

# Measurement of Arterial Viscoelastic Properties Using a Foil-type Pressure Sensor and a Photoplethysmography

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**Abstract**— This paper proposes a noninvasive method for estimating the dynamic characteristics of arterial walls using pulse waves measured in various parts of the body by a foil-type pressure sensor (FPS) and a photoplethysmography. The FPS not only has high sensitivity and flexibility but also features the ability to continuously measure the alternating-current component of pulse waves, and was employed to measure pulse waves based on the tonometry approach. Then a method of estimating changes in arterial viscoelastic indices was proposed based on the measured pulse waves and photoplethysmograms. First, in order to measure amplitude variation of the blood pressure wave shape accurately, we examined suitable mechanical forces externally applied to the FPS, and found that values of 5 – 25 [N] yielded the best performance. Next, in order to verify the time characteristics of the pulse waves, the brachial-ankle Pulse Wave Velocity (baPWV) was measured and found that baPWVs measured by the FPS and the noninvasive vascular screening device are quite similar. We then estimated the arterial viscoelastic indices of a radial artery and a dorsal pedis artery when mechanical pain stimuli were applied to the subjects. The results suggested the estimated indices could be used to quantitatively assess vascular response caused by sympathicotonia. We thus concluded the proposed method enabled noninvasive measurement of pulse waves and estimation of viscoelastic indices.

**Keywords**— Mechanical Impedance, Arterial wall, Pressure sensor, Arterial pressure, Photoplethysmogram.

## I. INTRODUCTION

Blood vessels are assumed to be pipes used to transport blood throughout the entire body. They have viscoelastic characteristics because they consist of smooth muscles and elastic fibers [1]. Blood pressure and blood flow are controlled by these vascular smooth muscles, which are contracted and relaxed by adjustments in the autonomic nervous and humoral regulation systems. The structural component of arterial walls is different from that of any other part of the body, with the arterioles having the highest percentage of smooth muscles in the body [1]. If the dynamic characteristics of an arteriole or near an arteriole can be quantified, it would be possible to evaluate autonomic nervous system activity.

Previously, many research groups have quantitatively studied the dynamic characteristics of the arterial wall. As an invasive method, an animals' aorta was used under exposed conditions to measure the viscoelastic characteristics of arterial walls [3], [4]. For example, Gow et al. [3] measured

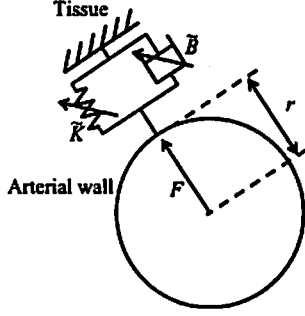


Fig. 1 Schematic description of the arterial wall impedance model

the arterial pressure and vessel diameter in a dog under anesthesia by using a hemodynamometer and calipers, and estimated the stiffness and viscosity of the arterial wall. Stefanadis *et al.* [4] measured vessel diameter by using a special catheter embedded with an ultrasonic probe, and estimated the stiffness of an arterial wall from this measured vessel diameter and the blood pressure. However, invasive methods carry a risk and cause discomfort to patients.

On the other hand, other groups have evaluated the dynamic characteristics of arterial walls by using data obtained with noninvasive methods. For example, Bank *et al.* [2] estimated the stiffness of the brachial artery from the measured vessel diameter and blood pressure by using an ultrasound device. Sakane *et al.* [5] measured the blood pressure and obtained finger photoplethysmograms, and then used these data to quantitatively estimate the dynamic characteristics of arterial walls in peripheral part. Ikeshita *et al.* [6] also estimated the stiffness and viscosity of the radial artery by using a similar method. However, in previous studies, the continuous blood pressure used to estimate the dynamic characteristics of blood vessels was measured only in the fingers and wrist. For example, to estimate the arterial viscoelasticity in the distal foot, the blood pressure needed to be measured at the distal foot. However, with the exception of the fingers and wrist, a noninvasive method of continuously measuring the blood pressure in a specific part of the body has never been proposed.

Therefore, this study proposes a noninvasive method of continuously measuring pulse waves and estimating the viscoelastic characteristics of arterial walls in various parts of the body by using a small, lightweight, foil-type pressure sensor (FPS) [7]. In particular, the pulse wave in the dorsal pedis artery was measured, and the change in vascular response caused by autonomic nerves was evaluated.

