Haptic Sensation Enhancement for Tasks Using Single and Multiple Fingers via Remote Stochastic Resonance Effects

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Abstract

Several tasks in our daily lives require a haptic perception, which results from the stimulation of mechanoreceptors generated by the manual exploration of an object. The haptic perception of the fingertip is very precise, which allows an accurate appreciation of light touch, proprioception, and discrimination. Due to a deterioration of the nerve endings in the finger pulp, the haptic perception tends to be weaker, which leads to a decrease in the haptic performance in our lives. To overcome this problem, enhancing the haptic sensation of the user's fingertip is crucial in order to have a better haptic performance. This thesis proposes approaches that utilize the Stochastic Resonance effects via mechanical noise to enhance the haptic sensation of the user's fingertip while performing the tasks using single and multiple fingers, where the mechanical noise for the stochastic resonance is applied a remote position away from the fingers.

Chapter 1 presents an overview of the scope and contribution of this thesis. We start with an overall explanation of how important the human haptic sensation is for several tasks. Moreover, we discuss the limitations that prevent the tactile sensation while the users perform the tasks. Additionally, we discuss the available solutions to enhance the human haptic sensation of the fingertip. Next, we explain the remote Stochastic Resonance phenomena and their applications to enhance the haptic sensation of the human fingertip. Finally, the main objective of this thesis is presented.

Chapter 2 reveals the motivation behind this study to understand how remote SR effects can enhance the haptic sensation. We first aim to investigate how the remote SR effects enhance the haptic sensation of the human fingertip while performing the tasks. To achieve this purpose, we investigate the relationship between the noise intensity propagated from the remote noise source to the fingertip and fingertip tactile perception. We then examine how the SR effects enhance the haptic sensation of the human fingertip while performing the tasks. After we understand that the noise propagates from the noise source to the fingertip proportionally, the vibration discrimination is conducted to examine the haptic performance when the noise is applied to the user with the several noise intensities. The outcomes show that the optimal noise level plays a crucial role in enhancing the haptic performance.

Chapter 3 reveals the remote SR effects for the multi-finger task by conducting a two-finger stiffness discrimination task while the mechanical noise is applied to a user with a remote position of a noise source. Considering the main feature of SR effects, we propose a method to enhance the haptic sensation of the two fingertips with a single vibrator. Then, we carry out a two-finger stiffness discrimination while the participants

are under the proposed method. The results show the SR effects can enhance the haptic sensation of two fingers even with a single noise source while the user performs the multi-finger task. Furthermore, the position of the noise source also plays an important role in increasing the haptic performance of the user. Moreover, the SR effects aim to enhance the cutaneous perception, which results in the overall haptic perception being enhanced even if the task requires both kinesthetic and cutaneous perception.

Chapter 4 reveals the remote SR effects for the motor learning by conducting a force-matching task while the mechanical noise is applied to a user with a remote position of a noise source. There is no study that investigates the effectiveness of the SR in the learning task. Moreover, in today's modern training though a haptic training system is ubiquitous in several areas. Nonetheless, the finger-holder which is used to communicate with a virtual reality environment reduces the user's cutaneous perception which might lead to the reduction of the training performance. We propose a motor learning method with the SR effects, and carry out the force-matching task with a comparison between with the SR-effect condition and without the SR effect condition. Thus, it is interesting to apply the SR effects to the motor learning task. We propose a motor learning method with the SR effects. There are two sub-tasks in this experiment: 1-D force-matching task, and 2-D force-matching task. The results indicate that the training performance when the noise is applied to the user has a faster learning process. Moreover, the results present the SR effects can enhance the haptic performance even if the user's finger is in the finger-holder while performing the fingertip-force training task.

Chapter 5 concludes the main findings and indicates the contribution of this thesis. A conclusion of our proposed method is also addressed in this chapter. Finally, we discuss future study problems, such as other interesting methods to enhance the haptic perception, the different methods to investigate how SR effects can enhance the haptic perception, and the SR effects for the retention phase.

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Contents

Chapter 1

INTRODUCTION

1.1 Background

Touch senses convey a variety of qualities or information about objects, making haptic perception essential for everyday tasks including turning knobs, holding objects, and typing on computer keyboards [1]. There are several tasks in our daily life related to a single finger and multiple fingers. Single-finger task is a task that manipulate by one finger, whereas multiple-finger task is a task that manipulate by multiple fingers. Therefore, a single-finger and multiple-finger task are parts of our daily life that are inevitable.

It is also known that dexterity is impacted by loss of haptic feeling at the fingertips [2–4]. Thus it would be useful to enhance the human haptic perception in terms of performing a task more accurately.

Several techniques, such as electrical stimulation [5–8], passive sensory stimulation [9], and a hybrid between electrical stimulation and vibrotactile stimulation [10], have been adopted to enhance the haptic sensation. Another notable method, the addition of noise, applies vibrotactile noise to various areas of a person's body (e.g., the feet [11, 12] and fingers [13]) to boost a weak signal such that it becomes detectable. Furthermore, there is a study that revealed the improvement in haptic ability by a short-time with white-noise vibration [14]. The enhancement of the detection of weak signals requires that the noise level not be excessively high or low [13, 15–19]. The phenomenon is referred to as Stochastic Resonance (SR).

1.2 Related Research

In this section, the use of Stochastic Resonance effects to enhance the haptic sensation is explained.

SR is a nonlinear phenomenon in which the introduction of random interference, or noise as it is almost always referred to, can improve the information content of a signal or improve the detection of weak stimuli. Maximum enhancement is achieved with just the right amount of additional noise; additional noise intensity increases only deteriorate detectability or information content. According to [20–24], the phenomenon does not arise in strictly linear systems, where the addition of noise to the stimulus or the system only results in a degradation of the signal quality. Stochastic resonance arises when a threshold, a subthreshold stimulus, and noise coincide. This is known as threshold SR or non-dynamical SR in its most basic form [25]. These components are commonplace in both natural and man-made systems, which explains why SR has been observed in a wide range of settings and fields. Another variation of the phenomenon, known as dynamical SR, is unique to stochastic, nonlinear dynamical systems. Throughout the majority of its existence, SR was believed to exist exclusively in its dynamical form. This belief dates back to when SR was first proposed as a potential explanation for periodic recurrences [20, 26, 27]. A thorough explanation of this type of SR necessitates an understanding of dynamical systems theory and mathematics, which are covered in [28].

Until now, there are two main methods to use the effects of SR. One is called "Normal Stochastic Resonance". while the other is called "Remote Stochastic Resonance". The definition and the related research of each method are described in the next section.

1.2.1 Normal Stochastic Resonance

Normal Stochastic Resonance is one method that the noise is applied at the position closed to the target position. For example, we would like to enhance the haptic sensation of the index fingertip. The given noise position will be located on the index finger.

Several studies have demonstrated an increase in haptic sensation via the normal SR effect [13, 16, 17]. Collins et al. [13] tested several levels of intensity of white Gaussian noise, including subthreshold and suprathreshold levels. They observed that the haptic sensation at the fingertip was enhanced when superimposing subthreshold noise on a mechanical stimulus applied to the fingertip of a participant whereas the force-detection ability diminished when they applied suprathreshold noise at the fingertip. Kurita et al.

[17] observed an improvement of the haptic sensation at the index finger when applying white Gaussian noise at the tip of the index finger.

However, there are three main problems of the normal SR. Firstly, this technique interfere the hand movement. Furthermore, the normal SR effects with only one source position could not enhance other fingers. Lastly, The normal SR effects with a single-noise source cannot enhance the sensation for multiple-finger task. To avoid these drawbacks, Remote SR technique is introduced.

1.2.2 Remote Stochastic Resonance

Remote Stochastic Resonance is one method that the noise is applied away from the target position. For instance, we would like to enhance the haptic sensation of the index fingertip. The applied noise position will be placed on the wrist.

Several studies have presents an enhancement of haptic sensation via the remote SR effect [18, 19, 29]. The remote SR effect can be induced when the noise source is placed at a distance from the fingertip [18, 19]. Enders et al. [18] observed that when white Gaussian noise was provided at a subthreshold level to a remote location (e.g., the dorsal hand, dorsal wrist, or volar wrist) of a stroke patient, the haptic perception was better than that for no-noise or a suprathreshold level of noise. Furthermore, Lakshminarayanan et al. [19] revealed the effect of remote white Gaussian noise at a subthreshold level when participants discriminated noise on the thumb or the index fingertip. Additionally, the remote SR effect has been demonstrated to improve haptic perception when a finger is placed in a finger holder [30]. Ikemura et al. [29] proposed a method of enhancing the tactile sensitivity of the fingertip via multiple vibrators placed at the volar and dorsal wrist when participants performed a texture discrimination task. They observed further enhancement of the haptic sensation for participants using the proposed method relative to the no-noise and single-noise conditions. The above studies showed that the remote SR effect enhances the haptic sensation of human users. Furthermore, several studies reveal an enhancement in kinesthesis or the perception of body movements by the SR effect [11, 31–33].

Based on the Stochastic Resonance via the mechanical noise addition method, there are two main methods (normal SR and remote SR) are developed for two main tasks (single-finger and multiple-finger task). The normal SR with a single vibrator can only improve the haptic sensation with only one finger. To enhance the haptic sensation of multiple fingers, normal SR with several vibrators technique is one solution. However, there are two main troubles from the use of this method are that the vibrator interferes a hand-movement and the several vibrators on the hand lead to load the weight to the hand. Therefore, remote SR with a single vibrator is interesting representative to use in universal conditions. The conclusion of the por and con of each method is showed in Fig. 1.1.

	Normal SR with one vibrator	Normal SR with several vibrators	Remote SR with one vibrator
Single-finger Task	o	o	o
Multiple-finger Task	x	o	o
Ease of Use	o	x	o
Lightweight	o	x	o

FIGURE 1.1: Overview of the advantage and drawback of each method of Stochastic Resonance.

1.3 Purpose of this Thesis

In this thesis, the goal is to realize the method that can enhance the haptic sensation of the fingertips for universal scenario, such as, single-finger and multiple-finger task. To achieve this purpose, there are three studies which are presented in this thesis.

In the first study which is presented in Chapter 2, the aim is to investigate the possible remote SR mechanism. This is because up until now the remote SR mechanism to enhance the haptic sensation is not clear. Therefore, it is interesting to investigate the the possible remote SR mechanism before the use of the method. In this study, we divided into two main experiments. One experiment is conducted to measure the propagated noise at the fingertip by the laser displacement sensor. In the following steps, we conducted a vibration discrimination task to investigate the remote SR behavior.

After that, the second study which is presented in Chapter 3, the purpose of this method is to examine the remote SR effects for the multi-finger task. Two-finger stiffness discrimination task is selected as a given task in this study because this task is one representative that requires user tactile sensation with multiple fingers to perform. In this study, there are three experiments that were conducted: Stiffness Discrimination in Real-world Environment without Finger-holders, Stiffness Discrimination in Real-world Environment with Finger-holders, and Stiffness Discrimination in Virtual-reality Environment with Finger-holders.

Furthermore, the aim of the third study is that we would like to investigate the effectiveness of the remote SR effects in the motor-learning, which the force-matching task is a representative of the motor learning task.In this study, there are two experiments that were conducted: Stiffness Discrimination in VR environment with Remote SR, and Force-matching with Remote SR.

1.4 Outline of this Thesis

This research study aims to enhance the haptic sensation of the user's fingertip and examine the reason why the effect of SR can enhance the haptic perception of the fingertip.

Chapter 2 first reveals the motivation behind this study to understand how SR effects can enhance the haptic sensation. We then examine how the SR effects enhance the haptic sensation of the human fingertip while performing the tasks. For this, we carry out the noise measurement at the fingertip while the noise is propagated from the noise source to the fingertip. After we understand that the noise propagates from the noise source to the fingertip proportionally, the vibration discrimination is conducted to examine the haptic performance when the noise is applied to the user with the several noise intensities. The outcomes show that the optimal noise level plays a crucial role in enhancing the haptic performance. We finally discuss the experimental results showing the user's haptic enhancement while performing the task.

Chapter 3 reveals the SR effects for the multi-finger task by conducting a two-finger stiffness discrimination task while the mechanical noise is applied to a user with a remote position of a noise source. Considering the main feature of SR effects, we propose a method to enhance the haptic sensation of the two fingertips with a single vibrator. Then, we carry out a two-finger stiffness discrimination while the participants are under the proposed method. The results show the SR effects can enhance haptic sensation of two fingers even with a single noise source while the user performs the multi-finger task. Furthermore, the position of the noise source also plays an important role in increasing the haptic performance of the user. Moreover, the SR effects aim to enhance the cutaneous perception, which results in the overall haptic perception being enhanced even if the task requires both kinesthetic and cutaneous perception.

Chapter 4 reveals there is no study that investigates the effectiveness of the SR in the learning task. Moreover, in today's modern training though a haptic training system is ubiquitous in several areas. Nonetheless, the finger-holder which is used to communicate with a virtual reality environment reduces the user's cutaneous perception which might lead the reduction of the training performance. We proposed a motor learning method with the SR effects, and carry out the force-matching task with a comparison between with the SR-effect condition and without SR effect condition. There are two sub-tasks in this experiment: 1-D force-matching task, and 2-D force-matching task. The results indicates that the training performance when the noise is applied to the user has a faster learning process. Moreover, the results present the SR effects can enhance the haptic performance even if the user's finger is in the finger-holder while performing the fingertip-force training task.

Chapter 5 concludes the main findings and indicates the contribution of this thesis. Future work related to the discussed issues is also provided. A conclusion of our proposed method is also addressed in this chapter. Finally, we discussed future study problems, such as other interesting methods to enhance the haptic perception, the different method to investigate how SR effects can enhance the haptic perception, applying the proposed method to a more complicated task, and the SR effects for the retention phase.

Chapter 2

PROPAGATED NOISE AT THE FINGERTIP FOR REMOTE STOCHASTIC RESONANCE EFFECTS

2.1 Introduction

A possible method of enhancing the haptic sensation of the user is to superimpose noise on the external force (signal to detect) and thus enhance the ability to detect a weak signal [13]. Seo et al. [34] monitored the peak-to-peak electric voltage using an electroencephalogram when subthreshold noise was applied to the wrist of a participant performing a motor task, and they compared their results with those obtained without noise. They found that as the noise source was placed farther from the fingertip, the noise intensity tended to decrease and the detection ability of the participant decreased. Seo et. al [35] suggested that the SR effect is a promising adjunctive therapy for upper-extremity recovery after stroke. This is one possible application if the SR effects enhance the haptic performance. Ikemura et al. [29] demonstrated that there is a relationship between the intensity of noise propagating to the fingertip and the haptic sensation at the fingertip; i.e., the haptic sensation of the fingertips is enhanced if the noise propagates sufficiently to the fingertip.

Several studies show the enhancement of the haptic sensation by the SR effects. However, it is unclear how the SR effects enhance the user's haptic perception. This chapter first reveals the motivation behind this study to understand how SR effects can enhance the haptic sensation. We then examine how the SR effects enhance the haptic sensation of the human fingertip while performing the tasks. For this, we carry out the noise measurement at the fingertip while the noise is propagated from the noise source to the fingertip. After we understand that the noise propagates from the noise source to the fingertip proportionally, the vibration discrimination is conducted to examine the haptic performance when the noise is applied to the user with the several noise intensities. The outcomes show that the optimal noise level plays a crucial role in enhancing the haptic performance. We finally discuss the experimental results showing the user's haptic enhancement while performing the task.

The aim of this chapter is to investigate how stochastic resonance effects can enhance the user haptic sensation. This chapter is based on our two journal papers [36, 37].

The present chapter is organized as follows. Section 2.2 describes the evaluation method. Section 2.3.3 presents the experimental results. The discussions of the user studies are described in Section 2.7. Finally, conclusions are provided in section 2.7.

2.2 Evaluation Method

A piezoelectric actuator (APA120S, Cedrat Technology, Inc.) is placed on the hand of the user to generate white Gaussian noise in the proposed method for enhancing the haptic perception at the fingertip. The response characteristics of the mechanoreceptive afferent units are taken into consideration when choosing the noise frequency range. For instance, Pacinian corpuscles react to a broad range of frequencies [38]. To cover all tactile receptors, white Gaussian noise with a 300-Hz low-pass filter is chosen. The Box–Muller method [39] is applied to generate the white Gaussian noise signal $x(t)$:

$$x(t) = \sigma\sqrt{-2\ln\alpha(t)}\,\sin(2\pi\beta(t)), \tag{2.1}$$

where $x(t)$ corresponds to the electric voltage signal used to control a piezoelectric actuator, t is time, σ is the noise intensity, and α and β are independent random variables in the interval (0,1).

2.3 Propagating Noise with a Distance

To comprehend the possibility that the vibrotactile noise effects of remote SR improve the haptic sensation at the fingertip, the mechanism of remote SR must be studied further. According to this theory, the noise superimposes on the outside force, improving the user's capacity for force detection [13]. Ikemura *et al.* [29] asserts that there is a connection between the level of noise and the haptic experience at the fingertip. Furthermore, it is interesting to investigate the difference range of the noise position. Thus, the pilot study was conducted to measure the propagated noise to the fingertip from a distance.

We used a laser displacement sensor (CL-L015, Keyence Inc.) to collect the displacement data for this pilot study (Fig. 2.1). The vibrator's noise was audible at the fingertip, according to measurements taken with the laser displacement sensor.

FIGURE 2.1: Overview of the experimental setup to measure the noise at a finger in this pilot study.

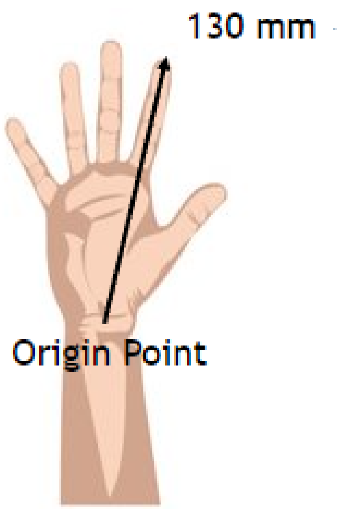


FIGURE 2.2: Overview of the measured range on the hand.

2.3.1 Participants

In the pilot study, three participants (mean age ± SD: 24.33 ± 1.53 years, all male) took part. The Graduate School of Engineering at Kyoto University's Ethics Committee approved the experimental protocol, which the participants understood and agreed to (No. 202012). To assess the likelihood of the noise reaching the fingertip, the displacement at the fingertip was measured.

2.3.2 Experimental Procedure

Initially, the dominant hand's wrist was used to attach the vibrator. The staircase method [40] was then used to measure the participant's sensory threshold (T), or the lowest level of noise from the piezoelectric actuator that the participant perceived. The subject maintained his fingers beneath the laser displacement sensor following the measurement of the sensory threshold. For ten seconds, a piezoelectric actuator was used to apply noise, and the noise intensity was set at $0.6T$ (60% of T).

2.3.3 Experimental Results

The outcomes of the experiment are displayed for one of the three participants in Fig. 2.3. The patterns of results for the other two participants were comparable. Whereas the vertical axes show the displacement spectrum determined by the fast Fourier transform, the horizontal axes show the frequency. Fig. 2.4 shows the overall propagated noise behaviour by the ratio between Amplitude at the wrist (A(0)), and Amplitude at the distant position (A(d)).

The behavior of the propagate noise is that the noise is slightly decrease, related to the distance, and the noise is not zero at the fingertip.

