A FOOT-SOLE PRESSURE SENSORY FEEDBACK SYSTEM FOR LOWER LIMB PROSTHESIS

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ABSTRUCT

A foot-sole pressure sensory feedback system was developed to impove the activity of the lower limb amputee, applying the fluidics technology that can handle both information and energy for stimulation with very simple and compact circuit.

Each pressure of heel, small and large ball is detected with small rubber pouch installed in the artificial foot, and is translated to the vibration frequency through fluidics circuit, for cutaneous tactile display as pressure vibration.

With this device, the closed loop control system is newly constructed between amputee and artificial legs. The extent of the improvement of control ability was tested experimentally about the postural sway in standing with and without external disturbance.

Using of the sensory feedback system, the sway of ZMP of the A/K prosthesis side increases, but one of the normal side decreases. It was proved that the control ability should be improved with this device.

1. INTRODUCTION

The lower limb amputee has lost not only (1) the structure of weight bearing, but also (2) the skin sensation, (3) the afferent sensory nerves and (4) the driving torque of the lost articulations. And the conventional prosthetics has supplied only (1).

From the view point of man-machine system, (2) and (3) can be supplied by information transmission as sensory feedback via tactile display, applying the engineering technology, and (4) by the externally powered prosthesis.

Especially, the sensory feedback can, only with itself, recover something a lack of muscular coordination of the stump without using the external power.

There were many studies about the sensory feedback for artificial hands, but were little for artificial legs.[1] And in these cases, electrical cutaneous stimulation is often used for its performance of compact and low energy consumption for information transmission from prosthesis to amputee Though, electrical stimulation is susceptible to influence from outside, often causes the fluctuation of stimuli magnitude with the amputee's sweat, and has low dynamic range and locally less sensitive than mechanical tactile display. Moreover, it can only transmit the on-off contact information of the foot on the floor.

This is the reason we got to work on this problem.

We have developed a foot-sole pressure sensory feedback system with mechanical vibrotactile stimulation method, applying the fluidics technology that can handle both information and energy with very simple and compact circuit.

With this device, the information of the foot-sole pressure can be transmitted continuously, and the closed loop control circuit is newly constructed.

First, we will describe on the fundamental characteristics of the developed devise, second, on the cutaneous information transmission characteristics on human body, and last, on the extent of the improvement of control ability, tested experimentally about the postural sway in standing with and without external disturbance.

2. FLUIDIC FOOT-SOLE PRESSURE SENSORY FEEDBACK SYSTEM

The overview of the developed system is shown in Fig.1 and the circuit is shown in Fig.2 . A bistable amplifier of pure fluidics component (CORNING CO. CF-05) is used as a feedback oscillator, for each channel of heel, small and large ball. Output pressure vibration P_0 is transmitted cutaneously as mechanical vibrotactile stimuli with pressure vibrator. Oscillation frequency is changed continuously through the flow control valve, which controls the output flow rate Q_0 of the oscillator by the foot-sole pressure $P_{F1} \sim P_{F3}$. Pressure adjuster is used to regulate the foot-sole pressure suitable for each subject.

Pressure vibrator is made of silicone rubber pouch (26 mm dia. and 8 mm thickness), compact[2] and superior endurance compared with the usual mechanical vibrator. The working fluid is 0.5 μ filtered dry air. The pressure vibration transducer circuit is only 150 g weight, and can be installed in the prosthesis.

Fig.1 Fluidic foot-sole pressure sensory feedback system installed in the lower limb prosthesis

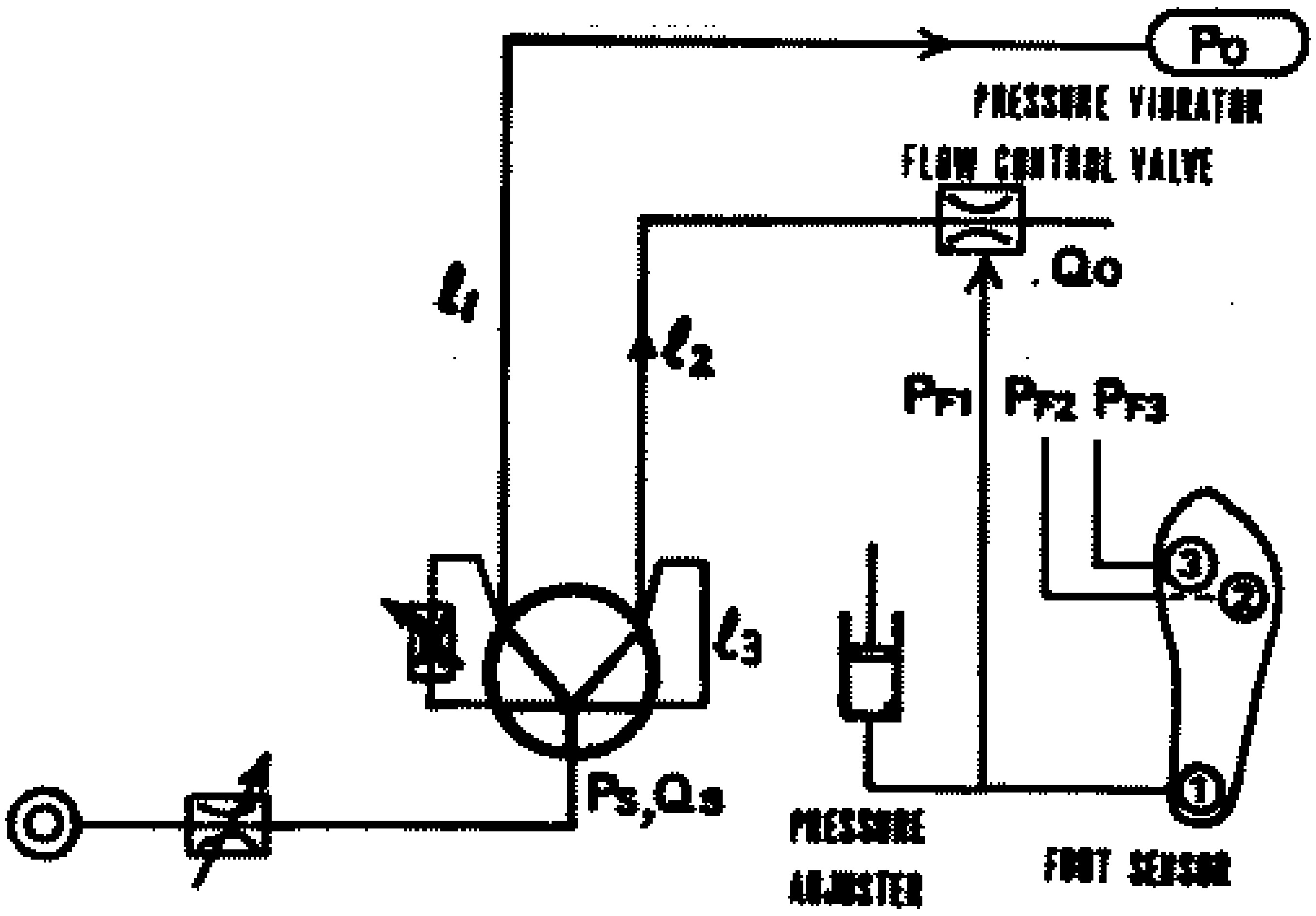


Fig.2 Circuit of the fluidic foot-sole pressure sensory feedback device

3. BASIC CHARACTERISTICS OF THE SYSTEM

Flow rate was measured by mass flow meter, and pressure and oscillation frequency were measured by the output wave form of the piezo-electric pressure transducer.