## II. ARTERIAL IMPEDANCE MODEL

Figure 1 illustrates the impedance model of the arterial wall [5]. This model only represents the characteristics of the wall in an arbitrary radius direction. When any reference time (for example, R wave timing) in the cardiac cycle was set, the impedance characteristic could be described using the stress and displacement of the arterial wall as follows:

$$dF(t) = Kdr(t) + B\dot{r}(t_0) \quad (1)$$

where  $dF(t) = F(t) - F(t_0)$ ,  $dr(t) = r(t) - r(t_0)$ ,  $d\dot{r}(t) = \dot{r}(t) - \dot{r}(t_0)$ .  $F(t)$  is the stress acting in the normal direction of the arterial wall;  $r(t)$  and  $\dot{r}(t)$  are the diameter of the arterial wall and its first derivative, respectively;  $t_0$  denotes the reference time which is defined as the timing when the R wave appears in each electrocardiogram (ECG) recognition cycle in this paper; and  $K$  and  $B$  are the coefficients of stiffness and viscosity, respectively. To estimate the impedance parameters given in (1), it is necessary to measure  $F(t)$  and  $r(t)$ . The stress exerted on the arterial wall is proportional to the arterial pressure as follows:

$$F(t) = k_f P_b(t_0) \quad (2)$$

where  $k_f$  is a constant and  $P_b(t)$  is the arterial pressure.

On the other hand, the diameter of the blood vessel in the radial direction  $r_v(t)$  was recorded using a photoplethysmogram:

$$r_v(t) = \frac{P_r(t) + A_D}{k_p} \quad (3)$$

where  $r_v$  is the summation of the vessel diameter in the measurement location,  $k_p$  is a constant,  $P_r(t)$  is the photoplethysmogram,  $A_D$  is the attenuation rate for the diameter of a blood vessel [5]. Therefore, from the above-mentioned relation, (1) can be expressed as follows:

$$dF(t) = \tilde{K}dr(t) + \tilde{B}d\dot{r}(t_0) \quad (4)$$

where  $dP_b(t) = P_b(t) - P_b(t_0)$ ,  $dP_r(t) = P_r(t) - P_r(t_0)$ ,  $d\dot{P}_r(t) = \dot{P}_r(t) - \dot{P}_r(t_0)$ , and  $\tilde{K} = K / k_f k_p$  and  $\tilde{B} = B / k_f k_p$  are the stiffness and viscosity of the arterial wall, respectively. In this paper,  $\tilde{K}$  and  $\tilde{B}$  are defined as the arterial viscoelastic indices.

For the estimation of the arterial viscoelastic indices, the arterial blood pressure needs to be measured, which measurement fulfills the following requirements:

- 1) The sensor has to measure a continuous blood pressure.
- 2) The sensor needs to have high sensitivity in order to measure pulse waves in various parts of the body.
- 3) The sensor needs to have flexibility to correspond to the shapes of various parts of the body.
- 4) In a long-term measurement, the sensor should be robust against drift.

In this study, an FPS to measure pulse waves is used because it satisfied the above four requirements.

## III. NONINVASIVE PULSE WAVE MEASUREMENT

Figure 2 shows the FPS (Foil-type Pressure Sensor) used to measure pulse waves [7]. When a pressure  $P(t)$  is applied to the FPS, the output voltage,  $V(t)$ , of the FPS can be described as follows:

$$V(t) = gIP(t) \quad (5)$$

where  $g$  is the specific output voltage constant for the



Fig. 2 Foil-type flexible pressure sensor

piezoelectric element,  $l$  is the distance between the electrodes. The low-frequency component of output voltage,  $V(t)$ , of the sensor is attenuated under the inner structure of the sensor, but the higher frequency component of the pulse wave is not. Thus, only the pressure variation of the alternating-current (AC) component of pulse waves can be measured [7].