2.4 Vibration Discrimination with Remote SR

After the results of the previous section shows that the behavior of the propagate noise is that the noise is slightly decrease, related to the distance, and the noise is not zero at the fingertip, we are interested to investigate the relationship between the propagated noise and the enhancement of user haptic sensation.

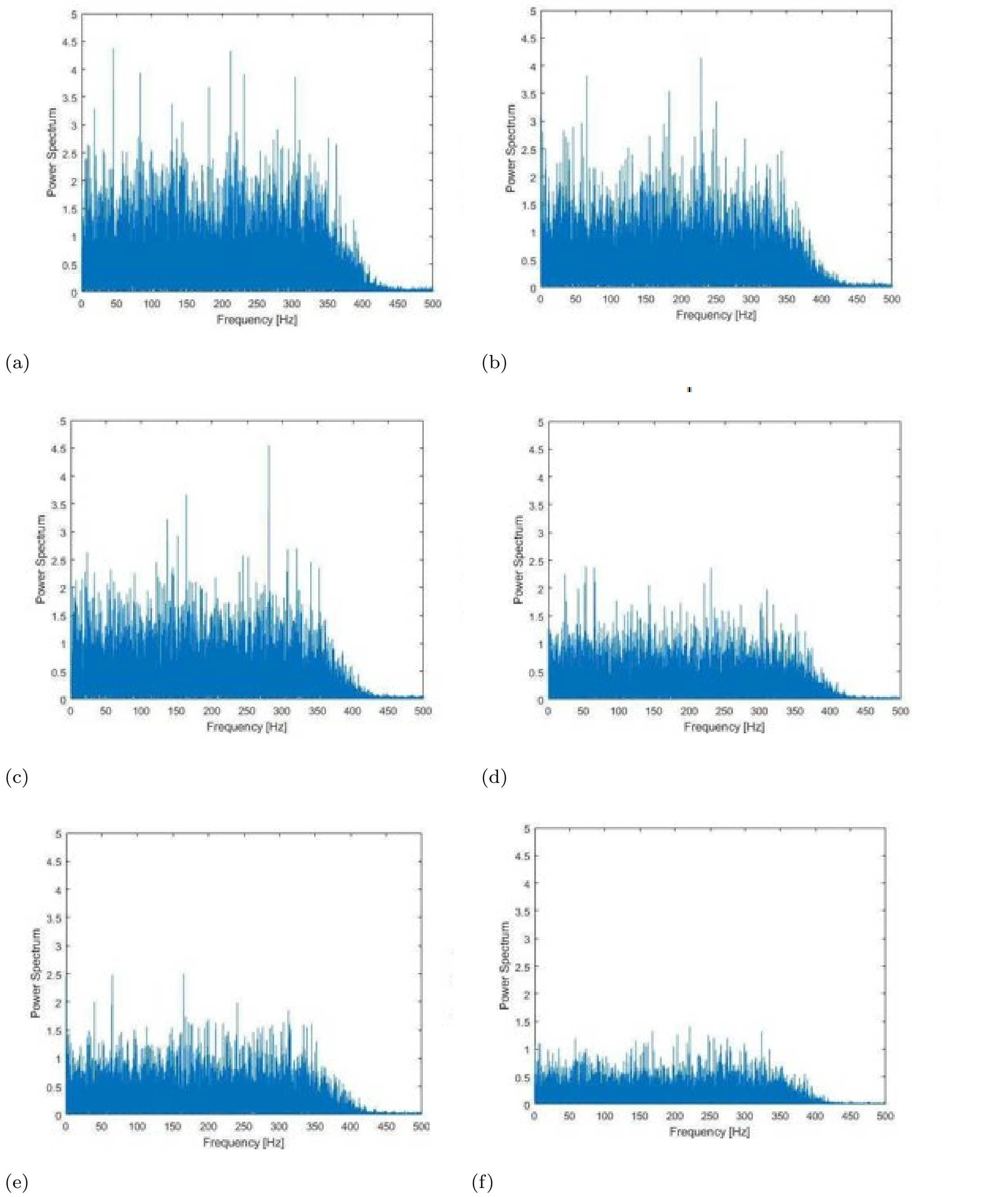


Figure 2.3: Power spectrum (PS) of displacement data for different measured positions of the noise source: (a) PS of displacement of 20 mm away from the noise source, (b) PS of displacement of 40 mm away from the noise source, (c) PS of displacement of 60 mm away from the noise source, (d) PS of displacement of 80 mm away from the noise source, (e) PS of displacement of 100 mm away from the noise source, and (f) PS of displacement of 120 mm away from the noise source

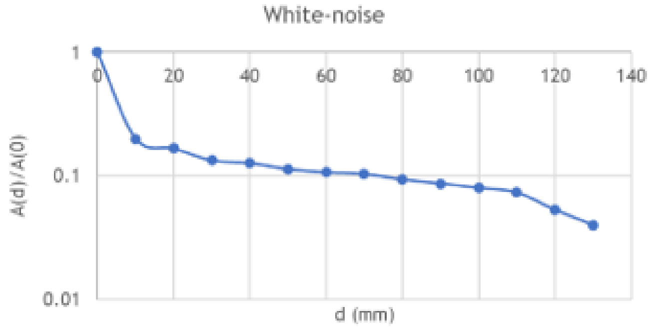


FIGURE 2.4: Decay rate of the noise propagation to the fingertip. A(o) is Amplitude at the wrist, and A(d): Amplitude at the distant position.

2.4.1 Participants

In the pilot study, five participants (mean age ± SD: 23.35 ± 1.42 years, all male) took part. The Graduate School of Engineering at Kyoto University's Ethics Committee approved the experimental protocol, which the participants understood and agreed to (No. 202012).

2.4.2 Experimental Procedure

2.4.3 Experimental Results

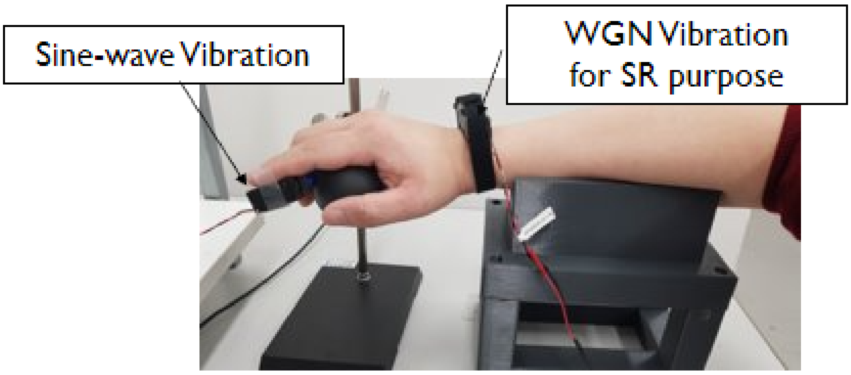
The normalized threshold at the fingertip that participants can detect in the vibration discrimination are shown in Fig. 2.6. Whereas the vertical axes show the normalized threshold at the fingertip that participants can detect, the horizontal axes show the vibration conditions for the SR purpose.

The results indicate that the noise level is important to enhance the haptic sensation of the user. By comparing between the noise position and performance, the noise position is also crucial to enhance the haptic sensation. For example, the performance of 0.6T(F) is better than 0.6T(W). The possible remote SR mechanism is that the sufficient propagated noise plays an important role to enhance the haptic sensation.

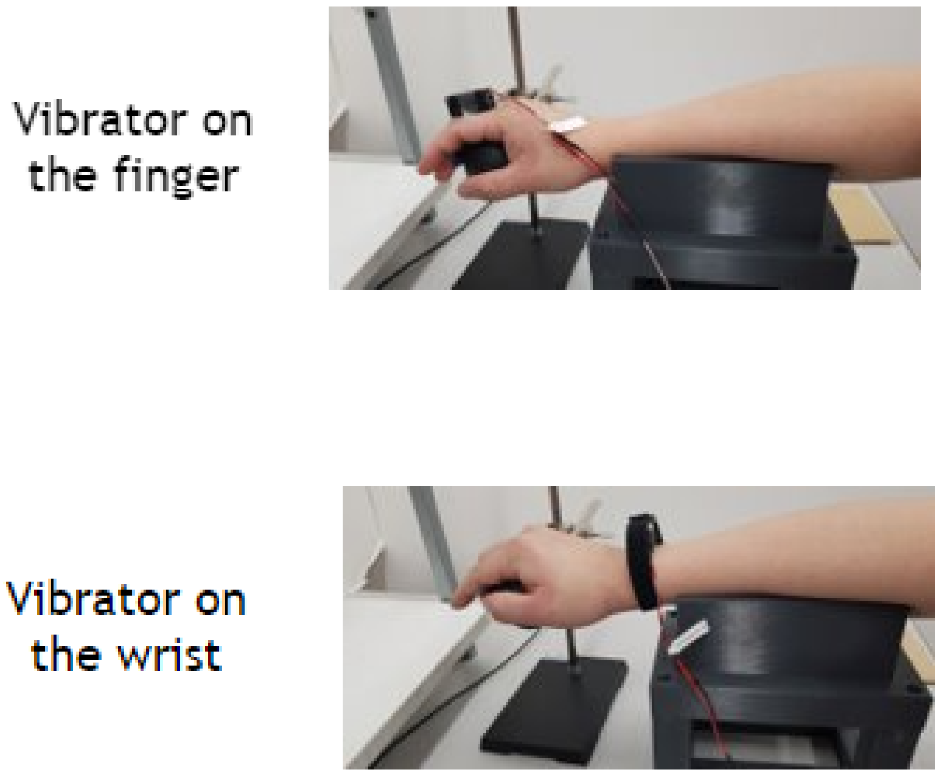
2.5 Propagating Noise with Two Finger-holders

The mechanism of remote SR must be investigated to understand the possibility that the remote SR effects in terms of vibrotactile noise enhance the haptic sensation at the fingertip. The noise is considered to superimpose on the external force, which enhances the force-detection ability of the user [13]. According to Ikemura *et al.* [29], there is a

Initially, the dominant hand's three positions were used to attach the vibrator. The staircase method [40] was then used to measure the participant's sensory threshold (T), or the lowest level of noise from the piezoelectric actuator that the participant perceived. The subject maintained his fingers on the support as shown in Fig. 2.5. There are 2 different noise positions as shown in Fig 2.5. Furthermore, there are two piezoelectric actuators in this experiment. One piezoelectric actuator was used to apply noise, and the noise intensity was set at 4 different levels ($0.4T$, $0.6T$, $0.8T$, and $1.0T$) and two different noise positions (on the finger and the wrist). The other actuator was used to provide the sine-wave vibration that participants have to tune to the smallest amplitude of the vibration that they can feel by increase and decrease the level through a keyboard.



(a)



(b)

FIGURE 2.5: (a) Overview of the experimental setup to conduct the vibration discrimination. (b) The two different noise positions (on the index finger, and on the wrist) in the vibration discrimination.

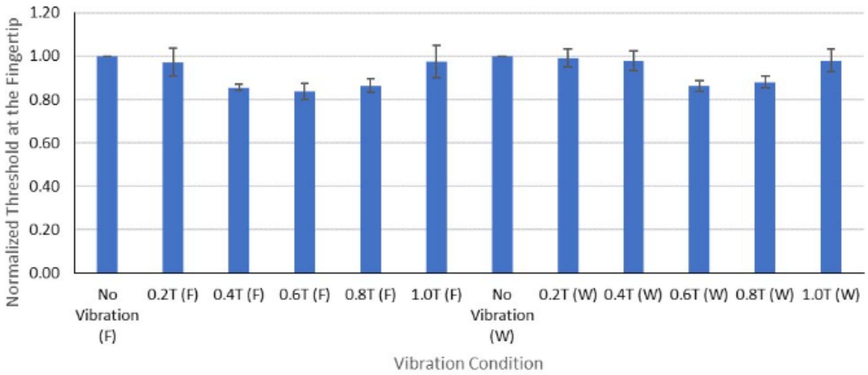


Figure 2.6: Normalized threshold at the fingertip that participants can detect in the vibration discrimination.

relationship between the noise intensity and haptic sensation at the fingertip. If the noise propagates sufficiently to the fingertip, the haptic sensation improves. Therefore, if the noise can propagate to multiple fingertips through a vibrator, the haptic sensation at the fingers can be enhanced. Thus, we first investigated the possibility of the noise reaching multiple fingertips from one vibrator before conducting the stiffness discrimination task.

The previous study shows the amplitude of the propagated noise is important to enhance the haptic sensation for a single finger. However, there are several tasks in our daily lives require multiple fingers to perform the task. The aim of this experiment is to investigate the behavior of the propagated noise for multiple fingers.

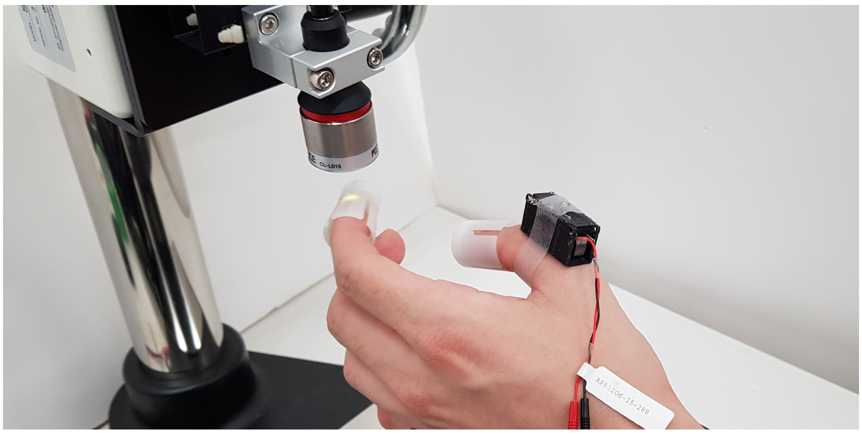
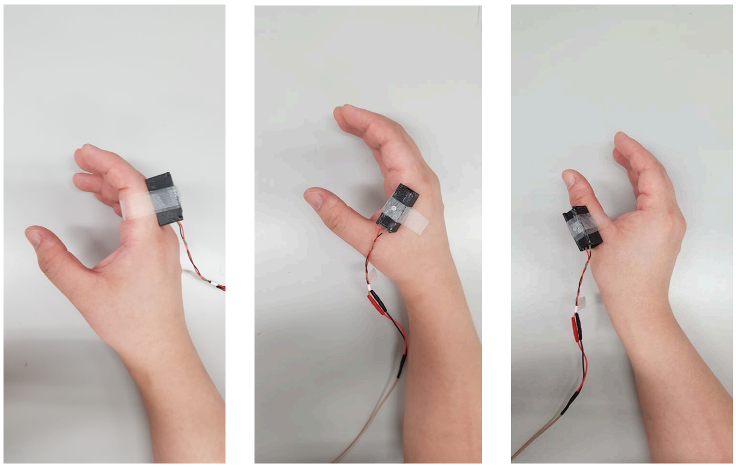


Figure 2.7: Overview of the experimental setup to measure the noise at a finger.

In this pilot study, we obtained the displacement data using a laser displacement sensor (CL-L015, Keyence Inc.) (Fig. 2.7). The measurements made using the laser displacement



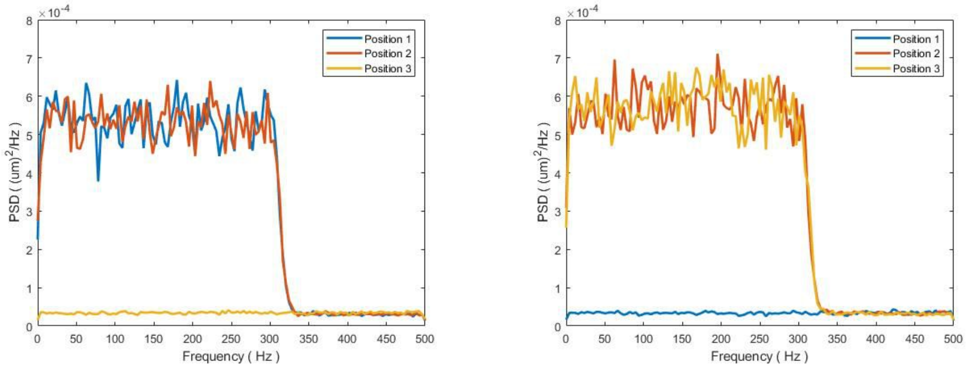
(a) (b) (c)

FIGURE 2.8: Three positions of the noise source: the vibrator at (a) Position 1, (b) Position 2, and (c) Position 3.

sensor revealed that the noise from the vibrator reached the fingertip. For instance, the higher displacement at the measurement point indicated the possibility that the noise reached the fingertip. We considered three different noise source positions (on the index finger (Position 1), between the index finger and thumb (Position 2), and on the thumb (Position 3), see Fig. 2.8). The first test position (Position 2) was between the index finger and the thumb. In the cases of Positions 1 and 3, the vibrator was on the index finger and thumb of the participant, respectively. We hypothesized that the vibrotactile noise from the vibrator at Position 2 reaches the tips of both fingers at sufficient levels. In contrast, noise from Positions 1 and 3 reaches only one finger, and the vibrator is close to the fingertip. For example, the noise from Position 3 reaches the tip of the thumb at a level higher than that of the noise reaching the tip of the index finger. Thus, this position might result in less improvement in user perception compared with Position 2.

2.5.1 Participants

Ten participants (mean age ± SD: 26.60 ± 3.31 years, six males and four females) participated in the pilot study. The participants were students and not clinical workers. The participants understood and consented to the experimental protocol approved by the Ethics Committee of the Graduate School of Engineering, Kyoto University (No. 202012).



(a) (b)

FIGURE 2.9: PSDs of the propagated noise: (a) PSD on the index finger and (b) PSD on the thumb. Blue, red and yellow lines show the results for the noise propagating from Positions 1, 2 and 3, respectively.

2.5.2 Experimental Procedure

First, the vibrator was attached to one of the three positions on the dominant hand. Subsequently, the sensory threshold (T) of the participant, which was the lowest level of noise from the piezoelectric actuator perceived by the participant, was measured using the staircase method [40]. After the sensory threshold was measured, the participant kept his fingers under the laser displacement sensor. The participants relaxed their hand on the stand during the experiment. The participants were tested for all three selected noise source positions (Fig. 2.8). Mechanical noise with the intensity level at $0.6T$ (i.e., 60% of the sensory threshold) was applied by the piezoelectric actuator for 30 s. According to several studies [18, 19, 30], the intensity level at $0.6T$ is one of the optimal noise intensity levels to produce the SR effect at the fingertip. Therefore, the noise level at $0.6T$ was used in this study. This study investigates six conditions (3 positions (Position 1, Position 2, and Position 3) x 2 fingers (Index finger and thumb)). There are five trials for each condition.

2.5.3 Experimental Results

A power spectrum density is used to describe the frequency components of noise in this experiment. The experimental results are shown in Fig. 2.10 for one of the ten participants. The results for the other nine participants have similar patterns. The horizontal axis represents the frequency whereas the vertical axis represents the PSD of the propagated noise calculated using Welch's method and a window of 200 ms and an overlap of 50%. The blue, red and yellow lines show the PSD for the noise source at Position 1, 2 and 3, respectively.