3.1 CHARACTERISTICS OF FLOW CONTROL VALVE

There was no useful device of pressure to frequency converter,so, a diaphram type flow control valve was newly manufactured for trial. The pressure P_F from the foot-sole shifts the silicone rubber diaphram from the initial position h_0 and change the output flow rate Q_0 of oscillator circuit. The thickness and material of rubber diaphram affect its characteristics. In Fig.3 and Fig.4, the mechanism and one of those characteristics are shown.

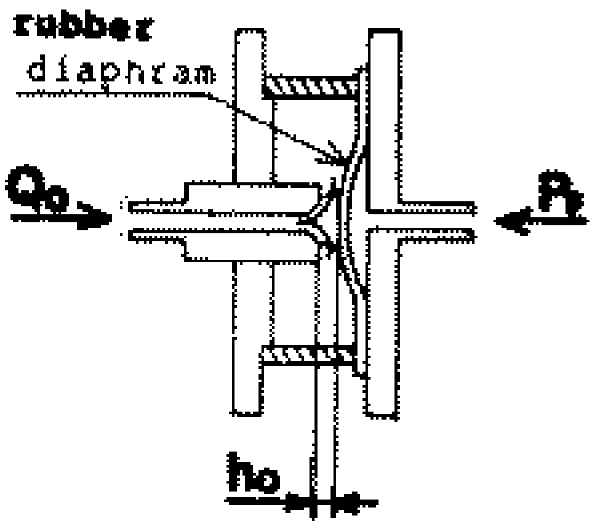


Fig.3 Construction of the flow control valve

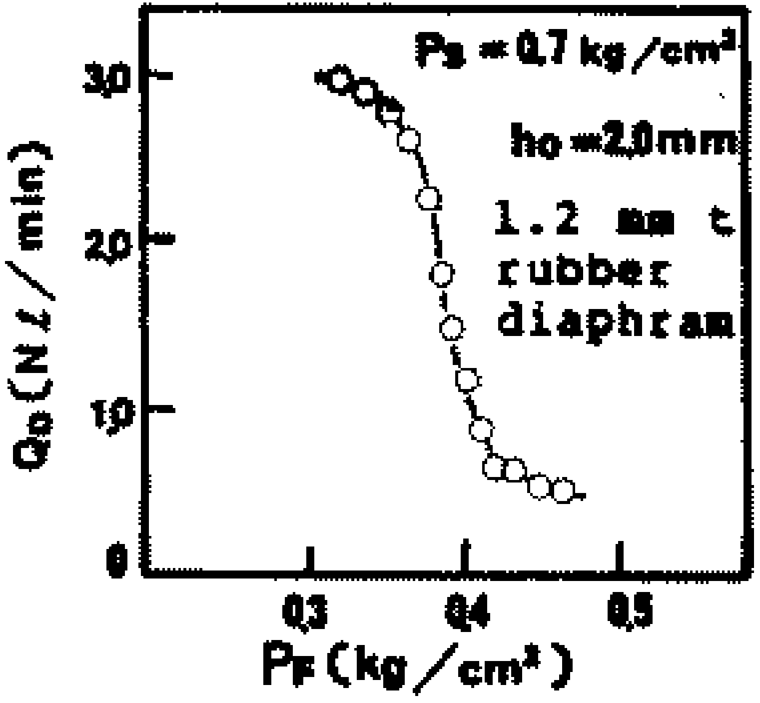


Fig.4 An example of the characteristics of the flow control valve

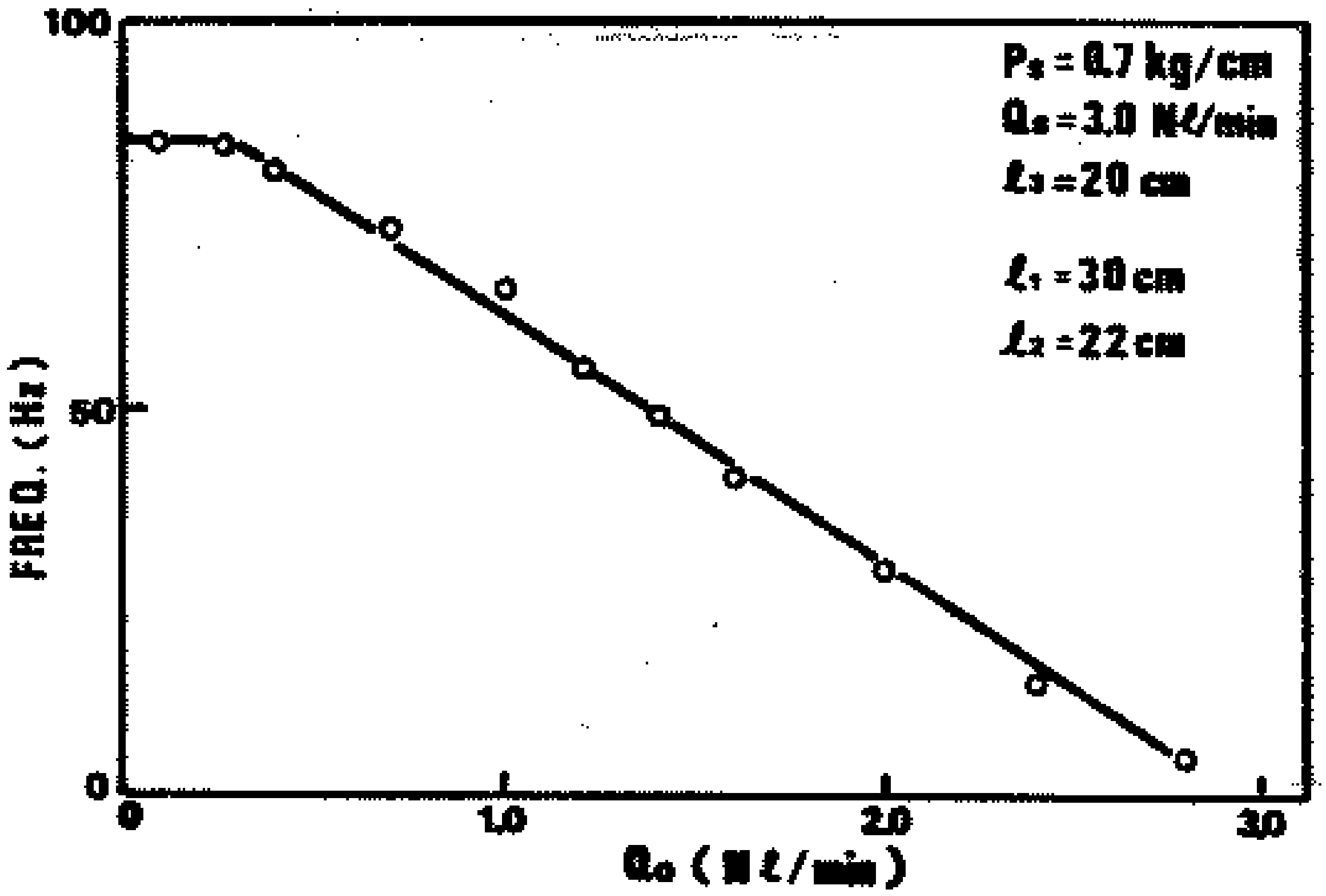


Fig.5 Static characteristics of stimuli frequency to output flow rate

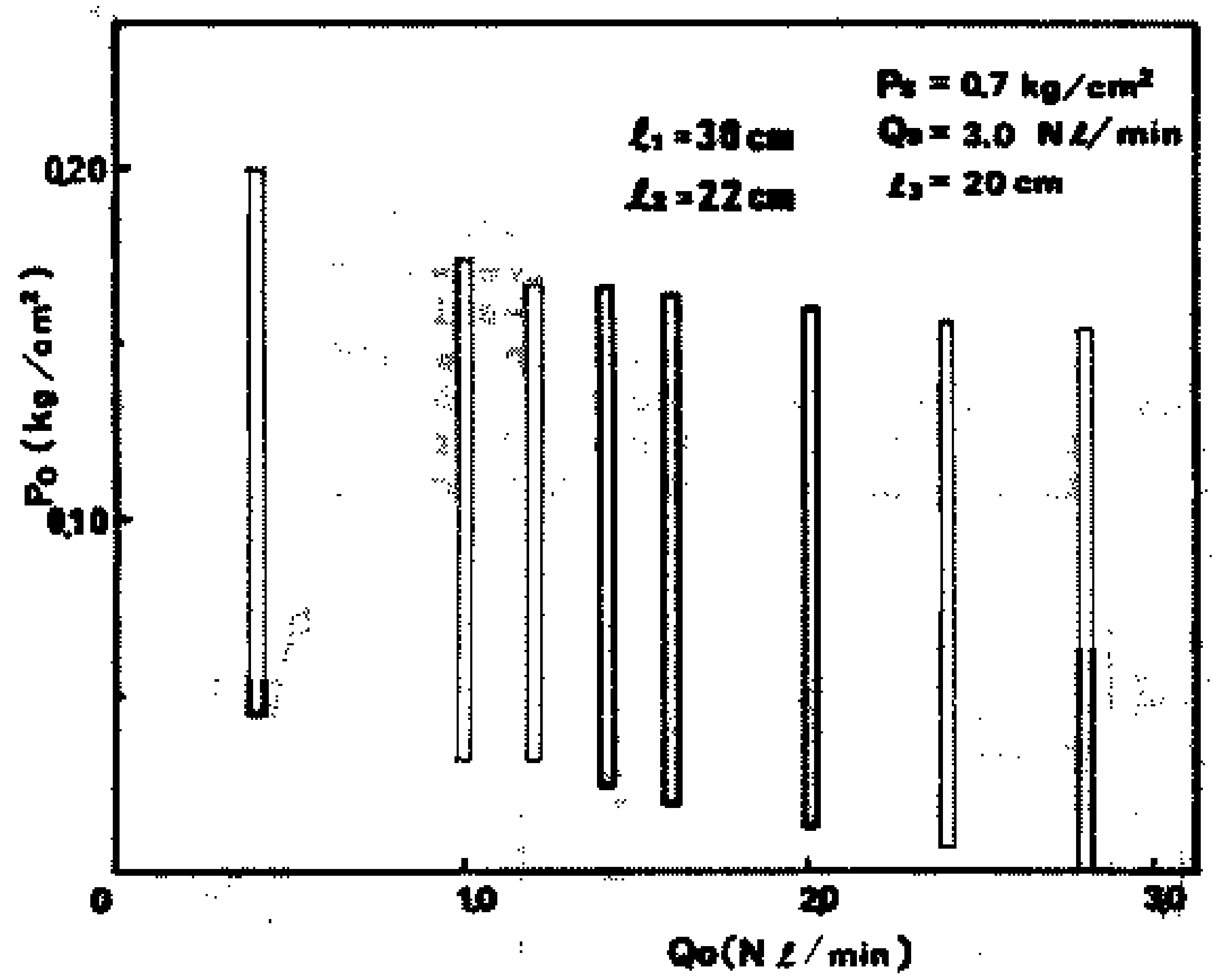


Fig.6 Static characteristics of stimuli amplitude to output flow rate

3.2 STATIC CHARACTERISTICS OF THE CIRCUIT

The tube length from the output port of pure fluidics component to pressure vibrator (ℓ_1) and to the flow control valve (ℓ_2) acts as resonator and provide maximum oscillation frequency. The oscillation frequency increases, as ℓ_1 and/or ℓ_2 are shorter. As the pressure in the feedback tube of pressure vibrator side is higher than one of another side, it was depressed by a flow rate control valve. And so, the feedback tube length (ℓ_3) does not affect the maximum oscillation frequency.

Supposing to install this device in the prosthesis, ℓ_1 was settled to be 30 cm and ℓ_2 to be 22 cm. In this case, output frequency and amplitude of stimuli to output flow rate are characterized as in Fig.5 and Fig.6. Oscillation frequency varies linearly from 10 to 80 Hz with the decrease of Q_e, but amplitude is rather constant.

3.3 DYNAMIC CHARACTERISTICS OF THE CIRCUIT

The response against the sinusoidal amplitude force input to the foot-sole pressure sensor is shown in Fig.7 and Fig.8. Gain is almost constant and slightly decreases over 20Hz. Delay time is about 10 msec over 10 Hz.

The response against the impulse force is shown in Fig.9 . The delay time is about 4 msec and it has enough responsibility compared with the stance phase period of about 400~600 msec.