In this paper, the tonometry method [8] was adopted for measuring pulse wave by using the FPS. Figure 3 shows a developed pulse-wave measuring apparatus. The constructed device was arranged to place the FPS and a rubber plate on the measured artery, and the device was fixed so that an external force of 1 [N] was applied to the measured part by using a band. An external force was applied from the normal direction of the FPS so that the arterial wall could flatten when the pulse wave was measured. The output values of the FPS did not contain the direct-current component of the measured pulse wave. Then, the output voltage  $V(t)$  is converted to a variation of the arterial pressure,  $\tilde{P}_b(t)$ , around mean arterial pressure. A variation of the arterial pressure  $\tilde{P}_b(t)$  can be described as follow:

$$\tilde{P}_b(t) = \frac{PP_{FJ}(t)}{V_{FJ}} V(t) \quad (6)$$

where  $PP_{FJ}$  is the pulse pressure measured by an automated sphygmomanometer, and  $V_{FJ}$  is the corresponding peak-to-peak voltage measured by the FPS.  $PP_{FJ}$  and  $V_{FJ}$  are measured simultaneously at the beginning of the measurement period. Thus, the values  $\tilde{P}_b(t)$  were assigned to  $dP_b(t)$ , and it was possible to estimate the arterial viscoelastic indices noninvasively.

#### IV. EXPERIMENT

##### A. Experimental setup

The signal measurement unit measured pulse waves from the left radial artery by using the FPS. The blood pressure and an electrocardiogram signal were also measured from the left radial artery and the chest by using a physiological monitor (BP-608, OMRON Colin), and a photoplethysmogram signal was measured on the second finger of the right hand by using a pulse oximeter (OLV-3100, Nihon Kohden). Mechanical stimuli were employed as noxious stimuli to increase the sympathetic nerve activity. The mechanical stimuli were

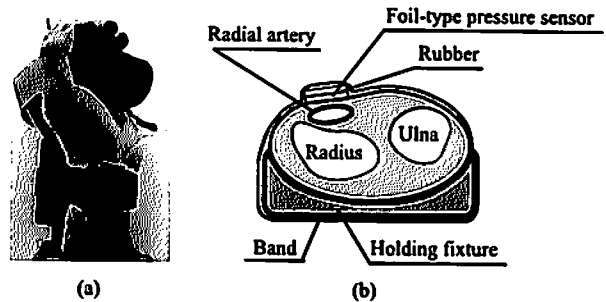


Fig. 3 Developed pulse-wave measuring apparatus: (a) A photo of the developed apparatus, (b) A schematic cross-sectional view

measured using a digital force gauge (FGP-5, Nidec-Shimpo) with a cone-shaped attachment (point diameter  $\phi = 0.36$  [mm]) that was pushed onto the dorsum of the subject's right foot while the pushing intensity was measured. All of the signals were simultaneously measured at 1005 [Hz] by using an analog-digital card (CSI-360116, Interface), and the values were entered into a computer. The signal from the FPS was converted to voltage signal by a charge amplifier (CH-1200, Ono Sokki) and entered into the computer.

##### B. Experiment for measurement of pulse wave

First, to accurately measure the amplitude variation of the blood pressure, the pulse waves recorded using the proposed method were compared with those recorded using the conventional arterial tonometry method. Seven healthy and male subjects (Subjects A – G) were recruited. All of the subjects were seated in a resting state, and the signals were measured in a minute. Then, an external force of 0 – 40 [N] vertical to the FPS was applied by using a force gauge with a columnar attachment ( $\phi = 12$  [mm]). To evaluate the suitable mechanical force, the amplitude of the pulse waves (the piezoelectric pulse wave amplitude) were measured by the sensor with respect to each RR interval of the ECG. Subsequently, the correlation coefficient of the wave shape in one minute and in one beat between the pulse waves measured by the FPS and blood pressure were calculated. Also, the coherence function and the phase of the cross-spectrum were calculated to compare the linearity of the pulse waves measured by the FPS with the blood pressure in the frequency domain.

Next, to verify the time characteristics of the pulse waves detected by the FPS, the brachial-ankle Pulse Wave Velocity (baPWV) [9] measured by using the noninvasive vascular screening device (form PWV/ABI, BP-203RPE II, Omron Colin) were compared with the one recorded using the proposed method. One subject (Subject G) was recruited. He was positioned supine in a resting state, and the signals were measured in 2 minute. The baPWV was measured on both sides of the body.