For the participant whose results are shown in Fig. 2.9, the sensory threshold values when the noise source was at Position 1, 2 and 3 were 0.08, 0.09 and 0.09, respectively. The average sensory threshold values when the noise source was at Position 1, 2 and 3 for all participants were 0.092 ± 0.011, 0.095 ± 0.011 and 0.092 ±0.01, respectively. Additionally, there were significant differences ($p < 0.01$) for all combinations of noise positions, as confirmed in one-way analysis of variance (ANOVA). Furthermore, two-way analysis of variance (ANOVA) of the PSD values indicated a significant interaction between the measurement position and noise position ($p < 0.05$). Moreover, the average PSD values at the index finger in the interval from 0 to 300 Hz when the noise source was at Position 1, 2 and 3 were calculated as $5.32 \times 10^{-4} \pm 0.49 \times 10^{-4}$, $5.32 \times 10^{-4} \pm 0.58 \times 10^{-4}$ and $0.35 \times 10^{-4} \pm 0.03 \times 10^{-4}$, respectively. In contrast, the average PSD values at the thumb in the interval from 0 to 300 Hz when the noise source was at Position 1, 2 and 3 were calculated as $0.34 \times 10^{-4} \pm 0.04 \times 10^{-4}$, $5.62 \times 10^{-4} \pm 0.05 \times 10^{-4}$ and $5.64 \times 10^{-4} \pm 0.06 \times 10^{-4}$, respectively. Moreover, there were significant differences in the average PSD values ($p < 0.01$) for all comparisons (i.e., Position 1–Position 2, Position 1–Position 3 and Position 2–Position 3 comparisons) in one-way analysis of variance (ANOVA) for both the index finger and thumb as the measurement position. Although the propagated noise having propagated from Position 2 was not as strong as that having propagated from Position 1 when the measurement position was the index finger, the noise having propagated from Position 2 was significantly stronger than that having propagated from Position 1 when the measurement position was the thumb. Position 2 was thus considered the optimal position of the noise source in this study.

The experimental results are shown in Fig. 2.10 for one representative of the three participants. The other two participants had similar patterns of the results. The horizontal axes represent the frequency, whereas the vertical axes represent the spectrum of the displacement calculated using the fast Fourier transformation.

The results indicate that the noise propagated to the tips of both fingers when it was applied at Position 2. First, when the noise was at Position 1, the displacement on the index finger was likely to be higher than the displacement on the thumb (Figs. 2.11 (a) and 2.11 (b)). When the noise was applied at Position 3, the displacement on the index finger was likely to be lower than that on the thumb (Figs. 2.11 (e) and 2.11 (f)). However, when the noise was at Position 2, the displacements on the index finger and thumb were nearly identical (Figs. 2.11 (c) and 2.11 (d)). Thus, there were sufficient levels of noise at the tips of both fingers, whereas the noise under the other conditions was likely to reach only one finger. Therefore, we observed that even the noise from one vibrator could propagate sufficiently to multiple fingertips, which were the thumb and index finger. We thus expected that Position 2 is a better option than the others to improve haptic performance using the thumb and index finger via the SR effects.

2.6 Discussion

In this study, we first examined the displacement between the fingertip and the laser displacement sensor, which was a parameter indicating the possibility of noise superimposing on an external stimulus at the fingertip (i.e., the measurement point in this study), before applying SR effects to enhance the user haptic sensation. According to the findings in Section 2.3.3, for various noise source locations, there was displacement between the fingertip and the laser displacement sensor at each measurement point that was not zero. This suggested that noise might enhance haptic perception by superimposing on stimuli.

2.7 Conclusion

THis chapter reveals the motivation behind this study to understand how SR effects can enhance the haptic sensation. We then examine how the SR effects enhance the haptic sensation of the human fingertip while performing the tasks. We first carry out the noise measurement at the fingertip while the noise is propagated from the noise source to the fingertip. After we understand that the noise propagates from the noise source to the fingertip proportionally, the vibration discrimination is conducted to examine the haptic performance when the noise is applied to the user with the several noise intensities. The outcomes show that the optimal noise level plays a crucial role in enhancing the haptic performance. We finally discuss the experimental results showing the user's haptic enhancement while performing the task.

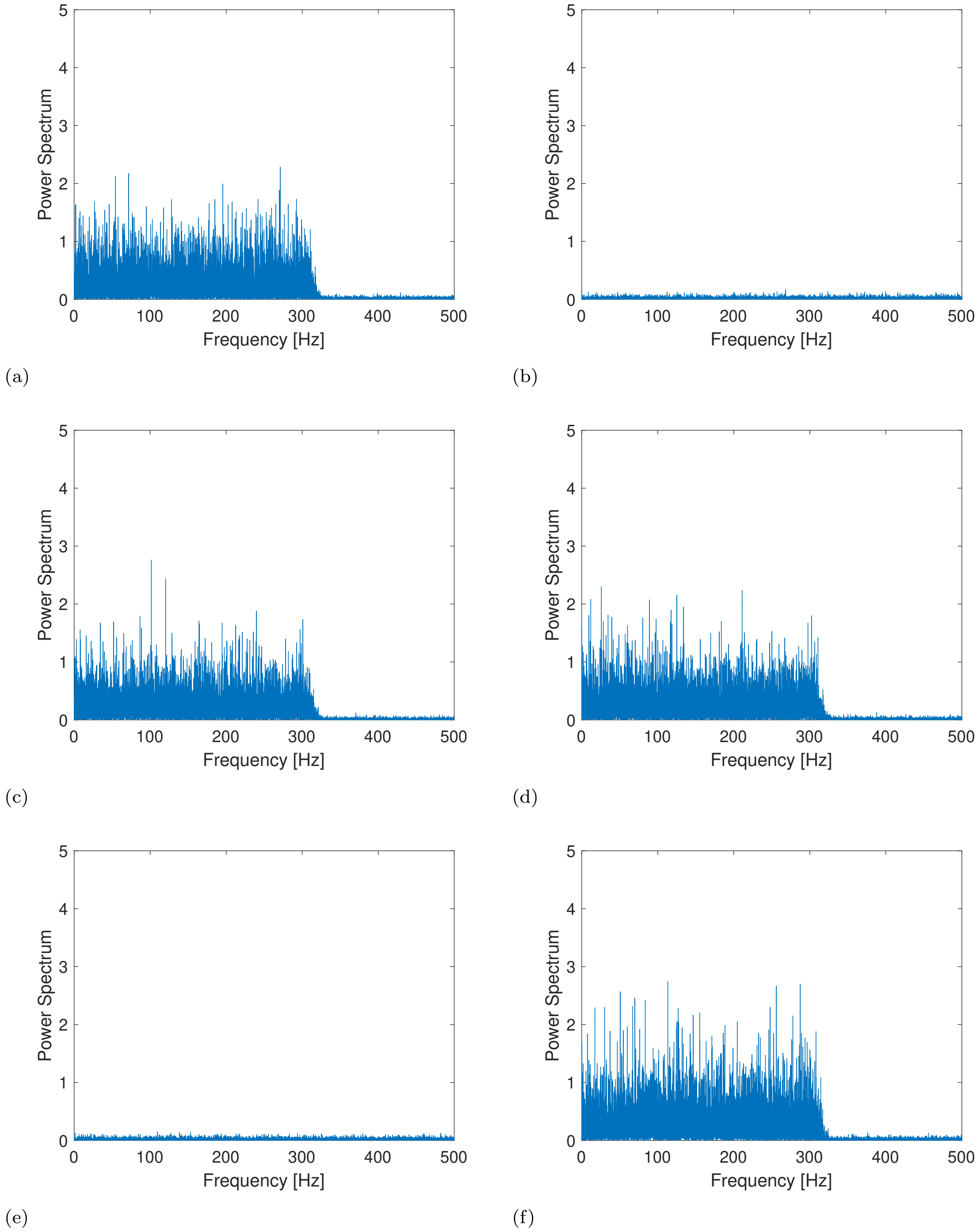


FIGURE 2.10: Power spectrum (PS) of displacement data for different fingers of one participant and different positions of the noise source: (a) PS of displacement on the index finger when the vibrator was at Position 1, (b) PS of displacement on the thumb when the vibrator was at Position 1, (c) PS of displacement on the index finger when the vibrator was at Position 2, (d) PS of displacement on the thumb when the vibrator was at Position 2, (e) PS of displacement on the index finger when the vibrator was at Position 3, and (f) PS of displacement on the thumb when the vibrator was at Position 3.

Chapter 3

REMOTE STOCHASTIC RESONANCE EFFECTS FOR TWO-FINGER STIFFNESS DISCRIMINATION

3.1 Introduction

Because touch conveys various properties or information about objects, haptic perception is essential for everyday activities (e.g., turning a knob, grasping an object, and typing on a computer keyboard) [1]. Moreover, decisions that depend on the haptic perception of an expert have an impact on the outcome in some specialties. It is challenging for beginners to quickly reach high levels of proficiency. Using a haptic training system that combines a haptic interface device and virtual reality environment (VE) is a well-known solution [41–43].

It is known that the spatial acuity and force sensitivity at the fingertip worsen when a hard finger holder covers the finger compared with those in the case of a bare finger [44]. Meanwhile, when we perceive a soft object, the size of the contact area between the finger and surface can be used to determine the magnitude of the applied force, even if the soft object is sandwiched between rigid plates [45]. We therefore consider that remote SR, which boosts the skin sensation, also contributes to stiffness discrimination when a finger holder covers the finger

As mentioned in Chapter 1, multiple-finger task is a task that manipulate by multiple fingers, and Stiffness Discrimination is one example that requires user tactile sensation with multiple fingers to perform. Our objective is that To examine the remote SR effects for the multi-finger task (Stiffness Discrimination) in two environments. This study focused on stiffness discrimination as a task using multiple fingers, in which the thumb and index finger were used to touch a real and a virtual object and perceive its stiffness with remote SR produced by a single vibrator. There is a relationship between the noise intensity and the enhancement of haptic sensation. Furthermore, the haptic sensation may be enhanced on multiple fingers if the noise can propagate sufficiently to the fingertips. Therefore, to improve the haptic sensation of multiple fingertips, it is not necessary to attach vibrators to multiple fingertips. Even if one vibrator is used, the haptic sensation at multiple fingertips may be improved by propagating noise to multiple fingertips. In the previous study that described in Chapter 2, we hypothesized that if the noise reaches the fingertip, the haptic sensation can be improved. Moreover, we examined the effects of remote SR, which enhances user haptic performance in a stiffness discrimination task involving multiple fingers on both hands in a real-world environment and a VE. It is known that perception of the stiffness at the fingertips is based on a combination of cutaneous information and kinesthetic information [45, 46]. This chapter is based on our two journal papers [36, 37].

The remainder of the chapter is organized as follows. Section 3.2 describes the experimental environment. Section 3.3 describes a method of evaluating the effect of remote SR in a stiffness discrimination task without the finger holders conducted using two fingers for a single vibrator, and Section 3.4 provides an experiment that performs the same task as in Section 3.3 with finger holders. Furthermore, Section 3.5 reveals an experiment that performs the same task as in Section 3.4 in a Virtual-reality Environment. The discussion of this study is presented in Section 3.6. Section 3.7 presents conclusions drawn from the study results.

3.2 Experimental Environment

In this study, we mainly investigated the stiffness discrimination task, where the thumb and index finger were used to perceive the stiffness of an object in both a real-world environment and a VE. Here, we describe the experimental environment for Section 3.3. Section 3.4 investigates the stiffness discrimination task when touch an object with the finger holders. See Section 3.4.2 for details. Furthermore, Section 3.5 investigates the stiffness discrimination task when touch a virtual object in a Virtual-reality Environment.

The haptic feedback from haptic devices in this study conveys the stiffness information of the object in the VE to the user, while the SR effect in terms of the noise generated by the vibrator boosts the haptic sensation of the user's two fingers. Two Geomagic Touch haptic devices provided haptic feedback to the user during the stiffness discrimination task. The original end effector of each device was modified to suit a task involving manipulation with fingers (Fig. 3.8). A finger holder fabricated from polyoxymethylene and a six-degree-of-freedom force sensor (Leptrino, CFS018CA101U) replaced the original pen stylus of the haptic device. Note that we did not use a force sensor in this study. The force feedback from the virtual object was calculated using Hooke's law; i.e., by multiplying the depth of the penetration of the finger into the displayed object and the stiffness of the touched object. The stiffness value was selected as that of body fat, as described in Section 3.3.3.

Meanwhile, a piezoelectric actuator (APA120S, Cedrat Technology, Inc.) was placed on the hand of the user to generate additive white Gaussian noise. The response characteristics of the mechanoreceptive afferent units were taken into consideration when choosing the noise frequency range. For instance, Pacinian corpuscles react to a broad range of frequencies [38]. To cover all mechanoreceptors, white Gaussian noise with a low-pass filter set at 300 Hz was chosen. Using the Box–Muller technique [39], the white Gaussian noise signal $x(t)$ was produced as eq. 2.1.

3.3 Stiffness Discrimination Using Two Fingers without Finger-holders in a Real-world Environment

3.3.1 Experimental Setup

Using the suggested approach, we examined stiffness discrimination in a multi-finger task wherein an object's stiffness was perceived by touching it with the thumb and index finger. Through pinching the object, the user was able to detect its rigidity, and the vibrator's SR effect enhanced the user's two fingers' haptic feedback.

Polyol and modified isocyanate, two different forms of silicone, were combined to generate the silicone models. Each experiment contained ten comparison stiffness models, or five comparison stiffness models on each side, in addition to one reference stiffness model. There are 44 pieces of silicone models in total (4 pieces for reference stiffness and 40 pieces for comparison stiffness). The dimensions of every model are 6.5 cm $\times$ 6.5 cm $\times$ 3 cm. The study's silicone model example is displayed in Fig. 3.2. Through force gauge measurements, the rigidity of the silicone model was determined. The aluminum spherical indenter has a diameter of one centimeter. Here, the force gauge squeezed the silicone model until the depth of penetration reached 10 mm while automatically moving at a steady pace of 5 mm/s. Following that, we conducted five repetitions of the measurements again to determine the average stiffness.

3.3.2 Participants

Twenty healthy participants (mean age ± SD: 26.05 ± 3.03 years, 12 males and 8 females) participated in the user study. Participants weren't medical professionals; they were students. The Graduate School of Engineering at Kyoto University's Ethics Committee approved the experimental protocol, which the participants understood and agreed to (No. 202012).Participants weren't medical professionals; they were students. The Graduate School of Engineering at Kyoto University's Ethics Committee approved the experimental protocol, which the participants understood and agreed to.

3.3.3 Experimental Procedure

The sensory threshold (T) at the desired position of the participant, which was the lowest noise intensity of the vibrator that the participant could perceive, was first measured for each participant using the staircase method [40]. Subsequently, participants performed the stiffness discrimination task for each of five noise intensities (i.e., no noise ($0T$) and 40% ($0.4T$), 60% ($0.6T$), 80% ($0.8T$), and 100% ($1.0T$) of the sensory threshold) for three positions of the noise source. The noise intensities were provided randomly to the participants to avoid learning effects. Furthermore, participants wore a passive noise-cancelling headset to avoid hearing the noise sound of the vibrator.

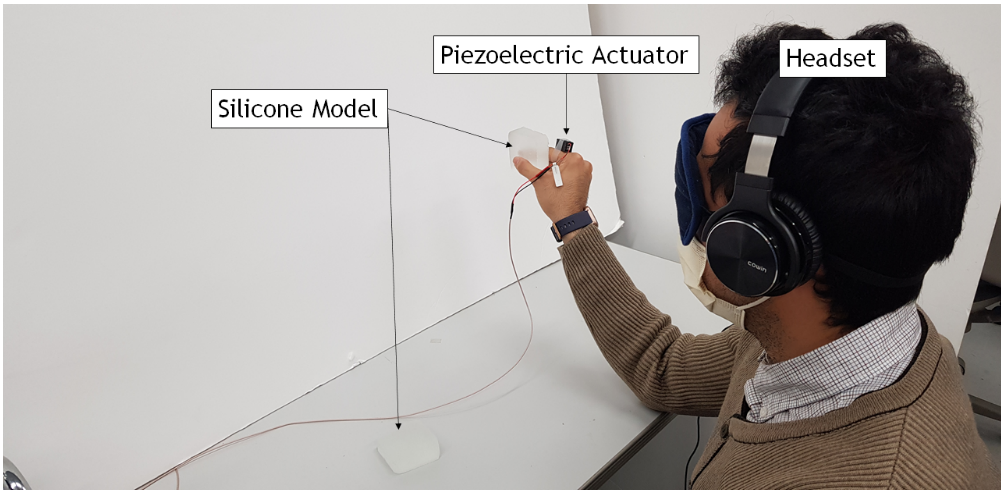


FIGURE 3.1: Overview of the experimental setup. The participant touched an object while receiving the effects of the SR via the vibrator.

In the stiffness discrimination task, two silicone models were placed in front of a participant (Fig. 3.1). Reference stiffness values were selected to be 1.5, 2.2, 3.0, and 3.8 N/mm. A given object was assigned one of the four reference stiffness values, whereas the other 10 objects of each reference stiffness were assigned a comparison stiffness. For example, the reference stiffness is 1.5 N/mm, whereas the comparison stiffness levels are

0.8, 0.94, 1.08, 1.22, 1.36 ,1.64, 1.78, 1.92, 2.06, and 2.2 N/mm. The stiffness of the silicone model was obtained from measurements made with a force gauge. Here, the force gauge automatically moved at a constant speed and pressed the silicone model until the depth of penetration reached 10 mm. We repeated the measurements for a total of five trials and obtained the average stiffness.

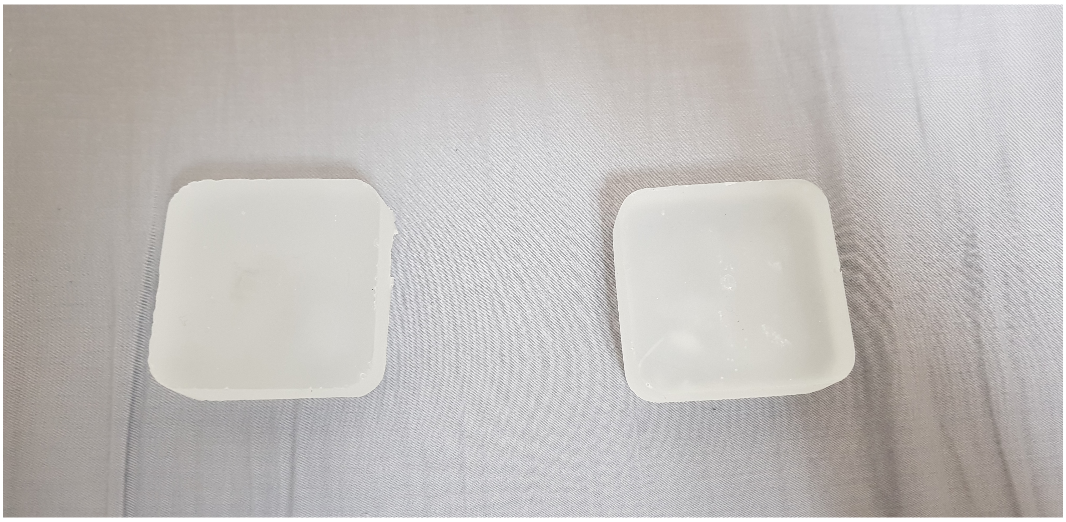


FIGURE 3.2: The example of silicone models to test in the stiffness discrimination task.

There was no time limit for touching the objects. All participants were instructed to do their best in each trial to reduce bias that could affect the performance. Each participant indicated which object he or she felt was stiffer and then began the next trial. The average time for one trial was approximately 15 s and there was no special event that occurred during the experiment. The experiment was conducted on a different day for each reference stiffness to avoid fatigue and a learning effect.

