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Skin Impedance Estimation System for Voltage-mode Electrical Stimulator with an AC Bridge Circuit

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***Abstract*— Neuromuscular electrical stimulation is used to improve the motor function of paralyzed limbs and prevent muscle atrophy in stroke patients. The system for electrical stimulation is broadly classified into current-mode stimulators and voltage-mode stimulators. The current-mode stimulator adjusts the amplitude of the current, whereas the amplitude of the voltage is adjusted for voltage-mode stimulators. Voltage-mode stimulators have the advantage that there is little risk of burns even if the electrode is partially detached. To perform arbitrary current-mode stimulation with voltage-mode stimulators, it is necessary to generate a stimulating voltage based on the skin impedance. As a primary experiment, the frequency characteristics of the electrode-skin impedance were measured using an impedance analyzer on 6 subjects, and the frequency band in which the skin impedance is equivalent to a parallel connection between resistance and capacitance was determined. A prototype bridge circuit with a skin impedance equivalent circuit implemented was designed, assembled, and tested to estimate the skin impedances of 3 subjects. The residuals were computed from the estimated skin-impedance resistance and capacitance of the bridge circuit, and the impedance-analyzer-measured resistance and capacitance. The residuals between the estimated and measured were up to 4.4 % in the resistance component, and up to 8.2 % in the capacitance component of the skin impedance measurements by the impedance analyzer.**

I. Introduction

Neuromuscular electrical stimulation is utilized to improve motor function and prevent muscle atrophy in paralyzed limbs of stroke patients [1, 2]. Electrical stimulation systems are broadly categorized as current-mode stimulators and voltage-mode stimulators. The current-mode stimulators regulate the amplitude of the current, whereas voltage-mode stimulators regulate the amplitude of the voltage [3]. Both stimulators have advantages and disadvantages, yet their characteristics are described by following the formula of resistance, Equation (1), and Ohm's law, Equation (2), where R is the resistance, ρ is the resistivity, L is the length of the conductor, S is the cross-sectional area of the conductor, V is the voltage, and I is the current.

$$R = \rho L / S, \tag{1}$$

$$V = RI. \tag{2}$$

When an electrode is applied to the skin, the cross-sectional area S is the electrode-skin contact area [4]. If the electrode becomes partially detached and the electrode-skin contact area decreases the resistance increases. As the skin-electrode resistance increases, V or I changes to satisfy the equation in (2). In current-mode stimulators, as the load resistance increases, the voltage and current density increase, and a large current flow in a narrow area. In contrast, with voltage-mode stimulators, the current decreases as the load resistance increases.

Hence, current-mode stimulators can provide stable current stimulation regardless of skin impedance. The disadvantage of current-mode stimulators is when the electrode is partially detached from the skin, a large current flow over a narrow area, which poses the potential risk of shock and burn. Voltage-mode stimulators have the advantage of lower risk even if the electrodes are partially detached. A disadvantage of voltage-mode stimulators is that the stimulation effect depends on unstable skin impedance. The skin impedance has a wide confidence interval, and the cause of the variation cannot be determined [5]. On stimulating muscles, which are highly deformed during joint movement, such as the biceps brachii, the voltage mode stimulator should be applied to reduce the risk of electrical stimulation. To perform arbitrary current stimulation with a voltage-mode stimulator, it is necessary to valuate a stimulating voltage based on skin impedance.

This research aims to develop a voltage-mode electrical stimulator that measures skin impedance during electrical stimulation with an AC bridge, generates a stimulation voltage based on measured skin impedance, and delivers current stimulation of arbitrary intensity. As a first report, this paper discusses three items. First, the measurement of skin impedance over the biceps brachii muscle and identification of an equivalent skin impedance circuit model. Second, system development to measure skin impedance with an AC bridge circuit with paralleling resistance and capacitance skin impedance circuit model. Third, validation of the developed skin impedance measurement system, and discussion of its characteristics and properties.