##### C. Experiment for evaluation of blood vessel function

By applying the suitable external force to the FPS, the pulse waves were measured while mechanical pain stimuli were delivered to the subject. The same seven male subjects

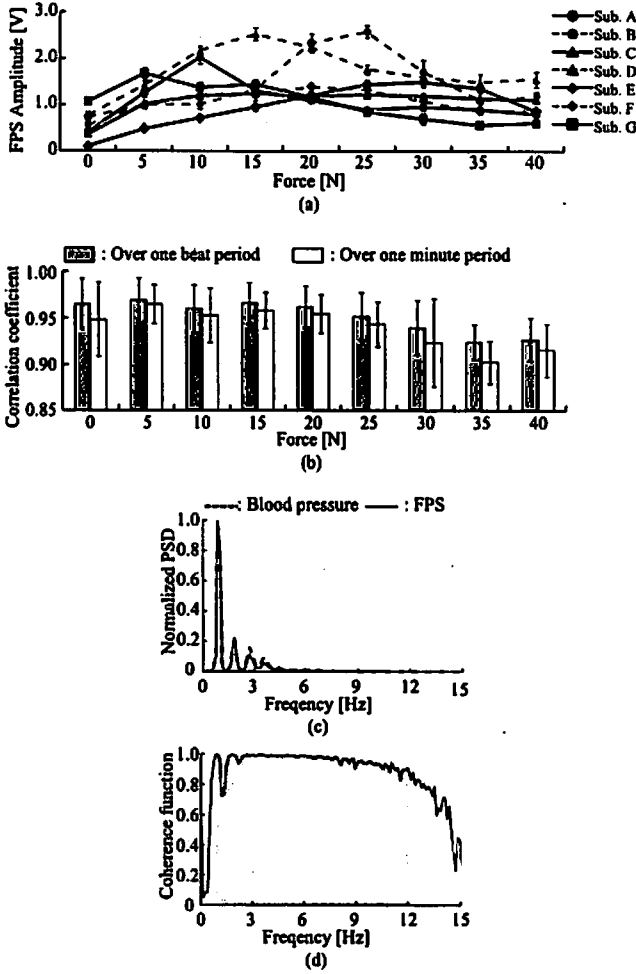


Fig. 4 Experimental results of measurement at rest: (a) Amplitude of pulse waves measured by the FPS, (b) Correlation coefficients between the pulse wave measured by the FPS and the wave of blood pressure, (c) Power spectral densities, (d) Coherence function

mentioned in section IV-B were recruited. The external force that yielded the best performance in the experiment described in section IV-B was used for the FPS.

Furthermore, to evaluate the effectiveness of the proposed method, the pulse wave of a dorsal pedis artery were measured and the arterial viscoelastic indices were estimated. Five subjects of section IV-B (Subjects B, C, D, F, and G) were recruited. In a sitting posture, each biosignal was measured from the left dorsal pedis artery and the digitus secundus of the left foot by using the FPS and a pulse oximeter, respectively. 15 [N] of the applied force of the FPS was used, as determined in the experiment of section IV-B. To avoid any psychological influence from the sight of the stimulator, none of them were allowed to see it. The measurements were repeated once for each stimulation intensity and were performed in a resting state (0 – 60 [sec]), a stimulated state (60 – 80 [sec]), and a resting state again (80 – 140 [sec]). The stimulation intensities was 3 [N] onto the subject's dorsum of right foot by using a digital force gauge.

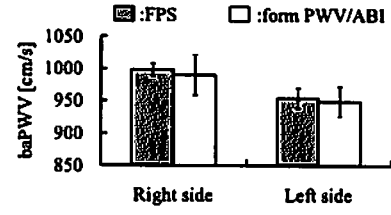


Fig. 5 Comparison between the baPWVs of both sides of the body measured by the noninvasive vascular screening device and the FPS (Subject G)

