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PAPER

Effect of Delay of Feedback Force on Perception of Elastic Force: A Psychophysical Approach

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SUMMARY The performance of a force feedback system is disturbed by delay that arises from the time required for transmission and processing of data. We used a psychophysical method to measure how much a user's subjective impression of elasticity associated with delays of feedback force deviated from the original physical elasticity. The results show that users' point of subjective equality (PSE) for their subjective impression of elasticity decreased as the delay of feedback force increased. We proposed a model that estimates the PSE of elasticity from the variables that can be physically measured. Another experiment was conducted to examine the model's prediction, which the results supported.
key words: *haptic display, psychophysical method, point of subjective equality (PSE), delay, elasticity*

1. Introduction

Force feedback devices or haptic displays have been used in teleoperations, computer supported cooperative work (CSCW), networked virtual reality (VR) systems, and so on. The performance of a force feedback system is disturbed by delay that arises from the time required for transmission and processing of data. An acceptable delay for feedback force is much smaller than for visual and audio information. For example, Matsumoto et al. [1], [2] reported that the maximum acceptable round trip delay is about 30 to 60 ms for feedback force.

Several control schemes that include force feedback have been proposed to reduce the effect of delay, delay jitter, and packet loss [2]–[7]. They have succeeded in improving the tractability of systems under the constraints of network performance. However there may be room for improvement in the accuracy of users' perception of force. It is important to measure how a user perceives force in order to improve the performance of haptic controls.

In this paper we measured the effect of delay of feedback force on the perception of elastic force. We used a psychophysical method that enabled us to measure how much the participant's subjective impression of elasticity associated with delays of feedback force deviated from the original (physical) elasticity. We proposed a model that estimates the PSE of elasticity from the variables that can be physically measured. Another experiment was conducted to examine the model's prediction of the PSE of elasticity. The results supported the model's prediction. The model can be applicable to the design of telecommunication networks and application systems that include haptic media.

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2. Psychophysical Method and Haptic Perception

2.1 Psychophysics

Psychophysics is the branch of psychology dealing with the quantitative relationship between perception and associated physical stimuli. Psychophysics has been used to determine the sensitivity and bias of perceptual systems to environmental stimuli. A typical task of psychophysics is measurement of psychophysical parameters that include thresholds and points of subjective equality. The absolute threshold or stimulus threshold (RL for the German *Reiz Limen*) is defined as the minimum intensity of stimulation required for a person to detect a stimulus. The difference threshold (DL for the German *Differenz Limen*) is defined as the smallest change in stimulation that a person can detect. The smallest change in stimulation that a person can detect which is larger or smaller than the original is called the upper difference threshold (UDL) or the lower difference threshold (LDL), respectively. Since the upper and lower difference thresholds do not always have the same value, the mean difference threshold (MDL) which is the mean value of the UDL and the LDL is often used as the difference threshold. Weber's law posits that the difference threshold is proportional to the intensity of the standard stimulus (rather than a constant amount). In Weber's law, the fraction given by the difference threshold divided by the standard intensity is called the Weber fraction. The point of subjective equality (PSE) is defined as the value of a stimulus that is perceived to be identical to another stimulus.

2.2 Constant Method

The constant method or the method of constant stimulus is a type of psychophysical procedure that repeatedly uses the same set of stimuli (usually between five and nine different intensities) throughout the experiment [8]. In the constant method, stimuli are presented numerous times, usually 100 times or more, in random order. In the method of limits, the stimuli are presented in an ascending series and a descending series. A limitation of the method of limits is that people may become accustomed to reporting that they perceive a stimulus and may continue reporting in the same way even beyond the threshold (error of habituation). Conversely, people may anticipate that the stimulus is about to become detectable or undetectable and may make a premature judgments (error of expectation). Therefore the constant method can be expected to obtain more accurate results than the method of limits.

2.2.1 Measurement of Stimulus Threshold

The procedures of the constant method are as follows. To measure the stimulus threshold (RL), an observer is required to judge whether the stimulus is present or absent. The probability of detecting the stimulus will increase as the intensity level is increased. The stimulus threshold is defined as the stimulus intensity for which the proportion of trials resulting in a stimulus "present" response is .50. Typically the stimulus threshold does not correspond to any of the stimuli used in the experiment. Therefore, the stimulus threshold must be estimated by a statistical method.