The number of times that participants identified the comparison stiffness as being stiffer than the reference stiffness was stored. A psychometric function was then fitted to the results of each participant and a psychometric curve was plotted using the MATLAB toolbox psignifit. Three values were used to evaluate the user's haptic performance: i) the point of subjective equality (PSE), ii) the stimulus value corresponding to the 25th percentile of a psychometric function (J_{25}), and iii) the stimulus corresponding to the 75th percentile of a psychometric function (J_{75}). We then determined the Just Noticeable Difference (JND) value as the average difference between the PSE and (J_{25})

and (J_{75}) as in (3.1) and determined the WF of each participant under each condition (3.2):

$$JND = \frac{(PSE - J_{25}) + (J_{75} - PSE)}{2}, \tag{3.1}$$

$$WF = \frac{JND}{\text{Reference Stiffness}}. \tag{3.2}$$

A WF of 0.01 means that a participant could detect a 1% change in the stiffness level with respect to the reference stiffness.

3.3.4 Experimental Results

Fig. 3.3 show the average WF values under each condition. The horizontal axes display the reference stiffness, while the vertical axes display the WF values. Each noise condition has five bars that represent the various noise intensities. The error bars reveal the standard deviation. There are significant differences ($p < 0.05$) in the average WF values at intensities of $0T$ and $0.6T$ in each of the three sub-figures for each reference stiffness in all figures, according to a two-tailed paired t-test. Additionally, the WF value was lowest at an intensity of $0.6T$.

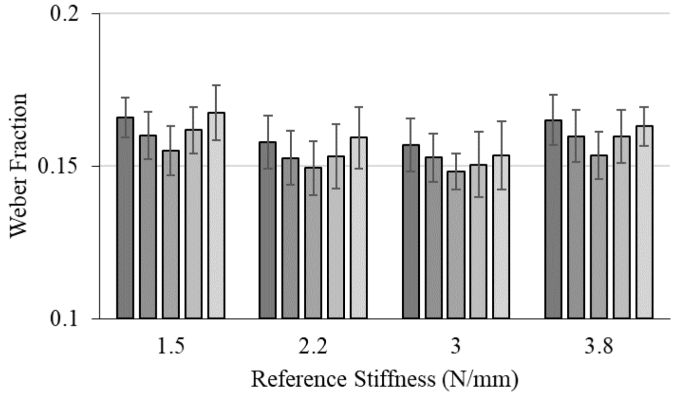
TABLE 3.1: Normalized WF values in each reference when the source is at Position 1

Reference Stiffness [N/mm]	Noise Intensity				
	0T	0.4T	0.6T	0.8T	1.0T
1.5	1.00	0.963	0.934	0.974	1.01
2.2	1.00	0.964	0.930	0.966	1.00
3	1.00	0.963	0.920	0.967	0.989
3.8	1.00	0.972	0.934	0.975	0.988

TABLE 3.2: Normalized WF values in each reference when the source is at Position 2

Reference Stiffness [N/mm]	Noise Intensity				
	0T	0.4T	0.6T	0.8T	1.0T
1.5	1.00	0.926	0.868	0.905	0.944
2.2	1.00	0.932	0.867	0.905	0.925
3	1.00	0.935	0.887	0.930	0.955
3.8	1.00	0.940	0.879	0.915	0.939

We conducted a three-way ANOVA using SPSS software to investigate the significant difference between the means of normalized WF values with respect to the three factors, namely the reference stiffness, noise intensity, and noise position. In particular, before conducting the ANOVA, the inverse transformation for negative skewed data $1/(\max(x)+1-x)$ was implemented to ensure the normality [47], where $x$denotes the data. The



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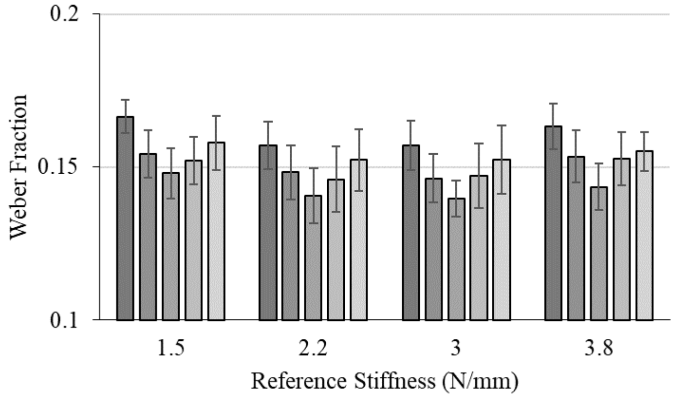

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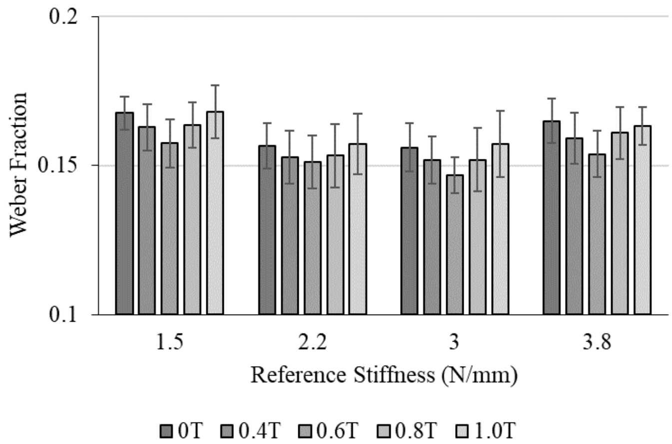


(c)

Figure 3.3: Average normalized Weber Fraction of the participants for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb. The error-bars indicate the standard deviation.

TABLE 3.3: Normalized WF values in each reference when the source is at Position 3

Reference Stiffness [N/mm]	Noise Intensity				
	0T	0.4T	0.6T	0.8T	1.0T
1.5	1.00	0.969	0.937	0.971	1.00
2.2	1.00	0.972	0.941	0.970	0.996
3	1.00	0.972	0.939	0.973	1.00
3.8	1.00	0.966	0.936	0.979	0.997

TABLE 3.4: Summary of three-way ANOVA of haptic perception under each condition

Effect	Degree of Freedom	F-value	p-value
Reference Stiffness	3	0.529	$<$ **0.01**
Noise Intensity	4	250.863	$<$ **0.01**
Noise Position	2	200.909	$<$ **0.01**
Reference Stiffness × Noise Intensity	12	0.672	0.780
Reference Stiffness × Noise Position	6	2.004	0.062
Noise Position × Noise Intensity	8	14.594	$<$ **0.01**
Reference Stiffness × Noise Intensity × Noise Position	24	0.594	0.939

results of the three-way ANOVA are summarized in Table 3.4. There were no significant differences between most factors (p-value > 0.05). However, we found a significant simple two-way interaction between the noise intensity and noise position (p-value < 0.05).

Furthermore, we carried out post hoc Tukey HSD multiple-comparison tests. We did not find any statistically significant differences between the positions of the noise source for zero noise intensity. We found significant differences between Positions 2 and 3 of the noise source (p-value < 0.05) for the noise intensity of $0.4T$ between Positions 1 and 2 (p-value < 0.01)) for noise intensities of $0.6T$, $0.8T$ and $1.0T$. Similarly, for the positions of the noise source, we investigated the significant differences between the noise intensities. As an example, we present only the results for Position 2. For Position 2, we found statistically significant differences (p-value < 0.01) for the pairs $0T$ and $0.4T$ ($p = 0.003$), $0T$ and $0.6T$ ($p < 0.001$), $0T$ and $0.8T$ ($p < 0.001$), $0T$ and $0.8T$ ($p < 0.001$), $0.4T$ and $0.6T$ ($p = 0.002$), and $0.6T$ and $1.0T$ ($p = 0.009$).

3.4 Stiffness Discrimination with Finger Holders in a Real-world Situation

In order to examine the relationship between the task and the effectiveness of the SR effects, we conducted the stiffness discrimination task using the finger holder in an actual setting. The setup is shown in Fig. 3.4.

3.4.1 Participants

Ten men and ten women, with a mean age ± SD: 26.05 years ± 3.03, comprised the twenty healthy participants in the study. The subjects in Section 3.3 were not the same as the subjects in this experiment. Every participant was aware of and gave their permission to the experimental protocol, which was approved by Kyoto University's Graduate School of Engineering's Ethics Committee (No. 202012).

3.4.2 Experimental Procedure

First, each participant's sensory thresholds (T) were measured using the *staircase method* [40] at three noise source positions. After that, participants completed the stiffness discrimination task for three positions of the noise source at each of five noise intensities: no noise ($0T$), 40% ($0.4T$), 60% ($0.6T$), 80% ($0.8T$), and 100% ($1.0T$). Since the intensity levels are directly related to the user's perception, the intensity was chosen as a variable. To prevent any learning effects, the participants were randomly assigned different noise intensities. In order to block out the vibrator's noise, participants also donned passive noise-cancelling headsets.

A participant was presented with two silicone models for the stiffness discrimination task (Fig. 3.4). The values of reference stiffness that were chosen were 1.5, 2.2, 3.0, and 3.8 N/mm. One of the four reference stiffness values was applied to a placed object, while a comparison stiffness was applied to the other object.

The objects could be touched at any time. After indicating which object they felt was stiffer, each participant moved on to the next trial. To prevent fatigue and a learning effect, the experiment was run on separate days for each reference stiffness. Furthermore, we calculated each participant's WF for each condition, following the guidelines in Section 3.3.3.

3.4.3 Experimental Results

The average WF values for each group (all participants, male participants, and female participants) under each condition are displayed in Figs. 3.5 – 3.7. Whereas the vertical axes show the WF values, the horizontal axes show the reference stiffness. The noise intensities are represented by each noise condition's five bars. The standard deviation is displayed by the error bars. A two-tailed paired t-test confirms that there are significant differences ($p < 0.05$) in the average WF values at intensities of $0T$ and $0.6T$ in each of

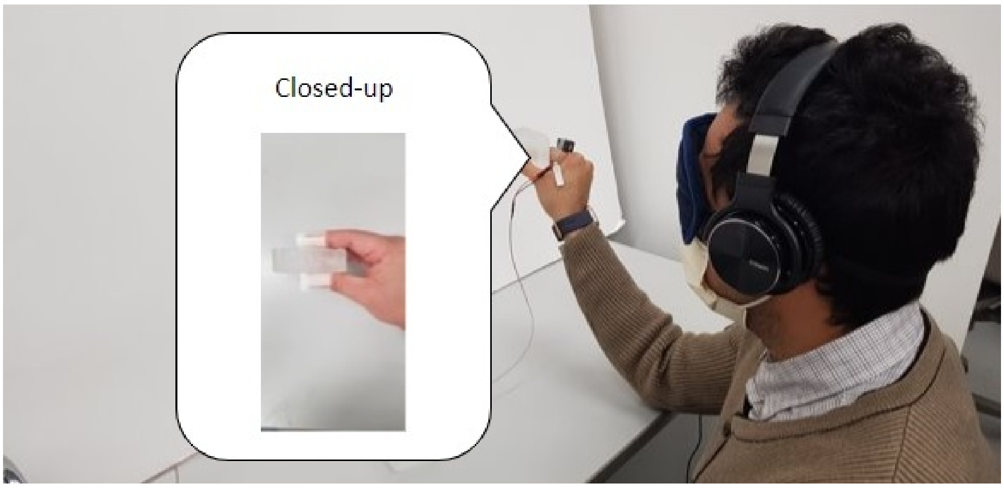


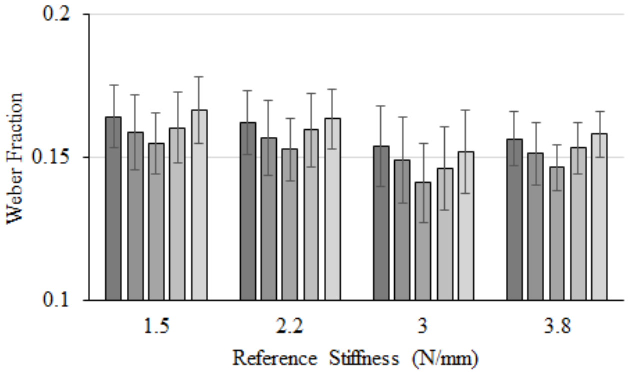
FIGURE 3.4: An overview of the experimental setup used to carry out the finger-holder stiffness discrimination task in a real-world setting.

the three sub-figures for each reference stiffness in all figures. Moreover, the WF value was lowest at $0.6T$ intensity.

Three factors—the reference stiffness, noise intensity, and noise position in each group — were the subjects of a three-way ANOVA. The same inverse transformation used in Section 3.3.4 was applied to ensure normality before the ANOVA was applied. The three-way ANOVA's findings were compiled in Table 3.5 – 3.7. In every group, there was no significant three-way interaction ($p > 0.05$). Nonetheless, in every group, we discovered a significant simple two-way interaction ($p < 0.01$) between the noise position and noise intensity.

Additionally, we performed multiple comparison tests using Post Hoc Tukey HSD. We did not find any significant differences between noise positions in any of the groups for the noise intensities $0T$. We observed significant differences between noise positions 2 and 3 for the noise intensities $0.4T$ ($p < 0.05$). We observed statistically significant differences between position 1 and 2 ($p < 0.01$) and between position 2 and 3 ($p < 0.01$) for the noise intensities $0.6T$, $0.8T$, and $1.0T$. In the same way, we looked into the notable variations in noise intensities at the noise positions. We only show the outcomes for the noise position 2 as an example. For the noise position 2, we found statistically significant differences ($p < 0.01$) for the pairs $0T$ and $0.4T$ ($p = 0.003$), $0T$ and $0.6T$ ($p < 0.001$), $0T$ and $0.8T$ ($p < 0.001$), $0T$ and $0.8T$ ($p < 0.001$), $0.4T$ and $0.6T$ ($p = 0.002$), and $0.6T$ and $1.0T$ ($p = 0.009$).

Additionally, we looked into how gender differences in haptic perception were perceived. To assess the gender differences, we performed Post Hoc Turkey HSD multiple comparison tests. $p-$values for all gender comparisons are shown in Tables 3.8–3.10. There was no discernible difference between the male and female participants in any of the conditions.



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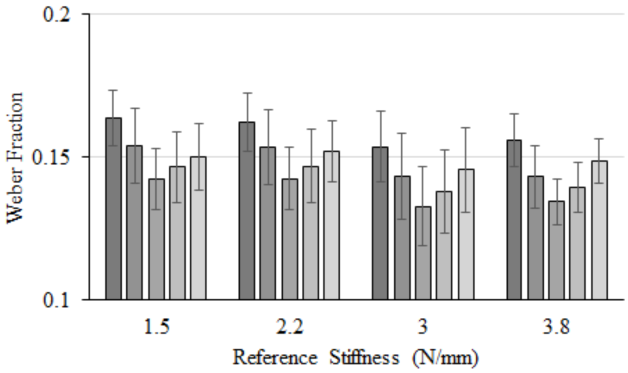

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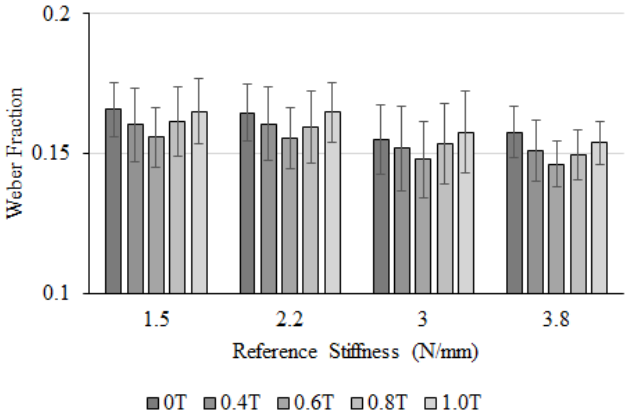
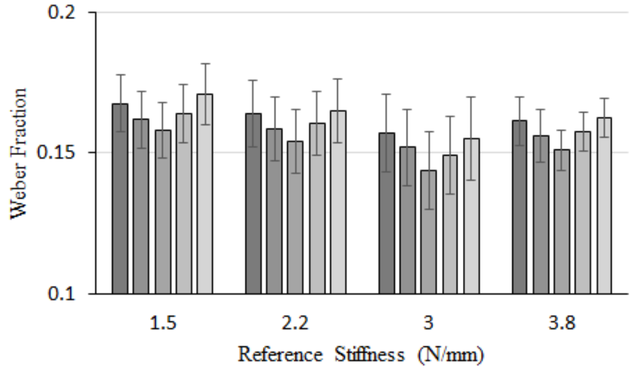


(c)

FIGURE 3.5: User perception of all participants in the real-world situation for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.



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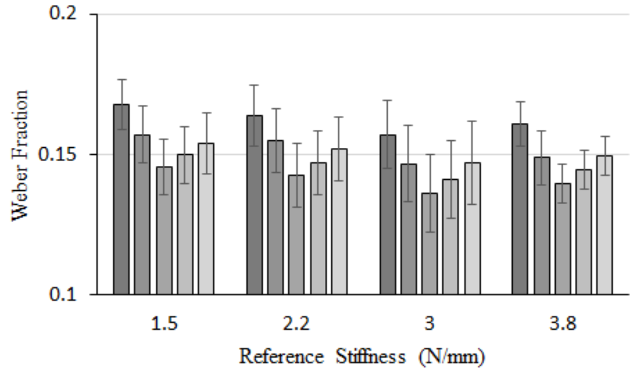

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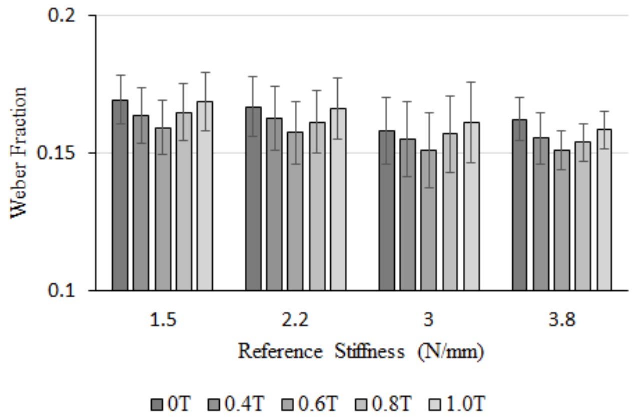

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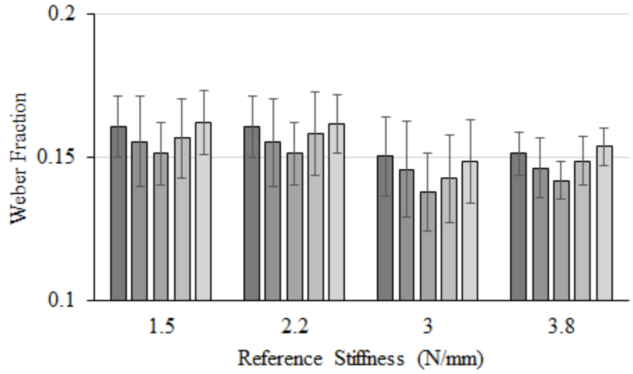
Figure 3.6: User perception of all participants in the real-world situation for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.