II. Methods

Skin impedance is approximated by a model in which a series resistance is connected to a parallel resistance and capacitance [6]. In this experiment, the frequency response of the electrode-skin impedance was measured with an

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impedance analyzer to determine the frequency band where the skin impedance is considered equivalent to a parallel connection of resistance and capacitance. A bridge circuit containing the skin impedance equivalent circuit was designed, and the skin impedance was estimated by the bridge circuit.

A. Skin Impedance Measurement with an Impedance Analyzer

The experiment was performed on 6 male subjects (Table 1). This experiment was conducted with the approval of the Human Bioethics Committee of Tokyo Denki University (#03-055). Depilatory cream was applied to the subject's upper arm skin for a few minutes and then wiped off, to ensure even electrode-skin contact before measurement. Subjects were seated in a chair with the elbow joint flexed at 90° and the forearm resting on the armrest. Disposable conductive gel electrodes (F-150S, NIHON KOHDEN) were used. One electrode was placed on the belly of the right biceps brachii muscle. Another electrode was placed approximately 5 cm distal to the first electrode, aligned with the muscle fiber (Figure 1). The electrode distance was determined referring the research by Yamamoto [7].

The skin impedance between the two electrodes was measured with an impedance analyzer (IM3570, HIOKI). The parameters of analysis were the parallel connected capacitance and resistance, and the frequency response was measured from 10 Hz to 1 MHz. The voltage between the open terminals was set at 1 V. At each frequency, the impedance was set based on the averaged waveforms of the output waveforms for 10 cycles measured by the impedance analyzer. Each decade was analyzed for 100 points, for a total of 501 analysis points. After the electrodes were attached to the skin, measurements were taken every 5 minutes up to 40 minutes to evaluate the contact state between the electrode and the skin in terms of time variation.

From the frequency characteristics of the skin impedance under a stable electrode-skin contact state, the frequency band where the skin impedance could only be considered as a parallel connection between resistance and capacitance was determined.

TABLE I. THE SUBJECTS ATTRIBUTES FOR METHOD A (MEAN ± SD).

Age	Height (cm)	Weight (kg)
23 ± 1.2	165.6 ± 6.7	61.5 ± 15.8

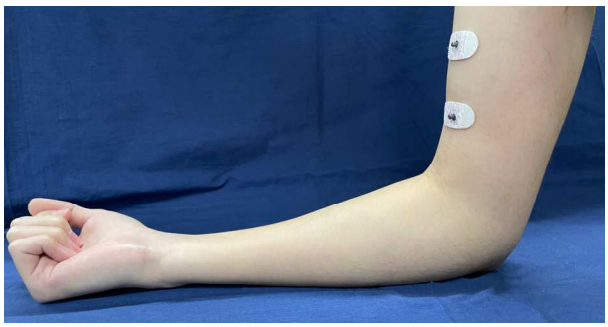

Figure 1. Example of electrode attachment position.

B. Skin Impedance Estimation with an AC Bridge Circuit

The bridge circuit was designed to estimate the skin impedance in the frequency range determined by the skin impedance measurement with an impedance analyzer (Figure 2). In the bridge circuit shown in Figure 2, the combined impedance of the parallel section consisting of R_c and C_c is

$$R_c / (1 + j\omega C_c R_c). \quad (3)$$

The combined impedance of the parallel circuit portion consisting of R_x and C_x is

$$R_x / (1 + j\omega C_x R_x). \quad (4)$$

Therefore, the bridge circuit equilibrium is

$$R_a R_c + j\omega C_x R_x R_a R_c = R_b R_x + j\omega C_c R_c R_b R_x. \quad (5)$$

R_x and C_x are obtained by comparing the real and imaginary parts of the two sides of Equation (5)

$$R_x = R_a R_c / R_b, \quad (6)$$

$$C_x = C_c R_b / R_a. \quad (7)$$

When R_b and R_c are varied and the equilibrium conditions in Equations (6) and (7) are satisfied, the output of the equilibrium detector decays. The skin impedance is estimated from the values of R_b and R_c when the output of the balanced detector is most attenuated. In the experiment, the capacitance C_x was estimated by first adjusting R_b and R_c while keeping them at the same value and satisfying the equilibrium condition in Equation (7). Next, the resistance R_x was estimated by adjusting only R_c while satisfying the equilibrium condition in Equation (6).

