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Original paper

Tactile Sensing of Stiffness with Fingers Corresponds Well with the Objective Elasticity Evaluation

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Abstract

The evaluation accuracy of fingers for assessing tactile stiffness was confirmed by comparing results of a finger sensitivity test with objective mechanical measurements obtained using a newly designed device that simulates the manner in which fingers press against materials. The probe of the mechanical measurement system was pushed against the material with very slight force in a sinusoidal manner at a frequency of 0.5 Hz, and millinewton-order loading force and micrometer-order displacement were measured using a combination of two differential transformers and a coil spring. Sensory stiffness was then measured by human fingers using 10 elastomer models with various levels of elasticity nearly equal to that of human skin tissue. Sensory evaluation was performed using nine female subjects who were asked to rank the 10 models in order of softness. The distance of each model from the softest one was measured, and normalized as softest = 0 and hardest = 100. The normalized sensory values and the values of the elasticity index obtained using the mechanical system showed a correlation coefficient of 0.994. Tactile sensing by human fingers was therefore found to have practical accuracy, and the novel measurement device used in this study was found to be useful for obtaining data corresponding to subjective sensing.

Key Words: elasticity measurement, displacement-force relation, correlation with tactile evaluation and objective measurement

1. Introduction

Tactile sensory evaluation of stiffness plays an important role in various fields such as medical diagnosis, rehabilitation, food production, industrial material inspection, etc. For tactile diagnosis in medicine, however, the accuracy of tactile sensation has not been fully discussed because an objective stiffness measurement technique for such soft and viscous materials as skin has not been established yet.

Various viscoelastic measurement devices have been developed during the past half century[1)]. The recent mainstream of skin elasticity measurement is based on the suction method[2)] or high-frequency vibration[3)]. Because of their principles and mechanisms, they are not available to obtain the basic elastic modulus directly. Furthermore, because of their manner of touching and probing the skin, which is quite dissimilar from typical contact by fingers, they are not appropriate for quantification of sensory stiffness evaluation. Moreover, as Dawes-Higgs et al.[4)] summarized, reproducible results cannot be obtained using some of these methods.

The basic and general expression of elasticity is the strain-stress or displacement-force characteristic curve[5)]. Regarding the skin, however, the force to deform the tissue and its displacement is too slight to measure because of its thinness and softness. A novel, simple, but highly sensitive probe was designed for displacement and force measurement using two differential transformers and a coil spring which was able to achieve measurement of millinewton force and micrometer displacement. The probe sensing method simulates the manner of palpating skin with fingers by loading onto it slowly. Through comparison with this mechanical measurement system, the accuracy of sensory stiffness evaluation using fingers was assessed using a set of elastic models whose softness is close to that of skin.

2. Methods

2.1 Mechanical measurement system

The novel instrument for assessing accuracy of the sensory stiffness evaluation with fingers is presented schematically in Figure 1. Two differential transformers (Noble Industry Co., Ltd., Tokyo) that can measure displacement from 0 to 3 mm with a resolution of 30 μm or less were combined using a coil spring (10 mm length) whose spring modulus is determined as 0.029 N/mm. The spring was selected from among various spring moduli, whose contraction within 3 mm causes about 1-mm depth hollow in the skin when the spring is pushed onto the skin. One differential transformer was set for measuring the object's deformation (displacement); the other was set for evaluating the applied force by measuring the coil spring displacement. The force was applied in a sinusoidal waveform using a pulse motor and crank mechanism with various frequencies. The frequency in this experiment was set to 0.5 Hz, simulating the manner of tactile sensing using human fingers.

The differential transformers were calibrated using the simultaneous measurement with a