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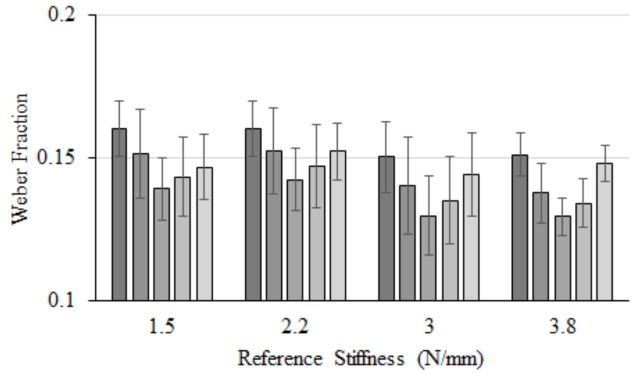

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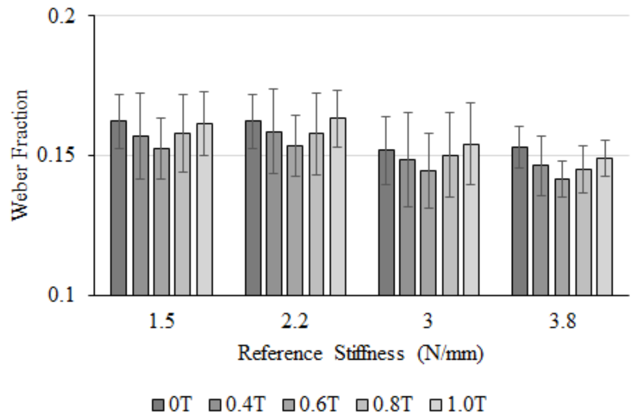


(c)

FIGURE 3.7: User perception of all participants in the real-world situation for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.

Table 3.5: Summary of three-way ANOVA of stiffness discrimination in the real-world situation of all participants.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	6	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	18	0.985
Reference stiffness × Noise position	6	0.39
Noise position × Noise intensity	12	< 0.01
Reference stiffness × Noise intensity × Noise position	36	0.966

Table 3.6: Summary of three-way ANOVA of stiffness discrimination in the real-world situation of the male.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	4	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	12	1.00
Reference stiffness × Noise position	6	0.339
Noise position × Noise intensity	8	< 0.01
Reference stiffness × Noise intensity × Noise position	24	1.00

Table 3.7: Summary of three-way ANOVA of stiffness discrimination in the real-world situation of the female.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	4	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	12	1.00
Reference stiffness × Noise position	6	0.553
Noise position × Noise intensity	8	0.021
Reference stiffness × Noise intensity × Noise position	24	1.00

In conclusion, the degree of noise intensity has a significant impact on improving the user's perception when completing tasks in an actual setting. For instance, the user's perception is generally lower when $0.8T$ of noise is applied to the task than when $0.6T$ of noise is applied. Furthermore, the outcomes demonstrate the significance of noise position in improving user perception when the participant completes the task in an actual setting and experiences the SR effects. For example, user perception tends to be worse when noise of the same intensity is applied at Position 2 than when it is applied at Position 1 or 3 while participants are performing the task in a real-world setting.

In this study, we first examined the displacement between the fingertip and the laser displacement sensor, which was a parameter indicating the possibility of noise

TABLE 3.8: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the real-world environment of Position 1 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.47	0.46	0.48	0.44
0.4T	0.57	0.54	0.52	0.49
0.6T	0.71	0.61	0.60	0.56
0.8T	0.63	0.52	0.59	0.52
1.0T	0.51	0.47	0.50	0.49

TABLE 3.9: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the real-world environment of Position 2 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.47	0.47	0.48	0.47
0.4T	0.52	0.56	0.54	0.50
0.6T	0.53	0.63	0.61	0.53
0.8T	0.47	0.56	0.53	0.48
1.0T	0.49	0.48	0.49	0.46

TABLE 3.10: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the real-world environment of Position 3 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.44	0.48	0.46	0.43
0.4T	0.55	0.54	0.51	0.49
0.6T	0.57	0.60	0.59	0.50
0.8T	0.49	0.53	0.51	0.49
1.0T	0.45	0.46	0.47	0.48

superimposing on an external stimulus at the fingertip (i.e., the measurement point in this study), before applying SR effects to enhance the user haptic sensation. According to the findings in Section 2.5.3, for various noise source locations, there was displacement between the fingertip and the laser displacement sensor at each measurement point that was not zero. This suggested that noise might enhance haptic perception by superimposing on stimuli.

The results of Section 2.5.3 support the result of Section 3.3.4 that better performance was achieved by adopting Position 2, compared to Position 1 and 3. This is because the noise reached the fingertips sufficiently to superimpose on the stimuli, enhancing the ability to detect a weak signal. A previous study [5] proposed a mechanism of SR for enhancing haptic perception using vibrotactile noise as vibrotactile noise enhancing the propagation of external mechanical stimuli through dermal tissue by adding mechanical energy to the stimuli, or the vibrotactile noise directly acting upon receptor endings. Meanwhile, the mechanism of remote SR, which is SR when the noise source is distant from the external mechanical stimuli such as in this paper, has not been clarified. For example, a study [34] claimed that the effects of remote SR are mediated by the central nervous system, because the imperceptible noise applied to the wrist is unlikely to reach the fingertips. However, another study [29] and Section 3 in this paper showed that imperceptible noise applied at a location away from the fingertips propagates to the fingertips, and the inferred mechanism described appears incorrect. In other words, a possible mechanism for enhancing the fingertip haptic sensation by remote SR is that the vibrotactile noise provided at a location away from the fingertips propagates to the fingertips through the bones and flesh and is superimposed on the finger's external mechanical stimulus to enhance the fingertip's haptic sensation. In any case, the principle of remote SR remains unclear. However, Ikemura et al. examined the potential mechanism of random noise enhancing the haptic sensation using a piezoelectric (polyvinylidene fluoride) film [29]. They investigated the acceleration of the noise at the fingertip in experiments and observed that the level of acceleration was higher when white Gaussian noise was applied to the volar wrists of participants with two vibrators compared with the no-noise and single-vibrator conditions. Therefore, in this study, the two fingers perceived a stronger haptic sensation owing to noise reaching the tips of both fingers compared with the scenario in which the noise source was located at Position 1 or 3.

Moreover, we observed that the user haptic performance was improved by the SR effect with a single noise source when participants performed a stiffness discrimination task. Our previous study [48] hypothesised that noise propagates to both fingers from Position 2. In this paper, to clarify this hypothesis, we demonstrated that the displacement between the fingertip and the laser displacement sensor at the two fingertips was almost the same for a noise source at Position 2 in an experiment verifying the SR effect. This supports the hypothesis that when the noise reaches both fingers at sufficient levels, the user performance increases because the haptic sensation is enhanced for both fingers. In contrast, when the noise source is at Position 1 or 3, the noise largely reaches only one fingertip, such that the haptic sensation of one finger may be enhanced while that of the other finger may be unaffected.

A real-world environment and virtual environment (VE) involve different stimuli. In a VE, a user has to carry out a task involving a non-physical object with a finger holder through a haptic interface system, while he or she tends to perform a motor task with bare fingers in a natural environment. A previous study [49] investigated stiffness discrimination tasks in which participants received force feedback and artificial skin stretch at the fingers. The study showed that adding low-frequency noise through artificial tactile skin stretch feedback, which humans can perceive, to the fingers reduces the stiffness discrimination ability in a VE. In the present study, we found that the perception of stiffness tended to worsen when the noise was large enough for the participants to perceive. In addition, the noise source position is an important factor that influences the haptic perception of the participant. For example, all three noise positions show the enhancement of the haptic perception at $0.6T$, relative to the no-vibration condition. However, the average WF results for the noise position at Position 2 are lower than those for the other two positions, which indicates the better haptic performance at Position 2, compared with the other two positions, as shown in Figure 3.3. Although there are differences in the frequency of the presented noise and the presentation method, noise that humans can perceive is considered to adversely affect the perception of stiffness. It is noted that a direct comparison between this study and our previous study [48] is impossible. This is because participants had to insert their fingers into holders in the VE experiment, which might result in different SR effects.

The results of the experiment on the stiffness discrimination task revealed that a single vibrator improved the performance when the participant performed a stiffness discrimination task using an index finger and thumb. Humans press or push a deformable object with their fingers in perceiving the softness or hardness of the object whereas they tap the surface of a rigid object with their fingers to perceive the hardness of a hard object [50]. Tapping an object causes vibrotactile signals that contribute to perception [51, 52]. Additionally, studies [53, 54] have proposed a metric for evaluating the perceived hardness of an object, namely the ratio of the force change and displacement velocity at impact, which correlates with the object's perceived hardness. However, in this paper, we focused on the perception of the stiffness of soft objects. It is a future topic to examine whether SR contributes to hardness perception through tapping. Figure 3.6 shows that the enhancement of the haptic sensation was highest when the noise level was $0.6T$. The results in our study show the enhancement of the haptic sensation by using the subthreshold vibrotactile as the other studies [13, 16–19, 29]. The experimental results show a U-shaped pattern, which is a characteristic of the SR phenomenon [16]. For example, in Fig. 3.6, the WF value decreases as the vibration intensity increases to a certain level but go up thereafter. This shows the optimal level at which to improve the haptic perception. Therefore, a noise level of $0.6T$ had the highest enhancement among the conditions considered in this study. Several studies have shown the potential of using SR effects to enhance the haptic sensation of the user, especially a user who faces difficulty in performing daily tasks. As an example, stroke patients struggle with haptic sensation at the fingertips, leading to difficulty in performing daily tasks such as squeezing toothpaste and picking up an item, and they can perform these tasks more easily while receiving SR [35].

One limitation of the present paper is that we only recruited the young groups (young males and females) to participate this study. However, in the elderly group and the stroke which have a poor sensation might have a better enhance from a use of SR as [16, 19]. Therefore, it is interesting to extend the use of the proposed method to other groups, such as the elderly and the stroke. Moreover, only stiffness discrimination was examined, and the study of other motor tasks has been left as future work.

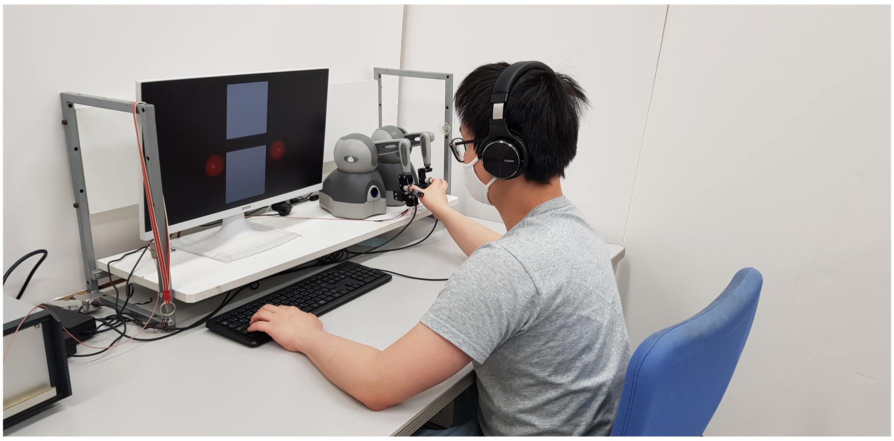
3.5 Stiffness Discrimination Using Two Fingers with Finger-holders

3.5.1 Experimental Setup

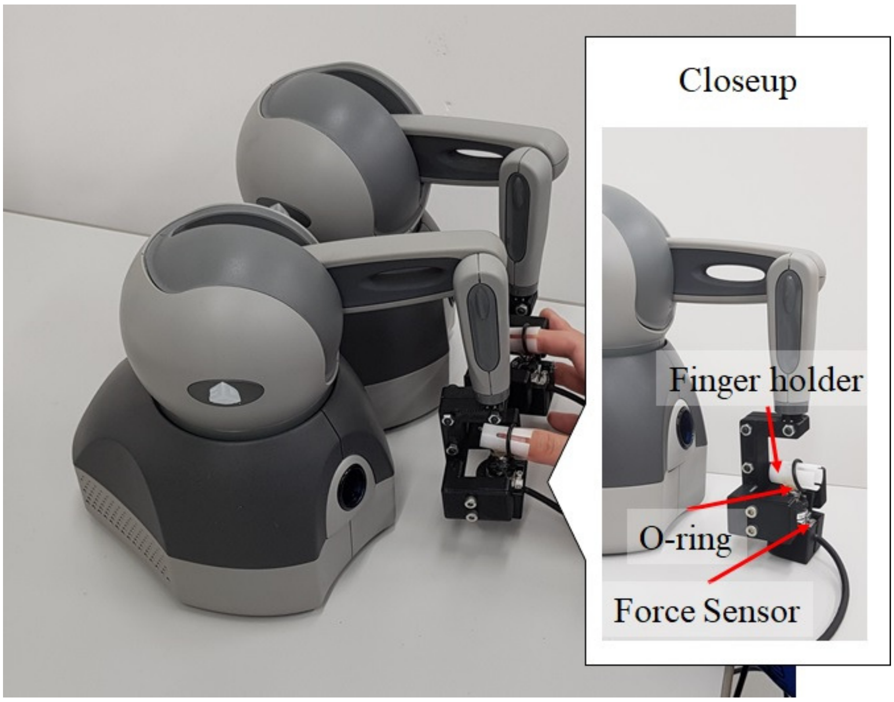
Twelve men and twelve women, with a mean age of ± SD: 25.54 ± 3.04 years, comprised the twenty-four healthy participants in the user study. The Graduate School of Engineering at Kyoto University's Ethics Committee approved the experimental protocol, which the participants understood and agreed to (No. 201707). To assess the user's performance, the stiffness perception's Weber fraction (WF) was calculated. As illustrated in Fig. 3.8, after participants placed their thumb and index finger in finger holders connected to haptic devices, two virtual objects were presented to them in a VE on a computer screen.

3.5.2 Experimental Procedure

Using the staircase method [40], the sensory thresholds at three noise source positions were first measured for each participant. Then, with the vibrator making noise, participants used their thumb and index finger to complete the stiffness discrimination task. Fig. 2.8 illustrates the three noise source positions (Position 1, 2, and 3) where the seven noise intensities (i.e., $0T$, $0.4T$, $0.5T$, $0.6T$, $0.7T$, $0.8T$, and $1.0T$) were found for the noise. Keep in mind that T has a distinct value for every location of a noise source. To prevent any learning effects, the participants were randomly assigned different noise intensities. Numerous studies indicate that the user's haptic perception is influenced by the intensity. For instance, a user's perception is diminished by excessively loud or low noise levels. In the meantime, applying the ideal level of noise intensity improves the user's haptic perception [13]. Thus, for the stiffness discrimination task in this study, we



(a)



(b)

FIGURE 3.8: Overview of the experimental setup. A participant received force feedback through haptic devices when he touched a virtual object with red cursors that represented finger positions on the screen. The finger holder was attached to the device arm.

selected noise intensity as the variable and examined the ideal level. In order to block out vibrations, participants also donned passive noise-cancelling headsets.

Two white virtual objects were shown in the VE for the stiffness discrimination task (Fig. 3.8). Because neither object could be bent, participants' visual feedback was unaffected. Reference stiffness values of 25, 35, 45, and 55 N/m were chosen because they were in the range of the stiffness of breast tissue's body fat (i.e., 35 N/m [55]). One of the four reference stiffness values was applied to one of the objects that was on

TABLE 3.11: Summary of three-way ANOVA of stiffness discrimination in the VE of all participants.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	6	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	18	0.99
Reference stiffness × Noise position	6	0.913
Noise position × Noise intensity	12	< 0.001
Reference stiffness × Noise intensity × Noise position	36	1.00

display, while the stiffness of the other object varied based on participant performance and initially varied by 10 N/m.

Touching the virtual objects had no time limit. After pressing a specific key on a keyboard to indicate which side of an object he felt was stiffer, each participant moved on to the next trial. When the participant was performing the task, the object was white; when the task was finished, it turned red. Each participant's time in the experiment lasted roughly two hours.

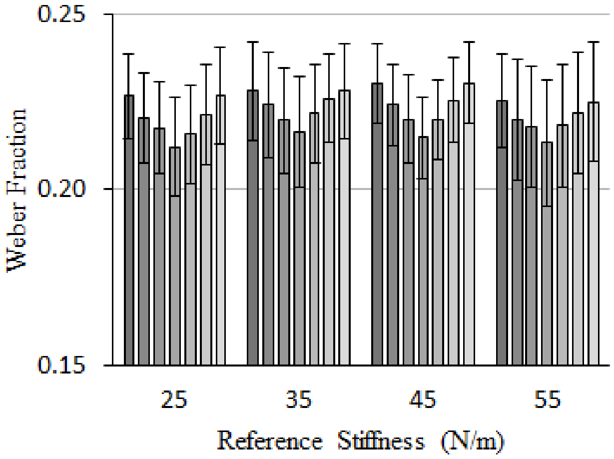
The Wald rule [56] was utilized to determine the point at which the stiffness of the comparison changed, while the PEST rule [56] was employed to choose the point at which the stiffness changed due to participant fatigue during the fixed-step task completion. As participants finished the task, reversal points—points at which the change in stiffness reversed direction—were noted. In order to determine the just noticeable difference (JND) of stiffness perception, the last four reversal points were averaged. Next, we ascertained each participant's WF for every condition:

$$WF = \frac{JND}{\text{Reference Stiffness}}. \tag{3.3}$$

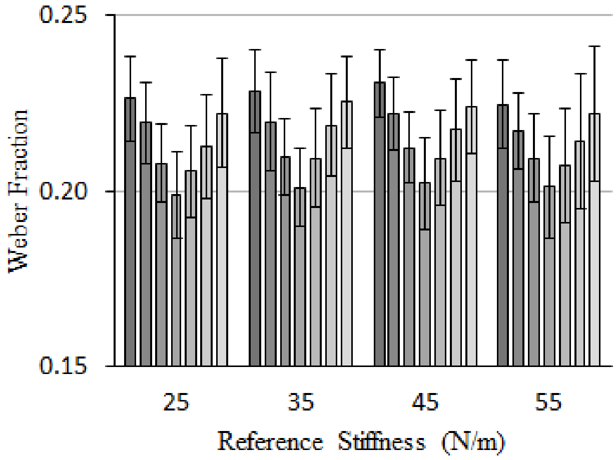
Here, a WF of 0.01 meant that a participant could detect a 1% change in the stiffness level.