Generally, because blood vessel pressures and photo-plethysmograms have individual differences, absolute values of viscoelasticity vary among individuals [10]. Therefore, the estimated values were normalized by the corresponding standard values at the time of the rest state. Thus, the normalizations of  $\tilde{K}$  and  $\tilde{B}$  were performed using the following equations:

$$\begin{aligned} K_{BPn} &= \frac{\tilde{K}_{BP}}{K_{BPr}} & B_{BPn} &= \frac{\tilde{B}_{BP}}{B_{BPr}} \\ K_{FPSn} &= \frac{\tilde{K}_{FPS}}{K_{FPSr}} & B_{FPSn} &= \frac{\tilde{B}_{FPS}}{B_{FPSr}} \end{aligned} \quad (7)$$

where  $K_{BPr}$  and  $B_{BPr}$  are the stiffness and viscosity estimated using the automated sphygmomanometer in a resting state and  $K_{BPn}$  and  $B_{BPn}$  are the normalized values of stiffness and viscosity, respectively. Also,  $K_{FPSr}$  and  $B_{FPSr}$  are the stiffness and viscosity estimated using the FPS in a resting state, and  $K_{FPSn}$  and  $B_{FPSn}$  are the normalized values of stiffness and viscosity, respectively.

## V. RESULTS

### A. Experiment for measurement of pulse wave

Figure 4 (a) shows the average piezoelectric pulse wave amplitudes for all of the subjects when various mechanical forces were applied. In Figure 4 (a), each subject's maximum value of external force is approximately 5 – 25 [N].

Figure 4 (b) shows the average correlation coefficients of the wave shapes for all of the subjects in one minute and one heartbeat between pulse waves measured by the FPS and blood pressure when various mechanical forces were applied. Figure 4 (b) shows that the correlation coefficients of the wave shapes in one minute and one heartbeat had values of 0.9 or greater for all of the subjects when an external force of 10 – 25 [N] was applied. Figures 4 (c) and (d) show the power spectrum density normalized by the maximum value and the coherence function of Subject A when an external force of 10 [N] was applied. In Figure 4 (c), the results show that the pulse waves measured by the FPS had the same properties as those of the blood pressure. Moreover, in Figure 4 (d), the coherence function is approximately 1 when the frequency is 0.74 – 12 [Hz]. The pulse waves measured by the FPS and blood pressure had a high linearity. Also, the phase of the cross-spectrum between the FPS and blood pressure was almost 0 in the frequency domain of 0 – 15 [Hz]. These

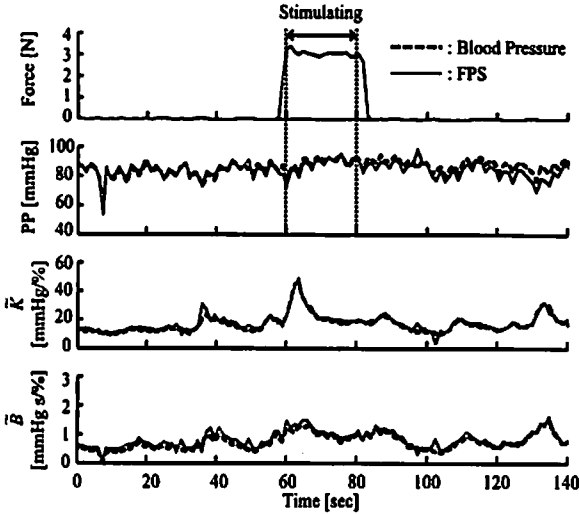


Fig. 6 Change of arterial wall viscoelasticity with mechanical stimuli

tendencies were confirmed for the results of all of the subjects. Thus, it was confirmed that the wave shape and frequency characteristic of the pulse waves measured by the FPS had a close correlation with those of the blood pressure when an external force of 5 – 25 [N] was applied. Consequently, an external force of 5 – 25 [N] is recommended to measure the pulse wave by using the proposed method.

Figure 5 shows the measurement results of the baPWV using by the noninvasive vascular screening device and the FPS. The result indicates that the baPWV measured by the FPS is quite similar to the one by the noninvasive vascular screening device.

### B. Experiment for evaluation of arterial viscoelasticity in a peripheral part

Figure 6 shows the experimental results for Subject A when an external force of 10 [N] was applied. These figures show, from top to bottom, the mechanical stimuli delivered to the subject, the pulse pressure, stiffness and viscosity estimated using the blood pressure and the proposed method.

