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Development of Measuring Method for Softness of Epidermis Using Rotational Step Response

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Abstract - We have proposed a new measuring method for the softness of epidermis using rotational step response. It can be proceeded that horizontal torsional step is given periodically to the human skin surface by rotational step motor. Then dynamically epidermal characteristic is abstracted selectively from the human skin minimizing influence of the subcutaneous tissue. The cylindrical rotor is attached to the shaft of step motor and its external area is surrounded by the cylindrical guard ring; Therefore, only human skin surface of inside the guard ring is screwed periodically by its rotor. At this moment, viscoelasticity of the epidermis is evaluated from analyzing the inducting coil of the step motor. The waveform of voltage of inducing coil can be characterized by overshoot P1, damping ratio D and undamped natural frequency ω_n. The softness Ks that indicates viscoelasticity of the epidermis can be calculated from these parameters. Many experimental results showed that the softness Ks corresponds to the human sense and it is rational as a parameter for the human skin characteristics. This system is very useful as the measurement can be done easily, in vivo, and non-invasively. It also can be constructed simply without special mechanical sensor because step motor acts as not only driving but also sensing.

I. INTRODUCTION

The human skin act importantly to live the living body, and it can be classified into the epidermis, derma and subcutaneous tissue from structural difference, and moreover, it involves the noticeable properties owing to intricate and specific structure. But it has not yet been established the method to observe in vivo the viscoelasticity of skin. Because the skin condition varies irregularly and corresponds to change in environmental; it is difficult to evaluate the viscoelasticity of skin. So the object of this paper is to present a measuring method that can be evaluate dynamically the softness of epidermis applying rotational step response[1[.

There are two kinds of method to make an observation of skin characteristics. The one method that vertical torsion is given to the surface skin is greatly influenced by the subcutaneous tissue rather than skin surface, and in consequence will exhibit the synthetically dynamical characteristics of the internal parts of the living body. The other method that horizontal torsion is given to the surface skin can be evaluated mostly dynamical characteristics of surface skin minimizing influence of derma and subcutaneous tissue . The rotational step response will be using in this paper, and is a one of "torsional methods" that gives horizontal torsion to be human surface skin. In addition it is very effective method of measurement, and can appreciate to be abstracted selectively epidermal characteristics of human skin. The advantage of this method is that it is able to evaluate viscoelasticity of epidermal analyzing only response voltage of the step motor when the surface skin is twisted by the step motor's rotor. It also can be constructed simply without special mechanical sensor in order to make possible to measure directly. We believe that this method can be applied to the fields of cosmetics and skin science.

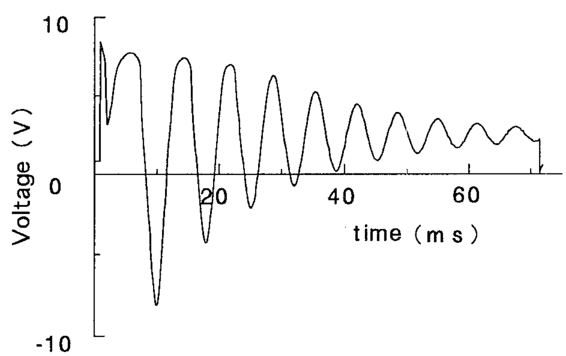

Fig.1. Measured wavefom.

II. MEASUREMENT PRINCIPAL

The measurement sensor with modified step motor has been attached the acrylic rotor and guard ring, the regular territory of the skin that can be twisted by its rotor has be defined previously. Hence, only the surface skin outside inner guard ring is twisted by the rotor, and the skin of guardring's outer territory isn't produced an influence upon measuring surface skin characteristic.

In measurement, the rotor revolves and twists human surface skin horizontally when the step voltage (9V, 7Hz) is applied to the step motor. The viscoelasticity of epidermal, that is, the dynamical motion, can be immediately estimated

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by measuring the voltage waveform of inducing coil then. The response voltage waveform obtained from the exciting winding of the step motor is shown in Fig.1. This waveform has been illustrated with a half period. This transient response waveform will be able to correspond to indicial response of second order lag element and we can identify this measured waveform with an indicial response. About this matter, the most distinctive parameters are abstracted from a transfer function of second order lag system (Their parameters are defined as fundamental parameters), and also utilize to analyze the viscoelasiticity of the epidermis. The process how to extract the fundamental parameters are explained as follows.

