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Correction of Apparent Viscoelasticity of Skin Surface

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SYNOPSIS

The body structures under the skin surface, such as bones and tendon, have an influence on the stiffness evaluation observed from the surface. In this case, the observed stiffness should be called an apparent stiffness. To obtain the biomechanical properties of skin itself, the influence of body structure should be removed. This study deals with the correction method of apparent viscoelasticity which calculated from apparent biomechanical impedance. This method is applied to the measured result of the forearm and the right chest to confirm its effectiveness.

1. INTRODUCTION

The measurement of biomechanical properties is important for all the medical fields. Manual palpation is one of the most popular and easiest way of medical diagnostic method. When we make use of tactile feeling to measure the physical properties of living tissues, it is inevitable that the results lack objectivity and it is hard to quantify them. Any reliable index of stiffness of the living tissues has not been proposed yet, though the various medical informations have been quantified following with the development of industrial technology. So an objective index of physical properties has been expected.

The biomechanical properties *in vitro* have been studied for a long time(1,2). As the biomechanical properties of tissues change with time in a measurement *in vitro*, it is difficult to obtain the properties of themselves. Therefore, to know the biomechanical properties themselves, it is essential to measure them *in vivo*. Some studies *in vivo* also have been reported(3,4). In any these measurements *in vivo*, a static preload, an impulse force, or a dynamic force (sinusoidal or random vibration) is applied to the skin surface, and we could know the biomechanical properties through the biomechanical response from the body.

When we measure the physical properties of the living tissues, it may occur that the properties measured from regions where there are bones underneath are different from those measured from regions where there are not any bones underneath. The same situation is observed in the manual palpation. At the body regions which contain bones underneath we feel harder than at the regions which contain none. In these cases, the obtained properties may contain the

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influence of bones under the skin surface, and are not those of the skin tissues / muscles themselves(5). It would be an obstacle when we need the biomechanical properties only nearby the skin surface. The authors have used the term "dependence of biomechanical properties on the body structure" to refer to these properties. In discussing the biomechanical properties of skin tissues / muscle, the influence of dependence of these properties on the body structure should be considered and removed as completely as possible. In this paper, the authors measure the apparent viscoelasticity by using the measurement system, which applies random vibration 30-1000Hz to the skin surface vertically, and propose the correction method for them dependent on the body structure. The correction method is also applied to the measured results on the living body actually.

2. BIOMECHANICAL IMPEDANCE

2.1 Measurement of biomechanical impedance

A diagram of the measurement system of the biomechanical impedance is shown in Fig.1(6). The pen-typed measuring probe is composed of a vibrator, a load cell, an impedance head and a vibrating tip. A small random vibration (30 - 1000 Hz) is applied to the skin surface vertically through the vibrating tip. A force f(t) and acceleration a(t) at the driving point are detected by the impedance head. The biomechanical impedance spectrum is calculated from force and acceleration data by using FFT (Fast Fourier Transform). When we introduce A(jω) and F(jω) defined as the Fourier transform of a(t) and f(t), the biomechanical impedance Z(jω) is defined as

$$Z(j\omega) = j\omega\frac{F(j\omega)}{A(j\omega)} = Z_r(\omega) + jZ_i(\omega) \qquad (1)$$

where ω is an angular frequency. The biomechanical impedance spectra is roughly classified into three patterns (soft, intermediate and hard). The Soft pattern, which $Zr(\omega)$ increases as the frequency increases is usually observed at most of soft regions of the body. The intermediate pattern, which $Zr(\omega)$ decreases at low frequency and increases at high frequency as the frequency increases, and the hard pattern, which $Zr(\omega)$ decreases as the frequency increases, is observed at

