

## *Principle of Biodynamic Analysis Using Human Limb Electrical Impedance*

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This paper describes a new measurement method and principle of detection of biodynamics using bioelectrical impedance method based on four-electrode technique with sinusoidal constant current. This method uses a human body itself as a part of the sensor. First, we show a bioelectrical impedance measuring device and the change of bioelectrical resistance is measured in human movement. Second, we propose a principle of detection of biodynamics based on correspondence of magnitude, form and stability of movement to impedance waveform. Hence we can use this method for the judgement of sports skill using the impedance characteristics.

### 1. INTRODUCTION

We are proposing a new measurement method and principle of detection of biodynamics in sports training and related fields using human limb impedance. This idea originates from the following reasons: first, there is the experimental fact that human movement causes impedance changes. Second, the impedance method satisfies measurement conditions and is applicable to daily use. The measurement conditions which are needed as follows:

- The measurement must be as non-restrictive as possible and easily done.
- The information of movement must be gotten instantly from the results of measurement.
- The measurement system must be at a low cost.

In conventional methods for measurement of biodynamics, some kinds of equipment have been employed which are the goniometer, the electromyography, the camera and the video camera. Each piece of equipment has unique advantages, but there are some problems with relation to each piece of equipment. Some examples are as follows [1], [2]: (a) The goniometer is not suitable for complex or fast movement, it is not durable and it restricts the movement of the subject, because it has a structure of mechanical parts. (b) It is difficult for the results of the electromyography to answer to kinematic- and kinetic- parameters. (c) The data from a camera can not be quickly processed, because it is necessary to develop film.

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(d) In analysing video information, a video analyser which is high in cost and not simple, is needed. The measurement space of the video camera is limited.

This method uses a human body itself as a part of the sensor, and the change of bioelectrical resistance is measured in human movement. This paper describes the measurement method of human limb electrical impedance and principle of biodynamic analysis.

## 2. HUMAN LIMB IMPEDANCE MEASURING METHOD

### 2.1 Electrode Technique

General electrode techniques are two-electrode technique, three-electrode technique and four-electrode technique. In this study human limb impedance is measured considering human body to ion conductive material. In case of this, the effect of polarization impedance is the problem. Hence four-electrode technique, which is not influenced by the effect of polarization, is selected in case of measurement of human limb electrical impedance. The human limb impedance of the part between two potential electrodes is measured. The electrodes are non-polarization Ag-AgCl skin surface type of 10 mm diameter.

Two-electrode technique and three-electrode technique are suitable for measurement of skin impedance. In case of the measurement of human limb impedance, it is difficult to apply those techniques on the grounds that stratum corneum impedance, which is the greater part of skin impedance, is more than a thousand times as large as the resistivity of muscle or blood.

### 2.2 Impedance Measuring Device

Figure 1 shows a block diagram of the measurement device of human limb impedance. The measurement method of impedance uses the four-electrode technique based on constant current (50 kHz, 500  $\mu$ A) [3]. The measurement device consists of a generator, a voltage to current converter, a differential amplifier, a multiplier(M1, M2), a low pass filter and an amplifier. The four electrodes technique is the method where four electrodes are put on in a line, constant current flows through the outside two electrodes (current electrodes:  $I^+$ ,  $I^-$ ) and the potential difference, which arises between the inside electrodes (potential electrodes:  $P^+$ ,  $P^-$ ), is detected.

Sinusoidal voltage  $e$  which the generator outputs and constant current  $i$  which the voltage-to-current convertor outputs are expressed by the following equations:

$$e = e_0 \sin \omega t \quad (1)$$

$$i = i_0 \sin \omega t. \quad (2)$$

The current  $i$  flows through a measured part of human limb. The impedance  $Z$  of this measured part is defined as  $Z = R_s - jX_s = |Z| \exp(-j\theta)$ . The potential voltage  $e_d$  between electrodes  $P^+$  and  $P^-$  is amplified by the differential amp (amplification degree :  $\mu$ ).  $e_d'$  which the amp outputs is expressed as

$$e_d' = \mu Z i = \mu |Z| i_0 \sin(\omega t - \theta). \quad (3)$$

where  $\omega = 2\pi f$  (angular frequency),  $f$  : frequency,  $t$  : time. The voltage  $e_d'$  and  $e$  are rectified synchronously by the multiplier(M1). The output voltage  $e_1$  of multiplier is expressed by

$$e_1 = e e_d' = \mu' |Z| \{ \cos \theta - \cos(2\omega t - \theta) \} \quad (4)$$