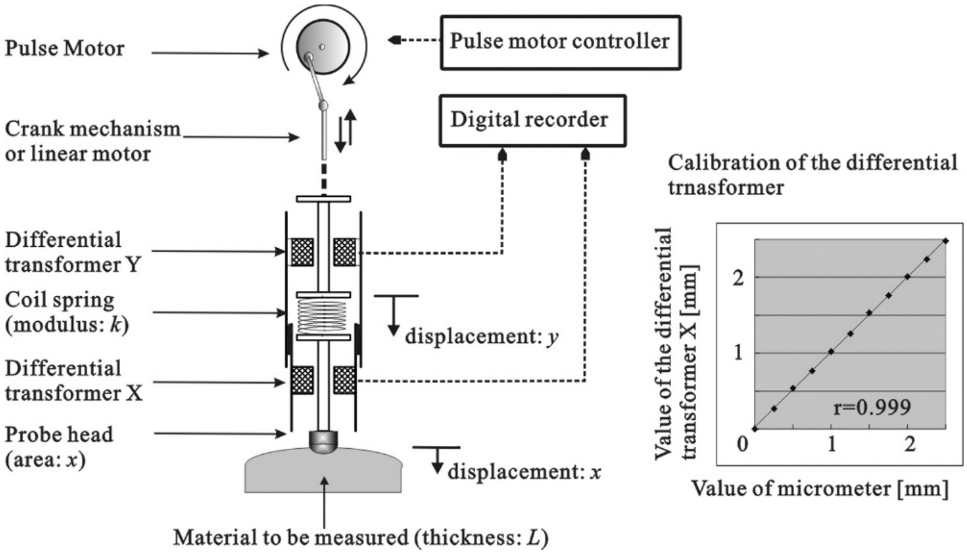

Figure 1 Construction of the viscoelastic measurement probe and system

micrometer with resolution of 0.001 mm (Mitutoyo Corp., Kawasaki). From the calibration, the differential transformers were confirmed to be sufficiently accurate for micrometer-order measurement (Figure 1).

The probe prototype is depicted in Figure 2. The probe shaft presses the skin or a material repeatedly with a frequency of 0.5 Hz, just as a finger might push it for probing stiffness. The stroke, which is adjustable using the crank mechanism, is usually set at 3 mm. The coil spring stroke and softness determines the displacement of the materials; they are tentatively selected for skin measurement. For measuring harder materials, stiffer springs are appropriate.

Several types (flat and concave) and sizes of the probe head were made of plastic material and assessed for use in soft material measurements. The probe head was finally determined as simulating the fingertips of female volunteers who participated in the sensory evaluation described below. The final probe head design was concave, with 6 mm diameter and 3 mm thickness. It was sensitive to skin and sufficiently stable to enable repeated measurements.

The probe outputs (namely displacement x and y in Figure 1) were recorded digitally (Model DL-750; Yokogawa Electric Corp., Tokyo). They were then transferred to a personal computer to calculate the viscoelastic property.

2.2 Calculation of elastic index in the mechanical measurement

When some force is applied on a part of an elastic object, its effect usually extends three-dimensionally. In this study, however, the applied force and the displacement are so minute that we hypothesized the one-dimensional force-displacement model. Thus, the property can generally be expressed by the following equation if the measurement object has an elastic property without a viscous characteristic, as

$$f / A = Ex / L \qquad (1)$$

where

f : force [N]
A: area for applying force [m^2]
E: Young modulus [N/m^2]
x : displacement [m]
L: material thickness [m]
f / A: stress
x / L: strain

Equation (1) posits that the thickness L is finite and the bottom of the material is fixed by a hard material.

In the model of Figure 1, force f is calculable using the following equation:

$$f = k (y - x + a + b) \qquad (2)$$

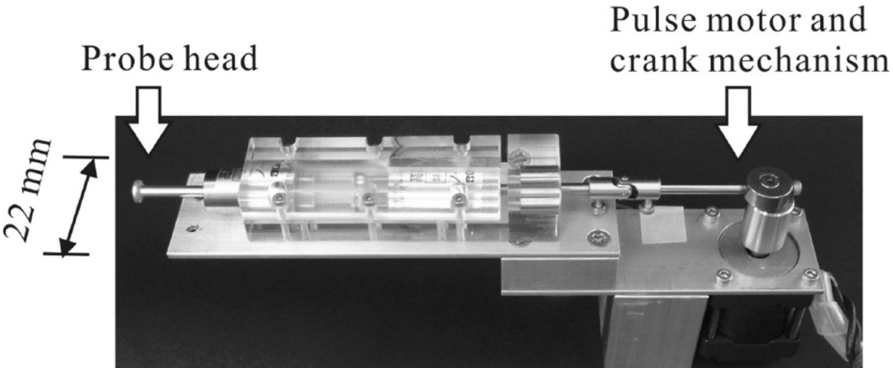

Figure 2 View and size of the novel probe to measure viscoelastic property

where

k: spring modulus [N/m]

x and y: displacements of the coil springs [m]

a: error or difference between x and y at the initial position [m]

b: initial error or displacement by the weight of sensor shaft when the probe is used vertically [m]