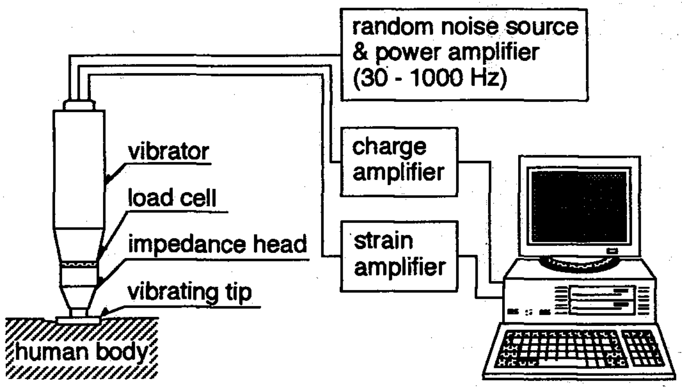


Fig.1 Block diagram of biomechanical impedance measurement system.

hard regions under which there are bones. The resonance frequency and the magnitude of impedance gradually become higher and larger in the order of the soft, intermediate, and the hard pattern. In the manual palpation, the measured regions also feel harder in the same order.

2.2 Biomechanical impedance spectrum

It is referred in the above chapter that the biomechanical impedance spectra have three spectra patterns. The spectra have other patterns different from the three patterns in details. The differences in these spectra are caused not only by the differences of biomechanical impedance of skin tissues / muscles themselves but also by the other factors. For example, under the different measuring conditions (*e.g.* at a different contact preload), the impedance spectra are different even if they are measured at the same region. The multiple layered structure, such as bones and skin, would cause the differences between the spectra measured at the regions where there are bones underneath and these measured at the near regions where there are not any bones underneath. These factors are connected complicatedly, and then the impedance spectra are formed. It seems that any of these factors change an appearance of propagation of vibrating wave. Therefore, the differences among impedance spectra can be considered to be the differences in the propagation of vibration.

2.3 Apparent stiffness

It is known experimentally that most of the living body tissues have the soft pattern of impedance spectrum. But at the regions under which there are bones, the spectrum is different from that of skin tissues itself.

The ultrasonic tomogram (7.5 MHz) at the forearm is shown in Fig. 2. This is a region where the distance between the skin surface and the bone becomes gradually longer from point I to III. The biomechanical impedance spectra, which are measured at three points with a tip diameter of 10 mm and a contact preload of 50 gf, are shown in Fig. 3. The three spectra show the soft patterns and the resistances becoming larger from point III to I. The magnitudes of impedance become

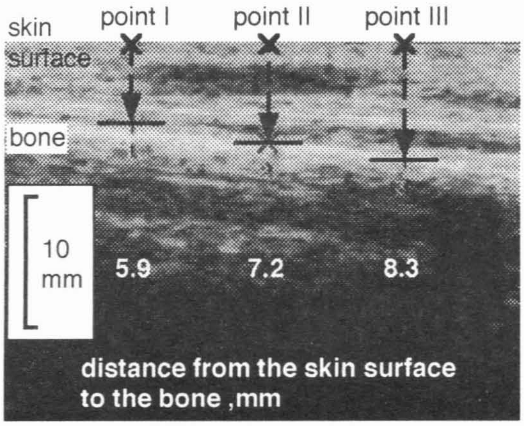


Fig. 2 Ultrasonic tomograph (7.5 MHz) of the forearm .

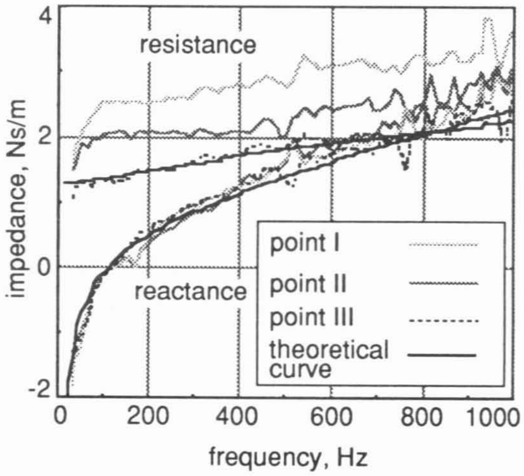


Fig. 3 Biomechanical impedance spectra measured at point I - III and the fitted curve by Eqn. 2.

larger from point III to I, and it may be said that the stiffness increases with the decrease of the distance between the skin surface and the bone. These characteristics are also experienced in manual palpation. It follows that the feeling of stiffness in the palpation includes not only the viscoelasticity of skin / muscle itself but also the influence of body structure. We will, hence, use the term "apparent stiffness" to refer to the examined stiffness dependent on the body structure.