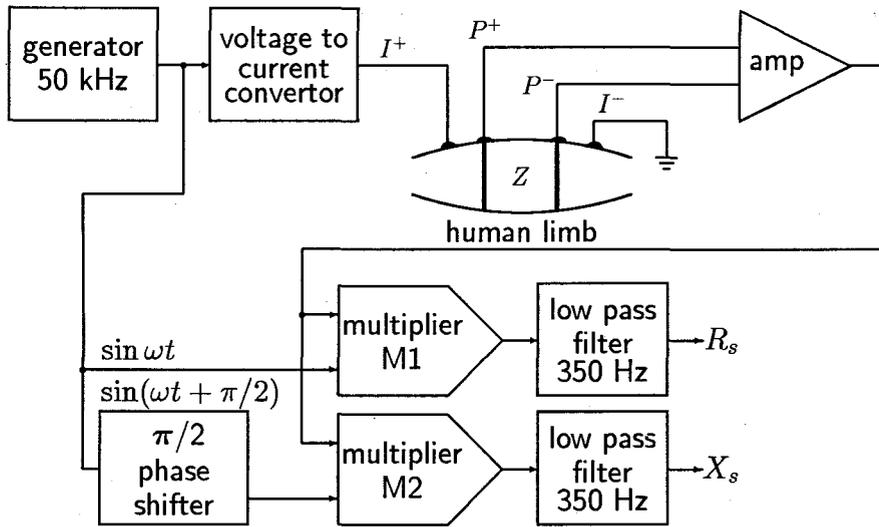


Figure 1 Block diagram of impedance measuring device.

where  $\mu' = -\mu e_0 i_0 / 2$ .  $e_1$  of high frequency component is eliminated by low pass filter (cut off frequency : 350 Hz). One of the final output of this device  $e_R$  is expressed by

$$e_R = \mu' |Z| \cos \theta = \mu' R_s. \quad (5)$$

Thus we can measure  $R_s$ . As well as the process of measurement of  $R_s$ , we can also measured  $X_s$  using  $e_0 \sin(\omega t + \pi/2)$  which replace  $e$  in equation (4).  $R_s$  and  $X_s$  are inputted to micro computer system throughout A/D convertor.  $|Z|$  and  $\theta$  are calculated using  $R_s$  and  $X_s$ .

### 3. CHARACTERISTICS OF HUMAN LIMB ELECTRICAL IMPEDANCE

The parameters of lower leg impedance — $R_s$ ,  $X_s$ ,  $|Z|$  and  $\theta$ — were measured. The subjects were 10 males aged 19–21 years old. The measured part was the center of venter of triceps surae, whose length was 10 cm. The results are shown in Table 1. The values of  $X_s$  is smaller than those of  $R_s$ . The values of  $R_s$  are nearly equal to those of  $Z_s$ .

We made a trial about multiple regression analysis using  $R_s$  as dependent variable and  $H$ ,  $W$  and  $C$  as three independent variables. The result is shown in equation (6).

$$R_s = -0.411H + 0.381W - 2.003C + 146.35 \quad (6)$$

There were strong relationships: the multiple correlation coefficient was 0.931 and the partial correlation coefficient between  $R_s$  and  $C$  was  $-0.912$ .

It is clear that equivalent series resistance (magnitude of impedance) is mainly influenced the shape of the measured part. This is a point to be next chapter 4. In this result the height and the weight of the subjects is not influenced well the parameters of impedance. The main reason is that body shapes of the subjects are similar. In other expression, ratio of bone, muscle, fat, blood and skin of the measured part are similar. It is likely that the height and the weight is influenced the impedance more in many subjects who have many body shapes.

We measured lower leg impedance during squat exercise (100 times / 150 s). Rissajous figure between  $|Z|$  and  $R_s$  is shown in Figure 2. The change of impedance is mainly caused

**Table 1** Parameters of lower leg impedance among subjects.

subject	body shape			impedance parameters			
	H(cm)	W(kg)	C(cm)	$R_s(\Omega)$	$X_s(\Omega)$	$ Z (\Omega)$	$\theta(\text{deg})$
A	170	75	43.1	19.4	7.1	20.7	20.2
B	176	70	39.6	23.0	8.5	24.5	20.3
C	180	60	37.6	21.8	6.8	22.9	17.4
D	172	63	38.1	25.2	9.4	26.9	20.4
E	172	63	37.0	22.7	8.9	24.4	21.3
F	168	48	30.8	36.6	13.0	38.9	19.5
G	175	62	36.4	20.8	6.7	21.8	17.9
H	171	61	33.0	33.5	12.5	36.0	20.3
I	172	54	33.2	28.0	9.6	29.5	28.9
J	168	53	40.2	16.1	5.0	17.0	17.5

