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Portable System for Measuring Biomechanical Properties

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Abstract -- Portable system has been developed for measuring a biomechanical impedance on skin surface. The system has a measuring probe and a measuring device. The biomechanical impedance is measured with the probe held in an experimentalist's hand. The new index 'SI' is proposed to evaluate a stiffness on skin surface. The stiffness distribution on skin is 3-dimensionally expressed by SI-map.

I. Introduction

Viscoelasticity on a skin surface gives a helpful information in clinical diagnosis. Since the biomechanical properties of skin must be measured *in vivo*, it becomes necessary to measure on the skin surface. A quantitative measurement of biomechanical properties has been insufficient; therefore a development of practical measurement system *in vivo* has been anticipated [1]. The concept of mechanical impedance has been used in the analysis of vibratory systems. The biomechanical impedance is an available estimation for biomechanical properties of skin [2].

As the biomechanical impedance is relatively small compared to a mechanical impedance in industry, it is difficult to measure it precisely. The authors proposed the measurement system of biomechanical impedance with applying a random vibration onto skin surface [3]. The system has a personal computer for data analysis and is not handy to carry. The purposes of this study are to develop a practical measuring system for portable use and propose a new index 'SI' of skin stiffness. The system is applied to a quantitative estimation of tooth mobility and palpation.

II. Measurement System

The biomechanical impedance $Z(f)$ on skin surface is defined as the ratio of an applied vibrating force $F(f)$ to resulting velocity $V(f)$ at the driving point.

$$Z(f) = F(f) / V(f) = j2\pi f F(f) / A(f)$$

$A(f)$, $V(f)$ and $F(f)$ are Fourier transforms of acceleration, velocity and force, respectively. f is a vibrating frequency. The small random vibration (30-1000 Hz) is applied onto skin by using a measuring probe.

The previous system comprises a vibrator, an impedance head, some amplifiers and a personal computer, which are standard commercial parts in industry [3]. It can not be insisted as an advantageous method to carry with a personal computer.

A. Measuring Device

The present system comprises a measuring probe and a measuring device which includes a random noise source, four amplifiers, A/D converter, a micro computer, a liquid crystal display and a floppy disk unit. It becomes a small-sized and portable one, since the small display and single board computer are adopted instead of the personal computer in the previous one.

Fig. 1 shows photographs of the measurement system from (a) the front-side view and (b) the back-side view. In the basement of device, a switching power supply (+5V, +12V, -12V) and 3.5" 2HD floppy disk drive (FDD) unit (single drive) are installed. 4" liquid crystal display and a set of input keys (←, →, ↑, ↓, esc, cr) are arranged on the front panel. Visible characters and figures are displayed graphically on the display. A selection of computer operations can be made with the key set. Input/output (I/O) connectors from/to the probe (for F, A, preload and driving of vibrator) and monitor connectors (for F, A and preload) are located on the rear panel.

The device has three circuit-boards of a single board computer, A/D converter and four amplifiers. The CPU of board computer is μ pD70325 (V25) of 8 MHz clock and the board computer has ROM(256KB), RAM(256KB), CRT interface (characters 80*25 and graphics 512*212), FDD interface (2HD) and 8-bit I/O data bus.

Fig. 2 shows a block diagram of measurement system. The noise source generates a white noise and its frequency range is restricted with 1 kHz by using a low-pass filter. The skin surface is vibrated with the vibrating tip of probe. The force and acceleration of driving point are detected from the impedance head of probe. They are amplified with two charge amplifiers, sampled with 12-bit A/D converter and processed with Fast Fourier Transform (FFT) algorithm by using the micro computer. The mechanical impedance spectrum is then obtained. The sampling interval is set as 333 μ s to obtain the spectrum below 1 kHz. FFT processing is performed for 256

data points with eight averages. Since the biomechanical impedance depends on an applied preload onto skin surface by the tip, it must be measured at a constant preload (for example, 50 gf in tooth mobility measurement). As the probe is held in an experimentalist's hand and there is a fluctuation in preload, the preload fluctuation also must be sampled. The force and acceleration signals are sampled automatically, while the preload fluctuation is kept within 5 %.