Therefore, the following pertains from (1) and (2).

$$k (y - x + a + b) / A = Ex / L \qquad (3)$$

The probe head area A is constant; in biological tissues the material thickness L is technically considered constant although the value cannot be determined in vivo. The practical elastic index is defined as $e = EA / L$, so that when both A and L are constant, as

$$y = (e / k + 1) x - a - b \qquad (4)$$

which means that e can be determined by the slope (dy/dx) of the x-y relationship line as

$$e = k (dy/dx - 1). \qquad (5)$$

2.3 Comparison with sensory evaluation

The measurement method was compared with sensory evaluations using 10 elastomer models. Nine female volunteers, who were informed of the experimental object and agreed, participated in the comparison test. Four were experts, employed in cosmetic product development, accustomed to evaluating skin stiffness well.

The elastomer models (specially made by Beulax Co., Ltd., Tokyo), each with a different level of elasticity produced by changing the rate of the hardener composition, were convex and 15 mm high, with 48 mm diameter (Figure 3a). Their levels of hardness were chosen by comparing them with tactile sensing of various human skin and tissues which include the undelying fat and muscle tissues. The elastic properties of the models were evaluated using the newly developed probe by calculating the value of the elastic index e described above.

Each panel volunteer was asked to arrange these 10 models in line on a desk, as shown in Figure 3b, in order of tactile softness from the softest to the hardest. Aside from the order of the models, the distances between them were deliberately determined according to the grade of softness. The distance of each model from the softest one was measured in millimeters, and was normalized as the softest=0 and the hardest=100.

3. Results and Discussion

Figure 4 presents a typical signal obtained from one elastomer model. The Lissajous figure (panel b) of x (displacement) and y - x (equivalent to the force applied to the model) indicates a viscous property of the material, in

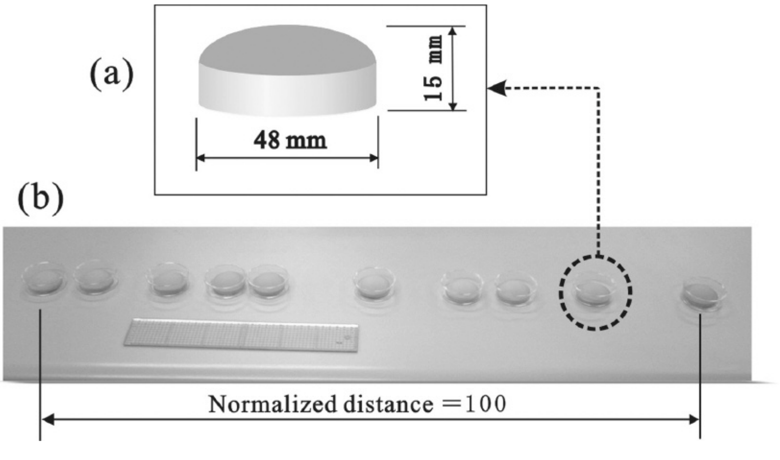

Figure 3 Elastomer model (a), and the example of models arranged in line by sensory stiffness evaluation (b)

which each of the loading phase and unloading phase has a different locus.

From the slope of the model line at the loading phase (panel c), the elastic index is calculable from (5) as