3. VISCOELASTICITY DEPENDENT ON THE BODY STRUCTURE

The mechanical impedance of an infinite, homogeneous, viscoelastic, compressible medium for a vibrating sphere has been theoretically proposed$^{(7)}$. In the case of an incompressible medium such as human tissues the mechanical impedance Z_s at low frequency is defined as follows:

$$Z_s = \frac{1}{2} \times$$

$$\left\{ 6\pi a^2 \sqrt{\frac{\rho\left(\sqrt{\mu_1^2+\omega^2\mu_2^2}+\mu_1\right)}{2}} + 6\pi a\mu_2 + j\omega\left(\frac{2\pi a^3\rho}{3}\right) + j6\pi a^2 \sqrt{\frac{\rho\left(\sqrt{\mu_1^2+\omega^2\mu_2^2}-\mu_1\right)}{2}} + \frac{6\pi a\mu_1}{j\omega} \right\} \qquad (2)$$

where a [m] : radius of a vibrating sphere, ρ [kg/m^3] : medium density, μ_1 [N/m^2] : coefficient of shear elasticity, and μ_2 [Ns/m^2] : coefficient of shear viscosity. These parameters are calculated by using the curve-fitting method with the least square approximation for Eqn. 2. As ρ is considered to be homogeneous, it is set to a constant (1100 kg/m^3). In this measurement from the skin surface, the vibrating medium is considered to be semi-infinite and therefore Eqn. 2 is multiplied by 1/2. The fitted curve (solid line) for the impedance spectrum at point III is shown in Fig. 3. It is possible to apply Eqn. 2 to the soft pattern spectra but not to the intermediate and hard pattern spectra.

At nine points including point I and III on the forearm, the biomechanical impedances were measured and the parameters, μ_1, μ_2, a were calculated. The distance between the skin surface and the bone was measured at each point by using the ultrasonic tomogram. Fig. 4 shows the relation between the distance and the parameters. μ_1 and μ_2 increase and a decreases with the decrease of distance. In this case, the applied vibration is reflected and restricted at the border of the bone at the distance of under 24 mm, and these measured parameters are different from the parameters measured at the regions, where the distances between bone and skin surface are over 24 mm. Therefore, the applied vibration is not considered reflected and restricted within this range, and these parameters do not depend on the body structure. We could therefore term the viscoelasticity dependent on the body structure as the "apparent viscoelasticity".

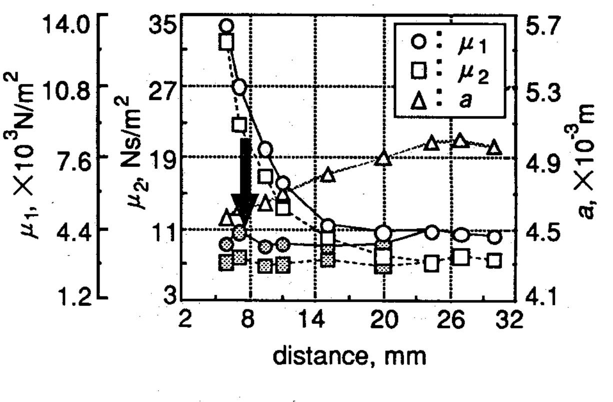


Fig. 4 Distance and μ_1, μ_2, a at the forearm.

