 7.1 MHz.

In addition, the frequency at which $|Z|$ reached its maximum was slightly different for each finger. The largest among these differences was approximately 50 kHz. These differences in maximum frequencies were considered due to the differences in the thickness and length of each finger, as was the case with $|Z|$. Thus, in addition to simple differences in $|Z|$, the utilization of the frequency characteristics of impedance will be useful in the future for improving the finger identification accuracy.

To examine the bioimpedance characteristics of each finger in detail, the rate of change in $|Z|$ for each finger at each measurement frequency was observed, as shown in Fig. 5, and the average $|Z|$ for all fingers was used as the reference. The dotted line indicates the average, while each solid line denotes the rate of change for each finger. Furthermore, while the $|Z|$ of the thumb showed a sufficiently high rate of change at every bandwidth with a difference of about −18% from the average, other fingers displayed rates of change between −6 and +12%.

Moreover, the results showed that the scale relation between the rates of change in $|Z|$ for the index and middle fingers reversed at around 7–9 MHz. This result indicates that distinguishing the thumb from the other four fingers is sufficiently possible with a bioimpedance measurement circuit, and the accuracy is sufficient to install it in a small mobile device.[15,16] Therefore, in this study, we inferred that the highly accurate differentiation of the thumb and other fingers would be the first step toward realizing the proposed method, and the focus of the following examination will be on the differentiation between the thumb and the index finger.

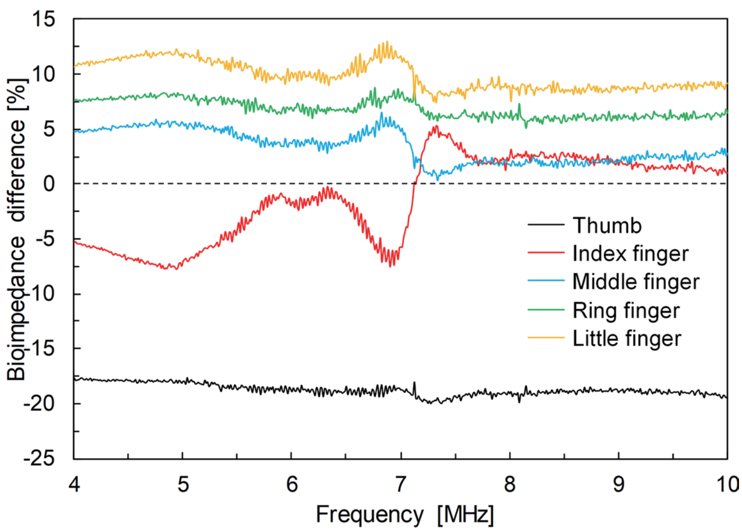

Fig. 5. (Color online) Bioimpedance differences in all fingers as a function of frequency, with their average as the reference.

4.2 Bioimpedance fluctuation due to individual differences

Depending on the body type or hydration state of users, each user displays different bioimpedance characteristics, even when the measurement circuit is the same.[17] In this section, the bioimpedances of five subjects obtained using the circuit that goes through the thumb and index finger are compared.

Figure 6 shows the frequency characteristics of the absolute bioimpedance $|Z|$ measured for each of the five subjects (#1–#5). This figure demonstrates that the bioimpedance characteristics of the thumb and index finger of the same subject can be clearly distinguished. On the other hand, when the $|Z|$ characteristics of the subjects were compared, the results showed that, depending on the measured frequency band, the scale relation of the $|Z|$ of the thumb and index finger was reversed.

As shown in Fig. 5, distinguishing between the $|Z|$ of the thumb and that of the index finger is easy. However, if the scale relations of $|Z|$ including the four fingers other than the thumb are evaluated for several subjects, further complication is expected. Therefore, the bioimpedance characteristics of each subject (user) must be measured and calibrated for developing an identification index in advance to perform highly accurate finger identification.

4.3 Bioimpedance fluctuation in repeated measurements

While using the proposed system, it is necessary to consider the possibility that the contact condition between the electrode and the skin may change within a very short time in accordance with how the mobile device is held or how strongly fingers are touching the device. Therefore, in this study, an average of 16 consecutive measurements of bioimpedance characteristics are used for the evaluation, as mentioned in Sect. 3.