First, we would regard the transient waveform as indicial response waveform[2] and then we obtain transfer function G(s)

$$G(s) = \frac{K}{1 + 2\zeta\left(\frac{s}{\omega_n}\right) + \left(\frac{s}{\omega_n}\right)^2} \tag{1}$$

Where K is gain constant, ω_n is undamped natural frequency, f is damping ratio, s is complex parameter.

The indicial response of this transfer function G(s) is given by the following expression.

$$C(t) = L^{-1}\left[\frac{K}{s\left\{1 + 2\zeta\left(s/\omega_n\right) + \left(s/\omega_n\right)^2\right\}}\right] \tag{2}$$

Since the measurement waveform in Fig.1 shows periodic damping, we obtain

$$C(t) = K\left\{1 - \frac{\exp(-\zeta\omega_n t)}{\sqrt{1-\zeta^2}}\sin(\omega_0 t + \phi)\right\} \tag{3}$$

$$\omega_0 = \sqrt{1-\zeta^2}\,\omega_n \tag{4}$$

$$\phi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \tag{5}$$

This equation is illustrated as shown in Fig.2.When, we compared the parts of maximum value and minimum value of waveform obtained from this measurement system, it was cleared that the parts of minimum value have been hardly affected by electric noise. We can therefore calculate fundamental parameters to direct our attention to the parts of minimum value. In the following equation, t_n shows the time that C(t) takes minimum value in Fig.2.

$$t_n = \frac{2n\pi}{\omega} \tag{6}$$

And minimum value $C(t_n)$ is given by equation as follows:

$$C(t_n) = K\{1 - \exp(-\zeta\omega_n t_n)\} \tag{7}$$

Overshoot P_n on the time t_n is given as follows:

$$P_n = K\exp(-\zeta\omega_n t_n) \tag{8}$$

Damping ratio D_n can be defined by minimum amplitude ratio every period, as following equation.

$$D = \frac{P_{n+1}}{P_n} = \exp\left(\frac{-2\pi\zeta}{\sqrt{1-\zeta^2}}\right) \tag{9}$$

Therefore, damping factor ζ is given by

$$\zeta = \frac{\ln D}{\sqrt{4\pi^2 + (\ln D)^2}} \tag{10}$$

and the following equation is given from (6)

$$t_{n+1} - t_n = \frac{2\pi}{\omega} \tag{11}$$

Furthermore, by applying (4),(10) and (11), we obtain undamped natural frequency ω_n as follows:

$$\omega_n = \frac{2\pi}{\sqrt{1-\zeta^2}\,(t_{n+1} - t_n)} \tag{12}$$

As a result of this procedure, we could get three fundamental parameters: overshoot P_n, damping ratio D_n and undamped natural frequency ω_n.

These fundamental parameters are defined as efficient parameters that constitute a characteristic feature of measured waveform, and will be able to be index to evaluate viscoelasticity of epidermis.

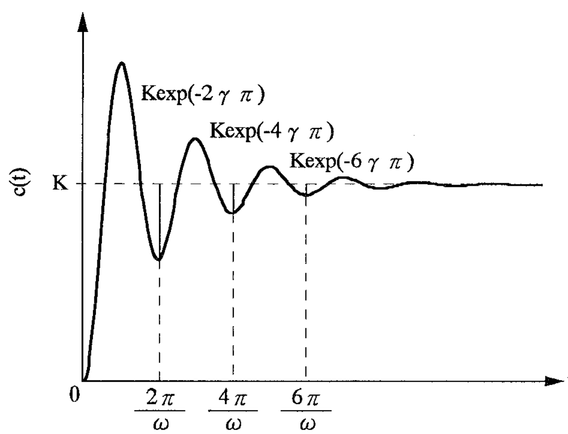

Fig.2. Indicial response.