It is often the case that the proportion of trials resulting in a "present" response P can be approximated to a cumulative normal distribution. In this case there is a simple statistical method to estimate the stimulus threshold. The P value can be transformed to the standard score or Z-score Z that is defined as

$$P = \int_{-\infty}^{Z} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{z^2}{2}\right\} dz \qquad (1)$$

Z plotted against stimulus value becomes linear. A P value of .50 is associated with a Z value of zero. Therefore, the stimulus threshold is the stimulus intensity for a Z value of zero. The stimulus threshold can be estimated precisely by the method of least squares.

2.2.2 Measurement of Difference Threshold and PSE

To measure the difference threshold (DL) an observer examines pairs of stimuli and judges which stimulus produces a sensation of greater magnitude. One of the stimuli of the pairs is given a fixed value and is called the standard stimulus (SS) which serves as a standard for comparison with other stimuli. The value of the other stimulus, which is called the comparison stimulus (CS), is changed by trials. Usually 5, 7, or 9 values of comparison stimuli, separated by equal distances on the physical scale, are employed. In a random sequence, each of the comparison stimuli is paired several times with the standard stimulus, and the observer reports which stimulus has the greater sensory value or that both have the same sensory value.

The lower difference threshold (LDL) is reached when the proportion of trials where the comparison stimulus is judged to be less than the standard stimulus is .50 (or .75)†. The upper difference threshold (UDL) is reached when the proportion of trials where the comparison stimulus is judged to be greater than the standard stimulus is .50 or .75. The DL is the stimulus range from the value of the standard stimulus to the .50 (or .75) point. The average of the lower and the upper DLs gives one DL which we call the mean DL (MDL). The point of subjective equality (PSE) is the point where the proportions of greater and less responses are equal.

The same statistical method as used to estimate the stimulus threshold shown above is applicable to estimate DLs and PSE. To calculate the PSE one response of "equal" is counted as a .50 response of "greater" and a .50 response of "less."

2.3 Haptic Perception

Since a consensus about terminology for tactual perception has not yet developed, we explain tactual perception based on [9]. Tactual perception, which is called "sense of touch" by laypeople, comprises two distinct senses, cutaneous sense (skin sense) and kinesthesis (proprioception) The cutaneous sense is conveyed by the receptors under the skin surface that are responsible for conveying sensations of touch, pressure, vibration, temperature, and pain. The receptors that supply sensations of touch, pressure, and vibration are referred to as mechanoreceptors. Proprioception is the sensing of the position of the body and limbs in space. The sensing of body and limb movement is called kinesthesis. These two terms are often used interchangeably. Proprioception is conveyed by the receptors in muscles, tendons, and joints.

Tactual perceptions are classified into tactile perception, kinesthetic perception, and haptic perception. Tactile perception refers to perception mediated solely by variations in cutaneous stimulation. The perception of mass as a result of putting an object on the stable palm of the person is an example of tactile perception.

Kinesthetic perception refers to perception mediated exclusively or nearly so by variations in kinesthetic stimulation, which involves movement of the body. Tactual perception with no cutaneous contribution is contrived.

Haptic perception refers to perception in which both the cutaneous sense and kinesthesis convey significant information about distal objects and events. Examples of the haptic perception include the perception of elasticity, viscosity, and inertia by pushing a spring, a viscous damper, and a mass object, respectively††. In this paper these perceptions are referred to as the haptic perception because it is natural to consider that the cutaneous sense plays some role in those perceptions. The perceptions of elasticity, viscosity, and inertia are inherently haptic perceptions because

†We adopt the .50 point to calculate the difference threshold.

††The perceptions of elasticity, viscosity, and inertia are often referred to as the kinesthetic perception [10]. It is not important in this paper to discriminate the haptic perception and the kinesthetic perception. However in this paper the perceptions of elasticity, viscosity, and inertia are referred to as the haptic perception because it is natural to consider the cutaneous sense plays some roles in those perceptions.

humans possess no known special receptors for elasticity, viscosity, and inertia [11]. Most everyday tactual perception and tactually controlled performance are a function of haptic perception. Since a haptic display is a device that outputs force toward a user's action, most of users' perceptions of the forces applied by a haptic display are associated with haptic perception.

