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Measurement System of Biomechanical Properties for Portable Use

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SYNOPSIS

It is difficult to evaluate a biomechanical properties quantitatively. The authors developed the measurement system of biomechanical properties formerly but it is on a large scale because of the use of personal computer. In this study, the portable measurement system of biomechanical impedance/mobility is developed. To establish a rapid measurement, a random vibration is adopted in input signal. The system consists of the measuring probe, amplifier, and a note-typed personal computer. The measurement probe is developed newly, and has an overall length of 9 cm (without a handle) and a total weight of about 500 g. The measurement program is also developed and is available to any computer which is worked under MS DOS compatible in Windows 95/98 operating system. The biomechanical mobility spectra of thigh, temple and forehead are obtained and they show three typical spectrum patterns.

1. INTRODUCTION

To evaluate a basic physical phenomena of living body, the diagnosis in such a percussion, pressation, and palpation is made in clinical examinations. When the human body surface is in contact with a vibrating structure, it shows a specific mechanical reaction which is determined by the constants of shear elasticity and viscosity of the studied tissue. Many various investigators tackled with the study in the determination of viscoelasticity (1,2). In this study, an impedance/mobility method is best suited to describe the mechanical behavior of the body surface and is available to the investigation of mechanical vibrations and their analysis of mechanical properties in a frequency range of 30-1000Hz (3).

Generally, a mechanical impedance/mobility is the complex ratio of the periodic force applied to an area of the body surface to the forced velocity of the area and is measured by attaching a sinusoidally vibrating cylindrical tip to a particular area of the body surface. The vibratory force exerted on the body surface by the vibrating tip and the velocity (acceleration) of the tip is measured. From these data, the mechanical impedance/mobility is calculated and it is a measure of the response of the body surface to vibrations. If the behavior of the body surface is investigated by other methods, as for instance by the application of non-periodical forces, as in the impact method, the results, although not given in terms of impedance, can be generally transformed into impedance values (4).

The aim of this study is a development of portable measurement system of biomechanical properties *in vivo*. The authors developed the measurement system of biomechanical impedance formerly (5). This system,

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however, was on a large scale because of the use of a desktop typed personal computer for data analysis. The portable system, which the authors have developed in this study, consists of a measuring probe, amplifier, and a hand-held (note-typed) personal computer. From the measured data, the mechanical properties of body tissue, the constants of elasticity and viscosity are calculated. The measuring conditions are considered in detail and in succession this method is applied to the study in the mechanical properties of the thigh, temple, and forehead.

2. Biomechanical Properties

2.1 Frequency Response Function

In the frequency domain, the relation between input *X(f)* and output *Y(f)* is given by

$$H(f)=\frac{Y(f)}{X(f)}=\frac{Y(f)\cdot X^{*}(f)}{X(f)\cdot X^{*}(f)}=\frac{G_{YX}(f)}{G_{XX}(f)} \tag{1}$$

where *X(f)* and *Y(f)* are the Fourier Transforms of time signals. The ratio of these estimates therefore gives a Frequency Response Function *H(f)*. The fundamental equation of *H(f)* is given by multiplying by X(f)* on both the numerator and denominator. * indicates complex conjugation. $G_{YX}(f)$ and $G_{XX}(f)$ is the Cross Spectrum and the Auto Spectrum, respectively. The Fourier Transform which is performed in practice is the so-called Discrete Fourier Transform (DFT). The Fast Fourier Transform (FFT) is just an algorithm which computes the DFT with a greatly reduced number of arithmetical operations compared to a direct computation.

Coherence of the signals is a function which on a scale from 0 to 1 evaluates the degree of linear relationship between the two signals at any given frequency. In this study, Coherence is also calculated. Coherence less than one can be due to one or more of the following situations: (1) Uncorrelated noise in the measurements of input signals; (2) Non-linearity of the investigated system; (3) Leakage in the analysis (resolution bias error); (4) Delays in the system not compensated for in the analysis.