III.MEASURMENT SYSTEM

A measurement system is shown in Fig.3 and Fig.4. A disk rotor step motor has been used as a measurement sensor in this system[3]. It is controlled by unipolar driving method that A phase and B phase are connected in series (where step degree is 6[deg], and holding torque is about 70[kg·cm]). The rotator shaft of the step motor has been attached an acrylic rotor which is diameter of 12 millimeter, and its body has been mounted an acrylic guard ring surrounding the rotor. At a measurement, only the surface skin of inner guard ring is horizontally twisted by the rotor, and then we can evaluate characteristics of surface skin by analyzing response waveform of step motor. On the occasion of practical measurement, we have paste up a both-sided adhesive tape on a contracting part of the rotor and guard ring, in order to fix the measurement sensor on skin surface. Therefore, the acrylic rotor can sufficiently twist the human skin surface without slip.

The measurement circuit in this system is explained as follows: In the part of DC voltage source, the voltage, supplied from regular voltage sources, is converted into DC voltage of 9[V]. Pulse signal (9[V],7[Hz]) can be created in the part of signal generation circuit , and these signals are inputted into the part of driving circuit. And then, exiting winding of A and B phases are excited mutually at a regular period correspond to input signal, and surface skin of inner guard ring can be horizontally twisted by the rotor.

We have also installed a level shift circuit into the circuit part, in order to improve analytic accuracy of measurement wave. This circuit combines differential-amplifier and inverter-amplifier. Using this circuit, the damped vibration on measurement waveform can be variably amplified between 5 to 8 times. Consequently, we could realize to improve resolution of voltage axis (amplification axis of waveform). Finally, measurement waveforms are converted from analog to digital signals with sampling frequency 10[kHz], and stored into a personal computer.

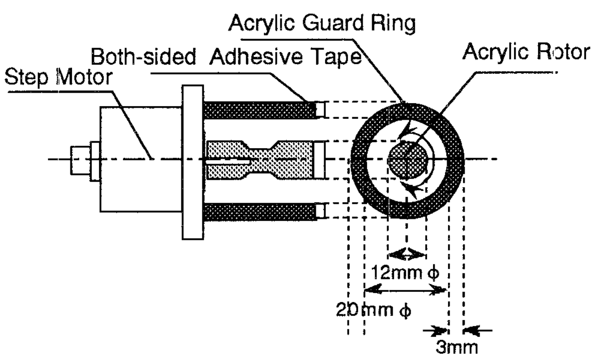

Fig.3. Measurement sensor.

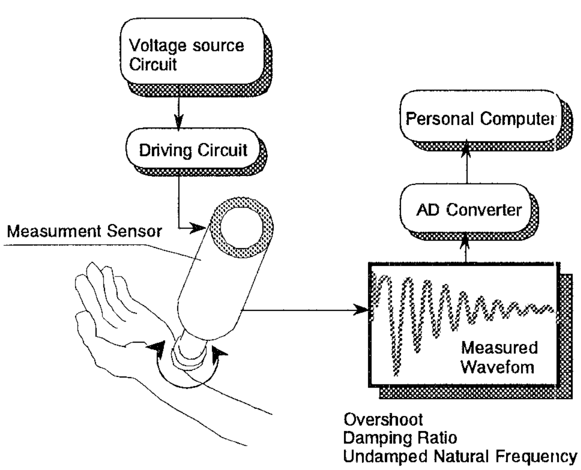

Fig.4. Measurement system.

IV. RELATIONSHIP BETWEEN THREE FUNDAMENTAL PARAMETERS AND VISCOELASTICITY OF EPIDERMAL

We extracted three fundamental parameters from twenty subjects, and have tried out whether there are possibilities to evaluate viscoelasticity of epidermis. On a human body four measurement regions, inner part of wrist, forearm, beside the hyoid of neck and down part of cheekbone (hereinafter referred to as wrist, forearm, neck, cheek) were measured each three times by this system. This measured result is shown in Fig.5. According to this result, we found that the overshoot and the damping ratio of a wrist are the smallest value in four measured regions. Conversely, the damped natural frequency of a wrist is the biggest value in four measured regions. To compare with three fundamental parameters of each measured regions, we concluded that there is the difference between several regions, and the differential between male and female beings can be notice.