2.4 Psychophysical Studies of Perception of Force

In the nineteenth century, Weber measured the DL of the perception of mass by putting objects on the stable palms of participants, and described the results as found Weber's law [12]. Psychophysical studies of the perception of step-like changes in pressure stimuli applied on the stable palm or fingertip were conducted in the early and mid-twentieth century [13]. These are mostly studies of tactile perception. Psychophysical studies of haptic perception of force are fewer than those of the tactile perception.

Jandura and Srinivasan [14] studied the perception of torques applied during pinch grasping (between the thumb and index finger), which involves haptic perception. Jones et al. [15] conducted psychophysical studies of the perception of the elasticity using a contra-lateral limb-matching procedure in which participants adjusted the stiffness of a motor connected to one (matching) arm until it was perceived to be the same as that connected to the other (reference) arm. Tan et al. [11] also conducted psychophysical studies of the perception of elasticity wheere participants grasped two plates between the thumb and index finger and squeezed them together along a linear track.

3. Overview of the Experiments

In this paper we measured the effect of delay of feedback force on the perception of elasticity. It is important to study the perceptions of elasticity, viscosity, and inertia first because a first approximation of the behavior of mechanical systems and deformable solid objects can be expressed as

$$f = kx + c\dot{x} + m\ddot{x},$$

where f is the total force applied on the object, x, $\dot{x}$, $\ddot{x}$ are the displacement, velocity and acceleration of the object, respectively, and k, c, m are stiffness (elasticity), viscosity, and inertia (mass), respectively. Among these perceptions, it is helpful to study the perception of elasticity first for the following reasons. First, elastic force often plays a dominant role in haptic perception because internal organs, skin, and muscles can be regarded as elastic objects. Second, the perception of elasticity is expected to be easier because the behavior of elastic force has the lowest order. We do not know how perception deviates as a function of delay although it is well known that delay affects perception. Therefore it seems better to study the perception ofelasticity first.

In the experiments in this paper, participants linearly pushed a virtual spring, which was constructed by a haptic display (SenSable PHANToM), in order to perceive the elasticity of the virtual spring. The motion of the task in the experiments is much simpler than typical tasks using a haptic display, such as a tele-control. It is worth studying the simple task because a complex task can be regarded as a sequence of simpler tasks or motions. Knowledge about a simple task is thus applicable to many tasks.

We conducted three psychophysical experiments examining the perception of elasticity when a person pushes a virtual spring constructed by a haptic display. In Experiment 1 we used the constant method to measure the difference threshold (DL) and the PSE for the perception of elastic force generated by a haptic display without delay to examine whether the results were consistent with general psychophysical laws even when a participant actively sensed the force, i.e., the pushed virtual spring and felt the feedback force. Previous studies had already succeeded in measuring the difference threshold of elasticity as described above. However in those studies, the participants moved only their forearm [15] or their thumb and index finger [11]. The motion of participants in those studies was too constrained compared to the motion in tasks using a haptic display, although those experimental procedures are valid as basic psychophysical studies of perception. Participantsin the experiments in this paper moved their forearms and upper arms although they only linearly pushed a virtual spring. Therefore it was necessary to examine whether the results were consistent with general psychophysical laws as a first step in our study.

In Experiment 2 we measured the effect of delay of feedback force on the perception of elastic force, which is the main objective of this paper. The psychophysical method enabled us to measure how much the participants' subjective impressions of elasticity associated with delays of feedback force deviated from the original (physical) elasticity.

We proposed a model that estimates subjective impressions of elasticity from the variables that can be physically measured based on the results of Experiment 2. Experiment 3 was examined the model's predictions.

4. Experiment 1: Psychophysical Measurement of Perception of Elastic Force by a Haptic Display

4.1 Method

4.1.1 Participants

One male and one female adult participated in the experiment.

4.1.2 Materials

Virtual springs[†] that have 21 different elasticities were constructed using a haptic display (SensAble Technologies, PHANToM PREMIUM 151AG). The haptic display was

[†]We call just "spring(s)" later.

Table 1 The elastic moduli of the stimuli. The unit is gf/10 cm.