A random signal is a continuous type of signal which never repeats itself and whose amplitude can only be predicted in terms of statistical parameters. Often the random signals found in practice have a gaussian amplitude probability density distribution. The random signal should preferably have a constant spectral density in the frequency range of interest *i.e.* the Autospectrum should be flat in this frequency range and the signal is called a band limited white noise signal. A pseudo-random signal is used in this study and it is specially designed for the DFT analysis which works on blocks of data. The pseudo-random can be considered as a number of sinewaves, having the same amplitude in the analysis frequency range but a random phase, and where the time record contains an integer number of periods for each sinewave.

The application of pseudo-random signal to a biomechanical measurement of living body produces a rapid measuring time. A smooth weighting function (such as the Hanning Weighting in this study) has to be applied which causes leakage in the spectral estimates. The amplitude *A(f)* and phase ϕ *(f)* of measured spectrum are power-averaged as follows:

$$\begin{aligned} A(f) &= \sqrt{1/n[A_1^2(f)+A_2^2(f)+\cdots A_n^2]} \\ \phi(f) &= 1/n[\phi_1(f)+\phi_2(f)+\cdots \phi_n(f)] \end{aligned} \tag{2}$$

The sufficient power averaging improves a signal-to-noise ratio.

2.2 Biomechanical Impedance/Mobility

The mechanical impedance/mobility is available for the Frequency Response Function in this study. The impedance of the body surface is determined by applying a known alternating force f(t) to a given surface area. The velocity v(t) of the vibrating area is then measured so that the velocity amplitude and its phaselag relative to the exciting force are known. The impedance is then given by the complex ratio between f(t) and v(t). The mechanical mobility $\lambda(f)$ is defined as the reciprocal of the impedance as follows:

$$\lambda(f)=\frac{V(f)}{F(f)}=\frac{A(f)}{j\omega F(f)} \quad \text{where} \quad \omega=2\pi f \qquad (3)$$

where $F(f)$, $V(f)$ and $A(f)$ are the Fourier Transforms of $f(t)$, $v(t)$ and $a(t)$, respectively. The driven tip was a piston, the circular base of which was attached to the body surface and vibrated it. The vibratory force and the velocity amplitude of the vibrating tip was picked up by means of an impedance head of the measurement probe.

3. Measurement of Biomechanical Properties

3.1 System Design

Fig.1 shows the block diagram of the measurement system for portable use. The system consists of a measurement probe, amplifier, and a hand-held (note-typed) computer (MN-340 U15, SHARP). The random vibration, in the frequency range of 30 – 1000 Hz, is applied on the body surface vertically, through the vibrating tip. The resulting acceleration and force at the driving point of the are detected by using the measurement probe. Sampled signals are fed into an ADC and processed by the FFT algorithm in the computer. The biomechanical mobility spectrum is then obtained. The sampling interval is 333 μs to obtain the mobility spectrum below 1kHz and the data points are 512 for one acquisition. The frequency resolution is about 5.88 Hz and the number of power averaging is 16. The measuring time is about 2.8 sec (333 μs x 512 x 16).

The fluctuation of contact pressure during a data sampling decreases the accuracy of measurement. In this system, the data sampling is executed only when the contact pressure is kept at the certain pressure (*e.g* 50±3 gf).

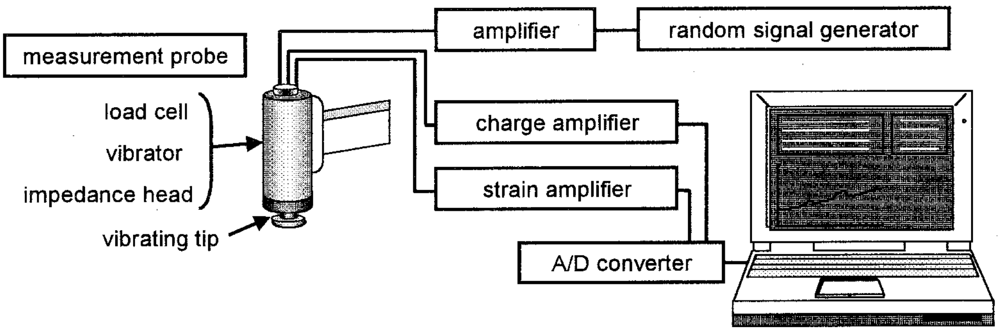

Fig.1 Block diagram of measurement system for portable use.