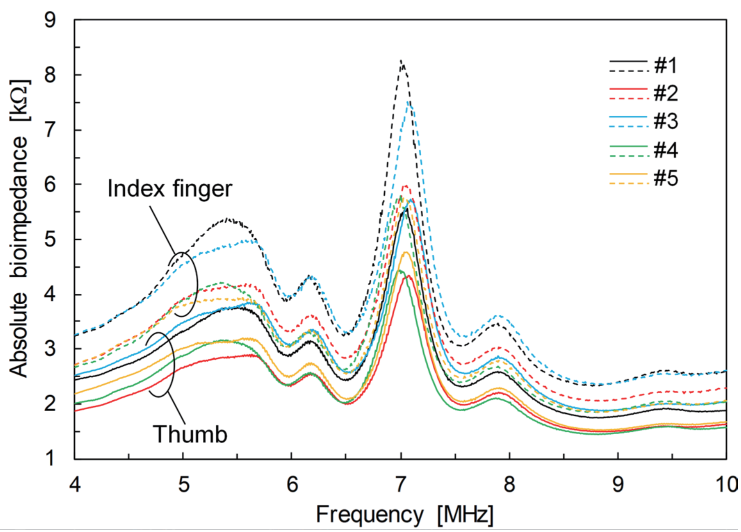

Fig. 6. (Color online) Bioimpedance characteristics of the thumb and index finger of each subject as a function of frequency.

Moreover, an examination of the situation where a user operates a mobile device discontinuously is discussed in this section. Specifically, the effects of changes in contact position or contact strength to the side electrode generated when the user puts away the mobile device and then holds it again and the effects of changes in skin surface condition that occur over time on the bioimpedance characteristics are evaluated through discontinuous measurement. This examination was conducted using a single subject selected from the five subjects, and ten measurements were conducted. There was a 10 min interval between measurements. The subject placed the mobile device on a laboratory table, thereby letting it go from his hand after each measurement, and held it again in his hand after the interval.

Figure 7 shows the frequency characteristics of the bioimpedance $|Z|$ of the thumb and index finger obtained via discontinuous measurement. For each finger, the minimum of the frequency characteristics is indicated by a solid line and the maximum is indicated by a dotted line. Figure 7 reveals that the $|Z|$ characteristics of the thumb and index finger were clearly differentiated even in the discontinuous measurement, where the state of how the case was held changed over time. This result implies that the highly accurate differentiation of the thumb and index finger is possible, even when the manner by which the mobile device is held changes over time.

4.4 Evaluation of identification algorithm

On the basis of the findings described in Sects. 4.1–4.3, an algorithm that distinguishes between the thumb and the index finger was implemented, and its accuracy was evaluated to examine whether it is possible to perform finger identification based on bioimpedance. In this study, a comparison of the reference bioimpedance $|Z_{\mathrm{Ref}}|$, which is an identification index prepared from prior measurements, and the bioimpedance $|Z|$, which was measured using the fingers to be identified, was employed as a finger identification algorithm that can be easily

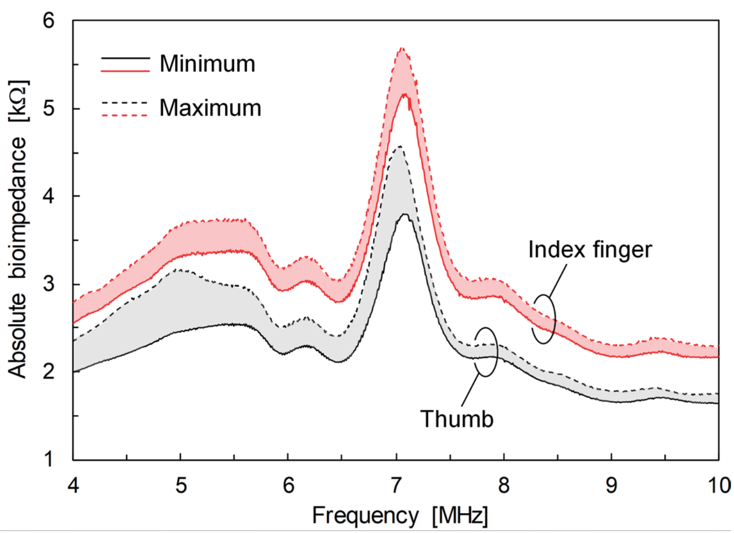

Fig. 7. (Color online) Bioimpedance characteristics measured in discontinuous measurement as a function of frequency.

installed with a small calculation load. As shown in Eqs. (1) and (2), $|Z_{Ref}|$ and $|Z|$ are the averages of the bioimpedances measured at every bandwidth (4–10 MHz).

$$|Z_{Ref}| = \frac{1}{n}\sum_{k=1}^{n}\frac{|Z_T(f_k)| + |Z_I(f_k)|}{2} \tag{1}$$

$$|Z| = \frac{1}{n}\sum_{k=1}^{n}|Z(f_k)| \tag{2}$$

Here, n indicates the number of measurement points in a frequency domain, f_k indicates the frequency of each measurement point, and $|Z_T(f_k)|$ and $|Z_I(f_k)|$ are the bioimpedances obtained when the thumb or index finger touched the front electrode, respectively. $|Z_{Ref}|$ indicates the average bioimpedance of the thumb and index finger obtained through prior measurements over the entire measurement bandwidth. Moreover, $|Z(f_k)|$ indicates the bioimpedance measured from the finger to be identified, and $|Z|$ indicates the average over the entire measurement bandwidth. By comparing the scale relations of $|Z_{Ref}|$ and $|Z|$, the finger to be measured, whether the thumb or index finger, can be identified, as shown in Eq. (3).

$$\text{Test finger} = \begin{cases} \text{Thumb,} & \text{if } |Z| \leq |Z_{Ref}| \\ \text{Index finger.} & \text{otherwise} \end{cases} \tag{3}$$

According to Eq. (3), when the difference between $|Z_{Ref}|$ and $|Z|$ was 0% or less, it was identified as the thumb, and when the difference was larger than 0%, it was identified as the index finger. Each instance of thumb identification was plotted with a circle and that of the index finger was plotted with a triangle.