		CS						
Condition	SS	1	2	3	4	5	6	7
C-109	109	100	103	106	109	112	115	118
C-218	218	200	206	212	218	224	230	236
C-436	436	400	412	424	436	448	460	472

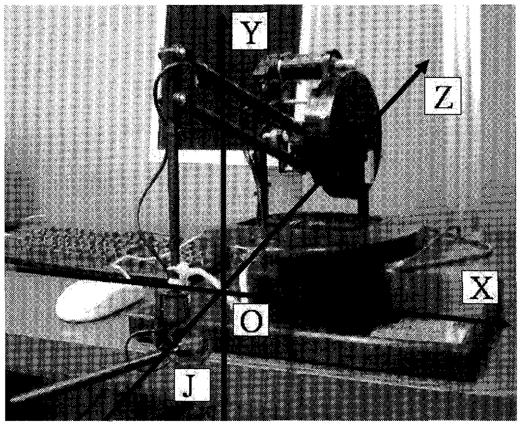

Fig. 1 Appearance of the haptic display and X, Y, and Z-axes.

connected to the personal computer (CPU: Intel Pentium4, 3.0 GHz, RAM: 1.5 GB, OS: Windows 2000 Professional SP4) that controlled the experimental procedure. The computer program for control of the experimental procedure was developed by GHOST (SensAble Technologies, ver. 4.0) and C++ language (Microsoft, Visual C++ 7.0).

The standard stimuli (SSs) were three springs whose elastic moduli were 109, 218, and 436 gf/10 cm, respectively. The comparison stimuli (CSs), shown in Table 1, were seven springs for each SS.

The feedback forces were generated as follows. The X, Y, and Z axes were defined as shown in Fig. 1. The position of the origin was located 90 mm in front of the haptic display and was the height of the rotating pedestal of the haptic display. When the joint of the stick of the haptic display ("J" in Fig. 1) was at the origin, the spring was at its natural length. The feedback force was calculated as the Z-axis value of the position of the J-point multiplied by the elastic modulus, and was the output. When the Z-value was less than 0, no force was generated.

4.1.3 Procedure

Participants were seated beside the haptic display and held the stick of the haptic display as shown in Fig. 2. Participants were instructed to push the stick of the haptic display along the Z-axis after a beep sounded. The maximum movable area was about 12 cm. Participants were instructed to push the stick for .50 s. Practice sessions where conducted for about 3 hours prior to the measurement phase.

In the measurement phase, participants pushed the SS and the CS sequentially. The order of the SS and the CS were random and participants were not told which spring they pushed earlier. Participants judged whether the stiffness of the spring they pushed later was greater or less than or equal to the spring they pushed earlier. Seven CSs for each of the 3 SS conditions were paired with the SS and were presented 10 times in random order. A session consisted of those 70 comparisons. Half of the comparisons in a session were set so that SS preceded CS, and the other half were set so that CS preceded SS. Participants completed 10 sessions of comparisons for each condition. Intervals of several minutes or longer were held between sessions. The order of sessions was the C-218, C-109, and then the C-436 condition.

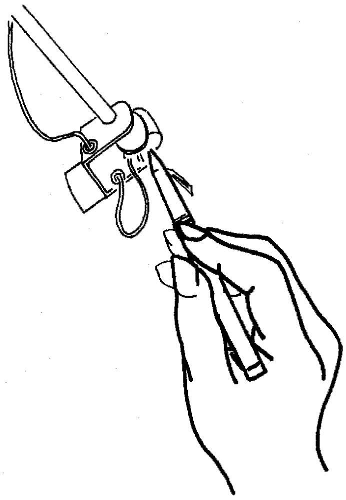

Fig. 2 The way to hold the stick of the haptic display.

Table 2 PSE and difference threshold.

Participant 1

	Elastic modulus of SS		
	109	218	436
PSE	109.29	217.53	435.73
UDL	4.34	7.36	14.08
LDL	4.34	8.47	16.38
MDL	4.34	7.92	15.23
Weber fraction	.040	.036	.035

Participant 2

	Elastic modulus of SS		
	109	218	436
PSE	108.84	218.55	436.41
UDL	4.45	9.79	19.41
LDL	4.77	9.46	18.27
MDL	4.61	9.62	18.84
Weber fraction	.042	.044	.043

4.2 Results and Discussion

The estimated PSE, DL, and Weber fraction are shown in Table 2. In the 218 gf/10 cm SS condition the PSE of Participant 1 was 217.53 gf/10 cm. This means that he felt elasticity of the spring to be 217.53 gf/10 cm although it was really 218 gf/10 cm. The upper and the lower thresholds were 7.36 and 8.47 gf/10 cm, respectively.