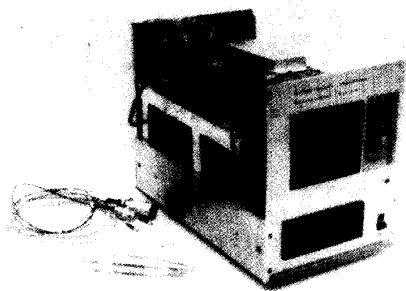
The pseudo-random vibration should be selected as an exciting force. It is desirable to perform a measurement rapidly, since it is impossible to keep a body in a same posture or condition for a long time. The random vibration method has basically the advantage that a transfer function (impedance) can be determined even though the measurement is disturbed by various noises. The linearity of output to input is required as the premise for applying this method. On outer forearm, the impedance linearity has been experimentally confirmed below 3.0 cm/s in velocity, 1.9 G ($G=9.8 \text{ m/s}^2$) in acceleration at 100 Hz [4]. In this study, the impedance is measured at 0.5 G in acceleration, 12 μm in displacement at 100 Hz, within the range of linearity.

The size of the measuring device is 18 cm wide, 30 cm deep and 23 cm high. It takes about 3 and 30 seconds in the measuring and data analyzing of mechanical impedance, respectively.

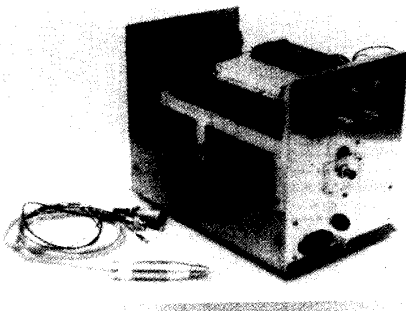
B. Measuring Program

The program of this system, 'automatic diagnosis program' is designed with emphasis on a measuring and a writing of data on floppy disk. The programs of data analysis of mechanical impedance, 'automatic analysis of tooth mobility' and 'automatic analysis of skin impedance' are executed as far as time permits. Fig.3 shows the measurement program of mechanical impedance for skin and tooth mobility.

In tooth mobility measurement, the mechanical mobility (reciprocal of impedance) is obtained, by applying a small vibration onto labial crown of tooth. The viscoelasticity of periodontium is calculated by a curve fitting to mobility spectrum and expressed as a mobility triangle figure (MT figure). The scores of linear discriminant functions of viscoelasticity can derive the objective tooth



(a) front-side view



(b) back-side view

Fig.1 Portable system for measuring biomechanical properties. (a) front-side view and (b) back-side view.

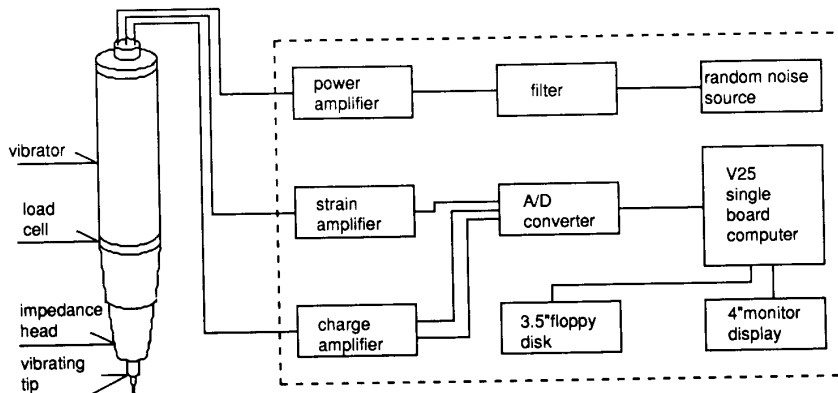


Fig.2 Block diagram of measurement system.

mobility, M0 to M3 [5].

In skin impedance measurement, larger vibration is applied onto skin surface. The viscoelasticity of skin is calculated by the curve fitting to impedance spectrum. The measuring program is almost the same as that in tooth mobility. As it takes a longer time to calculate the skin viscoelasticity, it had better use a personal computer of 12 to 20 MHz clock.

C.Measuring Probe

The measuring probe is a pen-typed one which comprises a vibrator, a load cell and an impedance head. The skin surface is randomly vibrated with the measuring probe held in the experimentalist's hand.

Fig.4 shows a detail structure of measuring probe. The vibrator has a permanent magnet and exciting coil. The vibrator housing is wholly vibrated. The load cell, located between the vibrator and impedance head, can detect an axial and static preload onto skin. The cell is made of four strain gauges. The impedance head has two PZT piezoelectric elements and can detect a force and acceleration. The vibrating tip in tooth mobility measurement is made of a diamond finishing burr. The tip in skin impedance is made of 5-20 mm ϕ

aluminum cylinder. The vibrating displacement at the tip for tooth is 3-4 μm and for skin, larger. The probe has an overall length of 13 cm, a diameter of 2 cm and a total weight of 90 g.