3.2 Measurement Probe

The acceleration and force signals are detected by using the measurement probe, which has been newly developed. It comprises an impedance head, vibrator, load cell, vibrating tip, and a handle, shown in Fig.2. The probe has an overall length of 9 cm (without the handle) and a total weight of about 500 g. The impedance head includes two piezoelectric disks for an acceleration sensor and a force sensor, and a seismic mass, and springs. The charge sensitivity is 16.8 pC/g and 1725 pC/kgf, respectively. As an output impedance of piezoelectric typed accelerometer is relatively high, to prevent or help minimize this effect it is essential that the signal from an accelerometer is fed through a charge amplifier.

This probe has a latent mass of 1.3 g of its own, which is added to the measured mechanical mobility.

3.3 Measurement Program

Fig.3 shows the measurement program of biomechanical impedance/mobility, which has been newly developed for the use of hand-held (note typed) computer. It is divide roughly into five programming routines: Measurement, Display, Data Save, System Parameters, and Analysis. After the system parameters (averaging number, mass of probe, diameter of vibrating tip, contact pressure, filename) are set previously, the mechanical impedance/mobility is calibrated by a known mass (vibrating tip). In this paper, the averaging number is 16, the diameter of tip is 10 mm, the constant pressure is 50±3 gf, and the sampling frequency is 3 kHz. The data points are 2^9=512 and the frequency resolution is 5.88 Hz. Fig.4 shows a flow chart of Measurement routine and FFT subroutine. The Hanning weighting function is applied to the sampled data. The measuring time is 2.8 sec (333 μs x 512 points x 16 averagings). The developed measurement program is available to any computer which is worked under MS DOS compatible in Windows 95/98 operating system.

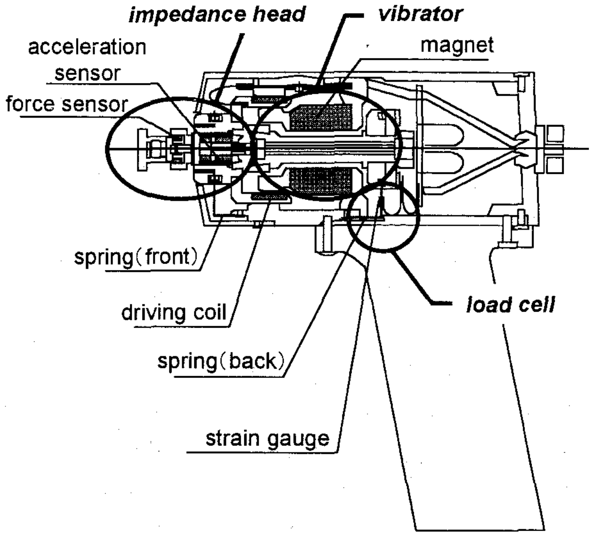

Fig.2 Measurement probe (9 cm in length and about 500 g in weight).

3.4 Cancellation of Measurement Probe Mobility

As mentioned above, the probe has a latent mechanical impedance/mobility, a mass of its own. The measured impedance/mobility includes that of the probe. Therefore the authors should remove the latent impedance/mobility λ_m from the measured result λ_M as follows:

$$\frac{1}{\lambda_s} = \frac{1}{\lambda_M} - \frac{1}{\lambda_m} \quad (4)$$

where λ_m is a mechanical mobility of the living body. The latent mass of the probe is based on the vibrating tip mass and a seismic mass under the force sensor of the impedance head.