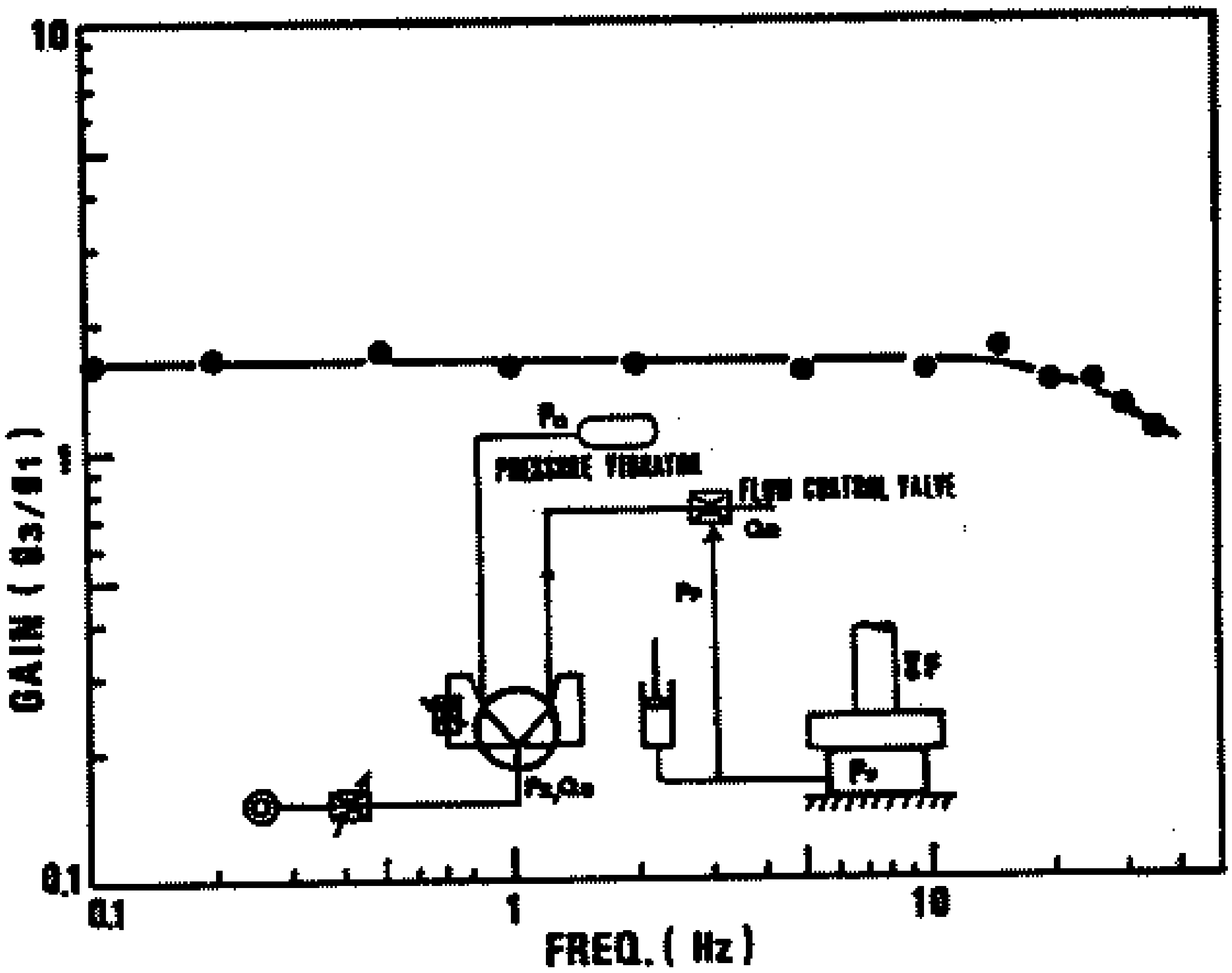


Fig.7 Frequency response (gain) of the system

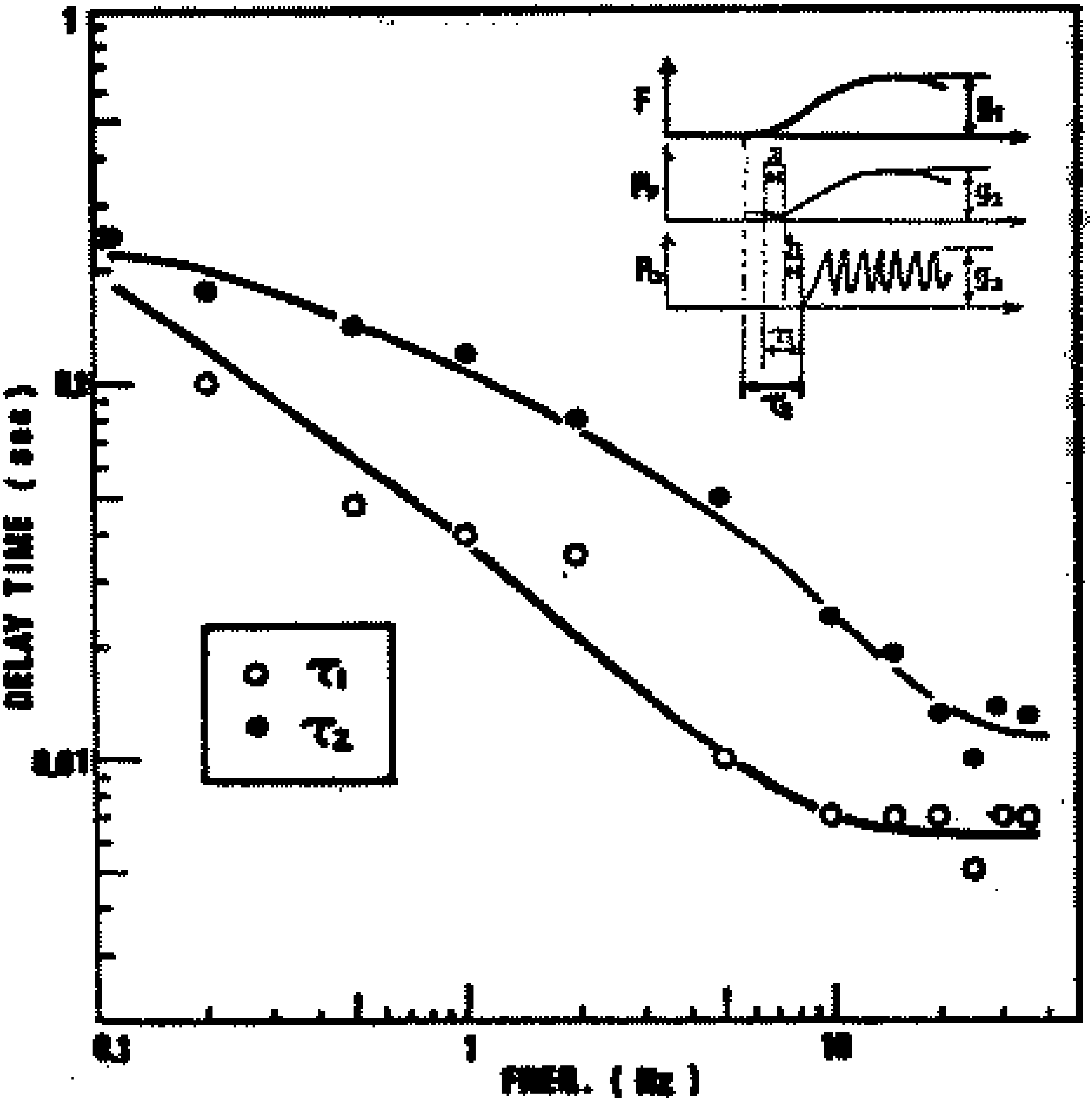


Fig.8 frequency response (delay time) of the system

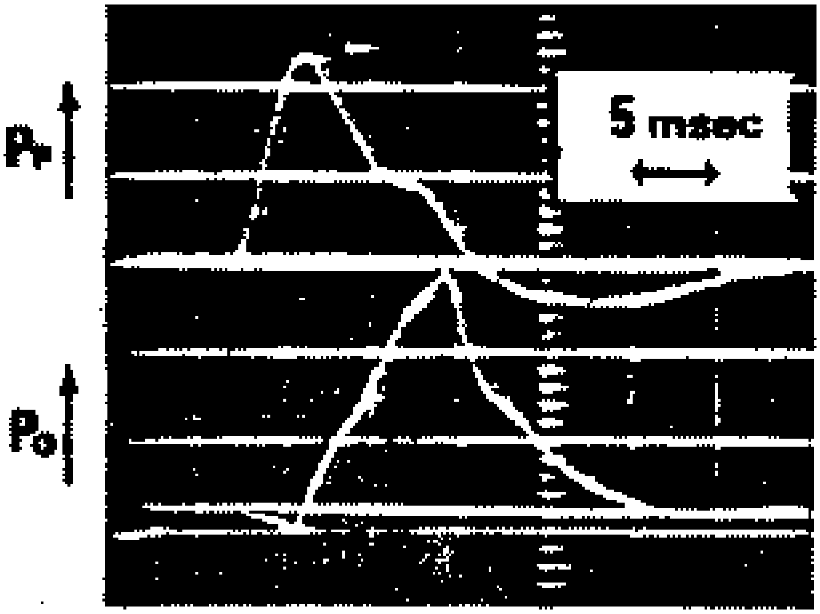


Fig.9 Impulse response of the system

4 INFORMATION TRANSMISSION CHARACTERISTICS

As the amputated position of lower limb is different to each other and cutaneous sensation is much affected with the amputation, the information transmission characteristics of the device were measured psychophysically about the right thigh of 3 normal subjects.