$$e = k\,(dy/dx - 1) = 112.0\ \mathrm{N/m}\ .$$

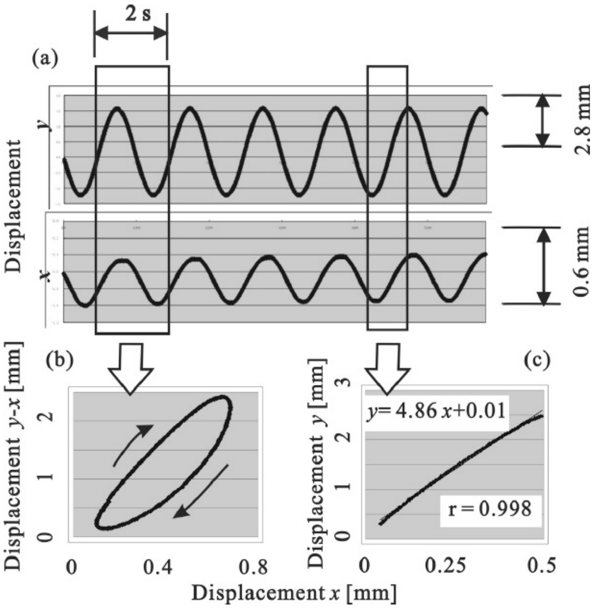

Figure 4 Typical signal of the probe (a), Lissajous figure (b), and correlation between two outputs of the differential transformers (c)

The viscoelastic properties (Lissajous figures) of 10 elastomer models were obtained as shown in Figure 5. The softer models showed a more prominent Lissajou (viscous) characteristic. Elasticity was evaluated by the slope of the loading phase (the value below each panel in Figure 5). Viscosity can be evaluated by the difference of wave shapes between the loading and unloading phase, although it is not analyzed in this study.

Figure 6 shows the result of a comparison between the novel probe and the tactile evaluation performed by the nine female volunteers. Both methods correlate well mutually; the correlation coefficient is 0.994. The relationship is nonlinear (logarithmic), which is a physiological phenomenon in sensory evaluations that is generally known as the Weber-Fechner Law. No significant difference between the cosmetic experts and non-experts was found from data in these experiments. The tactile sensing could be explained, as shown in the figure, by the mechanically measured data in which the simple one-dimensional elastic model is hypothesized excluding viscoelastic profile.

Among the various roles of the skin, its elasticity is important not only for absorbing mechanical stress but also for maintaining the

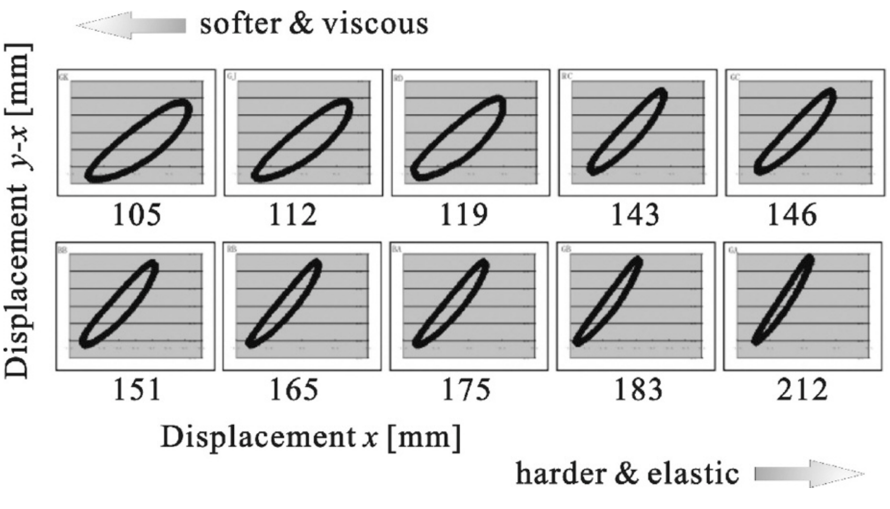

Figure 5 Lissajous figures obtained from 10 elastomer models (same scale as in Figure 4(b)) and the elastic index values (number below each panel, N/m)

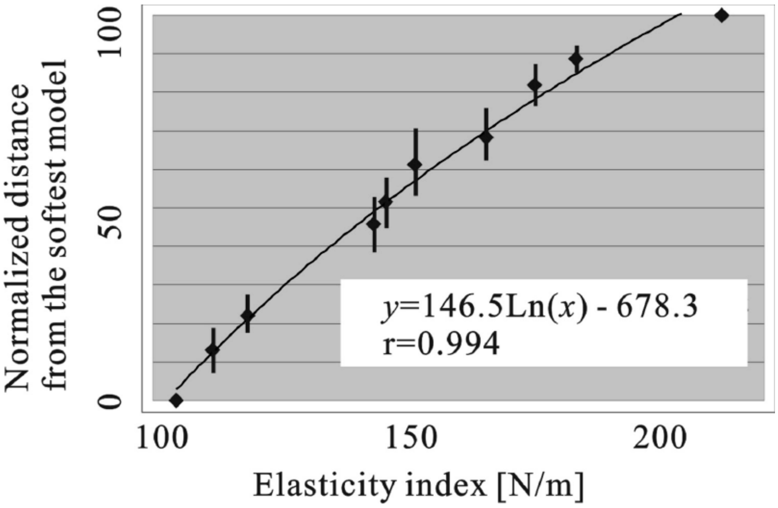

Figure 6 Correlation between the mechanical measurement and tactile evaluation. The vertical bar shows +-S.D.