In this study, the reference $|Z_{Ref}|$ was not calculated for each identification. Instead, the value calculated from the measurement data obtained from the same subject shown in Fig. 7 was used repeatedly for each identification. Moreover, the measurements used for calculating $|Z_{Ref}|$ and $|Z|$ were conducted on different days. The number of measurement points in a frequency domain was set to $n = 501$ for this identification.

Figure 8 shows the result of finger identification using the bioimpedances obtained from 10 separate measurements. The vertical axis indicates the difference between $|Z_{Ref}|$ and $|Z|$. As shown in Fig. 8, the thumb and index finger were differentiated without any errors in all 10 measurements. This result demonstrates that even an identification algorithm that uses a simple average bioimpedance can realize highly accurate finger identification if the necessary condition to differentiate between the thumb and the index finger of the same user is provided. However, while the index finger showed a difference of approximately 20% between $|Z_{Ref}|$ and $|Z|$ in every measurement, enabling identification with sufficient allowance, the difference exhibited by the thumb was only between 1 and 10%. Thus, preparing an optimized index for each user will be an effective method for achieving a higher finger identification accuracy; for instance, weighting

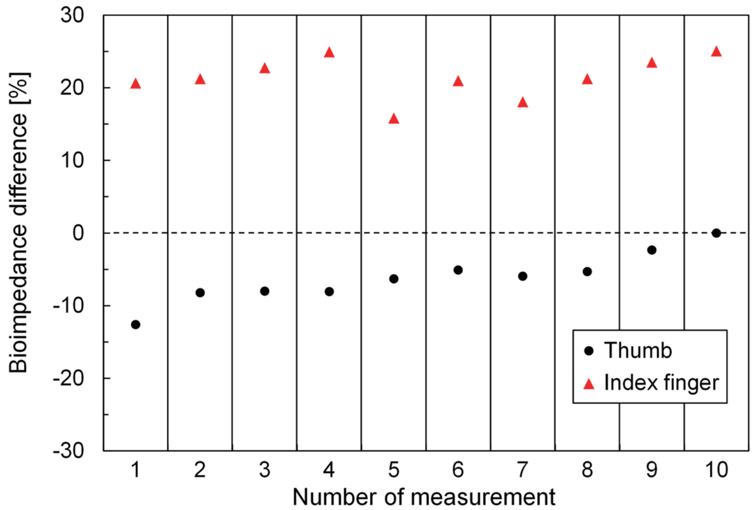

Fig. 8. (Color online) Differentiation result of the thumb and index finger.

the bioimpedance of each finger when calculating $|Z_{\mathrm{Ref}}|$ using Eq. (1) will improve the accuracy of the identification. Furthermore, while the bioimpedance characteristics from all measured bandwidths, namely, 4–10 MHz, were used in this study, if the bandwidth where the differences between the fingers are conspicuous could be identified, finger identification accuracy could be improved further by selecting the appropriate evaluation bandwidth.

5. Conclusion

In this study, a finger identification system was proposed to identify the fingers operating a device based on the finger's bioimpedance characteristics to realize an extended input interface that would improve the information input function of mobile devices. First, the impedance characteristics of five fingers were elucidated through an experiment involving a subject. This was followed by a discussion on the possibilities of finger identification; then, we focused on methods to differentiate between the thumb and the index finger. Moreover, we evaluated the differences between the bioimpedance characteristics of each finger of the subjects and clarified that while there are differences among the bioimpedances of different subjects, the scale relation of the bioimpedance for a particular finger remains the same if it is from the same subject. Furthermore, we measured the bioimpedance of the same subject when they changed the manner by which they held the case or touched the electrodes. The results demonstrated that the bioimpedance characteristics of the thumb and index finger could be clearly differentiated even in discontinuous measurements. Finally, an identification algorithm was implemented and evaluated, where the index is the reference bioimpedance prepared from previous measurements. The results demonstrated that the highly accurate differentiation of the thumb and index finger is possible. We are planning to study methods of improving the finger identification accuracy by selecting an appropriate evaluation frequency band and implement an algorithm capable of identifying all five fingers by working with a larger number of subjects. Furthermore, we aim to introduce various sensor applications beyond finger identification, which utilize bioelectromagnetic response sensing.

Acknowledgments

Part of this research was funded by the Tateisi Science and Technology Foundation and NAKAJIMA Foundation.

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