3.1 Dependence of biomechanical properties on the body structure

The human body is consisted of different tissues, such as bones, muscle, fat, and skin. The human body is therefore inhomogeneous medium. They are connected each other and form layer structure. Each of them has its own biomechanical properties. However, when we measure the biomechanical impedance from the skin surface, it is difficult to specify each of them, and we would obtain synthesis of them as the results. So the results are influenced by these layer body structure. The soft patterns of impedance spectral properties are observed at the regions under which there are not any bones and the hard / the intermediate patterns are observed at the regions under which there are bones for this reason. The applied vibration is reflected and restricted at the border of these layers, and the measured impedance differs from that measured at homogeneous medium. Therefore, Eqn. 2 which holds only for the homogeneous media can not be applied to the hard and the intermediate patterns of impedance spectra but fits to the soft patterns well. The reason for dependence of biomechanical properties on the body structure is the change of situation of vibration spreading, such as reflection and restriction on the border of the bone. Then, how the degree of dependence on the body structure is decided? In this study, to simplify the problem, we supposed the human body to be a model consisted of two layers: one is soft tissues like a skin and the other is hard tissues like a bone, though the human body is more complicated in practice.

The distance from the skin surface to the bone is the most important factor, which decides the degree of dependence on the body structure. The degree of dependence on the body structure is in inverse proportion to the distance from the skin surface to the bone (see Fig. 4). This is because that the longer is the distance from the skin surface to the bone, the smaller is the degree of reflection or restricion of the vibration. If the distance is enough long, the applied vibration can not reach to the border of the bone and is not reflected or restricted there. In this case, the results are not influenced by the dependence on the body structure.

The viscoelasticity of a surface medium (skin) and viscoelasticity of an underlying medium (bones) are also an important factor for deciding the degree of dependence on the body structure. We can feel the presence of the underlying medium through the surface medium for the dependence on the body structure. In manual palpation, we can feel the presence of bones under the skin surface by touching from the skin surface, too. This measured apparent stiffness is the intermediate stiffness between the stiffness of skin and the stiffness of bones. Therefore, it is probable that the apparent stiffness is a consisted stiffness of the stiffness of skin and bones. In this constitution, the stiffness of skin and stiffness of bones are weighted and are added to each other. This rate of weighting is decided by the viscoelasticities of skin / bone and the distances between skin surface and bone. Therefore, the higher is contributory rate of stiffness of bone to the apparent stiffness, the larger the degree of dependence on the body structure is and the apparent stiffness gets near to the stiffness of bone. In Fig. 3, the apparent stiffness becomes larger from point III to I, though they are all soft patterns. In this case, the contributory rate of stiffness of bone to the apparent stiffness become larger from point III to I in inverse proportional to the distance from the skin surface to the bone, though it is not enough high to change the impedance spectra into the intermediate or the hard patterns. Therefore, the viscoelasticity calculated from these spectra are influenced by the dependence on the body structure even if they are soft patterns of impedance spectra.

As mentioned above, the degree of dependence on the body structure depends on the distance between skin and bone and each contributory rate of stiffness of skin / bone to the apparent stiffness at the distance. Accordingly, we can remove the influence of bone from the apparent viscoelasticity and obtain the viscoelasticity of skin tissue itself. We may be able to obtain the viscoelasticity of the underlying medium by removing the influence of surface medium from the apparent viscoelasticity on the contrary. But we can not consider the distance between bones and skin to be a parameter which signifies the degree of dependence on the body structure as it is difficult to measure the distance exactly in practice. Theoretically, when we apply the Eqn. 2 to the impedance spectra measured at inhomogeneous medium like a human body, though they are the soft patterns, we must introduce some variables and expand it to signify the degree of dependence on the body structure. Then we apply another experimental means to this case in our study.

3.2 Effective vibrating volume

The degree of dependence on the body structure is considered to be different at each measured region to correct the apparent viscoelasticity. It is important to consider the distance between the skin surface and the bone, though it is difficult to measure the distance in practice.