We subsequently tried to touch our hands to measurement regions in order that we might verify how a softness of human sensation corresponds well with measured result. We consequently became apparent that the softest region with human sensation is a neck, and on the contrary the hardest region is a wrist. Almost every subject indicated similar this result, though there was an exception that softness of a forearm was softer than cheek. At the time, the overshoot and the damping ratio of a cheek region is smaller than forearm region, and conversely damped natural frequency of a cheek region is bigger than a forearm region. And TABLE I is shown by numerical values of three fundamental parameters. We can also suppose same result as TABLE I.

We could recognize the corresponding relation by this analyzed result, a overshoot and a damping ratio of measured regions giving soft touch feel with human sensation become big value, and then damped natural frequency become small value to the contrary. While hard measurement regions become in contrast with this value.

Eventually, we have concluded that we can evaluate viscoelasticity of epidermis by using those fundamental parameters correspond to softness of human sensation.

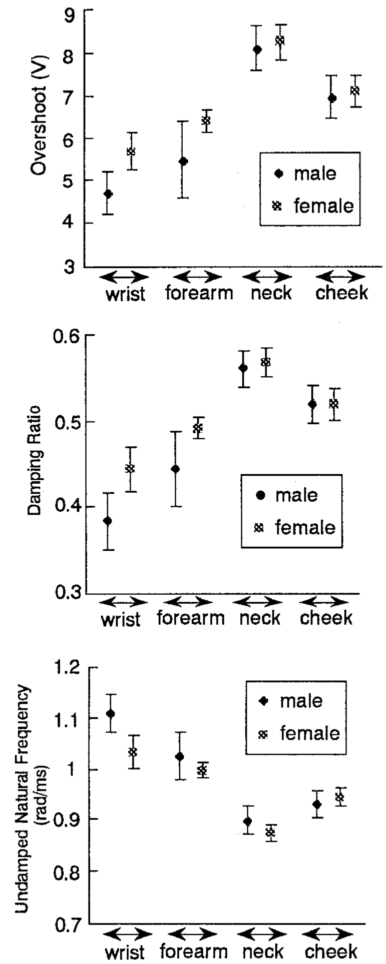

Fig.5. Measured result that three fundamental parameters

TABLE I
MEASURED RESULT THAT THREE FUNDAMENTAL PARAMETERS

OS	subject A	subject B	subject C	subject D	subject E
wrist	3.67	5.04	5.29	4.27	5.70
forearm	5.16	7.59	3.45	7.84	5.63
neck	7.19	6.96	9.17	8.91	8.86
cheek	6.29	5.99	6.65	8.15	7.52

DR	subject A	subject B	subject C	subject D	subject E
wrist	0.327	0.408	0.419	0.323	0.428
forearm	0.416	0.552	0.345	0.55	0.469
neck	0.514	0.52	0.594	0.594	0.586
cheek	0.498	0.47	0.514	0.57	0.554

DNF	subject A	subject B	subject C	subject D	subject E
wrist	1.182	1.052	1.046	1.201	1.073
forearm	1.103	0.907	1.080	0.914	0.982
neck	0.992	0.967	0.851	0.848	0.857
cheek	1.004	0.959	0.925	0.874	0.878

OS : OverShoot DR : Damping Ratio DNF : unDamped Natural Frequency

V. INDEX SHOWING VARIOUS EPIDERMAL CHARACTERRISTICS

In the foregoing chapter, we have shown the possibility evaluating the visocoelasticity of the epidermis by analyzing three fundamental parameters. But it was troublesome to judge the softness of epidermis using directly those three parameters, accordingly we would enhance the analyzing method which can evaluated by using only one parameter. The point of this chapter is to indicate one parameter, which has a correlation with three fundamental parameters and can represent epidermal characteristics. We are therefore using a method of principal component analysis (PCA). This method represents several variable quantities by one or some independent principal component, and it is also calculated simply by software program. The result that has been performed PCA is shown in Fig.6. To compare with a scattering of each principal component, first principal component is the most widely scattering in the component, and the contribution ratio of first principal component is 96.5% as shown in TABLE II. We can consider that the first principal component has contained approximate information of three fundamental parameters obtained by diverse measured waveforms. Consequently, an information composed with many parameters can be expressed easily by only first principal component. Next, we show a technique viscoelasticity of skin surface is represented by one parameter.