In both Equations (6) and (7), the frequency is not relevant to the equilibrium condition, and the input frequency is therefore arbitrary if the frequency band works so that the skin impedance is just a parallel connection of resistance and capacitance. Since the skin impedance is a frequency-dependent characteristic, the estimated value varies with the input frequency. Therefore, in this experiment, skin impedance was estimated at a fixed frequency.

In this experiment, a skin impedance estimation system was composed using an oscillator, a bridge circuit, a skin impedance measurement electrode, a balanced detector, and an oscilloscope. A function generator (SG-4222, IWATSU) was used as the oscillator, and a sine wave was adjusted from 2 V_{p-p} to 20 V_{p-p} amplitude and applied to the bridge circuit. The frequency of the sine wave was set at 120 Hz, which is not a harmonic of 50 Hz, to avoid the influence of noise from the commercial power supply.

The voltage output from the balanced detector of the bridge circuit was monitored with an oscilloscope (SDS1104, OWON), and the variable resistor in the bridge circuit was changed to maximize the attenuation of the amplitude of the output waveform. The variable resistors in the bridge circuit are 500 Ω to 64 kΩ metal film resistors connected in parallel to the eight-channels slide switch, which is manually adjustable from 0 Ω to 127.5 kΩ in 128 steps.

An instrumentation amplifier (LT1167, Analog Devices) was used as the balanced detector in the bridge circuit, with the gain set to approximately 20 dB.

The resistance value was recorded when the output waveform of the balanced detector was most attenuated. The recorded resistance values were substituted into the equation for the balance condition to estimate the skin impedance. Skin impedance estimation with a bridge circuit was performed on 3 male subjects. The subject's information is given in Table 2. Electrodes were placed on the subjects under the same conditions as for skin impedance measurement with an impedance analyzer.

Thirty minutes after the electrodes were applied, the skin impedance between the two electrodes was estimated with a bridge circuit skin impedance estimation system. To assess the accuracy of the estimates, the skin impedance was measured by an impedance analyzer before and after the skin impedance was estimated by the bridge circuit.

TABLE II. THE SUBJECTS ATTRIBUTES FOR METHOD B (MEAN ± SD).

Age	Height (cm)	Weight (kg)
22.3 ± 0.8	166.7 ± 6.7	63.0 ± 19.1

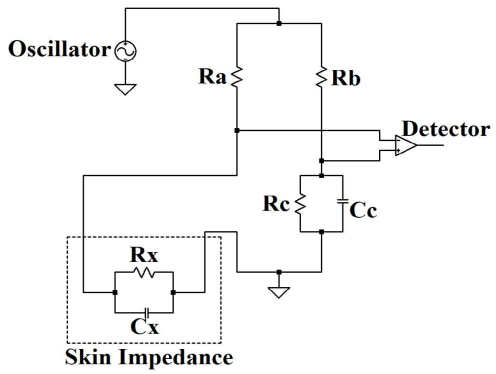

Figure 2. The bridge circuit for skin impedance.

III. RESULTS

A. Skin Impedance Measurements with an Impedance Analyzer

The time course of skin impedance at 120 Hz for the 6 subjects is shown in Figure 3. The sample means and standard deviations of skin impedance at 120 Hz for 4 of the 6 subjects, excluding Subjects C and E, are shown in Table 3. The skin impedances of Subjects C and E are more than three times the standard deviation shifted from the sample mean of the 4 subjects, and therefore, are considered outliers. Figure 4 shows the frequency response of the skin impedance of the 4 subjects, excluding Subject C and E, 30 minutes after the attachment of the electrodes.