human shape. Much attention has been given to the evaluation of viscoelasticity of the skin in clinical situations, such as edema evaluation[6)], and in dermatological and cosmetic fields, where good correlation between the objective measurement and the tactile evaluation by palpation is often necessary for medical doctors, patients, and customers[7)]. The result portrayed in Figure 6 shows that the previous palpation has some accuracy: it is an easy, practical method for stiffness evaluation of skin and soft materials. Results obtained through the experiment also suggest that a standard reference model, such as an elastomer model, is necessary to maintain palpation accuracy because sensory evaluation is accurate when used for relative comparison.

There still exist the doubt, on the other hand, that the result of high correspondence beteween tactile sensing and mechanical measurement is not general but unique to the present elastomer models. To solve the problem, the same comparison study should be applied to the skin and other various materials.

Results also showed that the mechanical measurement system that was newly developed in this study was sufficiently practical to obtain objective data corresponding to subjective sensory evaluation. One advantage of this device is that lower frequency characteristics are obtainable than in any previous device. The simple and basic expression of the elastic object is Young modulus; its value can be measured directly through a low-frequency or static experimental procedure. The mechanism of slow back-and-forth motion achieved good correlation with palpation with fingers. The simple mechanism using a coil spring is also an advantage of this device, whose measurement range is changeable from softness to hardness by selecting a coil spring with appropriate stiffness.

As already shown in previous studies, the mechanical property of the skin can be demonstrated by Payne as a nonlinear relationship between the strain and stress[10)]. According to a study by Manschot and Brakkee, the phenomenon is related to basic collagen fibril properties[9)]. The present system can confirm the property in vivo.

The mechanical property of elastic or viscoelastic materials varies depending upon how much pressure is loaded and the degree to which the object is deformed. When the load is lighter, its influence is limited to the surface of the object, and then one-dimensional simple model can be applied as shown in this study. Conversely, when the stroke is longer or the applied load is higher, a wider surface area is deformed. The present device can easily adjust the stroke when using a linear-motor driving force and the load by changing the coil springs; a three-dimensional model is required to obtain the elasticity data.

This device is expected to help quantify various sensory evaluations performed in medical diagnostic fields, cosmetic effectiveness evaluation, and industrial material inspections.

4. Conclusion

The accuracy of sensory stiffness evaluation with fingers was assessed by comparing it with results obtained using the objective mechanical measurement device. For this study, a novel elastic property measurement system was developed, imitating the manner of fingers' palpation of the object to be evaluated. A comparative experiment was performed using 10 elastomer models using sensory evaluation and mechanical measurements. Results show that the tactile sensory evaluations correlate well with the mechanical measurements; the relationship was logarithmic with a high correlation coefficient (0.994).

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人の指による物体の硬さ知覚と客観的計測値の相関

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要旨

触診に近い原理、即ち指で物体を押す方式を真似て、皮膚のように非常に柔らかい素材の弾性を計測する装置を開発した。本装置では弾性特性を得るために、μmレベルで検出可能な差動トランス式位置センサと弾性係数が既知のコイルばねを用いて、物体に加わる力とそれによる物体の変位を求めた。人体表面の触診を想定した様々な硬さのエラストマー素材の弾力モデルについて、本装置を用いて弾性を測定し人の触感による硬さ評価と比較した結果、従来の心理物理学で確認されてきたWeber-Fechnerの法則に則り、両者は対数関数を介して非常に良い相関を示した（r=0.994）。これにより、指の触診による硬さの大小評価は、体表面の触診程度の比較的柔らかい範囲において十分精度を有すること、および新たに試作した測定器が触感と相関の高いデータを得るのに有用であることが明らかになった。

キーワード：弾性特性測定、変位－荷重関係、触覚と客観計測の相関

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