Figure 7 shows the correlations between the results measured by FPS and automated sphygmomanometer. Figure 6 and Figure 7 (c) – (f) indicate that mean values of  $\tilde{K}_{FPS}$ ,  $\tilde{K}_{BP}$ ,  $\tilde{B}_{FPS}$ , and  $\tilde{B}_{BP}$  are increased when the mechanical stimulus was applied. Also, these figures show that variations of  $PP_{FPS}$ ,  $\tilde{K}_{FPS}$ , and  $\tilde{B}_{FPS}$  tend to follow those of  $PP_{BP}$ ,  $\tilde{K}_{BP}$  and  $\tilde{B}_{BP}$ , respectively. The correlation coefficients between  $PP_{FPS}$  and  $PP_{BP}$ , between  $\tilde{K}_{FPS}$  and  $\tilde{K}_{BP}$ , and between  $\tilde{B}_{FPS}$  and  $\tilde{B}_{BP}$  are  $0.810 \pm 0.084$ ,  $0.936 \pm 0.058$ ,  $0.886 \pm 0.121$ , respectively. Figure 7 (g), (h) show that all of the mean values of normalized parameters,  $K_{FPSn}$ ,  $K_{BPn}$ ,  $B_{FPSn}$ , and  $B_{BPn}$  are more than 1; the stiffness and viscosity values increased by application of the stimuli. The slopes of the regression lines were about 1. Therefore, the proposed method could capture changes in the arterial viscoelastic indices during the application of mechanical pain stimuli as accurately as the

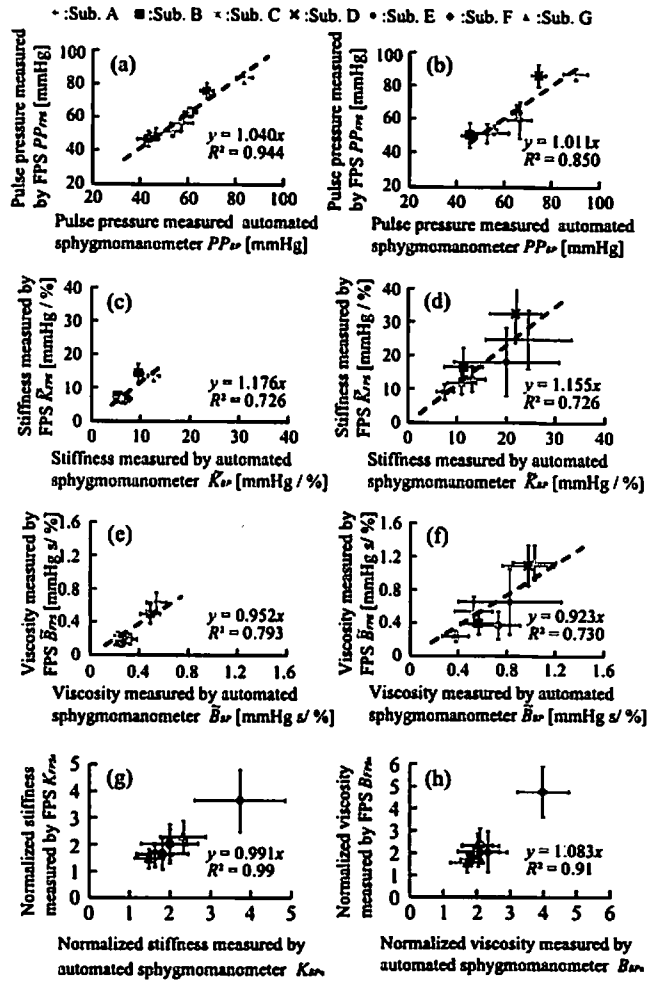


Fig. 7 Comparison between the results measured by FPS and automated sphygmomanometer: (a)  $PP$  at rest, (b)  $PP$  during stimulation, (c)  $\tilde{K}$  at rest, (d)  $\tilde{K}$  during stimulation, (e)  $\tilde{B}$  at rest, (f)  $\tilde{B}$  during stimulation (g) Normalized  $K$ , (h) Normalized  $B$

method using blood pressure could.

Figure 8 (a) shows an example of the measured signals for the dorsal pedis artery for Subject C. The tendencies in Figure 8 (a) are similar to those in Figure 6. These figures plot the stimulation intensity, piezoelectric pulse wave amplitude,  $\tilde{K}_{FPS}$ , and  $\tilde{B}_{FPS}$ . Figure 8 (b), (c) show the average values of  $K_{FPSn}$  and  $B_{FPSn}$  in the rest and stimulation periods.  $K_{FPSn}$  and  $B_{FPSn}$  significantly increased in the stimulation period compared with the rest period.