4.1 THRESHOLD OF SENSATION

The threshold value of sensation amplitude is measured by a method of conductor adjustment.[3] The threshold amplitude becomes high sharply over the compressive force of 0.1 kg/cm on the skin. (see Fig.10) , and becomes slightly low with increase of the stimulus frequency (see Fig.11). Maximum stimulus amplitude is over 20 dB of the threshold, and can be raised supplying higher pressure to the device, so, enough dynamic range can be obtained.

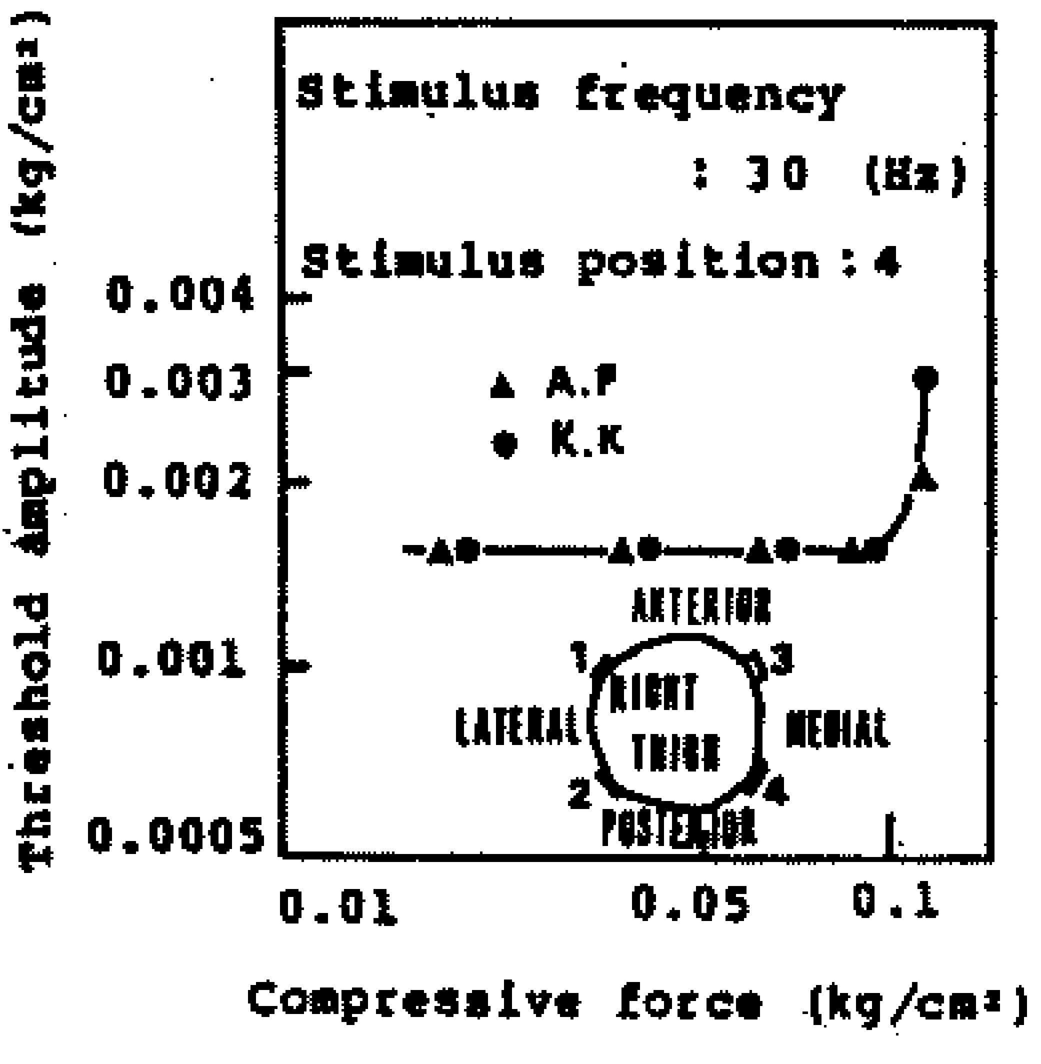


Fig.10 Threshold amplitude to compressive force on the skin

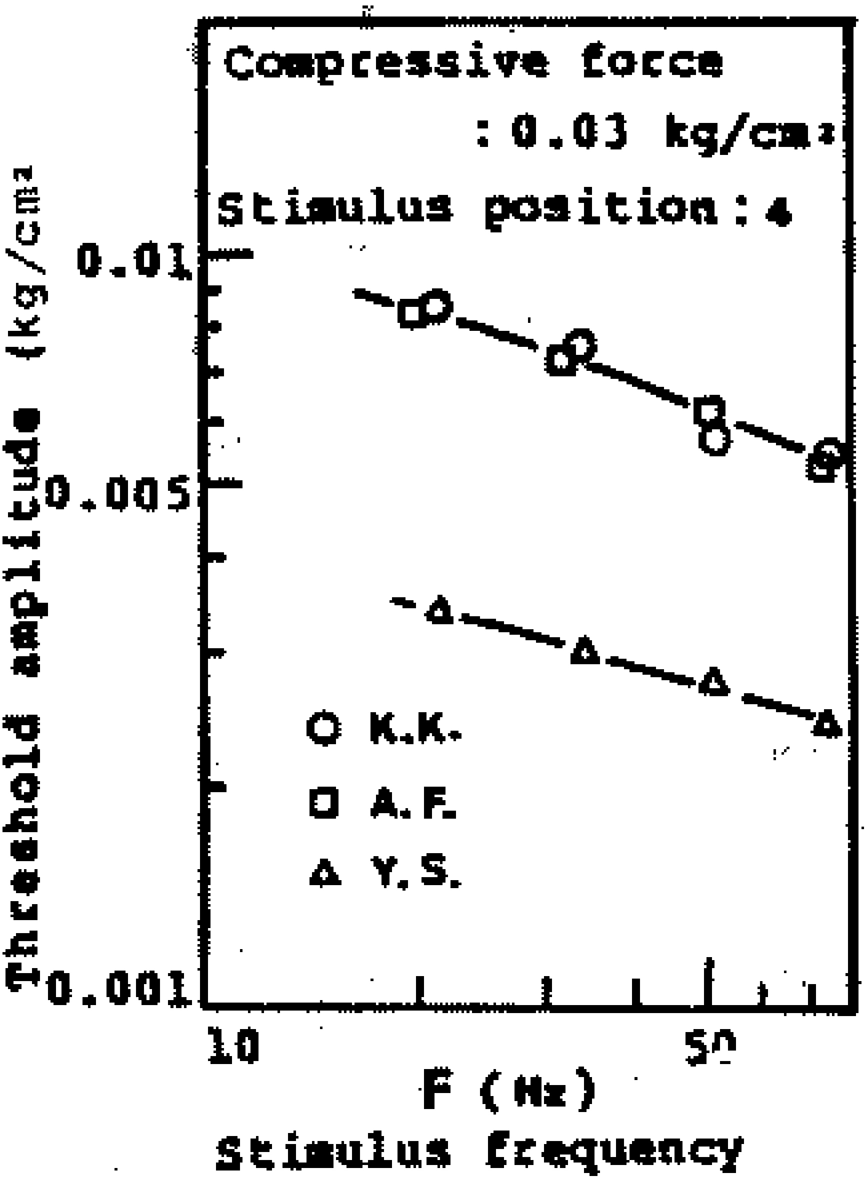


Fig.11 Threshold amplitude to stimulus frequency

4.2 JUST NOTICEABLE DIFFERENCE

Just noticiable difference (j.n.d.) of frequency was measured with a method of constant stimuli.[3] The result is shown in Fig.12 . From the j.n.d., the channel capacity N is calicu-lated from

$$N = \log_2 \int_{\Gamma} \frac{dF}{\Delta F} \qquad \cdots\cdots \quad (1)$$

where, ΔF is the j.n.d. of frequency and Γ is the dynamic range (10-80 Hz). In our device, the channel capacity is approximately 4 bits about the normal subjects.