The difference method is used to identify the inflection points in the skin impedance frequency response. Figure 5 shows the difference between the normal logarithm of the frequency response of the skin impedance, and the normal logarithm of impedance at approximately 1.0233 times of each frequency. From Figure 5, the inflection point of the frequency response of the skin impedance of subjects A, D, and F is estimated to be approximately 1 kHz. The inflection point of the frequency response of the skin impedance of Subject B is estimated to be approximately 300 Hz. From the frequency characteristics of the skin impedance, We assumed that the impedance between the skin electrodes is dominated by the parallel connection element of resistance and capacitance, in the frequency band inferior to the inflection point. Yet, for the frequency band superior to the inflection point, the impedance between the skin electrodes is dominated by the series connection element of resistance and capacitance.

Consequently, the equivalent circuit model of skin impedance at frequencies inferior to the inflection point, which we target, is approximated by a parallel circuit of resistance and capacitance. Based on the experimental results, in the frequency range of 10 Hz to 300 Hz, the identified skin impedance equivalent circuit acceptedly matched the parallel circuit model.

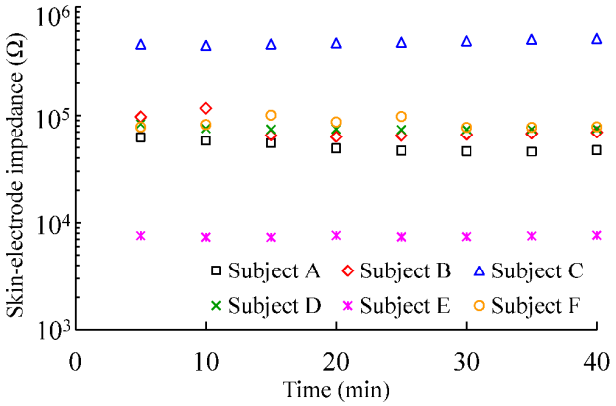

Figure 3. The time variation of skin impedance.

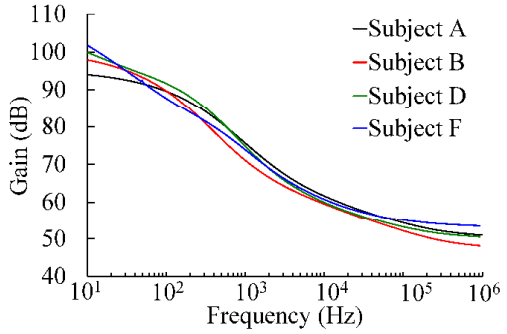

Figure 4. The frequency response of the skin impedance.

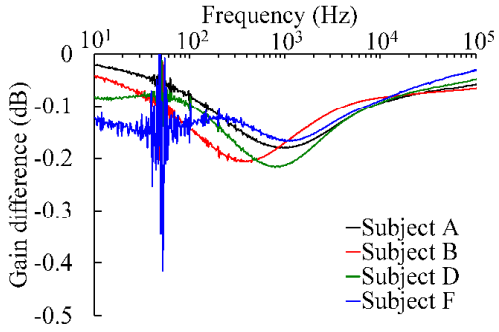

Figure 5. The inflection points of the frequency response.

TABLE III. THE SAMPLE MEANS AND STANDARD DEVIATION OF SKIN IMPEDANCE AT 120 HZ FOR FOUR SUBJECTS.