The constant errors of both participants, which are the differences between the PSE and the physical intensity of SS, were smaller than 1 gf/10 cm in both conditions. The

Weber fractions were about 1/25 and the variances were small between conditions and between participants. Participants' impressions of elasticity are likely to vary depending on the way they push the spring. In this measurement participants were instructed how to hold the stick of the haptic display and how to push the spring although their pushing was not strictly controlled. The fact that the constant errors and the variances of the difference threshold were small showed that the measurement was valid.

5. Experiment 2: Measurement of the Effect of Delay of Feedback Force on the Perception of Elastic Force

5.1 Method

5.1.1 Participant

Participant 1 of Experiment 1 also participated in Experiment 2.

5.1.2 Materials and Procedure

The materials and procedure were identical to Experiment 1 except for the following. The stimuli were only the C-218 condition in Experiment 1. The delay conditions were 0, 5, 10, 15, 20, 25, 30, 40, and 50 ms. The delay was generated by the computer which was connected with the haptic display using a FIFO queue in order to simulate transmission delay. The delays were inserted when the participant pushed the spring that was the SS and were not inserted when he pushed the springs that were the CSs. The order of the sessions in the conditions was random and the participant was not told the order.

5.2 Results and Discussion

Table 3 shows the change of PSE and DL related to the delay. The PSE linearly decreased as the delay increased, as shown in Fig. 3. This means that the participant felt that the elasticity of the spring was less as the delay became longer. The PSE decreased even when the delays were only 5 and 10 ms, and the differences were larger than the constant error in the no-delay condition.

We constructed a model that explains the mechanism by which the PSE decreased as the delay increased. Participants perceive a force of kL when they push the spring whose elastic modulus is k for length L if there is no delay. On the other hand they perceive a force of $k(L - \int_0^D v\,dt)$ when they push the spring for length L with velocity v if the delay is D. They perceive the feedback force as a physical quantity, as shown by the thick line in Fig. 4. Since the participants in the preliminary experiments reported that they felt the elasticity was smaller when the delay was inserted, and they did not feel the delay, we assume that the participant's perception was linearly smoothed. Thus their subjective impressions of the elastic modulus k' is expressed as

$$k' = k\left(1 - \frac{\int_0^D v\,dt}{L}\right). \tag{2}$$

It was difficult to obtain $\int_0^D v\,dt$ because the start and the end of the pushing motions were not strictly controlled.

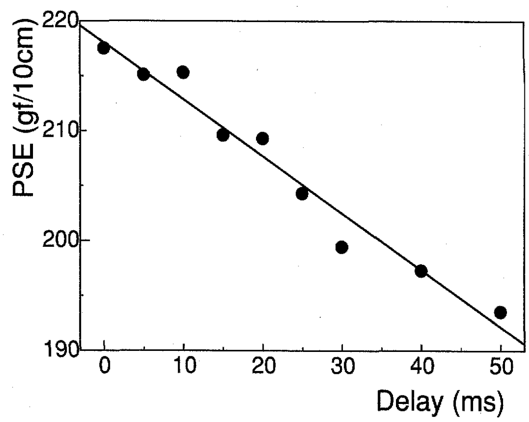

Fig. 3 Change of PSE related to delay. The thick straight line stands for the regression line.

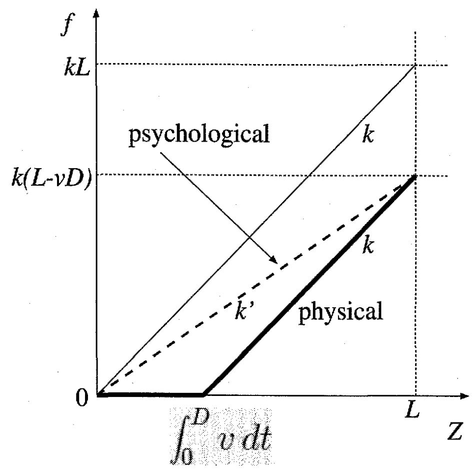

Fig. 4 Explanation of change of PSE related to delay.

Table 3 Change of PSE and difference threshold related to delay.

