Haptic Illusion of Elasticity by Tactile Suppression during Motor Activity

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ABSTRACT

We found a new haptic illusion that is induced by a combination of a tactile stimulus and motor activity. When we presented a continuous vibratory tactile stimulus to the palm while moving the forearm vertically, a feeling of elasticity or "a soft rubber ball bouncing on the palm" is generated. We hypothesized that this illusion is caused by a well-known tactile suppression during motor activity. In the first of two experiments, we measured the optimal vibratory frequency for the illusion. In the second experiment, we measured the temporal behavior of tactile sensitivity to the vibration on the palm during periodical forearm motion. Based on the results of the experiments, we considered the mechanism of the illusion.

KEYWORDS: Haptic illusion, sense of elasticity, movement-related gating.

INDEX TERMS: H.1.2 [User/Machine Systems]: Human factor—Human information processing.

1 INTRODUCTION

In previous haptic studies, numerous haptic / tactile illusions have been reported, such as apparent movement and funneling illusions [1]. These illusions were frequently discussed in terms of similitude with visual or auditory counterparts. There are also multimodal haptic illusions, such as pseudo-haptic [2][3], which are induced by a mismatch between the modalities.

On the contrary, we found a new illusion that is induced by a combination of a tactile stimulus and motor activity. When we present a continuous vibratory tactile stimulus to the palm while periodically moving the forearm vertically, a feeling of elasticity or "a soft rubber ball bouncing on the palm" is generated (Figure 1). Numerous combined illusions of skin sensation and visual or auditory sensations have been reported, including the pseudo-haptic illusion; however, to our knowledge, the tactile illusions induced by a combination of tactile and proprioceptive sensations are rare. In this paper, we clarify the mechanism of this new illusion.

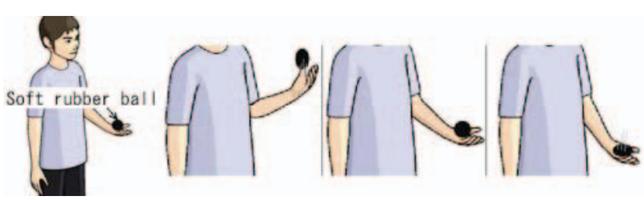

Figure 1. Image of the new haptic illusion

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1.1 Related Works and Hypothesis

Since the feeling of elasticity is only perceived during forearm movements, the correlation between forearm motion and cutaneous sensitivity should be the first suspect, since tactile suppression during motor activity is a well-known phenomenon [4][5][6][7]. Milne et al. [8] showed that the threshold on the finger for electrical stimuli increased during finger movement. Likewise, Post et al. [9] showed that the threshold for vibratory stimuli also increased during motor activity.

However, these previous observations do not fully explain the "feeling of elasticity"; if the suppression occurs continuously, the dynamic perception, particularly the bounce of a soft rubber ball, could not occur.

We propose a hypothesis that the vibratory threshold on the palm changes dynamically during the forearm movement, and this dynamic sensitivity generates the dynamic illusion.

1.2 Structure of the Paper

We first measured the optimal vibratory frequency for the occurrence of the illusion (Experiment 1). Then we measured temporal changes of the vibratory threshold on the palm during periodical forearm movements (Experiment 2). Based on these observations, we show that the dynamic changes of threshold are considered as the cause of the "elasticity" illusion.

2 EXPERIMENT 1: MEASURING THE OPTIMAL VIBRATORY FREQUENCY FOR THE ILLUSION

2.1 Materials and System

In this experiment, we used an audio speaker (Leed Sound Co., ltd., LW060P1-W) as a vibrator, because it can easily output vibratory stimuli from low to high frequency. Because the occurrence of the illusion involves the forearm movement, Velcro was installed on the speaker to fix it to the palm (Figure 2). Stimulation waveforms were output from a PC via a DA board (Interface co., PCI-3523A), amplified with the audio amplifier (Maxim Integrated Products, Inc., MAX9704) and presented by the speaker.

Figure 2. A speaker as a stimulator

2.2 Methods

Participants included 4 males and 1 female (21-22 years old) who could perceive the illusion in the preliminary test. Seven sine waves with different frequencies (15, 30, 45, 60, 120, 240 and 480 Hz) were used. Before the main experiment, participants adjusted the amplitude of each stimulus so that the subjective intensity became equal.