3.5.3 Experimental Results

Tables 3.9 – 3.11 show the average WF values for each condition for each group (all participants, male, and female). Whereas the vertical axes show the WF values, the horizontal axes show the reference stiffness. A participant's lower haptic performance is indicated by a higher WF value. The noise intensities are represented by the seven bars. The standard deviation is displayed by the error bars. A two-tailed paired t-test confirms that the average WF values at intensities of $0T$ and $0.6T$ in all three sub-figures



(a)



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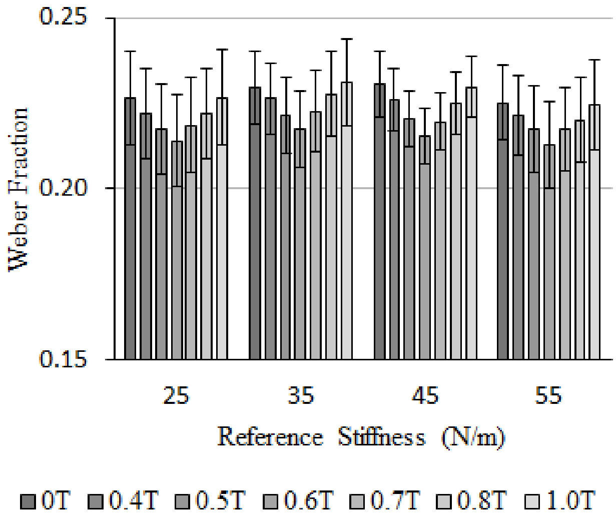
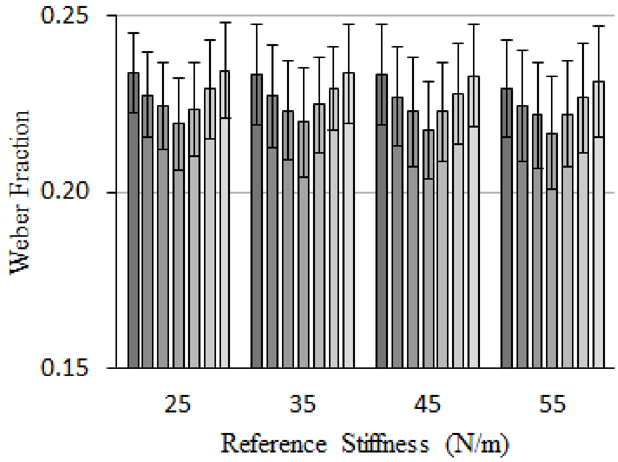
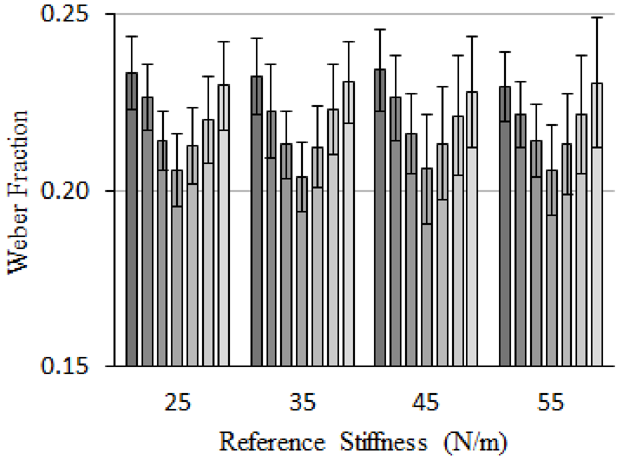


(c)

FIGURE 3.9: User perception of all participants in the VE for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.



(a)



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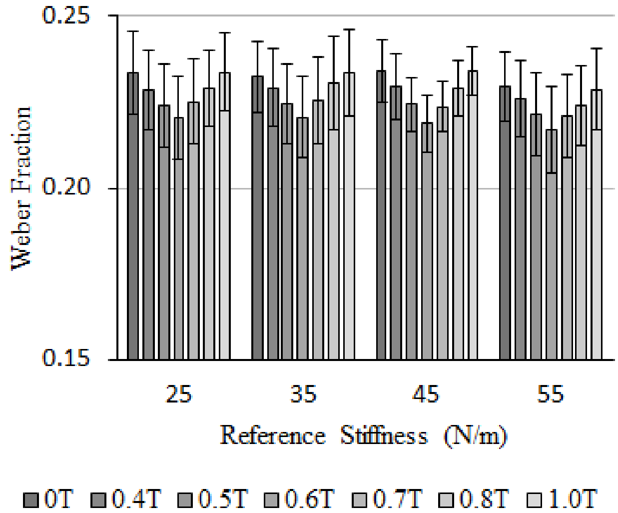


(c)

FIGURE 3.10: User perception of the male participants in the VE for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.

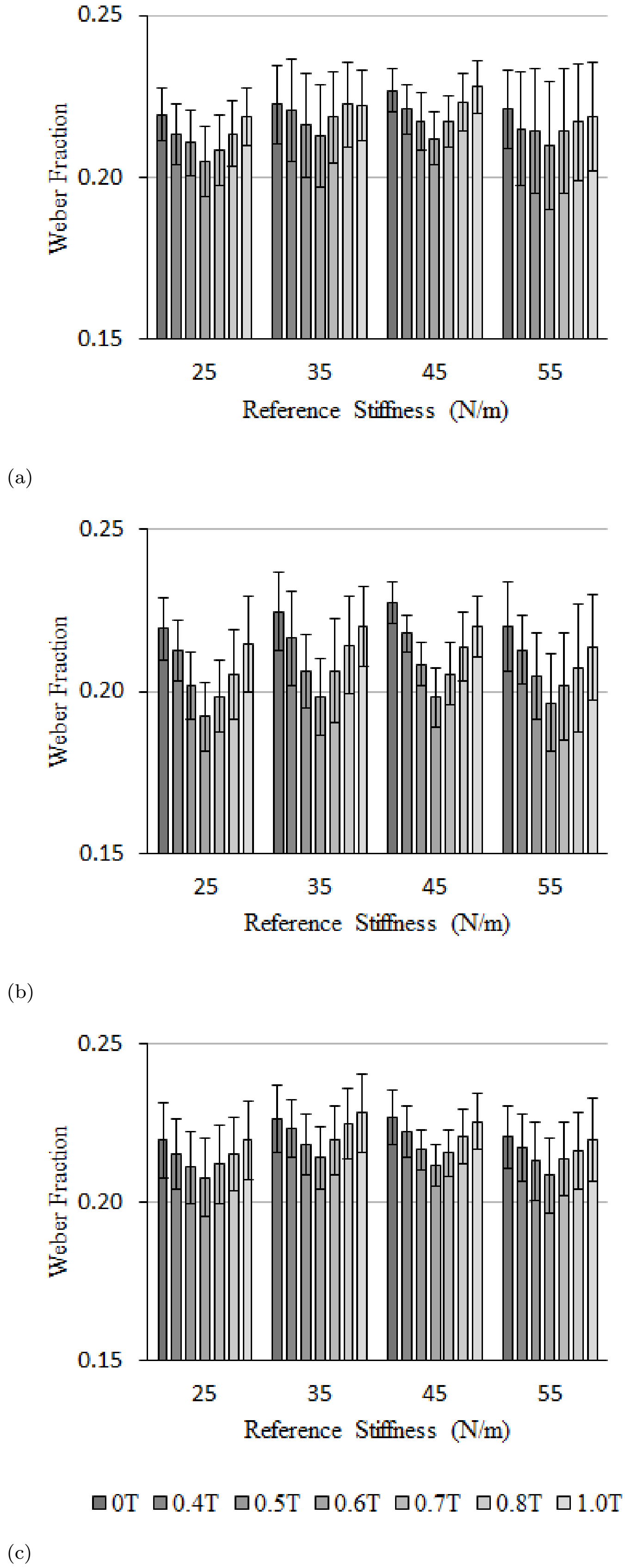


FIGURE 3.11: User perception of the female participants in the VE for each position of the noise source: (a) on the index finger, (b) between the index finger and thumb, and (c) on the thumb.

TABLE 3.12: Summary of three-way ANOVA of stiffness discrimination in the VE of the male.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	6	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	18	1.00
Reference stiffness × Noise position	6	0.889
Noise position × Noise intensity	12	0.011
Reference stiffness × Noise intensity × Noise position	36	1.00

TABLE 3.13: Summary of three-way ANOVA of stiffness discrimination in the VE of the female.

Effect	Degree of Freedom	p-value
Reference stiffness	3	< 0.01
Noise intensity	6	< 0.01
Noise position	2	< 0.01
Reference stiffness × Noise intensity	18	1.00
Reference stiffness × Noise position	6	0.625
Noise position × Noise intensity	12	0.03
Reference stiffness × Noise intensity × Noise position	36	1.00

TABLE 3.14: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the VE of Position 1 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.46	0.45	0.47	0.42
0.4T	0.57	0.58	0.59	0.49
0.5T	0.63	0.66	0.65	0.59
0.6T	0.67	0.72	0.67	0.62
0.7T	0.65	0.67	0.64	0.60
0.8T	0.59	0.60	0.59	0.51
1.0T	0.47	0.48	0.49	0.50

for each reference stiffness in Figs. 3.9 – 3.11 differ significantly ($p < 0.05$). Moreover, the WF value is lowest at $0.6T$ intensity.

We performed a three-way analysis of variance (ANOVA) on three variables: each group's noise position, noise intensity, and reference stiffness. To ensure normality [47], the inverse transformation for negative skewed data $1/(\max(x) + 1 - x)$ was specifically applied before performing the ANOVA, where x is the data. The three-way ANOVA's findings were compiled into Tables 3.11 – 3.13. In every group, there was no significant

TABLE 3.15: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the VE of Position 2 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.48	0.46	0.48	0.44
0.4T	0.55	0.56	0.57	0.48
0.5T	0.65	0.63	0.60	0.53
0.6T	0.68	0.67	0.66	0.60
0.7T	0.62	0.62	0.61	0.57
0.8T	0.56	0.57	0.58	0.59
1.0T	0.48	0.46	0.48	0.51

TABLE 3.16: $p-$values of Post Hoc Tukey HSD multiple comparison tests of stiffness discrimination in the VE of Position 3 between genders.

Noise Intensity	Reference Stiffness [N/mm]			
	1.5	2.2	3	3.8
0T	0.47	0.45	0.48	0.45
0.4T	0.54	0.54	0.54	0.51
0.5T	0.67	0.61	0.65	0.56
0.6T	0.65	0.66	0.66	0.63
0.7T	0.67	0.64	0.67	0.58
0.8T	0.54	0.54	0.54	0.52
1.0T	0.46	0.47	0.47	0.46

three-way interaction ($p > 0.05$). Nonetheless, in every group, we discovered a significant simple two-way interaction ($p < 0.05$) between the noise position and noise intensity.

Additionally, we performed multiple comparison tests using Post Hoc Tukey HSD. In all groups, we did not find any significant differences between noise positions for the noise intensities $0T$, $0.4T$, and $1.0T$. We observed statistically significant differences between position 1 and 2 ($p < 0.05$) and between position 2 and 3 for the noise intensities $0.5T$, $0.6T$, $0.7T$, and $0.8T$. In the same way, we looked into the notable variations in noise intensities at the noise positions. As an illustration, we only display the results for position 2 here. For all combinations of any two of the five noise intensities, we discovered statistically significant differences ($p < 0.05$); the exceptions were for the pairs $0T$ and $1.0T$ ($p = 0.941$), $0.4T$ and $0.8T$ ($p = 0.934$), $0.4T$ and $0.8T$ ($p = 0.934$), $0.4T$ and $1.0T$ ($p = 0.284$), $0.5T$ and $0.7T$ ($p = 0.997$), and $0.6T$ and $0.7T$ ($p = 0.057$).

We also examined the differences in haptic perception between the genders (male and female). To calculate the gender difference, we used Post Hoc Turkey HSD multiple comparison tests. The $p-$values for each comparison between genders are provided in

Tables 3.14–3.16. For each condition, there was no discernible difference between the male and female participants.

As a result, the findings indicate that, when a participant completes the task in the VE while experiencing the SR effects, the noise position significantly improves user perception. For example, user perception tends to be higher when participants complete the task in the VE with noise applied at Position 2 than when the same intensity of noise is applied at Position 1 or 3. Additionally, enhancing the user's perception further depends on the intensity of the noise. The lower Weber fraction values show that, for instance, user perception tends to be better when there is $0.6T$ of noise present during the task than when there is $1.0T$ of noise.

3.6 Discussion

In this study, before applying SR effects to enhance the user haptic sensation, we first investigated the displacement between the fingertip and the laser displacement sensor, which was a parameter indicating the possibility of noise superimposing on an external stimulus at the fingertip (i.e., the measurement point in this study). The results presented in Section 2.5.3 indicate that the displacement between the fingertip and the laser displacement sensor was non-zero at each measurement point for different locations of the noise source. This indicated the possibility that noise superimposes on stimuli to enhance haptic sensation.

Furthermore, the results for Position 2 of the noise source indicated that the amplitudes of the noise on the index finger and thumb were almost equal, suggesting the possibility that noise vibration at this source position can better enhance the haptic sensation than noise vibration at Position 1 or 3. Indeed, the results for Positions 1 and 3 indicated different noise amplitudes for the two fingers, such that the user haptic sensation was insufficiently enhanced on the fingertip farther from the noise source. Moreover, the results of Section 2.5.3 support the results of Sections 3.3.4 and 3.4.3 in that better performance was achieved by adopting Position 2. This is because the noise reached the fingertips sufficiently to superimpose on the stimuli, enhancing the ability to detect a weak signal. Seo *et al.* investigated the potential mechanism of random noise enhancing the haptic sensation using an electroencephalogram [34]. They assessed the electrical activity when conducting experiments and observed that the level of electrical activity was higher when white Gaussian noise was applied to the volar wrists of participants compared with that in the no-noise condition. In our study, we measured the noise using a laser displacement sensor. The results indicated that the noise reached the tips of both fingers. Furthermore, displacement data were compared for the three positions of the noise source. The results suggested that the two fingers perceived a stronger haptic sensation owing to noise reaching the tips of both fingers compared with that in the scenario in which the noise source was located at Position 1 or 3.

Moreover, we observed that the user haptic performance was improved by the remote SR effect with a single noise source when participants performed a stiffness discrimination task. Our previous study [48] hypothesized that noise propagates to both fingers from Position 2. This study demonstrated that the displacement between the fingertip and the laser displacement sensor at the two fingertips was almost even for a noise source at Position 2 in an experiment verifying the SR effects. This supported the hypothesis that when the noise reaches both fingers at sufficient levels, the user performance increases because the haptic sensation is enhanced for both fingers. In contrast, when the noise source is at Position 1 or 3, the noise largely reaches only one fingertip, such that the haptic sensation of one finger may be enhanced while that of the other finger may be unaffected.

Furthermore, we investigated the stiffness discrimination task with the finger holder in a real-world situation to investigate the relationship between the SR effects and the task. It is known that the haptic sensitivity of the fingertip decreases when a finger holder covers the finger [44]. Meanwhile, when we perceive a soft object, the size of the contact area between the finger and surface can be used to determine the magnitude of the applied force, even if the soft object is sandwiched between rigid plates [45]. That means that cutaneous information exists even if the finger holder covers the finger. Thus, even if finger holders cover the fingers, more or less cutaneous information contributes to the stiffness discrimination. We therefore consider that remote SR, which boosts the skin sensation, also contributes to stiffness discrimination, as suggested by the experimental results.

A limitation of this study is the small number of participants in the first experiment. Additionally, the sample demographics (young men) did not vary. Moreover, only stiffness discrimination was examined, and other motor tasks can be tested in future work.

3.7 Conclusion

Our method emphasizes the stiffness discrimination ability of multiple fingers in a real-world environment and a VE for a single vibration. This method involves haptic feedback and the effects of the remote SR. Before applying SR effects to enhance the user haptic sensation, we first conducted an experiment to investigate the displacement between the fingertip and the laser displacement sensor of noise at the fingertips. The results of this user study indicated that noise reached the tip of each finger, suggesting that noise can superimpose on external stimuli. Subsequently, an experiment was conducted to investigate the SR effect while participants performed a stiffness discrimination task using multiple fingers with one noise source. Moreover, we investigated the stiffness discrimination task with the finger holder in a real-world situation to investigate the relationship between the SR effects and the task. Our method has the potential to increase the haptic sensation of two fingers in a stiffness discrimination task with one noise source.

Chapter 4

REMOTE STOCHASTIC RESONANCE EFFECTS FOR FORCE-MATCHING TASK

4.1 Introduction

People learn and acquire motor skills through training and experiences in what is known as motor learning [57, 58]. A learner receives augmented feedback, which is additional performance information exchanged between a trainer and trainee such that his/her motor performance improves [59]. It is nevertheless difficult for beginners to acquire new skill sets such that they perform tasks as efficiently as experts. Although visual feedback and auditory feedback regularly guide a learner so that he or she performs better, it is not intuitive to learn certain motor skills through these two channels because it is complicated to convert such feedback into a desired action.

Because haptic feedback is easier for learners to understand than other forms of feedback, it can guide a trainee into a desired motion more successfully. Haptic feedback primarily comes in two flavors: gross resistance and gross assistance[41, 42, 60]. One way to provide trainees a force that directs them toward the desired movement is through gross assistance. A representative example of this method is haptic guidance. Although the user performance improves while haptic guidance is provided, the user performance worsens after the haptic guidance is withdrawn [59, 61]. In contrast, gross resistance is a method of increasing the task difficulty over the training session by providing haptic feedback that interferes with the movement [62]. By using this method, the student is motivated to lessen the amount of artificial resistance and gains an understanding of how to complete the same task more effectively without resistance through repetition.

By increasing task dynamics, error augmentation—a type of gross resistance—enables healthy adults to adjust to the viscous force field [63]. According to several research [61, 62, 64, 65], haptic feedback is a useful tool for motor learning when it comes to learning new motor skills.

However, the increase in feedback due to gross assistance can cause the learner to rely on the haptic feedback with less motivation and lead to worse performance in a retention test showing long-term improvement [59, 61], whereas larger errors in gross resistance tend to increase the motivation of the learner to learn by trying to reduce the error. Therefore, gross resistance is chosen as a representative haptic feedback in our study because our long-term goal is to enhance performance in terms of both short-term and long-term improvement.

It is vital to carry out a task with accurate forces and movements when obtaining fine motor skills. Several researchers have studied haptic training systems that train the trainee how to exert a force appropriately using his or her fingertips [43, 66–70]. A trainee usually has to place a finger in the holder of a haptic training system to communicate with the haptic device. Lederman *et al.* [44] indicated that the use of a rigid finger holder reduces the force-detection capability of the user's fingertip. This consequence prevents the user from correctly receiving haptic feedback, which is information for training. In other words, the haptic feedback is not perceived precisely by a human user because of the reduction of tactile sensation. In particular, the gross resistance is chosen as representative haptic feedback in our study. The finger holder is important for interaction with the haptic training system and the necessity of enhancing the force-detection capability even when the user's finger is enclosed within the holder thus has to be considered so that the user performance increases in the process of obtaining motor skills. Our hypothesis is that an increased fingertip force-detection capability may improve the user performance in motor haptic learning.

A variety of methods have been investigated to improve the user's haptic experience, including sensory discrimination [71], temporary deafferentation [72], and passive sensory stimulation [73]. Including sensory noise is a helpful technique. This approach applies vibrotactile noise through the human skin so that the haptic sensitivities of the human body in different areas, such as the feet [11] and fingers [13], are activated. In this context, stochastic resonance (SR) is applied on the basis that an undetectable signal can be made detectable by adding white noise. Through the use of SR, the sensitivities of mechanoreceptors increase in several body parts; this includes visual perception [74] and tactile sensation [13].

SR improves performance by optimizing the grasping force when a person performs a motor skill task [17]. When adopting this method, the vibration source is placed directly on the desired target. Mendez-Balbuena *et al.* [75] generated a force using a manipulandum and provided the participant's finger with Gaussian noise in the range from 0 to 15 Hz at different intensity levels. In their force control task, participants had to compensate for the force using their index finger. The finding of the study [75] shows that SR enhances force detection in a motor task. Meanwhile, applying a subthreshold mechanical vibration to a remote position, such as the dorsal wrist, volar wrist, and other positions on the dorsal hand, enhances the tactile sensation felt by stroke survivors [18]. Supporting this idea, there is evidence that SR improves the haptic sensation of the user's fingertip when the actuator is attached at a distance from the fingertip (i.e., at the dorsal wrist) [19, 34, 76]. This means that the effect of SR can be applied at several positions on the human hand to increase the haptic sensitivity of the fingertip. However, no study has investigated the effects of SR on the fingertip force-detection capability when a finger is enclosed within a finger holder and the motor learning of the fingertip force.