## VI. DISCUSSION

Figures 4(a), (b) show that the wave shape and frequency characteristic of the FPS signal showed close correlation to those of the blood pressure when external forces of 5 – 25 [N] were applied, where the maximum value of the piezoelectric pulse wave amplitude was obtained for all of the subjects. Thus, the proposed method could measure as accurately as the method using the blood pressure could, when considering

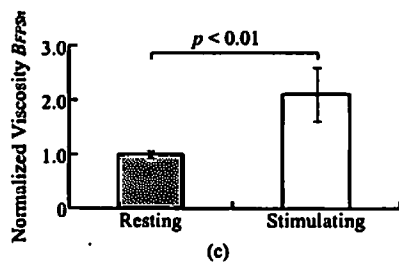
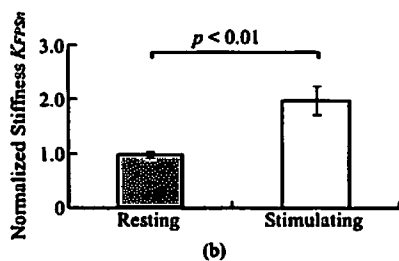
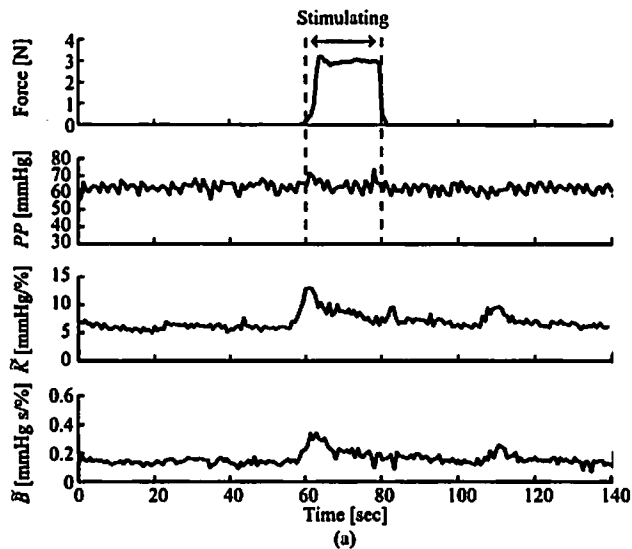


Fig. 8 Experimental results during rest and stimulation to the right foot dorsal skin: (a) Change of arterial wall viscoelasticity (Subject C), (b) Comparison results of normalized stiffness between resting period and stimulation, (c) Comparison results of normalized viscosity between rest and stimulation

individual differences during the application of constant external forces of 5 – 25 [N]. Also, Figure 5 shows that the baPWVs measured by the noninvasive vascular screening device and FPS are quite similar. Thus, the proposed method could measure the amplitude and time variation of the blood pressure.

Figures 6, 7 show that the output voltage of the FPS is able to be converted to a variation of the arterial pressure, and these show that the proposed method captures changes in the indices during the application of mechanical stimuli as accurately as the method using the blood pressure could. Previously, Kohno *et al.* [10] confirmed that the value of stiffness estimated from the pulse pressure and photopleth-

smogram amplitude were significantly changed by different levels of stimulation intensity and shape. The proposed method may be capable of quantitatively evaluating the changes in response to mechanical stimuli.

Figure 8 shows that the proposed method could be used to measure pulse pressure waves, not only at the radial artery but also at the dorsal pedis artery. In addition, the mean value of the determination coefficients obtained when estimating the arterial viscoelastic indices for all of the subjects was  $0.979 \pm 0.002$ . It was confirmed that the proposed method can estimate the arterial viscoelastic indices.

## VII. CONCLUSION

This study proposed a noninvasive method for measuring pulse waves and estimating changes in the dynamic characteristics of arterial walls by using a FPS and a photoplethysmography. As results, the pulse waves of a dorsal pedis artery were measured and the arterial viscoelastic indices were estimated, thus confirming the effectiveness of the proposed method.

In future work, a measurement method of average blood pressure to convert the output value the FPS to a blood pressure value should be considered, and more elderly subjects should be tested. Also, an evaluation method for organic and functional changes in the arterial viscoelastic characteristics should be explored.

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