As shown in Figure 3, participants were asked to swing their left forearm repeatedly 10 times at about 1 cycle / s by flexing and extending their elbow with their left palm upturned and with their left upper arm comfortable. At each trial, they evaluated the strength of the illusion (1: "not perceived at all" to 5: "perceived clearly") after the motor task. The trials were carried out five times for each of the seven frequencies (total 35 times).

Figure 3. Experiment 1: Subjective evaluation of the illusion of elasticity with different vibration frequencies

2.3 Results

Figure 4 shows the results of Experiment 1. Interestingly, the illusion was remarkably perceived at the low frequency stimuli (15 and 30Hz), while the illusion was not perceived at all at the high frequency stimuli (more than 60 Hz).

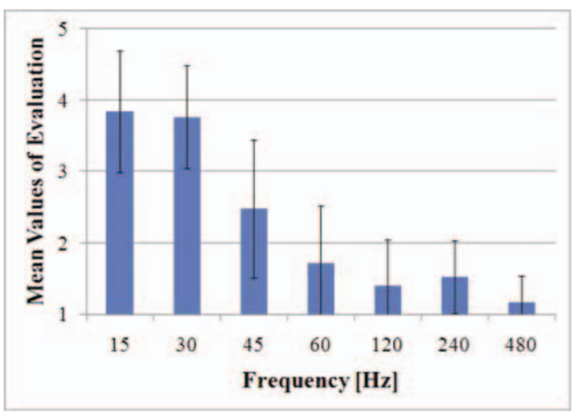

Figure 4. Results of Experiment 1: The haptic illusion of elasticity mainly occurred at 15-30 Hz. There was significant inter-frequency variation in perception of the illusion (ANOVA, F = 61; p < 0.001). Error bars indicate standard deviations.

3 Experiment 2: Measuring temporal changes of the vibratory threshold on the palm during periodical forearm movement

The purpose of this experiment was to observe any dynamics of suppression, which we hypothesized as the cause of the illusion.

3.1 Methods

We used the same speaker-based stimulator as in Experiment 1.

As shown in Figure 5, the participants sat on the chair with their left elbow vertically flexed and their left palm upturned. The stimulator was fixed on their left palm with Velcro. A vertically oscillated sphere image was displayed on a PC monitor, and the participants were asked to swing their left forearm repeatedly according to the image. Amplitude of the oscillation was 10 cm (so when the position of the image was at the bottom (-10 cm), the elbow was flexed vertically), and frequency was 1 Hz. During the testing interval, the stimulator periodically stimulated the palm, as described below.

The participants were asked to adjust the amplitudes of the vibratory stimuli to find the vibratory threshold of the palm.

Figure 5. Experiment 2: Measurement of the vibratory threshold during forearm motion

The stimulation procedure was as follows. A single cycle of the motion (1 s) was equally divided into nine intervals (0-0.11, 0.11-0.22, 0.22-0.33, 0.33-0.44, 0.44-0.56, 0.56-0.78, 0.78-0.89 and 0.89-1 s). For each trial, a single interval was randomly selected and the stimulus was applied to the palm during the interval. The duration of the stimulus was 0.11 s, and the stimuli cycle (SOA) was 1 s.

Figure 6 shows an example of a stimulating waveform from the PC. From the results of Experiment 1, a 30 Hz sine wave (easy to perceive the illusion) and a 240 Hz sine wave (cannot perceive the illusion) were used. The Hamming window was multiplied to these waves to reduce onset effects. The initial amplitude of the stimulation was set randomly at the value that was smaller or larger than the threshold estimated by the preliminary test.