III.Measurement of Biomechanical Impedance

A.Correction of mass and viscosity

The mechanical impedance of known mass is measured to examine the accuracy of system in mass. The solid lines in Fig.5 show the reactance (imaginary part of impedance) spectra of mass 1, 2, 3 and 4g. They are in good agreement with the theoretical lines (dotted). Compared with theoretical value of 1g at 500 Hz, the measurement errors are 5.86% (2g), 0.98% (3g) and 7.62% (4g).

The impedance of standard viscous liquid, JS20H and JS60H for viscometer in Japan is measured to examine the accuracy of system in viscosity. Table 1 shows the mean viscosity and error (standard deviation / mean) of five measurements. The viscosity of liquid is corrected at room temperature 25.2 $^{\circ}\text{C}$.

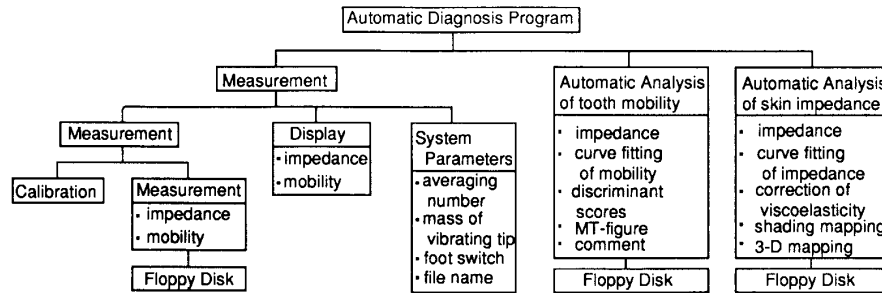


Fig.3 Measuring program of biomechanical impedance on skin surface and tooth mobility.

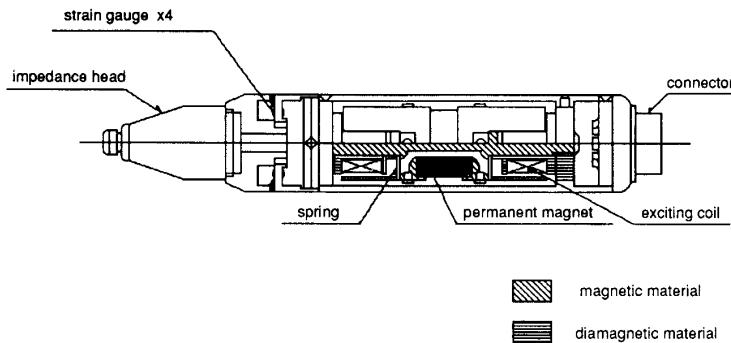


Fig.4 Measuring probe.

Table 1. Viscosity of standard viscous liquid.

standard viscous liquid	viscosity of liquid (Pa · s)	measured viscosity (Pa · s)	standard deviation /mean (%)
JS20H	9.23	9.22	8.29
JS60H	29.3	31.1	4.55

B. Biomechanical impedance

In a soft skin the resistance (real part of impedance) spectrum shows a monotonous increase with increasing frequency [6]. The solid lines in Fig.6 show the spectra of typical soft pattern on forearm and the broken lines show the curve fittings. When a skin impedance gets larger, a reactance in low frequency gets larger and a resonance frequency gets higher. The soft pattern has the resonance frequency below 1 kHz.

The solid line in Fig.7 shows the mobility spectrum of maxillary left central incisor with healthy periodontium. The broken line shows the curve fitting. When the periodontium has a pathological condition, the magnitude of mobility decreases.

IV. Stiffness Index on Skin Surface

Though many studies have been done to evaluate a skin stiffness, it is yet insufficient to express a tactile stiffness on skin. The authors propose a new index 'SI' of skin stiffness and express a stiffness distribution on skin with a 3-dimensional mapping.

A. Stiffness Index (SI)

The solid line in Fig.8 shows the impedance spectrum on forearm. The reactance Z_i is a negative value in low frequency and becomes zero at the resonance frequency f_0 .