4. Discussion

4.1 Measuring Conditions

The biomechanical impedance depends remarkably on the measuring conditions. When the mechanical mobility is measured on a surface of silicone model in contact with the vibrating tip, the influences of

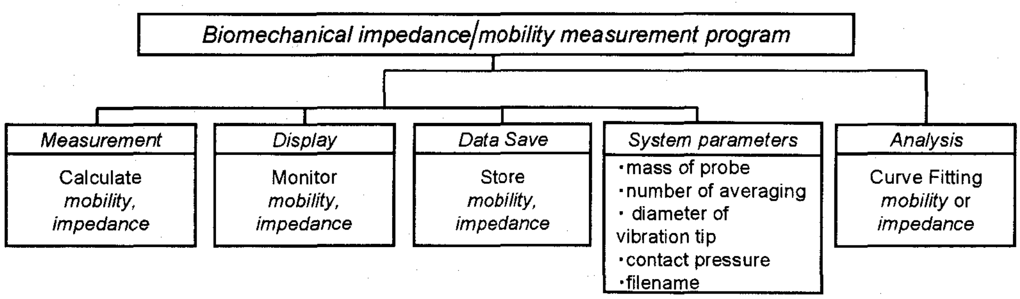

Fig. 3 Measurement program of biomechanical impedance/mobility.

vibrating amplitude, contact pressure, and diameter of the tip, have been examined. Fig. 5(a) shows the magnitude of mechanical mobility in case of vibration at five amplitudes. As is obvious from the figure, the mobility of silicone model is independent of vibrating amplitude and a linear relationship is established between the mobility and the amplitude within this range. The authors have already reported the linearity of living body within the vibrating velocity of 0.1 – 3 cm/s [6].

Fig.5(b) shows the mobility when the contact pressure changes from 10 to 100 gf and Fig5(c) shows the mobility when the contact area of vibration tip changes from 5 to 20 mm in diameter. It is clear from the figure that the mobility of the silicone model depends on the contact pressure and area. In the measurement of biomechanical properties of living body, the authors should consider the contact pressure and area, when comparing the measurement results, which are obtained by different researchers, different methods, or different subjects.

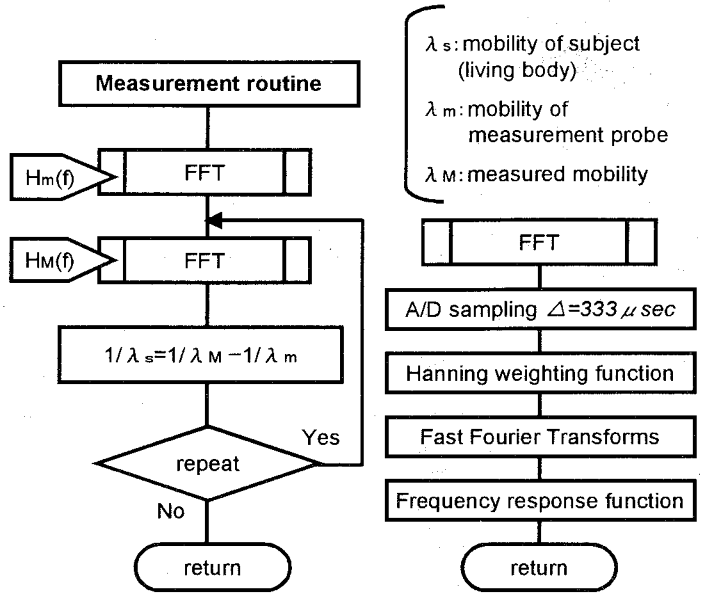

Fig.4 Measurement routine of the program.

4.2 Measurement of Biomechanical Properties

This measurement is applied to the living body. The measuring areas of body surface are thigh, temple, and forehead of the male subject, 23 years of age. The diameter of vibrating tip is 10 mm and the contact pressure is 50 gf. Fig.6(a), (b), and (c) show the biomechanical mobility spectra of thigh, temple, and forehead, respectively. They can be roughly classified into three spectra patterns: soft, intermediate, and stiff [7]. When converting three spectra to mechanical impedances, the resistance spectra of impedance show a monotonous increase with increasing frequency in a soft tissue, a nearly monotonous increase in a stiff tissue, and a decrease and increase in an intermediate tissue. The soft and intermediate patterns have a resonant frequency below 1 kHz, unlike the stiff pattern. Generally the larger gets the impedance magnitude the higher gets the resonant frequency.