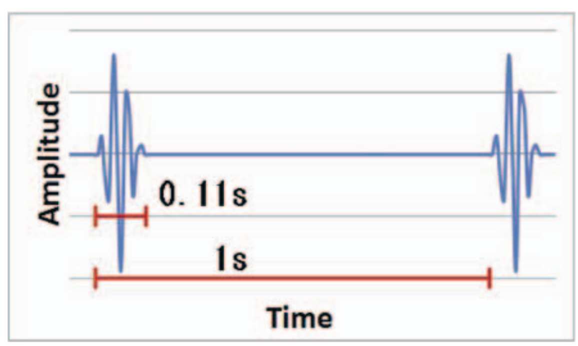

Figure 6. A stimulating waveform for Experiment 2

For each frequency, the measurement was carried out three times while the forearm was fixed (static threshold), and three times for nine intervals while the forearm was in motion (dynamic threshold). The total number of trials was 30 (= 3 + 3 * 9). The measurement at 30 Hz was carried out by 6 participants (5 males and 1 female, ages 21 -22 years old). The measurement at 240 Hz was carried out by 5 participants (4 males and 1 female, ages 21 -22 years old). Auditory cues were masked by white noise during the measurements.

3.2 Results

The data obtained from the experiment were output values from the PC. At this stage of the analysis, one participant's data of the measurement at 30 Hz were eliminated, because the data exhibited approximately three times as large a standard deviation at each interval. We normalized the dynamic threshold (threshold while the arm was in motion) by the static threshold (threshold while the arm was fixed). This normalization was done for each participant.
Figure 7 and Figure 8 show the results of Experiment 2. The threshold for the 30 Hz vibratory stimulus (Figure 7) was consistently much greater than 1, indicating that the vibratory threshold increased during the forearm motion, as reported in the previous literature [9]. The threshold dynamically changed with time (ANOVA, $F = 2.4$; $p < 0.05$). The threshold for the 240 Hz vibratory stimulus (Figure 8) also exceeded 1, but the values were much smaller. Using a Two-way Repeated-Measures ANOVA, we found a significant inter-frequency difference in vibratory threshold ($df = 1, 8, 8$; $F = 671$; $p < 0.001$).

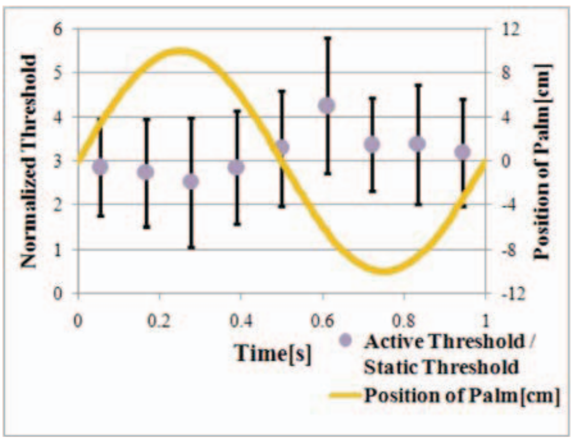

Figure 7. Results of Experiment 2: Vibratory threshold and palm position (30 Hz). Error bars show the standard deviation of the normalized vibratory threshold.

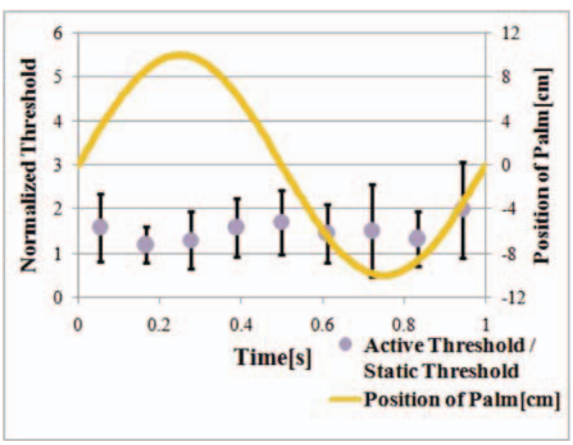

Figure 8. Results of Experiment 2: Vibratory threshold and palm position (240 Hz). Error bars show the standard deviation of the normalized vibratory threshold.

4 Discussion

4.1 Tactile suppression

The results of Experiment 2 show the dynamics of the vibratory threshold on the palm during periodical forearm motion. The value of the vibratory threshold can be considered as insensitive, and hence, the inverse of the threshold can roughly be regarded as the vibratory sensitivity. Figure 9 shows the inverse of the vibratory threshold for the 30 Hz vibratory stimulus and the palm position.