In order to enhance the user's performance in completing a task, the current paper suggests a novel haptic training method that combines haptic feedback (from a haptic device) and SR (from a vibrator). Our long-term objective is to improve user performance in terms of the motor learning process over the short and long terms. In the training method, the gross resistance serves as a haptic feedback. Additionally, we use the SR phenomena in our haptic training method to enhance the perception of the haptic feedback. By using SR in the gross resistance method, we anticipate improved training performance using this approach. There is no evidence that SR can enhance motor learning effects, i.e., there is no evidence of short- or long-term improvements, despite the claims of several studies [17] that it can enhance the haptic sensation during the performance of a motor task, such as grasping an object with the fingers (i.e., not a learning task). As a first step toward our objective, the current study concentrates on short-term improvement. In subsequent research, we will look into long-term improvement, which is essential to the process of motor learning. In this case, the mechanical vibration is for SR and the haptic feedback is information for learning. A piezoelectric actuator applies the subthreshold vibration to the user's dorsal wrist. First, we conduct a user study to investigate how well SR works with a finger inside a finger holder. We then use the fingertip to assess the user's performance on two force motor learning tasks. The performance results of two methods—i) haptic feedback with SR (i.e., the proposed method) and (ii) haptic feedback without SR (i.e., the comparative method) — are compared in this experiment.

The present chapter reveals the effectiveness of SR from one-dimensional (1D) space, as investigated in [77], to two-dimensional (2D) space [30]. Furthermore, the present chapter includes the 1D force learning task and an experiment in which trainees learn a

2D force learning task. The 2D force learning is conducted to determine the effectiveness of SR in the force learning tasks. This chapter is based on our one journal paper [30].

The present chapter is organized as follows. Section 4.2 describes the proposed haptic training method, details of user studies conducted for evaluating the effectiveness of SR, and the motor learning tasks. Section 4.3 presents the experimental results. The discussions of the user studies are described in Section 4.4. Finally, conclusions are provided in section 4.5.

4.2 Proposed Method

When it comes to improving the user's haptic experience at their fingertips, SR offers a number of advantages. We suggest a haptic training approach for learning finger-based motor skills that combines haptic feedback and SR. Please take note that in our study, the haptic feedback is gross resistance. The trainee's goal in the suggested learning method is to make his or her fingertip force track the intended forces. In order to achieve this, we select the gross-resistance kind of haptic feedback for the suggested technique. Similar to the haptic training system in [69, 70], the haptic device provides the desired force F_d in the opposite direction (i.e., $-F_d$, called the haptic cue) as the gross resistance in this study. By using this technique, the trainee adjusts his finger to counteract the force that the haptic device presents by learning the fingertip force based on the haptic cue. Active performance of the motor task by the trainee is essential for learning.

As mentioned in the previous section, in most haptic training systems, the trainee must place a finger in a holder to interact with the system. The finger holder decreases the user force-detection capability of the fingertip and it thus becomes difficult for a trainee to perceive the haptic cue accurately. The proposed learning method uses SR to overcome this problem, where a subthreshold vibration is applied to the dorsal wrist of the user's hand. As the effects of SR on the force-detection capability of a fingertip placed within a finger holder are completely unknown, we first established a setup to investigate the effect of SR in such a situation. A Geomagic Touch haptic device was used in our study to provide haptic cues to the user. The original pen stylus was modified so that the trainee could perform the task using a finger as shown in Fig. 4.1. A circular finger holder, made from polyoxymethylene, and a force sensor that recorded the force information with six degrees of freedom were installed as the end-effector of the haptic device.

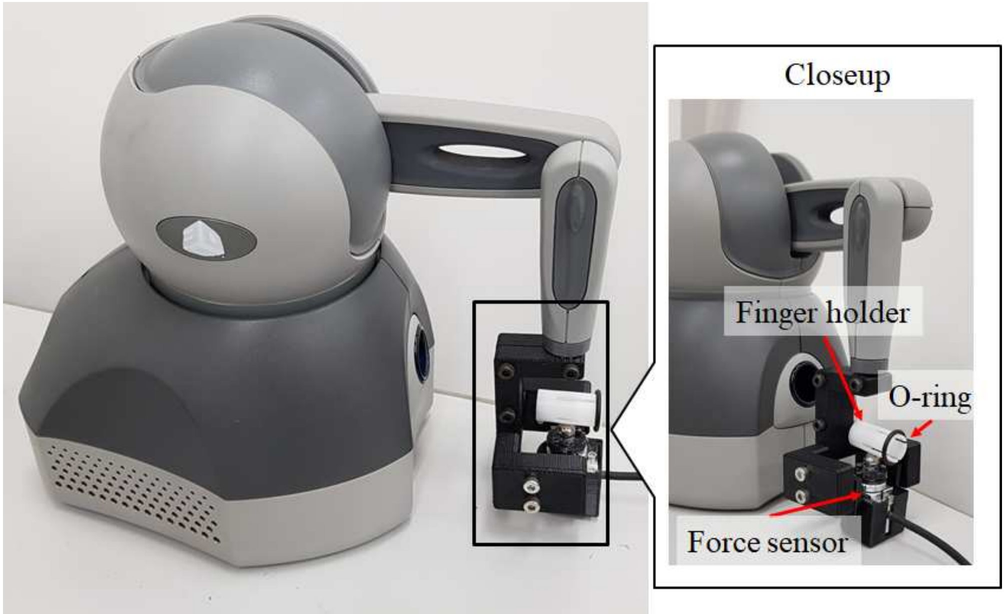


FIGURE 4.1: Overview of the modified Geomagic Touch haptic device used in the present study and in [77]. The finger holder is fastened with the device arm through a locking mechanism. A black O-ring is used to fix the finger holder with the user's finger.

The data from the force sensor (Leptrino, CFS018CA101U) were obtained at a sampling rate of 2.4 kHz. The modified haptic device was connected to a virtual-reality environment constructed using the open-source CHAI3D library [78].

A piezoelectric actuator (Cedrat Technology Inc.: APA400M) was placed at the dorsal wrist of the user hand to generate additive white Gaussian noise and gain the effect of SR. The frequency range of the vibration was considered using the responses of mechanoreceptive afferent units. Pacinian corpuscles are active at frequencies between 0.5 and 400 Hz [38]. The piezoelectric actuator therefore generated a white-noise vibration that is low-pass filtered at 400 Hz. The Box–Muller method [39] was implemented to generate the white-noise signal $x(t)$ as eq. 2.1.

4.2.1 Effects of SR on a Finger Placed within a Holder

4.2.1.1 User Study

Before utilizing SR for motor skill learning, it is necessary to examine its value in improving the fingertip force-detection abilities when the finger is inserted into a holder. We carried out an initial experiment in order to achieve this. There were two primary goals for the experiment. The initial goal was to ascertain how SR affected the user's index finger's haptic experience when it was inserted into a holder. The second goal,

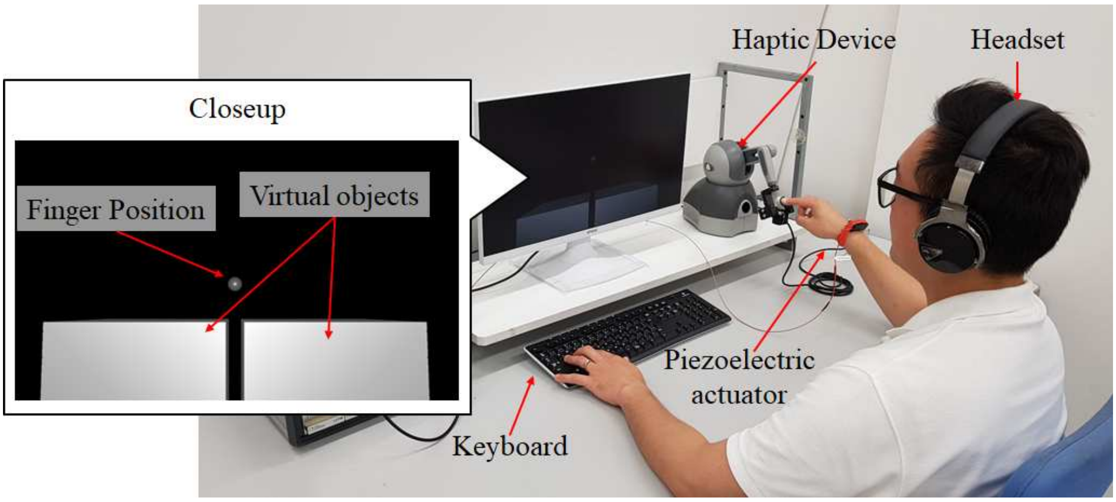


FIGURE 4.2: Experimental setup for studying the effectiveness of SR when the finger is placed within a holder. A force feedback is provided to participants through the haptic device when they touch virtual objects. The finger position is displayed as a gray sphere in VR. Participants then give their response via a keyboard.

which was covered in Section 4.2.3, was to determine the ideal vibration intensity to employ in the subsequent force learning motor skill tasks.

4.2.1.2 Experimental Setup

In the pilot study, twelve healthy individuals, all male and with a mean age of ± SD: 24.5 ± 1.88 years, took part. The experimental protocol, which was approved by the Graduate School of Engineering, Kyoto University's Institutional Review Board (No. 201707), was understood by all participants, and their consent was obtained. To compare participant abilities to detect the fingertip force, stiffness perception was measured using the just noticeable difference (JND). As seen in Fig. 4.2, the participants were instructed to place their index finger in the finger holder attached to the haptic device while two virtual objects were presented to them through a virtual-reality environment.

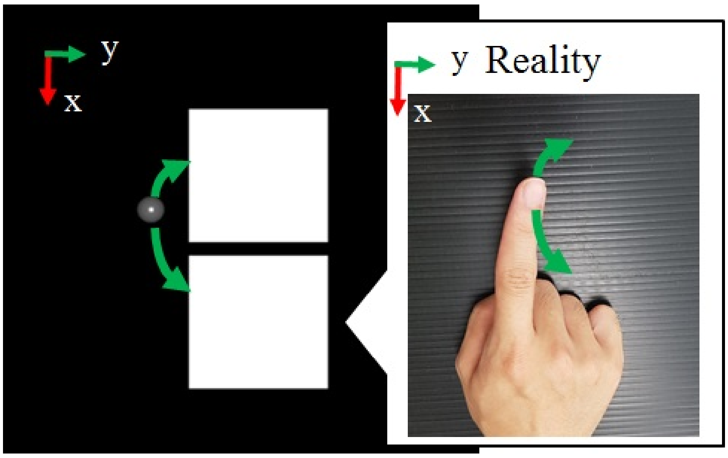
4.2.1.3 Experimental Procedure

Using the *method of limits* [13], each participant's sensory threshold (T) was determined in the first step. In particular, the sensory threshold—the lowest vibration intensity that the participants could feel—was selected, and the piezoelectric actuator's vibration magnitude was progressively increased or decreased. Following the determination of each participant's sensory threshold, each of the six selected vibration intensity levels—no vibration and 40%, 60%, 80%, 100%, and 120% of the sensory threshold—was tested on the participants' ability to distinguish between stiffness. For example, when a subject completed a task involving vibration at 0.4T, the piezoelectric actuator's vibration was applied at 40% of the subject's sensory threshold. To prevent any potential learning effects, the participants were given the vibration intensities in a random order. In addition, the participants wore passive noise-cancelling headphones in order to block out the piezoelectric actuator's vibration sound.

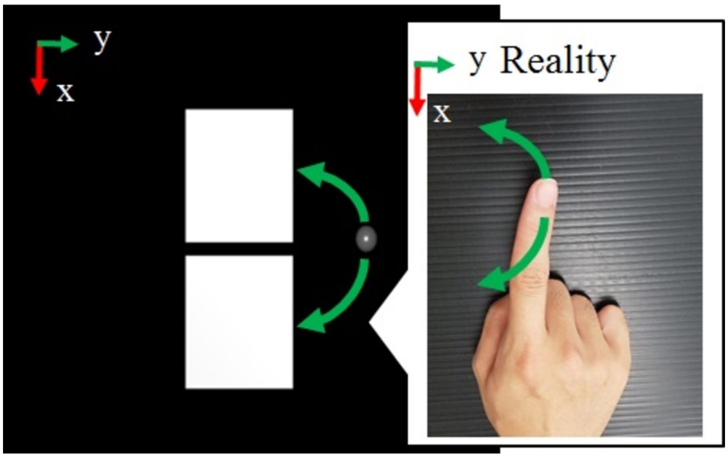
The VR environment displayed two virtual objects, as depicted in Fig. 4.2. It was not possible to clearly deform either of the displayed objects to escape the visual feedback. Body fat and breast tissue fibroadenoma, which have stiffness values of about 35 and 60 N/m, respectively, were taken into consideration when choosing stiffness values [55]. While the other object's stiffness was randomly presented at 8.75, 14, 19.25, 24.5, 29.75, 35, 40.25, 45.5, 50.75, 56, or 61.25 N/m, the standard stiffness value was 35 N/m for one object. Each stiffness comparison was put through five tests. For one intensity level of vibration, there were fifty-five trials. Numerous techniques, such as sensory discrimination [71], temporary deafferentation [72], and passive sensory stimulation[73] , have been studied to enhance the user's haptic experience. Adding in sensory noise is a useful trick.The participants could touch the virtual objects for as long as they liked. The force feedback provided to the participants was calculated using Hook's law, which multiplies the stiffness of the touched object by the depth of the finger's penetration into the virtual object. The participants touched the two virtual objects, then chose the stiffer object by pressing a particular key on the keyboard. Once the participants had made their choice, the next trial began. The objects turned red, indicating that the task was finished.

4.2.1.4 Task Description

There were three tasks in the present study. These three tasks focused on the perception of three areas of the fingertip: i) the left side of the fingertip, ii) the right side of the fingertip, and iii) the finger pad (Fig. 4.3). Each task presented two virtual objects and the participants touched the objects with each area of the fingertip. As an example, we consider the task in which a user touched the objects using the right side of the fingertip. In this task, two virtual objects were vertically displayed side by side as shown in Fig. 4.3. The participant then moved his index finger as shown by the green arrow in 4.3 and investigated the stiffness of the virtual objects. In the other two tasks, two virtual objects were displayed as shown in Fig. 4.3 but the participants could touch and perceive the stiffness of objects with different areas of the fingertip.



(a)



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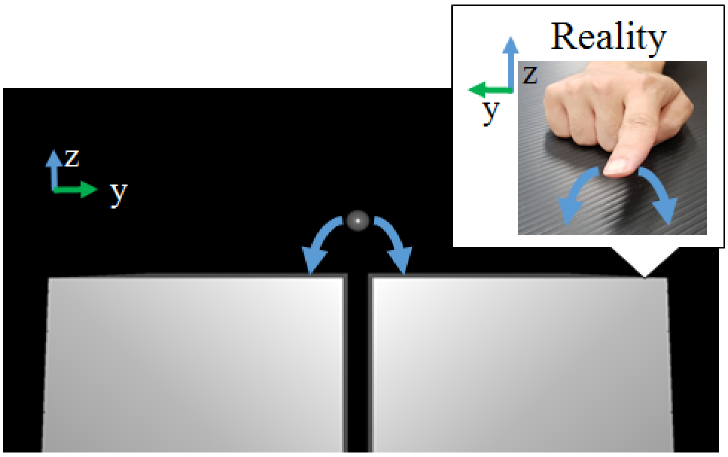


(c)

FIGURE 4.3: Virtual-reality environments in the experiment are described in section 4.2.1. Two virtual objects are displayed in each virtual-reality environment. The gray cursor is the user finger position. The reality images show how the finger moves in the real world. Arrows represent the movement of the fingertip in touching the virtual objects.(a) Task in which a user probes objects with the right side of his finger. (b) Task in which a user probes objects with the left side of his finger. (c) Task in which a user probes objects with his finger pad.

4.2.2 Effect of the Wristband

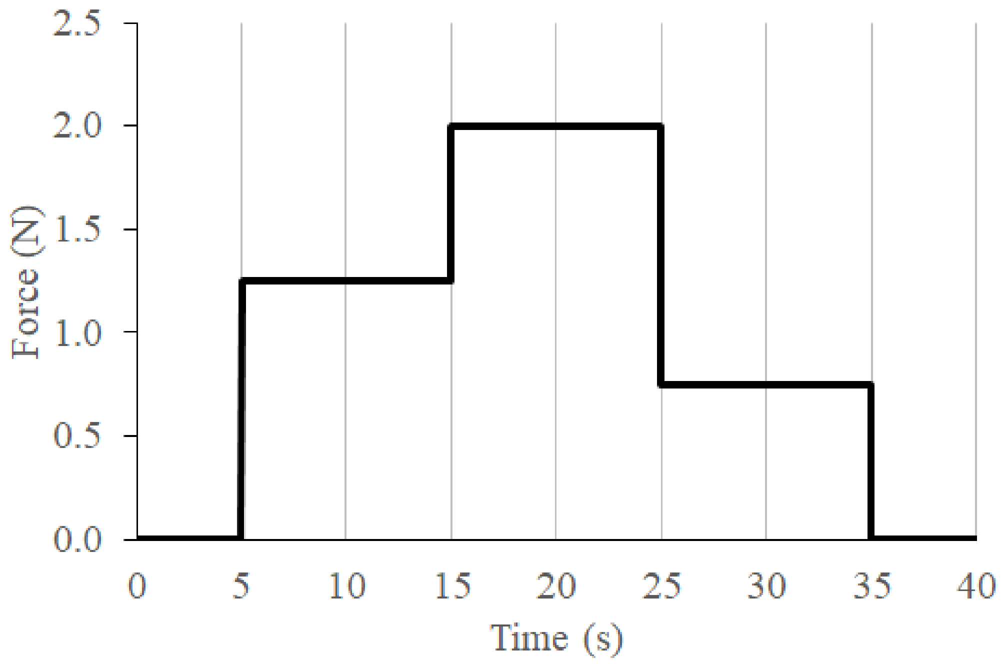
Using a polyvinyl chloride wristband, the piezoelectric actuator for producing additive white Gaussian noise was positioned at the dorsal wrist. To verify the hypothesis that a tight wristband between the user's wrist and the actuator has no discernible effect on results, we conducted an experiment. The prior preliminary study's experimental protocol was the same. But the current study only examined performance at 0T, or zero vibration intensity, with and without the wristband on the wrist. Additionally, 10 individuals (mean age ± SD: 24.7 ± 2.00 years, all male) completed only the task that required them to use a finger pad to touch objects (Fig. 4.3).