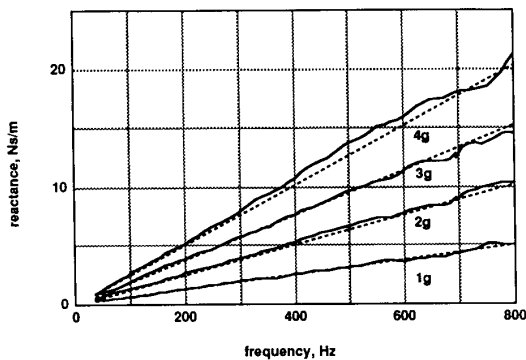


Fig.5 Reactance spectra of mass 1, 2, 3 and 4g.

The stiffer is a skin surface, the larger is the magnitude of Z_i in low frequency and the higher becomes f_0 . Thus the shadowed area in the figure becomes larger. SI (Stiffness Index) is defined as an integration value of reactance between 40 Hz and f_0 as follows;

$$SI = \int_{40}^{f_0} Z_i(f) df$$

Oestreicher proposed a theoretical radiation impedance of vibrating sphere in a viscoelastic medium [7]. von Gierke applied it to the biomechanical impedance analysis on skin surface [2]. A shear viscosity, a shear elasticity and a density of skin can be derived from their theory. The reactance in low frequency can be calculated with the viscosity, elasticity and density. Since the dimension of SI is [N/m], SI can represent a synthetic elasticity including viscosity and inertia.

SI is interpreted visually by a 3-dimensional mapping with a bi-cubic Spline interpolation. Fig.9 shows the SI-map on right thorax and has a symmetry with respect to the median line. The vertical axis of map expresses the apparent stiffness on a log scale, which depends on the body structure.

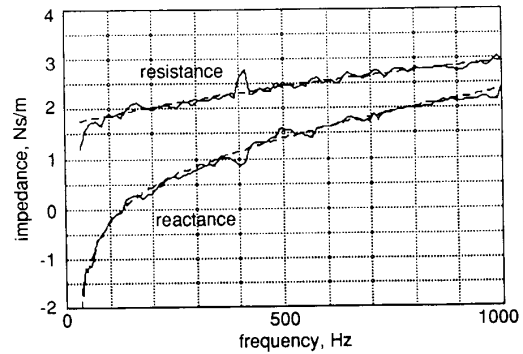


Fig.6 Mechanical impedance of typical soft pattern on forearm.

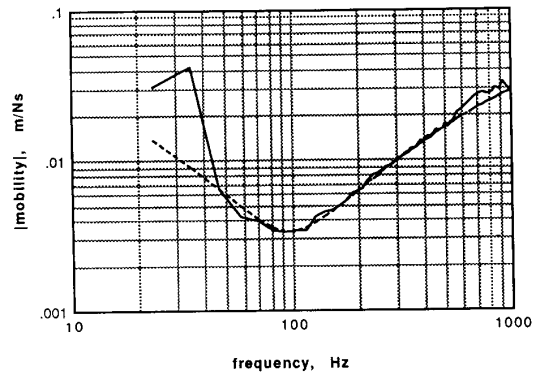


Fig.7 Mechanical mobility of maxillary left central incisor with healthy periodontium.

The shape of ribs on thorax can be found. SI magnitude depends on whether or not there is a bone underneath the skin, in case of a uniform stiffness of skin. Thus SI is the index relating to the depth to bone underneath a skin, when the mechanical properties of skin seems homogeneous.

B. Palpation and SI

Palpation is an important and simple diagnosis in clinics. The manual palpation can sensuously observe various physical properties, however it is a method based on experience and a subjective evaluation.

The biomechanical impedance is measured and compared with palpation on 40 measuring points of dexter lateral shank shown in Fig.10. First, a therapist and a masseur palpate all the points and score up a skin stiffness in five degrees. Then the impedance is measured on 20 points of genu side. Next, they palpate wholly a second time and the impedance is measured on 20 points of tarsus side. Lastly, they palpate wholly a third time. The vibrating tip is 10 mm ϕ and the preload is 50 gf. The therapist reported that three muscles, anterior tibialis, peroneus and sural triceps, were indistinguishable in case of the subject.

Fig.11 shows shading maps of (a) palpation scores and (b) SI. The color depth expresses a state of stiffness (a scale of 14 colors from black = stiff, to white = not stiff). Both maps show that the stiffness gets harder toward shank and tarsus. SI-map is characterized by a few darker areas on peroneus and anterior tibialis. The palpation-map also shows a darker area but an obscure pattern. The three muscles is not distinguished in the palpation-map but in SI-map.