	Delay								
	0 ms	5 ms	10 ms	15 ms	20 ms	25 ms	30 ms	40 ms	50 ms
PSE	217.53	215.11	215.31	209.60	209.30	204.31	199.45	197.29	193.57
UDL	7.36	5.56	4.07	−1.34	.56	−6.18	−11.70	−12.63	−12.36
LDL	8.47	10.56	9.54	16.32	17.04	20.63	24.18	30.21	34.60
MDL	7.92	8.06	6.81	7.49	8.80	7.23	6.24	8.79	11.12
Weber fraction	.036	.037	.031	.034	.040	.033	.029	.040	.051

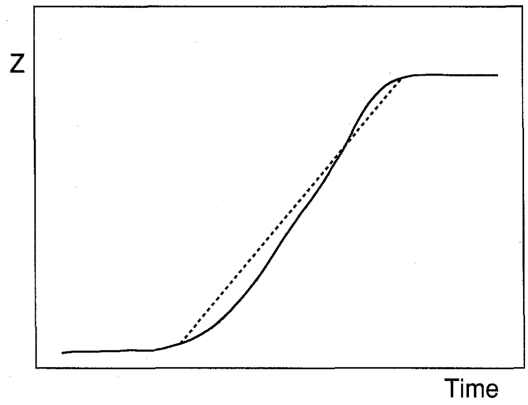

Fig. 5 An example of displacement profiles of the participant's pushing motion.

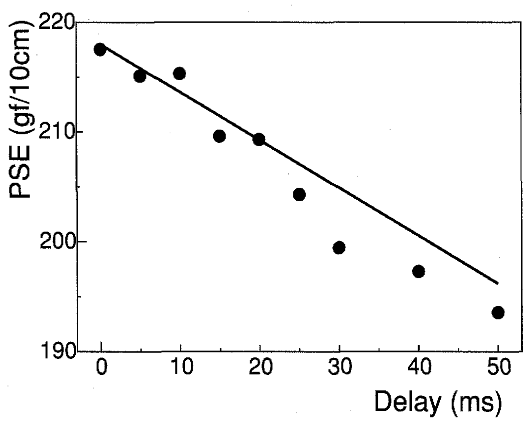

Fig. 6 Prediction of PSE by the model. The thick line stands for the model's prediction.

It is known that displacement profiles in goal-directed arm movements resemble sigmoid curves in general [16], [17]. Fortunately the displacement profile of the participant's pushing motion approximated a straight line, as shown in Fig. 5. The model can be expressed as

$$k' = k(1 - \bar{v}D/L) = k(1 - D/T) \tag{3}$$

where $\bar{v}$ is the mean velocity and T is the time while which the participant pushes the spring. PSEs were estimated from Eq. (3) where T was set at .50 s, as the participant was instructed, and are shown in Fig. 6. These estimated PSEs correspond well to the measured PSEs, with no free parameter.

The mean difference threshold seemed to increase when the delay was 50 ms. This means that the 50 ms delay disturbed the participant's discrimination judgment of elasticity. The relation between the upper and lower difference thresholds and the delay is a little complex. The upper difference threshold decreased as the delay increased while the lower difference threshold increased as the delay increased, as shown in Fig. 7. The fact that the upper difference threshold decreased as the delay increased may seem strange because it can be interpreted as the delay making participants' senses more sensitive. This arose from the fact that the PSE decreased as the delay increased. Since the elastic modulus of the SS was perceived as smaller according to the delay, the elastic modulus of the CS was perceived as greater even when the elastic modulus of the CS was smaller than the point that was the upper threshold when no delay was inserted. To resolve this problem we adopted another definition of the difference threshold, i.e., the stimulus range from the PSE to the .50 point. The adjusted UDL and LDL are shown in Table 3 and Fig. 8. There is no longer a complex relationship between the upper and the lower difference thresholds and the delay.