1. Because of the differences in unit of three fundamental parameters (overshoot, damping ratio and damped natural frequency), we would performed standardization using these parameters that are expressed by X_1, X_2 and X_3.
2. PCA has been using standardized parameters, and we could obtain a following equation.

$$Z_1 = 0.57636X_1 + 0.58433X_2 - 0.57129X_3 \quad (13)$$

$$Z_2 = 0.61401X_1 + 0.15167X_2 + 0.77459X_3 \quad (14)$$

$$Z_3 = -0.53926X_1 + 0.79722X_2 + 0.27136X_3 \quad (15)$$

Where Z_1 is first principal component, Z_2 is second principal component and Z_3 is third principal compo nent.

3. The contribution ratio of Z_1 is 96.5% as shown in TABLE II. We can consider that Z_1 almost contains the information of each fundamental parameter.
4. Finally, we have proposed a following equation in order to represent Z_1 by intelligible numerical value.

$$Ks = \frac{Z_1}{\sigma} \times 10 + 50 \quad (16)$$

σ is a standard deviation that is calculated by all subject's datum of Z_1. And by using this equation, many epidermal characteristics are represented by simple and intelligible numerical value that is a value between 0 and 100. We would define the softness Ks that calculated by (13) as showing diverse epidermal characteristics. Next, using measuring data in foregoing chapter, Ks was analyzed as shown in Fi.7.

The softness Ks of a wrist is the smallest value compare with other regions. The other hand, the softness Ks of a neck

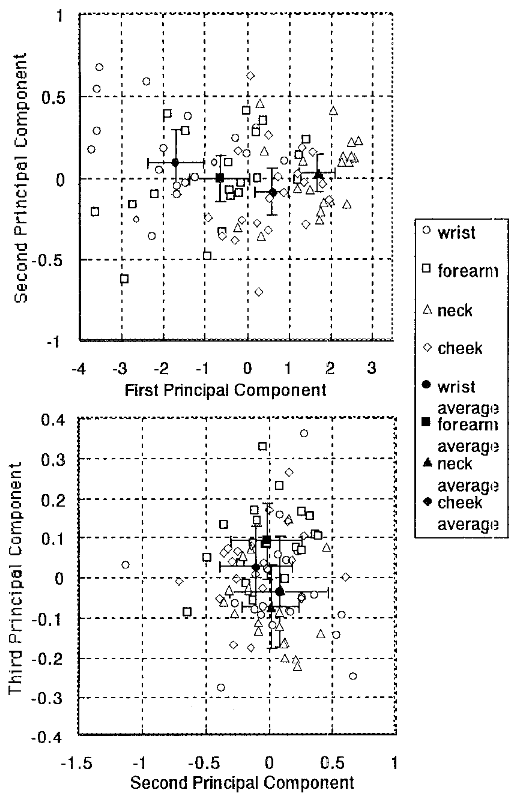

Fig.6. Result that performed principal component analysis.

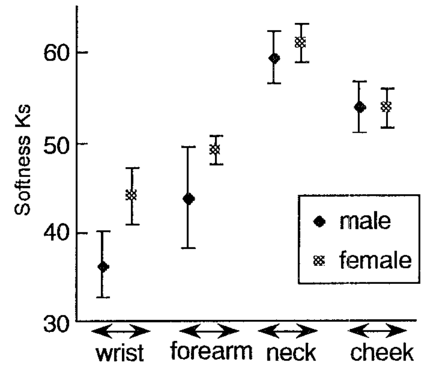

Fig.7. Meaured Softness Ks.