In Fig. 5, the apparent viscoelasticity is plotted again, setting a to the transverse axis. There is an adequate correlation between a and the distance. There is also an adequate correlation between the viscoelasticity and a. This suggests that a is the parameter which signifies the degree of the dependence of viscoelasticity on the body structure. The reason why a decreases according to the decrease of distance is considered as follows: When the applied vibration is reflected or restricted at the border of the bone in the body structure, the vibrating volume becomes smaller than that in the case without the reflection and restriction of vibration. The a of the vibrating tip becomes smaller accordingly to the case of the reflection and restriction of the vibration. Although a was the radius of the vibrating tip and should be constant in itself, we can consider it a variable. a therefore becomes the "apparent" radius, the parameter, which is not related to the radius of the vibrating tip directly but rather the vibrating volume. We will, hence, use the term "effective vibrating volume" to refer to a.

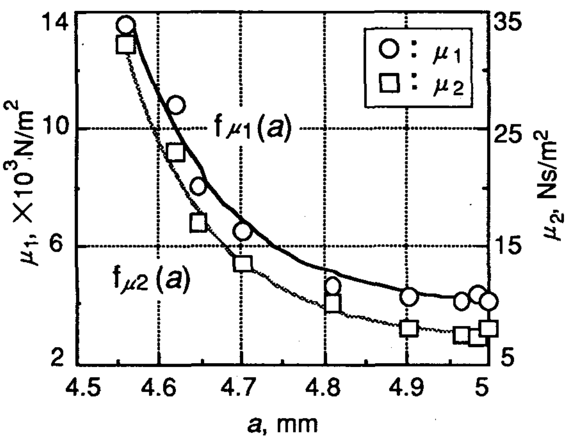


Fig. 5 Apparent viscoelasticity and a at the forearm.

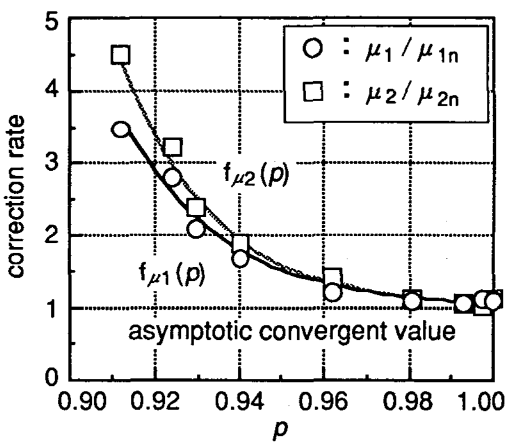


Fig. 6 Correction functions at the forearm.

3.3 Correction function

The relations between a and the viscoelasticity shown in Fig. 5 are roughly expressed as follows:

$$\mu_i(a)=\alpha_i \exp(-\beta_i a)+\mu_{in} \qquad (i=1,2) \qquad (3)$$

The solid and broken lines in Fig. 5 show the fitted curves ($f\mu_1(a)$ and $f\mu_2(a)$) to Eqn. 3 by the least square approximation. Since $\mu_i(a)$ converges to the constant μ_{in} in the limit of a, μ_{in} is considered to be the viscoelasticity without the dependence on the body structure. We introduce a_0 which is the radius of vibrating tip used in the measurement (= 5 mm in this measurement) to normalize the obtained effective vibrating volume. In Fig. 6 (plotted from Fig. 5,) the vertical axis is μ_1/μ_{1n} (correction rate) and the transverse axis is p ($=a/a_0$, coefficient of correction). We define the correction function as follows:

$$f\mu_i(p)=\alpha_{ci} \exp(-\beta_{ci} p)+1 \qquad (i=1,2) \qquad (4)$$

The constants α_{ci} and β_{ci} are calculated from the constants α_i, β_i and μ_{in} as follows:

$$\alpha_{ci} = \alpha_i/\mu_{in} \qquad \beta_{ci} = a_0\beta_i \qquad (5)$$

The correction function curves (solid : $f\mu_1(p)$ and broken : $f\mu_2(p)$) are drawn in Fig. 6. We can calculate the corrected viscoelasticity μ_{c1} and μ_{c2}, by using the correction function $f\mu_1(p)$ and $f\mu_2(p)$ as follows:

$$\mu_{ci} = \mu_i \;/\; f\mu_i(p) \qquad (6)$$

However, it is not necessary to correct the measured results which don't depend on the body structure. We should therefore define an inflection point of p. Although $f\mu_i(p)$ converges to 1 at an infinite p, it doesn't become a convergent value in practice. We define the point p_{ni} at which $f\mu_i$ (p) is close enough to the convergent value 1 (within 5 %) and apply the correction function in the case of $p < p_{ni}$. In Fig. 5, p_{n1} and p_{n2} were 1.00 (a = 5.00). The corrected viscoelasticity μ_{c1} and μ_{c2} are shown in Fig. 4. μ_{c1} and μ_{c2} are roughly equal to μ_1 (= μ_{1n}) and μ_2 (= μ_{2n}) without the dependence on the body structure.

4. APPLICATION TO THE THORAX STRUCTURE

The correction method is applied to the region with more complicated body structure underneath, the right thorax.

4.1 Apparent viscoelasticity mapping

The biomechanical impedance of the right thorax was measured and its spectrum showed the soft pattern. The measured region is shown in Fig. 7 and the measured points were 78 (13 x 6) with a lattice space of 2 cm. Each point was measured twice and averaged. The diameter of the vibrating tip was 10 mm and the contact preload was 50 gf. Fig. 8 shows the apparent viscoelasticity mapping which is

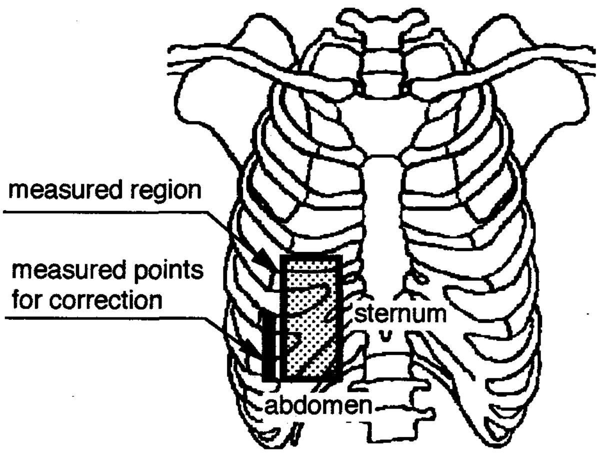
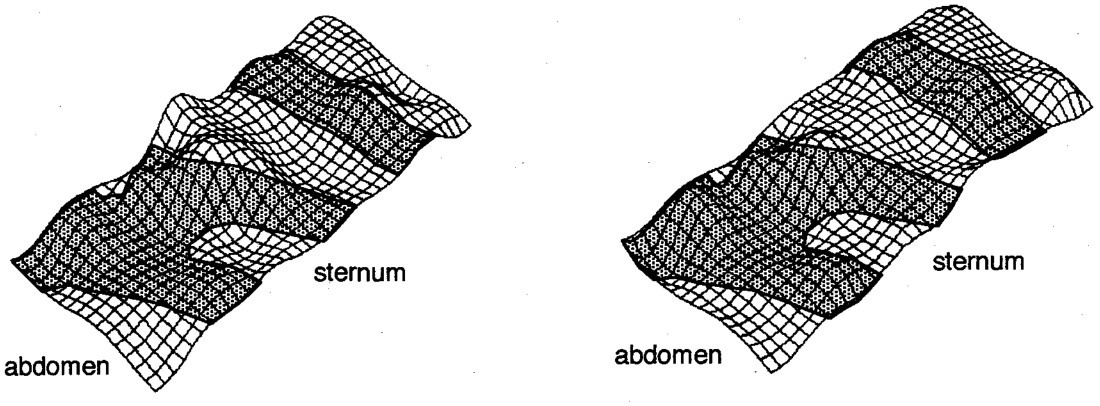


Fig. 7 Measured region on the right thorax.



(a) μ_1 (b) μ_2

Fig. 8 Apparent viscoelasticity mapping.

drawn by means of the bi-cubic spline interpolation. The vertical axis of the mappings indicates the value of the viscoelasticity. The apparent viscoelasticity results are larger at the points which contain the ribs underneath, and both figures closely resemble each other. Because of the complicated reflection of applied vibration in the complex body structure, the shape of the ribs is not clearly reconstructed.