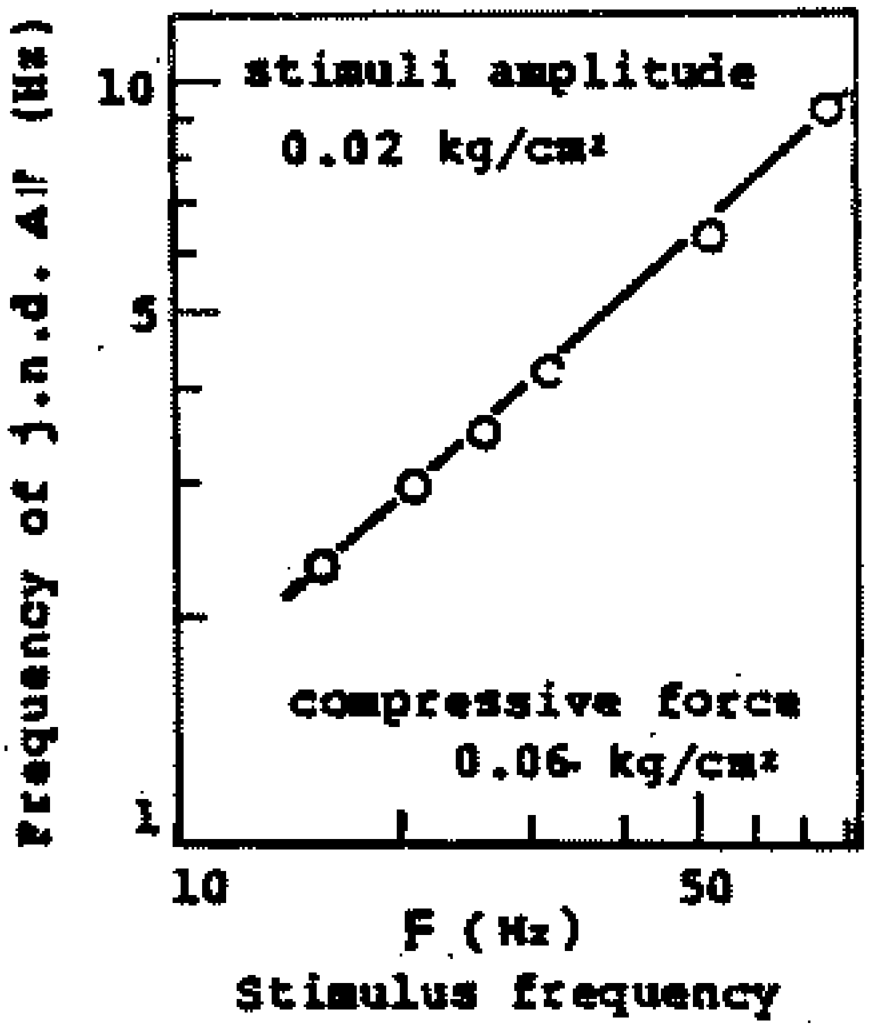


Fig.12 Frequency of just noticeable difference to stimulus frequency

5 EVALUATION

With the foot-sole pressure sensory feedback device, the property of the lost sensory feedback loop is remarkably compensated and the improvement of the control ability of weight bearing balance is expected. This was examined experimentally by measuring the sway in standing posture. The experiments were taken place under the condition of external disturbance and no disturbance. The sway of standing posture was adopted because of its simple control compared with walking et al.

Two A/K amputees were subjected. Each vibration signal from the 3 places of the foot-sole was transmitted to the corresponding position in the prosthetic socket apart about 10 cm from the stump end. Heel was corresponded to the posterior of the stump, small ball to the anterior lateral side, and large ball to anterior medial side. The phantom sensation was not observed from the introspection of the subject.

The experimental conditions are listed in Tab.1 . Eye mask was used and eyes were not closed. This is due to shut off the visual sensation of subject without losing the sense of equilibrium of his body. External disturbance was given by the abrupt relaxation of backward tension force.

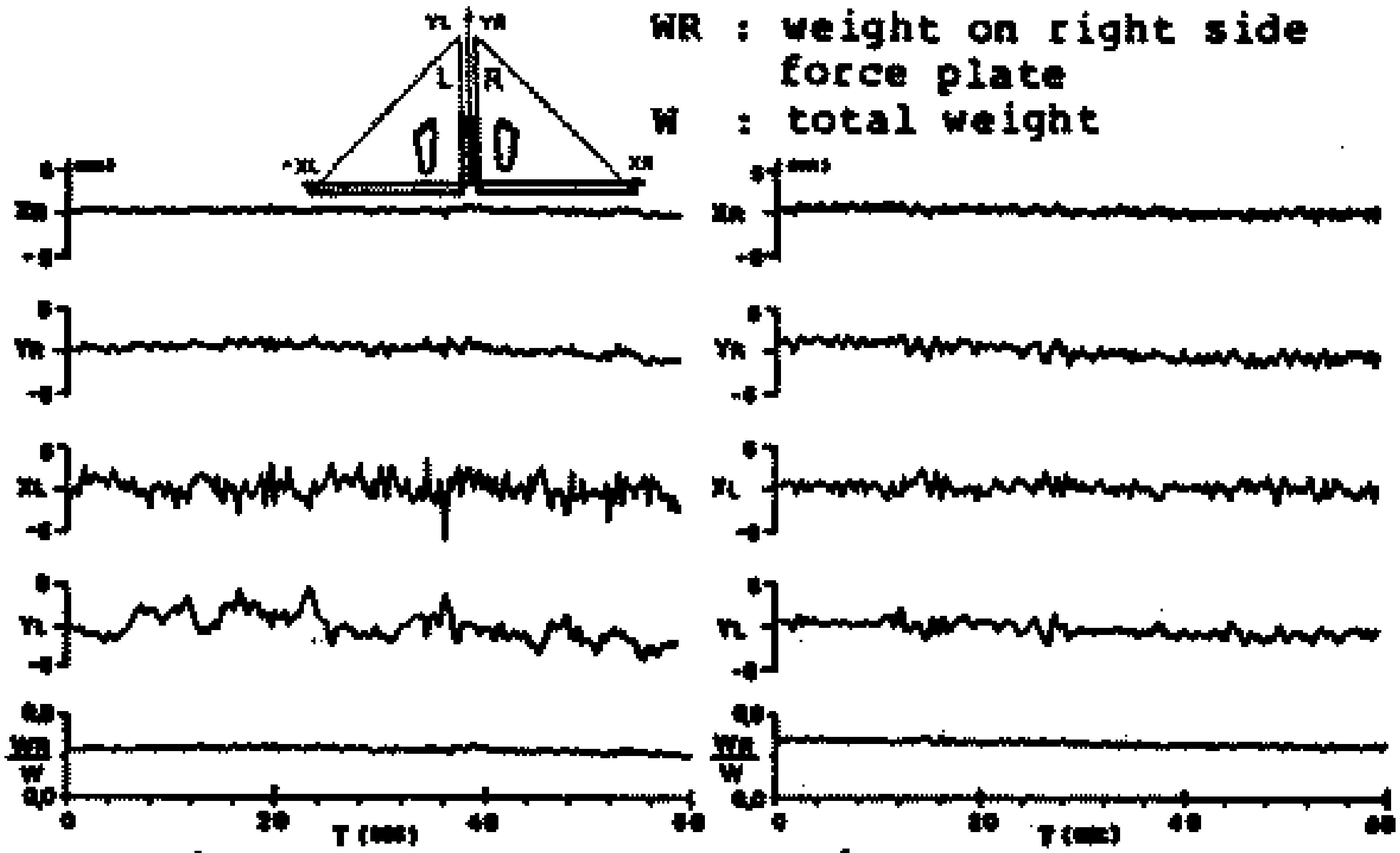
The subject wearing the sensory feedback device was asked to stand on the two force plates,right and left legs separately. And the sway of ZMP was measured during 5 min. Between each experiment, the subject takes a rest more than 5 min.