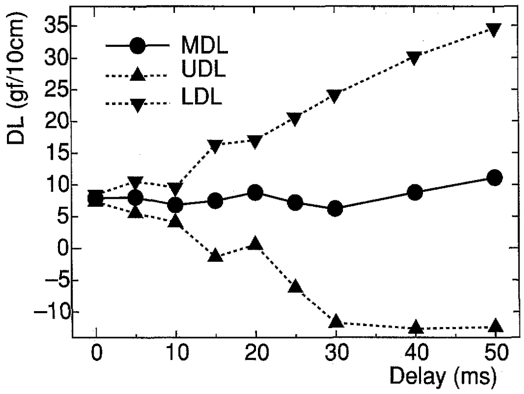

Fig. 7 Change of difference threshold related to delay

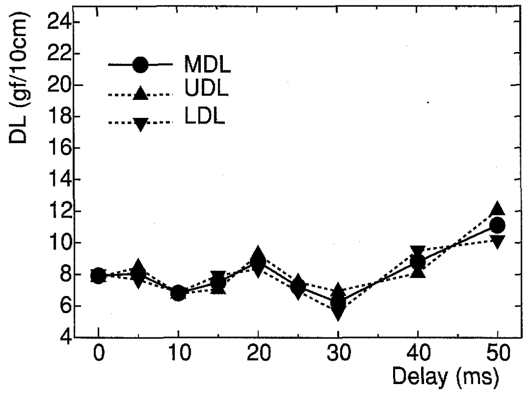

Fig. 8 Adjusted difference threshold.

6. Experiment 3: Examination of the Model

6.1 Method

6.1.1 Participant

An adult who had not participated in the previous experiments.

6.1.2 Materials and Procedure

The materials and procedure were identical to Experiment 2 except for following. The delays were 0, 10, 20, 30, and 50 ms. The participant was instructed to push the stick of the haptic display for .30 s.

Table 4 Change of PSE and difference threshold related to delay.

	Delay				
	0 ms	10 ms	20 ms	30 ms	50 ms
PSE	218.10	213.07	204.70	197.71	180.27
UDL	5.32	2.16	−4.84	−10.12	−26.51
LDL	5.96	13.84	24.03	30.12	49.30
MDL	5.64	8.00	960	10.00	11.40
Weber fraction	.026	.037	.044	.046	.052

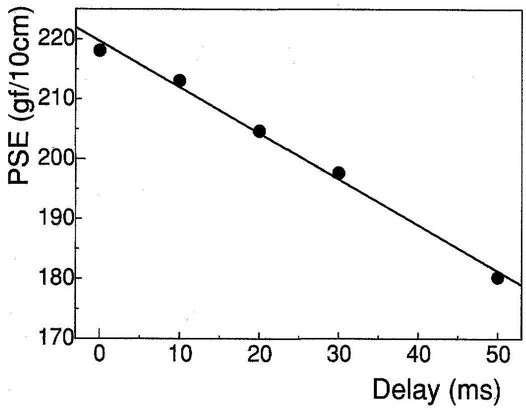

Fig. 9 Change of PSE related to delay. The thick straight line stands for the regression line.

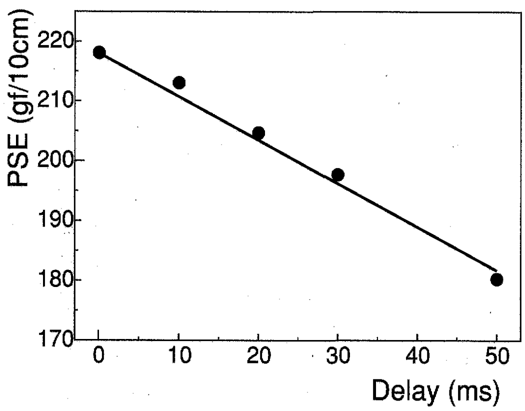

Fig. 10 Prediction of PSE by the model. The thick line stands for the model's prediction.

6.2 Results and Discussion

Table 4 shows the change of PSE and DL related to delay. Figure 9 shows that the PSE linearly decreased as the delay increased, in the same manner as the PSE in Experiment 2.

PSEs were estimated by the model where T was set at .30 s, as the participant was instructed, and are shown in Fig. 10. They correspond well to the measured PSEs. The results support the validity of the model.

The change of the original and the adjusted DLs related to the delay are shown in Fig. 11 and Fig. 12, respectively. Although the results show similar tendencies to the results in Experiment 2, the MDL increased as the delay increased over the whole range of the delay. Further research is needed to clarify how the difference threshold changes relate to the delay.

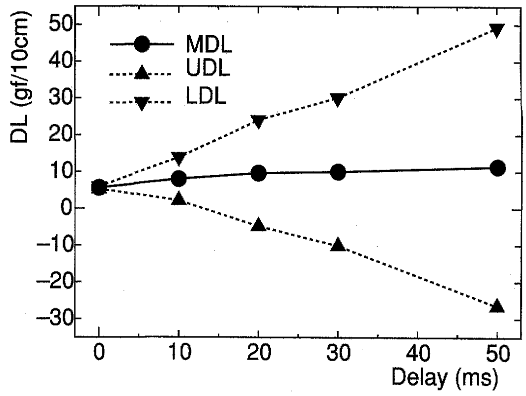

Fig. 11 Change of difference threshold related to delay.