4.2 Corrected viscoelasticity mapping

The correction functions are obtained from the region with bones underneath, close to the measured area, in which the biomechanical properties are roughly equal to those of the measured area. The seven points were measured for the correction function at the bold line in Fig. 7. The correction functions $f_{\mu1}(p)$ and $f_{\mu2}(p)$ were obtained from as stated above. Fig. 9 shows the relation between p and the correction ratio of viscoelasticity.

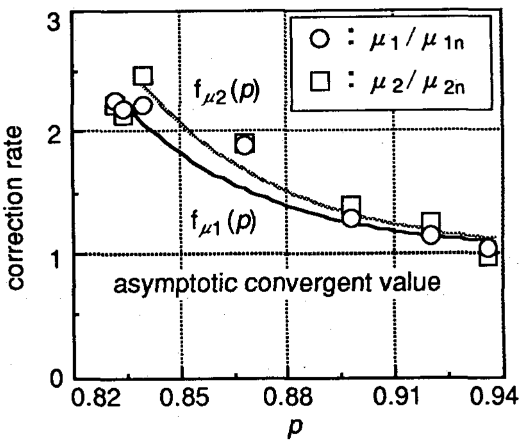
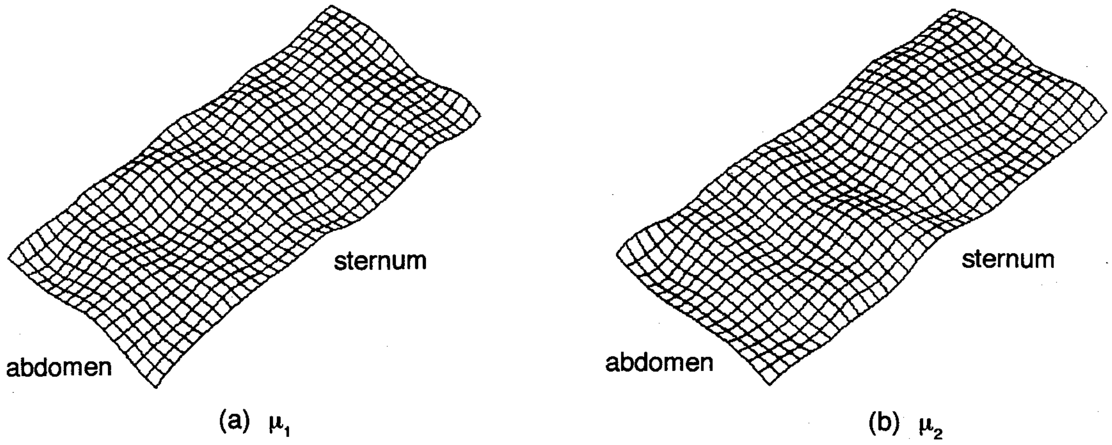


Fig. 9 Correction functions on the thorax.

The obtained $f_{\mu1}(p)$ and $f_{\mu2}(p)$ were applied to the measured results in Fig. 8, and the corrected viscoelasticity mappings are shown in Fig. 10. The dependence of viscoelasticity on the body structure is inconspicuous in comparison with Fig. 8. When a dependence on the body structure is not seen in the corrected mappings, the viscoelasticity of the measured area is considered to be roughly uniform. It is therefore experimentally confirmed that the above correction method is effective for eliminating the dependence of viscoelasticity upon the body structure.



(a) μ_1 (b) μ_2

Fig. 10 Corrected viscoelasticity mapping.

5. CONCLUSIONS

The dependence of biomechanical properties on the body structure significantly influences the results measured at the skin surface. In this study, we have made clear the dependence of biomechanical properties on the body structure and have proposed the correction method. The effectiveness of this correction method has been confirmed at the thorax structure. The correction functions are obtained at the forearm and the thorax, and they are slightly different. It is necessary to clarify the individual and the regional differences in the correction function in the future.

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