Data were processed with HP-1000 mini-computer and all the results were graphed on X-Y plotter. Each data sampled on data recorder was converted to digital signal at 30 Hz sampling rate. Auto correlation function is caliculated from 1024 data about 10 times. Power spectrum was caliculated from Fourie transform of the mean of the auto correlation functions.

The sway component subtructed a constant mean value is shown in Fig.13. The RMS value and power spectrum of the same data are shown in Tab.2 and Fig.14. With the sensory feedback system, weight support ratio of the prosthetic side increases from 0.27 to 0.37 , and the sway of ZMP of the same side increases, but one of the normal side decreases. this is not found from the total sway, only which hitherto studies objected. About the power spectrum component below 10Hz, the prosthesis side increases and the normal side decreases with the sensory feedback, but not so clear as the RMS values.

The results dealed the external disturbance is shown in Fig.15. In the case, ZMP of both sides indicate same behavior when the sensory feedback system works.

From these results, it is proved that this foot-sole pressure sensory feedback system can improve the control ability of the lower limb amputee without using the external power.

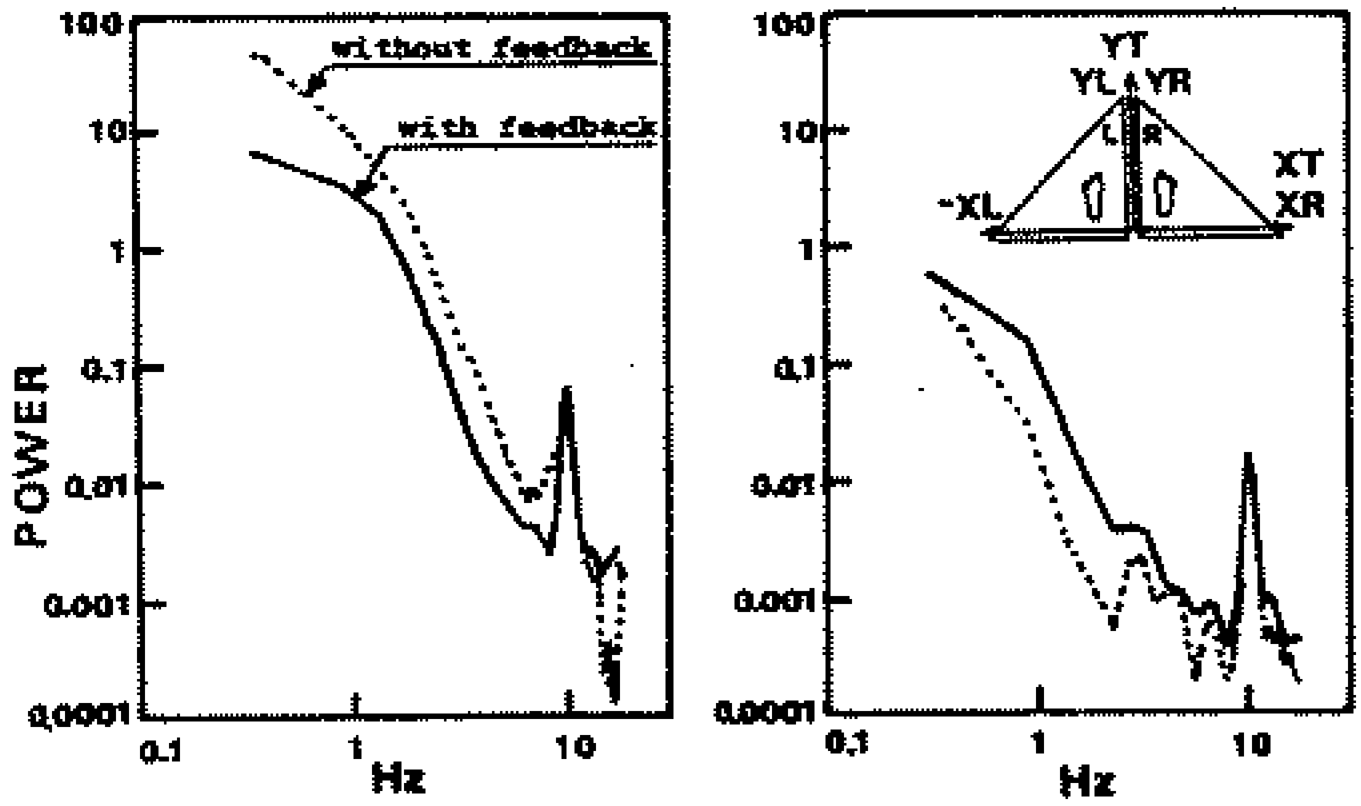


a without feedback b with feedback

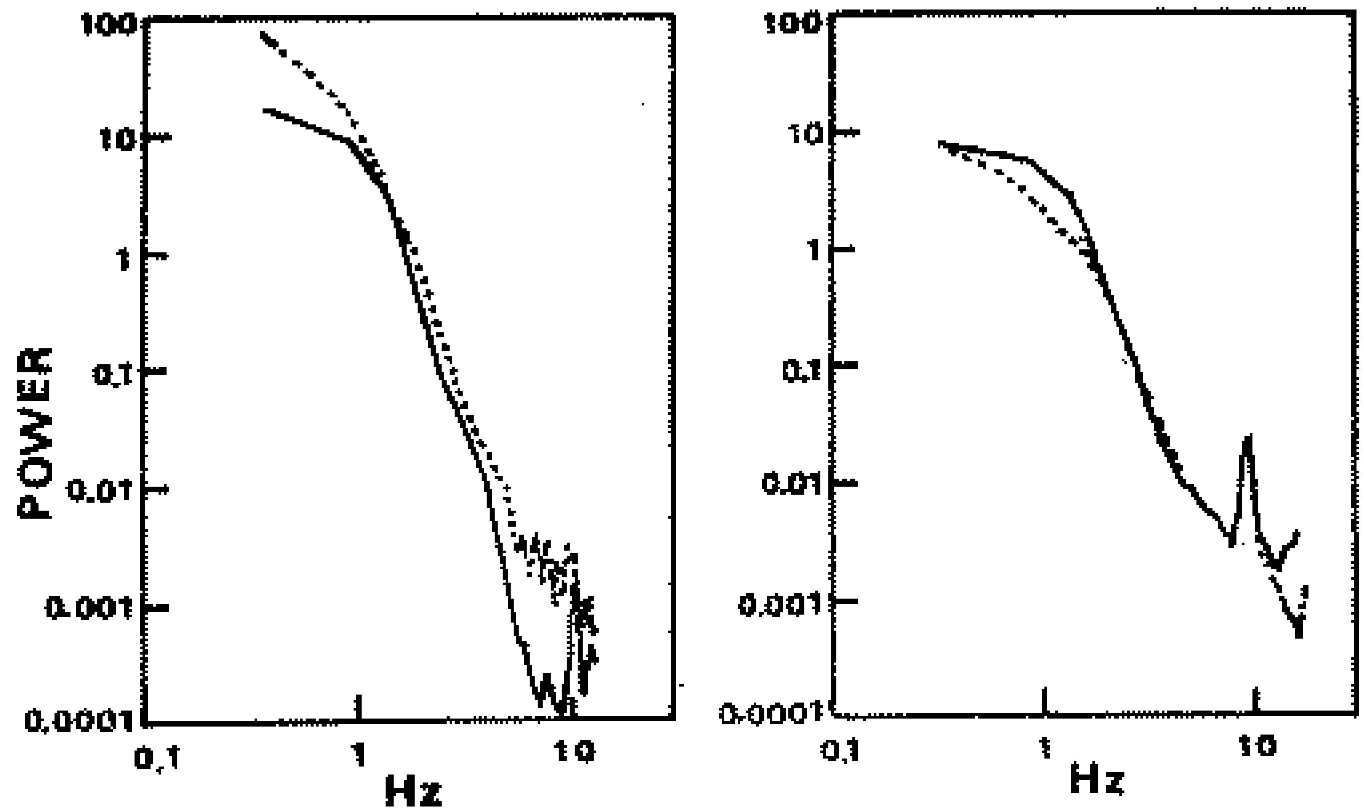
Fig.13 Sway component of ZMP in standing posture without external disturbance (subject: right side A/K shut off visual sensation with eye mask)