Fig.12 shows a correlation of SI with the palpation scores. The coefficient of correlation is 0.797 and suggests an adequate correlation. Thus SI can be considered as the stiffness index corresponding to the palpation.

V. Conclusion

The authors have developed a portable system for measuring biomechanical properties. The measurement system comprises a measuring probe and a measuring device. The probe is a pen-typed one. The device includes a random noise source, amplifiers, A/D converter, a micro computer, a liquid crystal display and a floppy disk unit. The biomechanical impedances on skin surface are measured and the skin viscoelasticity are obtained. SI is proposed as the new index of skin stiffness. The coefficient of correlation between SI and palpation scores is 0.797.

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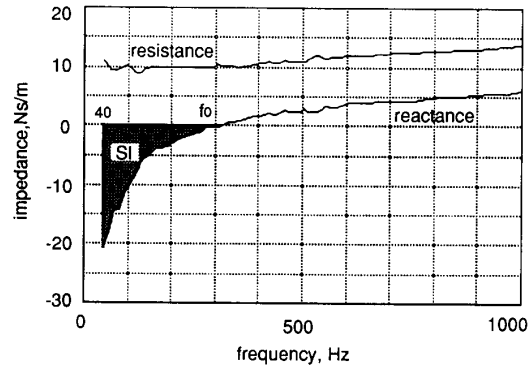


Fig.8 Definition of SI (Stiffness Index).

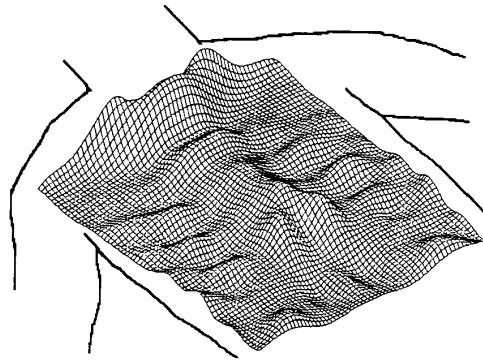


Fig.9 SI-map on right thorax.

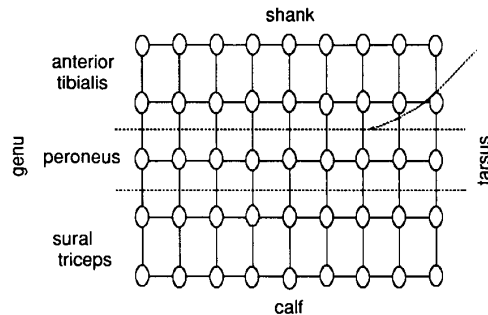


Fig.10 40 measuring points on dexter lateral shank.

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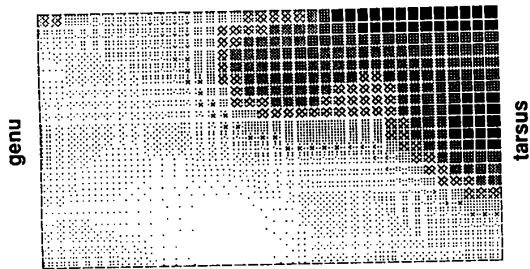
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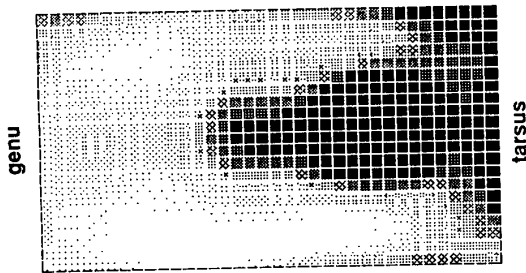
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(a) Palpation-map



(b) SI-map

Fig.11 Shading maps on dexter lateral shank. (a) Palpation-map and (b) SI-map.

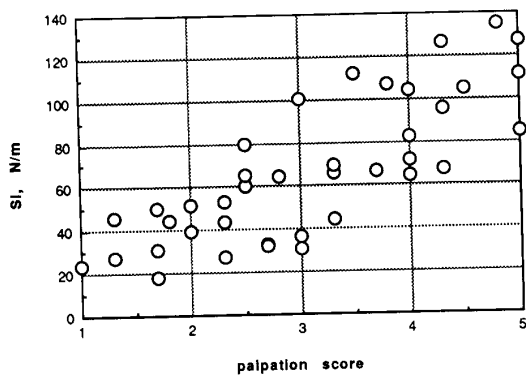


Fig.12 Correlation of SI with the palpation scores.