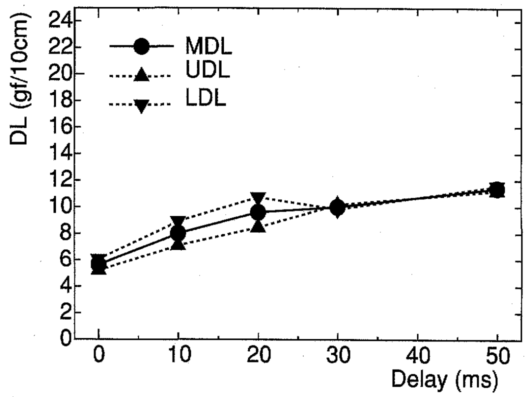

Fig. 12 Adjusted difference threshold.

7. Conclusions

In this paper we measured quantitatively the effect of delay of feedback force on the perception of elastic force. The results revealed that the PSE linearly decreased as the delay increased. We proposed a model that estimates the PSE of elasticity from the variables that can be physically measured.

The results that the participants felt elasticity that was smaller than the physical elasticity when the feedback force was delayed suggest that delay can cause misjudgments in perception-based examination tasks such as palpation and operation errors in perception-based control tasks such as a surgical operations. Let us consider how the delay disturbs a perception-based control task. Assume that a user pushes an elastic object using a haptic display and controls the force of pushing. If the feedback force is delayed, the user feels an elastic force smaller than expected although he or she pushed the object enough. The user may consider that he or she has not pushed the object enough. If so, he or she does not stop pushing the object and the feedback force becomes larger than the target force. Note that the user finally feels the force larger than the target force because a physically larger force is generated. This is not an effect of delay on perception.

The results suggest that psychophysical methods can be applied to the evaluation of application systems that include haptic media. There are some other methods to evaluate user level QoS (quality of service) for transmission of haptic data. A subjective QoS evaluation [1], [2] clarifies the criterion of a user's subjective satisfaction. A QoS assessment based on a user's performance [7] provides an objective assessment of QoS without depending on the users' verbal report. A psychophysical method provides information about the degree that a user's perceived sensory experience deviates from a normal or ideal state. Since these different methods provide useful information about the performance of the system to be evaluated from different viewpoints, they can be appropriately combined depending on the purpose of the evaluation.

There are control methods which compensate for delay [3], [4]. They cannot necessarily maintain the regularity of users' sense although they can maintain the stability of the system. Therefore, the psychophysical evaluation is still effective even if the system includes a delay compensation technique. Moreover, the model can be applicable to the design of telecommunication networks and application systems that include haptic media since the model can also estimate the maximum allowable delay from the precision required in the task if the maximum v/L in the given task can be estimated.

The results of the experiments in this paper show that the PSE of elasticity decreased as the delay of feedback force increased. This does not mean that perceptions of force always decrease according to the delay. Some other factors may change the perception of force. First, the effect of delay on perception depends on the dynamics of the object touched by the participant and on the participant's motion. For example, we conducted preliminary experiments which examined the effect of delay on perceptions of viscosity and inertia by by pushing a viscous damper, and a mass object, respectively. The results showed that the PSE of viscosity linearly decreased and the PSE of inertia did not decrease as the delay of feedback force increased. Second, visual information affects perception of force. For example, in the discrimination task involving pushing the object the participant tends to feel that the mass of the object decreases if the visual motion of a the manipulated virtual object is amplified when compared to the actual motion of the participant's hand [18].

We could not get clear results about how the difference threshold changes related to delay, which we hope to clarify in future research. The psychophysical method can be applied to the evaluation of effects of variable factors of network and application systems that include haptic media related to the perceptual experience of the user, although we measured only the effect of constant delay of feedback force on the perception of elastic force. We plan to measure the effects of other network impairments such as insufficiency of spatial and temporal resolution, packet loss, and delay jitter on the perception of force by using the psychophysical method.

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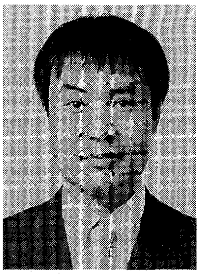

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