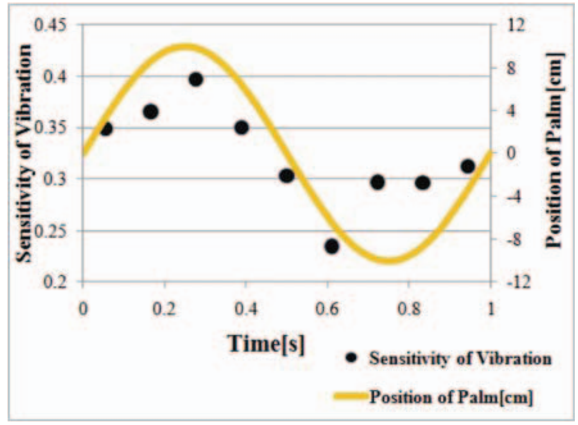

Figure 9. Sensitivity for vibration (30 Hz) and position of the palm

On the other hand, as we have shown in Figure 7 and Figure 8, the threshold change for the 240 Hz vibratory stimulus was quite small as compared with that of 30 Hz. Therefore, we speculate that the dynamic behavior of tactile sensitivity for a low frequency vibration caused the "elastic" illusion on the palm during the forearm motion (see bellow for details), which is consistent with our hypothesis.
In neurophysiological experiments with primates, Seki et al. [10] observed evidence for presynaptic inhibition, which suppresses cutaneous input to the spinal cord during voluntary movements. They suggested that this presynaptic inhibition potentially underlies the increases of perceptual thresholds during active movement. Furthermore, they also observed that the suppression of afferent information during active movement precedes electromyographic (EMG) onset.
In Figure 9, the negative peak of the sensitivity is around 0.6 s, while that of palm position is 0.75 s. As the acceleration (that can be regarded as EMG) takes maximum value at the negative peak of the position, it implies that the suppression precedes EMG, which is consistent with their observations.

4.2 Perception of Elasticity

Figure 10 shows a viscoelastic layer between the palm and the mass. In this situation, when the forearm is swung vertically, the stimulus from the mass to the palm is delayed in comparison with palm movement by the viscoelastic layer. This delayed stimulus is thought to be one of important factors of the perception of elasticity. The present study showed that the suppression preceded the movement of the palm. This behavior of the suppression makes us perceive that there is delay between the movement of the palm and the intensity of the vibration, which induces the feeling of elasticity. Thus, it would appear that the cause of the elasticity illusion is tactile suppression that precedes the movement.

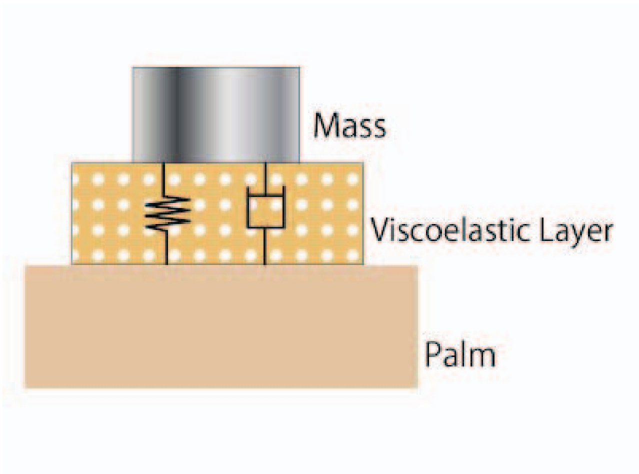

Figure 10. Viscoelastic layer between palm and mass

5 Conclusion and Future Work

This paper describes the haptic illusion of elasticity that we observed during forearm motion and constant tactile stimulation. We considered the mechanism of the illusion focusing on the change of sensitivity for vibratory stimuli during periodical forearm movement. We showed the similarity between the dynamic behavior of the sensitivity and the dynamic behavior of a true viscoelastic object. We also conducted a control experiment using a 240 Hz vibratory stimulus and showed that, at 240 Hz, the sensitivity was quite constant as compared with 30 Hz, and the illusion was not observed.

Currently, we cannot explain why the behavior of the sensory suppression for 30 and 240 Hz vibratory stimuli are so different. Since a 30 Hz vibration is mainly perceived by the Meissner corpuscle and a 240 Hz vibration is mainly perceived by the Pacinian corpuscle, one hypothesis is that the suppression mechanism is different for each type of receptor. Our next step is to confirm this hypothesis based on information processing of the somatosensory cortex.

Acknowledgement

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