H : height, W : weight

C : circumference length of venter of triceps surae

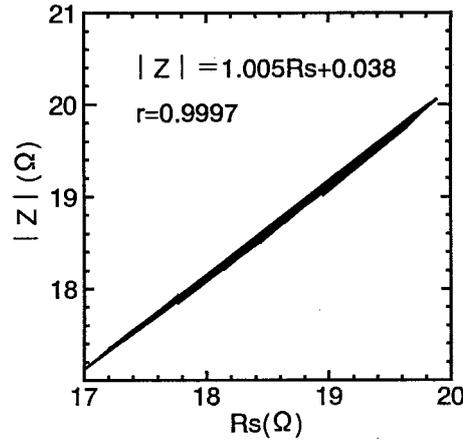
by the sectional area of muscle of the measured part [4]. There were no change of the strong relationship between  $Z$  and  $R_s$  during biodynamics. In this case there are also relationships between  $\theta$  and  $Z$ , and between  $X_s$  and  $Z$ . It may be safely be assumed that Cole-Cole arc changes with keeping similar figure due to degree of deviation from Debye type and central relaxation time with impedance changes [5]. Hence we can use one parameter of impedance  $R_s$  in analysis of human movement in short term with impedance methods. The reasons why we select a parameter  $R_s$  are follows:  $R_s$  changes larger than  $X_s$ . The impedance measuring device can be constructed simply. When a subject moves hardly or for long time, the fluid volume in human limb changes. It is possible that each parameter varies in complex relationship among other parameters.

#### 4. PRINCIPLE OF DETECTION OF BIODYNAMICS

Biodynamics is characterized by magnitude of movement, form of movement and stability of movement. A summary of the magnitude of movement and the form of movement is defined as the movement pattern.

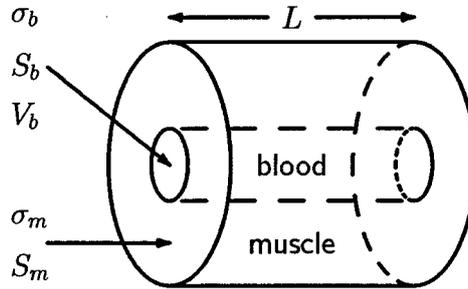
**Table 2** Correspondence of human movement to impedance waveform.

human movement	impedance waveform
magnitude	pattern
form	
stability	reproducibility



**Figure 2** Rissajous figure between  $|Z|$  and  $R_s$  during biodynamics.

It is very important to evaluate these exactly. We propose to analyse biodynamics using impedance characteristic, because human limb impedance varies with human movement. We try to evaluate the movement pattern using the pattern of impedance waveform (*i.e.* impedance pattern) and the stability of movement using the reproducibility of impedance waveform. The human limb has a complicated structure which consists of bone, muscle, fat, blood and skin. A constant current of frequency 50 kHz flows almost through the tissues of muscle and blood whose resistivity is lower than the others [3]. The human limb is approximated by the parallel conductor model which consists of tissues of muscle and blood (Figure 3). Equivalent series resistance  $R_s$  is expressed by the following equation [6]:



**Figure 3** Parallel conductor model of human limb.

$$R_s = \frac{L}{\sigma_m S_m + \sigma_b S_b} = \frac{L}{\sigma_m S_m + \sigma_b \frac{V_b}{L}} \quad (7)$$

where  $\sigma_m$  : conductivity of muscle,  $\sigma_b$  : conductivity of blood,  $S_m$  : cross-sectional area of muscular tissue,  $S_b$  : cross-sectional area of blood portion,  $L$  : length of measured part,  $V_b$  : volume of blood.

Considering the equation (7), the changes of conductivity of tissues in short time interval were very small and can be disregarded, and thus this is a constant value as well as the length of the measured part. Taking the position that the changes in  $S_m$  and  $V_b$  cause the

changes of impedance during some sorts of movement, we try to measure and analyse human movement through the changes of impedance. The changes of  $S_m$  mean the changes in a sectional area of muscular tissue, and the changes of  $V_b$  mean the changes of blood volume in the measured part. Though  $S_m \gg S_b$ ,  $V_b$  concerns the change of impedance because of  $\sigma_m \ll \sigma_b$ .

This method has the following advantages: It can be used with the telemetry system and does not have a spatial limitation for measurement. The data can be compressed and measured continuously for long hours. The results can be displayed simply. Various analysis methods can be done, superimposed periodic movement is one of the examples. The subject who puts small electrodes on his body, is scarcely restricted in movement and is not given mental pressure.

## 5. CONCLUSIONS

This paper describes a new measurement method and principle of detection of biodynamics using bioelectrical impedance method based on four-electrodes technique with sinusoidal constant current. There is strong relationship between magnitude of impedance and shape of measured part including shape of body. There are relationships among variations of parameters of impedance. Hence we select one parameter which is equivalent series resistance as an index of biodynamic analysis. We have proposed to evaluate the movement pattern using the pattern of impedance waveform and the stability of movement using the reproducibility of impedance waveform. We expect to be able to find applications for various sports training and related fields.

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