Tab.1 Experimental condition

sensory feedback	with
	without
visual sensation	eyes open
	eyes open and closed with eye mask
external disturbance	not dealed
	dealed



(a) XL (b) XR



(c) YL (d) YR

Fig.14 - Power spectrum of ZMP (from the same data of Fig.13)

Tab.2 RMS values of ZMP sway
(from the same data of Fig.13)

	without feedback	with feedback
XR	0.50mm	2.41 mm
YR	3.59	8.02
XL	6.13	3.78
YL	11.37	7.21
XT	5.51	4.22
YT	7.57	7.04

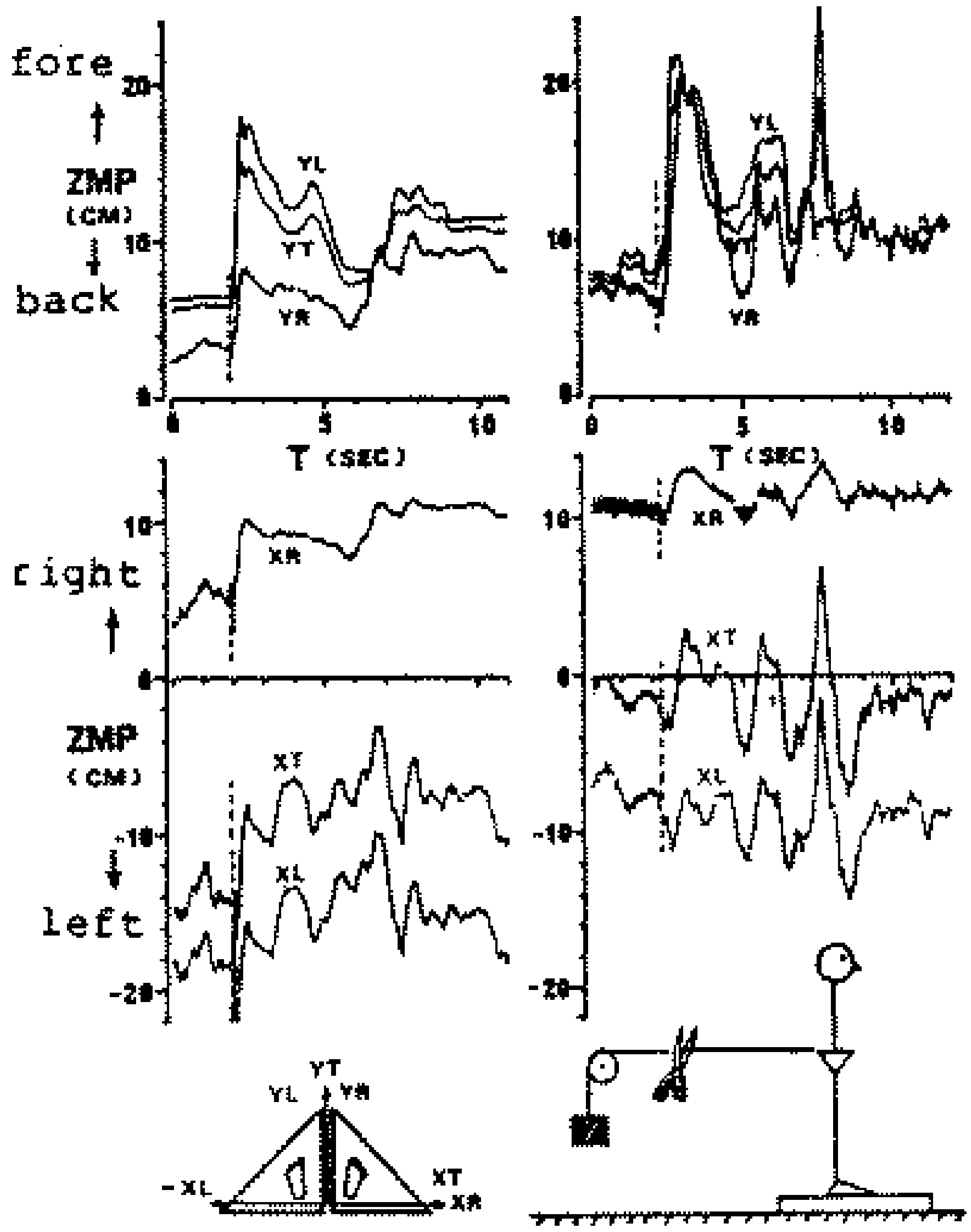


Fig.15 Sway of ZMP with external step disturbance
(at the dotted line, the step disturbance dealed
subject: right side A/K , shut off visual sensation
with eye mask)

6. CONCLUSION

To improve the activity of the lower limb amputee, a useful foot-sole pressure sensory feedback system has been developed.

The device is constructed only from the pnewmatic and fluidic parts applying the fluidics technology. Mechanical vibrotactile stimuli is displayed cutaneously on the amputee′s stump surface over the frequency range of 10~80 Hz continuously proportional to the foot-sole pressure. Each cutaneous display channel has approximately 4 bits capacity and phantom sensation was not observed from the introspection of subjects.

The effectiveness of this device was examined experimentally about the standing postural sway with and without external disturbance. With the sensory feedback, the sway and the weight support ratio of the prosthesis side increase and those of the normal side decrease. This is confirmed about the wave form, RMS values or power spectrum components of the sway of each side ZMP. These have not been obtained from hitherto studies which objected only the total sway. And against the external disturbance, the prosthetic side indicates the active effort to recover stable condition. From these, the availability of the developed system has been proved.

The future works are left as follows,

1. To measure the information transmission rate from prosthesis to amputee, to know if enough information should be conveyed in the short period of stance phase of walking et al.
2. To develop compact and right power source for amputee always to wear the system,and for clinical study to be possible.

and should be solved one by one and will be presented next opportunity.

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References

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