	Elapsed times (min)			
	10	*20*	*30*	*40*
Sample mean (kΩ)	83.275	68.533	66.067	67.640
Standard deviation (kΩ)	21.476	14.154	12.221	12.336

B. *Skin Impedance Estimation with an AC Bridge Circuit*

Table 4 shows the estimated skin impedance values (R_{BC}, C_{BC}) at 120 Hz for the three subjects and the measured skin impedance values (R_{IA}, C_{IA}) with the impedance analyzer after the bridge circuit skin impedance estimation. The residuals of the resistance R_{BC} and capacitance C_{BC} with the bridge circuit, along with the measured resistance R_{IA} and capacitance C_{IA} with the impedance analyzer were determined. The percentages of residuals between the estimated and measured were 4.4 %, 1.3 %, and 3.9 % for the resistance component and 0.7 %, 8.2 %, and 5.5 % for the capacitance component in subjects A, B, and C.

Figure 6 shows the time variation of the synthetic resistance of the skin impedance measured by the impedance analyzer pre- and post-estimation of the skin impedance by the bridge circuit. In Figure 6, the horizontal axis is the time elapsed from the impedance analyzer skin impedance measurement before skin impedance estimation. Between the pre- and post-measurements of the three subjects, the resistance component changed up to 3.53 kΩ and the capacitance component up to 4.43 nF.

TABLE IV. ESTIMATED AND MEASURED SKIN IMPEDANCE

Subject	Resistance (kΩ)		Capacitance (μF)	
	R_{IA}	R_{BC}	C_{IA}	C_{BC}
A	48.1	50.2	0.0803	0.0797
B	32.0	32.4	0.0657	0.0711
C	28.3	29.4	0.0985	0.1039

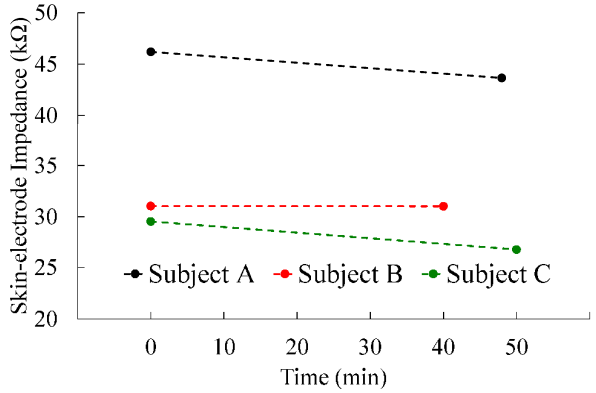

Figure 6. The time variation of skin impedance.

IV. DISCUSSION AND CONCLUSION

The residuals between the estimated and measured values were 5 % or less for the resistance component and 9 % or less for the capacitance component. In the bridge-circuit skin impedance estimation, the variable resistance is adjusted by incrementing 500 Ω with a slide switch. From this mean, the variable resistance is discrete and a residual of up to 250 Ω is to occur from the resolution of the prototype system. If the resistance R_a is 64 kΩ, the maximum residual capacitance C_R due to the discrete values of the variable resistances R_b and R_c is given by substituting the values in Equation (7) as follows:

$$C_R = (0.1 \times 10^{-6}) \times (0.25 \times 10^{3}) / (64 \times 10^{3}) \quad (8)$$
$$= 0.390625 \text{ (nF)}.$$

This is smaller than the residuals generated in the experiment. Therefore, we believe that the residuals due to the discrete values of the variable resistance are not the main cause of the residuals generated in this experiment.

The pre- and post- impedance-analyzer-measured values of skin impedance varied up to 3.53 kΩ for the resistance component and up to 4.43 nF for the capacitance component. This experiment took over 40 minutes due to manually switching and adjusting the variable resistance of the prototype system to detect the point at which the amplitude of the output waveform was most attenuated. This effect should be resolved by speeding up the switching of variable resistors and reducing the time spent on impedance estimation, in other words, by automating the switching and introducing automatic adjustment methods.

In conclusion, the bridge circuit skin impedance measurement system proposed in this paper is capable of detecting the equilibrium of a bridge circuit containing an equivalent circuit model of skin impedance in the low-frequency band to estimate the approximate skin impedance. The accuracy problem should be resolved to meet the tolerance in future work by reducing the delay with the implementation of automated adjustments.

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