TABLE III
MEASURED FIGURE OF SOFTNESS KS

Softness Ks	subject A	subject B	subject C	subject D	subject E
wrist	29.03	40.26	41.51	29.49	41.82
forearm	39.04	57.39	33.02	57.59	46.76
neck	51.79	52.44	64.25	64.25	63.47
cheek	48.68	48.42	53.01	60.59	58.37

OS : OverShoot DR : Damping Ratio DNF : unDamped Natural Frequency

TABLE II
CONTRIBUTION RATIO OF PERFORMED PRINCIPAL COMPONENT ANALYSIS

	First Principal Component	Second Principal Component	Third Principal Component
Eigen Value	2.893	0.091	0.016
Contribution Ratio	0.965	0.030	0.005
Comulative Contribution Ratio	0.965	0.995	1.000

is the biggest value in those regions. (By human sensations, a wrist of both sexes is hardest region in four measurement regions. Conversely, a neck is the softest region.) We could accordingly consider the softness Ks that was identical to analyzed result by using three fundamental parameters. In addition, the parameter enables to measure a differential of male and female beings, and of individual. It may be given as a conclusion that the softness Ks is useful index that indicates various epidermal characteristics distinctly, and we can evaluate viscoelasticity of the skin surface by using only one index.

VI. MEASUREMENT OF HYDRATION PROCESS

In this chapter we show concrete example to measure the skin surface condition changes with time using softness Ks.

We have measured the situation of the skin hydration utilizing our measurement system. The hydration experiment is to investigate the state that epidermal skin absorbs water and become softer when dehydrated surface skin is given moisture. This experimental result is shown Fig.8. The softness Ks is abruptly increase by about two minutes; and then, it holds approximately constant value. This phenomenon is explained that dried epidermis first absorbs moisture suddenly, it thereafter becomes in saturation condition nothing to take in superfluous water. Therefore we believe that the softness Ks is an effective index to observe precisely the skin surface conditions change with time. On comparing each fundamental parameters and softness Ks by Fig.8, it may be seen that those parameters are different in range of fluctuation. Each fundamental parameter have a dispersion with time passage, but scattering of softness Ks is smaller than those parameters because the softness Ks was obtained from PCA using fundamental parameters. We can conclude that the softness Ks is an useful index for stable measurement that analysis based on three fundamental parameters.

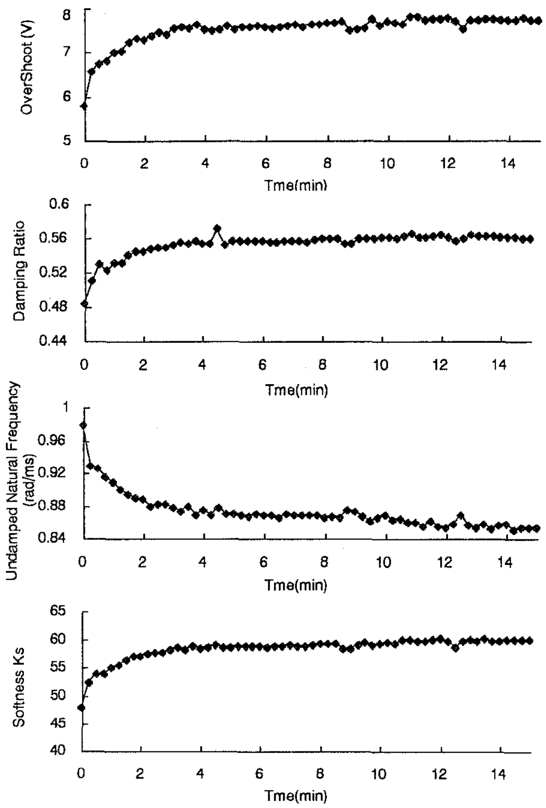

Fig.8. The hydration of skin.

VII.CONCLUSION

1. To measure by sensor applying step motor, we could performed to measure epidermal characteristics with complex system or special mechanical sensor.
2. The visocoelasticity of skin surface can be evaluated to abstract three fundamental parameters (overshoot, damping ratio, undamped natural frequency) from measured waveform. Utilizing first principal component that is calculated by principal component analysis, the softness Ks is also a simple and useful index to evaluate epidermal characteristics.
3. In this system we notice by hydration experimentation that the softness Ks can observe various epidermal conditions change with time, and are able to evaluate of skin surface state.

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