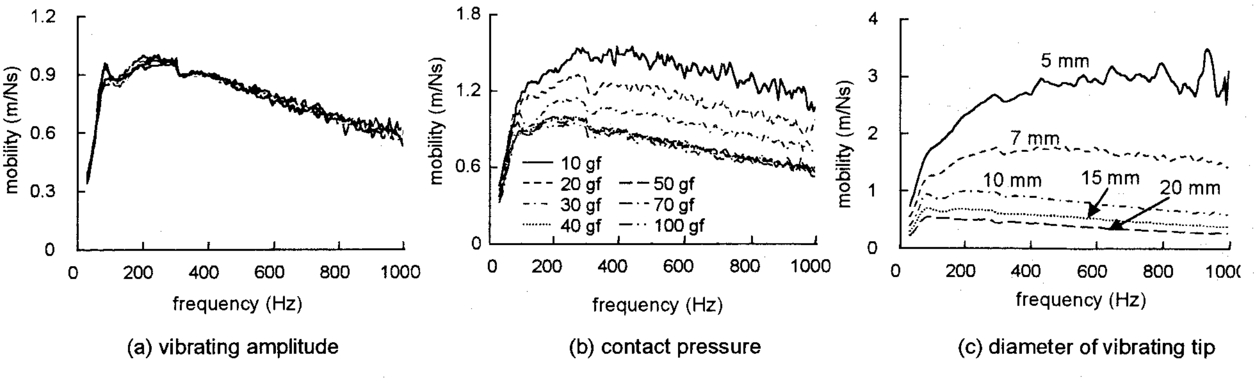

Fig.5 Mechanical mobility of silicone model under different measuring conditions.

The biomechanical properties obtained on the body surface also reflect a body structure [7]. The authors have experienced daily that the body structure influences tactile sensation and stiffness evaluation. The internal structure under the skin such as bone and muscle gives different measurement results. The biomechanical mobility spectrum in the figure (c) may show the dependence of body structure because of the thin skin of forehead.

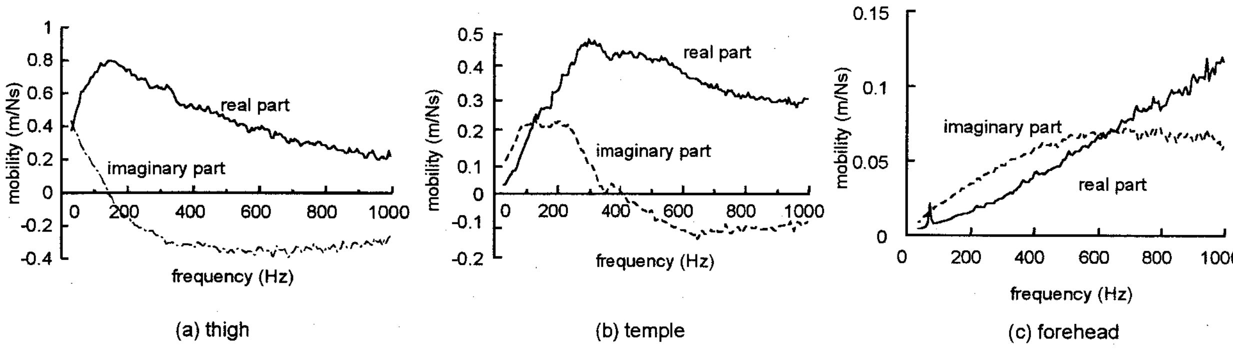

Fig.6 Mechanical mobility of thigh, temple and forehead (diameter of tip: 10 mm, contact pressure: 50 gf).

5. Conclusions

The aim of this study is to develop a portable measurement system of biomechanical impedance/mobility which can be used widely in the field of industry, skin science, sports science, rehabilitation *etc.* The system consists of the measuring probe, amplifier, and a note-typed personal computer. The developed measurement program is available to any computer which is worked under MS DOS compatible in Windows 95/98 operating system.

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