4.2.3 Force-Matching Tasks

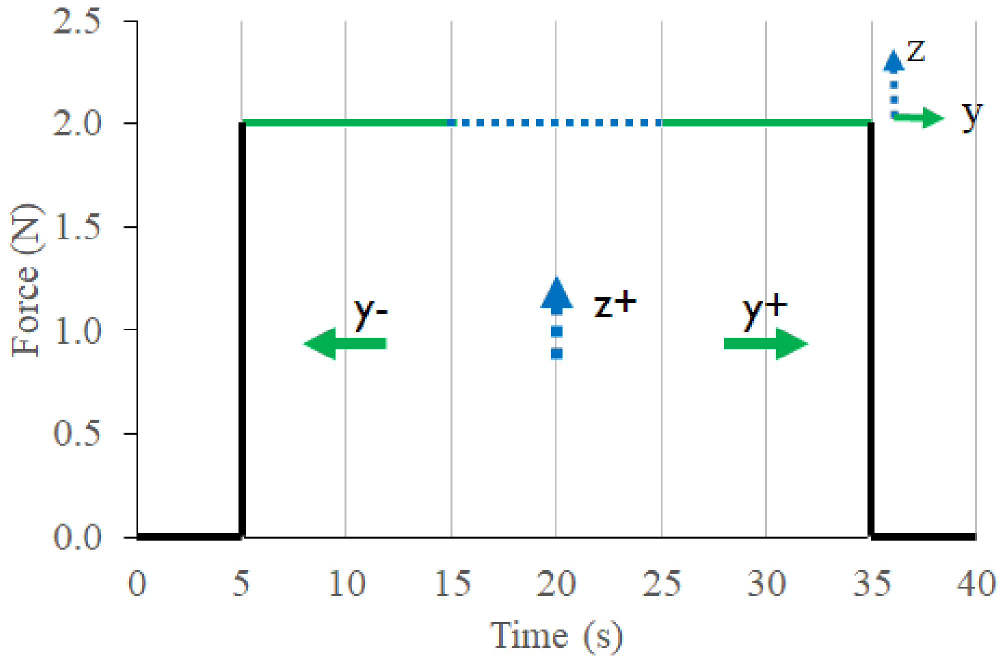
A trainee must acquire the proper knowledge of a force with a specific magnitude or direction for a number of motor skill tasks. A doctor could injure the patient or damage an organ if, for example, they palpate the breast skin with an improper force magnitude. We conducted an evaluation experiment on the suggested approach in order to build a haptic training system that enhances user performance. The participants' task was to use their index fingertip to track a force pattern that was displayed, as seen in Fig. 4.4. User performances were compared between the comparison method, which offers only haptic cues (Method 2), and the proposed method, which uses haptic cues with SR (Method 1). In Task 1 (Fig. 4.4(a)), the haptic cue was only given in an upward direction; in Task 2 (Fig. 4.4(b)), however, it was given in both upward and left—right directions. In order to prevent their finger from moving, the participants had to apply force with their fingertip to cancel the haptic cue. When using the suggested method (Method 1), participants completed the task while the piezoelectric actuator produced white-noise vibration at the ideal level of the sensory threshold, as determined in the preliminary study in section 4.2.1. The piezoelectric actuator in Method 2 (comparison method) was positioned on the dorsal wrist, but it remained stationary and did not cause any vibration to be felt by the participants.

4.2.3.1 Experimental Setup

An overview of the experimental setup can be found in Figure 4.5. Similar to the initial investigation, every individual inserted his index finger into a holder, and the haptic apparatus produced a haptic cue. Through the dorsal wrist's piezoelectric actuator, white Gaussian noise was presented. In order to prevent unwanted movement of the hand and arm, participants were instructed to relax their arm on a support. In order



(a) Task 1: 1D force learning task



(b) Task 2: 2D force learning task

FIGURE 4.4: Two desired force patterns: (a) Task 1 and (b) Task 2. The arrows for Task 2 present the direction of the haptic cue from the haptic device. The coordinate system (x-y-z) is the same as that shown in Fig. 4.5. A blue dashed arrow represents the force direction of the haptic device along the z axis while a green solid arrow shows the force direction along the y axis.

to counteract the impact of visual cues, participants also turned their heads to face the

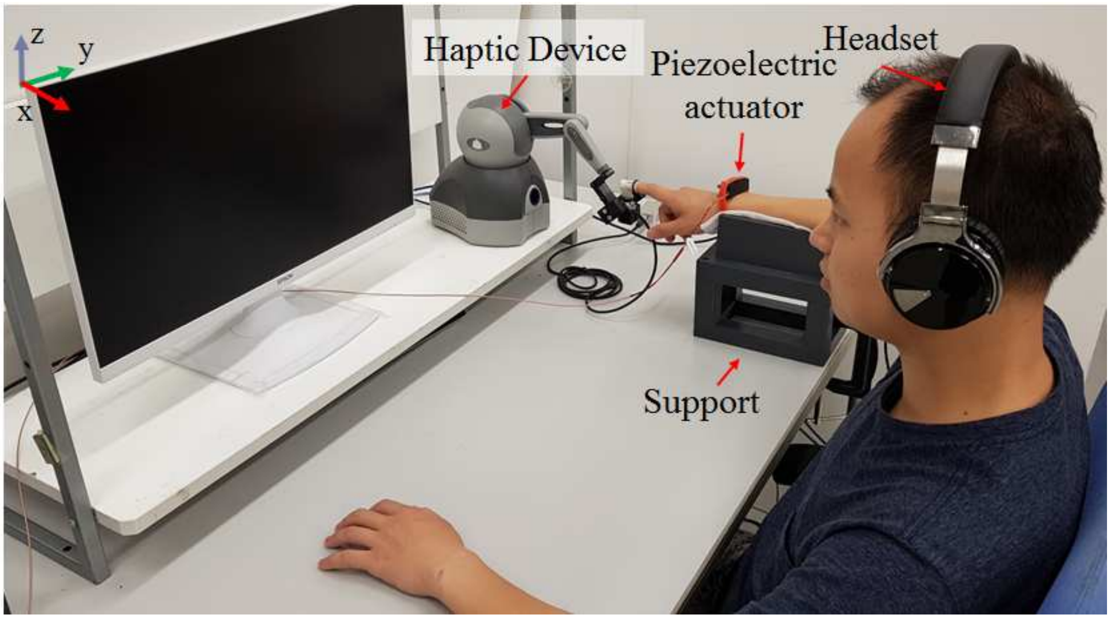


FIGURE 4.5: Experimental setup for the force learning tasks. The desired force is displayed to the participants via the haptic device. While performing tasks, participants looked at a black screen on a monitor. Participants placed their arm on a support to relax their arm and avoid undesired movement during the study.

center of a monitor that displayed a black screen. Participants also wore headphones to block out outside noise. The Geomagic Touch was operated by impedance control [79].

4.2.3.2 Task Description

We considered two tasks in the experiment.

Task 1 focuses on the 1D force provided in only the upward direction. There were three different force magnitudes, namely 1.25, 2.0, and 0.75 N. The force pattern for Task 1 is shown in Fig. 4.4(a). On the other hand ,in Task 2, haptic cues were provided in 2D space (in an upward direction and left–right directions). The force magnitude was given as only 2 N in all displayed directions. The haptic cues were displayed in the right direction from 5 to 15 seconds, in the upward direction from 15 to 25 seconds, and in the left direction from 25 to 35 seconds. The force pattern for Task 2 is shown in Fig. 4.4(b). Arrows in the force pattern graph present the direction of the haptic cue from the haptic device to the user's finger.

4.2.3.3 Experimental Protocol

The study included ten healthy participants, all of whom were male and had a mean age of ± SD: 24.9 ± 1.97 years. The experimental protocol, which was approved by the

Graduate School of Engineering, Kyoto University's Institutional Review Board (No. 201707), was understood by all participants, and their consent was obtained.

Two groups of participants were formed. On the first day, participants in group A used the training method with haptic cues and SR (Method 1); on the second day, they used the method with haptic cues alone (Method 2). On the first day, participants in group B used Method 2, and on the second day, they used Method 1. This division prevented over-exposure to the practiced tasks, which could have an impact on performance results. Every participant adhered to the identical protocol, which involved familiarization and training.A summary is displayed in Fig. 4.6.

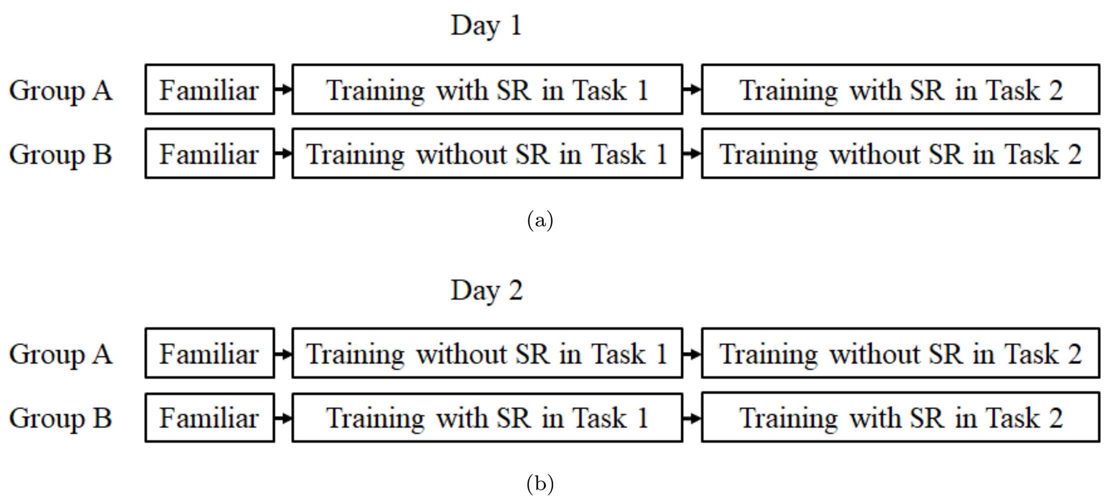


FIGURE 4.6: Overview of force adjustment tasks on (a) Day 1 and (b) Day 2. On Day 1, participants in Group A began by familiarizing themselves with the haptic training system and then performed Task 1 with the effect of SR. After Task 1, the participants took a break for 10 minutes and then performed Task 2. On Day 2, participants in Group A followed the same procedure as on the first day but without the SR effect. Participants in Group B performed the same procedures as those in Group A except that they performed the tasks without SR on Day 1 and with SR on Day 2.

The task description and the ideal arm position were given to each participant during the familiarization phase. The purpose of this step was to make sure everyone was fully comfortable with the system.

During the training phase, each participant used his finger to practice the force pattern in 15 different tasks. Prior to beginning Task 2, the participants rested for ten minutes after completing Task 1 training.

4.3 Experimental Results

4.3.1 Effects of SR on a Finger Placed within a Holder

A record of the frequency with which participants chose the comparison stiffness value over the standard stiffness value was kept. Using the psignifit MATLAB toolbox, a psychometric function was then fitted for each participant's results to create a psychometric curve. The example plot of a single participant is displayed in Fig. 4.7. The evaluation of the user's haptic performance was based on three related values: i) the stimulus value corresponding to a proportion of 0.25 (J_{25}), which indicates the 25th percentile of a psychometric function; ii) the point of subjective equality (PSE), which is a point halfway between the minimum and maximum of the psychometric function; and iii) the stimulus value corresponding to a proportion of 0.75 (J_{75}), which indicates a proportion of 0.75. We then determined the JND value as the average value of the differences between the PSE and both J_{25} and J_{75} values:

$$JND = \frac{(PSE - J_{25}) + (J_{75} - PSE)}{2}. \tag{4.1}$$

Three sub-figures of Fig. 4.8 plot the average JND values of each vibration intensity. The JND value is displayed on the vertical axes, and the vibration intensity applied to the user's wrist is displayed on the horizontal axes. For instance, a level of 0.4T indicates that the vibration intensity level on display is 40% of the sensory threshold. A user with a higher haptic sensitivity is implied by a lower JND value. To verify whether there is a significant difference in the haptic performance, a two-tailed paired t-test is performed. As can be seen in Fig. 4.8, the average JND values at 0T and 0.6T in the three sub-figures differ significantly ($p < 0.05$). Moreover, among vibration intensity levels, the user performance at 60% of the sensory threshold has the lowest JND values. Moreover, the U-shaped pattern seen in the experiment results is a characteristic of the SR phenomenon. The JND value, for instance, drops as vibration intensity rises to a certain point in Fig. 4.8(a) but then rises again. This denotes the ideal threshold for improving the haptic experience. Applying subthreshold levels of mechanical noise can improve haptic sensation more than the user's performance with suprathreshold tactile stimulus, per [13, 19]. Furthermore, it is important to note that the vibration intensity should not be too high as to compromise the ability to detect, but rather high enough to boost a weak signal above the sensory threshold and achieve improved performance [13, 19]. In the current study, giving participants a sensory threshold of 60% results in the lowest JND value. This indicates that compared to other vibration intensities, there is a greater chance of improving the haptic user experience at 0.6T. These findings

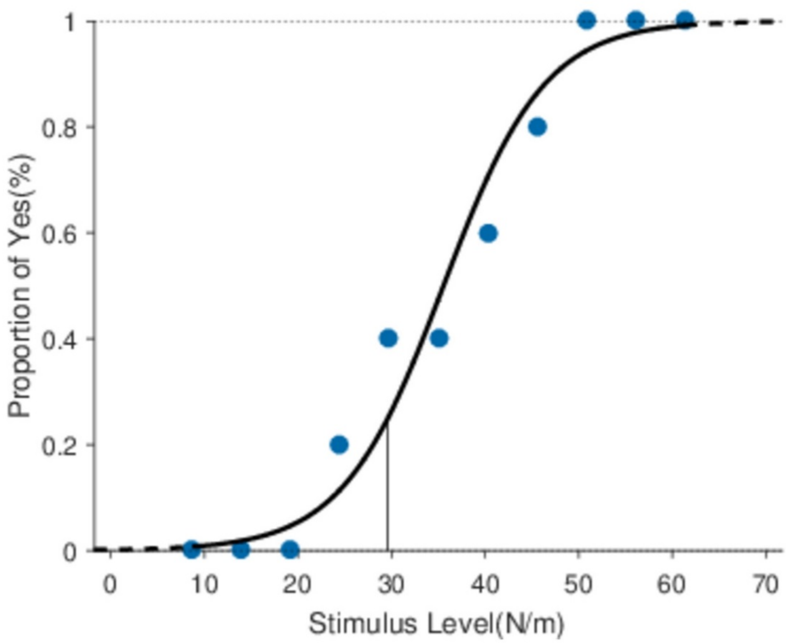


FIGURE 4.7: Example psycophysical data and psycometric function fits for a representative participant in Effects of SR on a Finger Placed within a Holder study. The vertical axis represent the portion of "yes" response (i.e., the comparison stiffness is stiffer than the standard stiffness.) while the horizontal axis show the comparison stiffness level. Each data point indicate the proportion of "yes" over 5 trials of each comparison stiffness.

demonstrate that even with the finger encased in a rigid holder, the user's fingertip force-detection ability improves. For the force learning experiment, we thus utilized 60% of the sensory threshold.

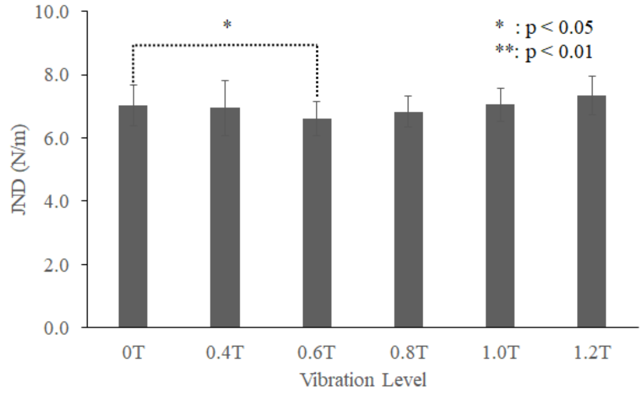
4.3.2 Effect of the Wristband

The results show that there is no significant difference between the two conditions. We therefore conclude that the wristband does not affect the user haptic performance.

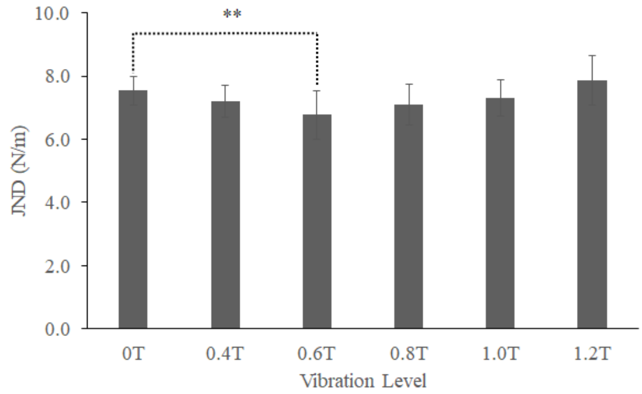
4.3.3 Force-Matching Tasks

We calculated the root-mean-square error (RMSE) in terms of the difference between the desired force (f_d) and the measured force for the participants (f_m) to compare user performance outcomes:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(f_d - f_m)^2}{N}}, \tag{4.2}$$



(a)



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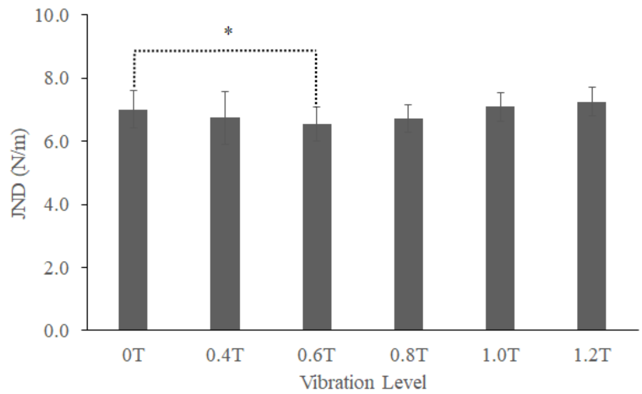


(c)

FIGURE 4.8: Average JND values of participants for each considered vibration level. T represents the sensory threshold of each participant, as determined in a preliminary study. Error bars indicate standard deviations while asterisks indicate a significant difference (*: $p < 0.05$ and **: $p < 0.01$).(a) Average JND values when using the finger pad. (b) Average JND values when using the left side of the fingertip. (c) Average JND values when using the right side of the fingertip.

where N is the sample size per trial.

Ten participants' average RMSE values over 15 trials are shown in Figures 4.9–4.14. The corresponding RMSE is displayed on vertical axes, and the number of trials is displayed on horizontal axes. Method 1 (i.e., the suggested method) results are indicated by dark bars, and Method 2 results are indicated by light bars. The presence of a significant variation in performance outcomes between trials was verified using a two-tailed paired t-test.

4.3.3.1 Task 1

The average RMSE values for Task 1 are displayed in Figure 4.9. Three phases of the results were examined separately: the completed phase, the transient phase, and the steady phase. The goal of the phase's analysis is to comprehend the training session's overall performance outcomes. It takes between five and thirty-five seconds to obtain the results for the finished phase. As seen in Fig. 4.4(a), the steady phase has three segments in the desired force pattern. The steady phase is divided into eight, eighteen, and twenty-eight segments, each lasting seven seconds. In order to eliminate the impact of the transient phenomenon caused by a change in force magnitude, the steady phase is investigated. When there is a sudden change in the force magnitude, the transient phase is measured to analyze the performance. At 5, 15, and 25 seconds, there are transient segments that last for three seconds each.

When it comes to the finished phase, most trials' average RMSE values for Method 1 are lower than those for Method 2 (Fig. 4.9(a)). Both approaches' performance curves exhibit comparable patterns. Trial 1 and all trials after Trial 3 for Method 1 show significant differences ($p < 0.05$), whereas Trial 1 and all trials after Trial 4 for Method 2 show significant differences ($p < 0.05$). Likewise, for Method 1, there are significant differences ($p < 0.01$) between Trial 1 and every other trial following Trial 5, and for Method 2, there are significant differences ($p < 0.01$) between Trial 1 and every trial following Trial 6.The two learning approaches are similar to each other in a major way. It's interesting to note that Method 1's average RMSE values decrease more quickly than Method 2's average RMSE values. For example, Method 1's RMSE drops from 0.77 N in Trial 1 to 0.67 N in Trial 5, while Method 2's RMSE drops from 0.80 N in Trial 1 to 0.70 N in Trial 6.

Fig. 4.9(b) illustrates how each method performed during the training sessions in the steady phase. For both approaches, the RMSE values in Trial 15 are substantially lower than those in Trial 1. For Method 1, there are statistically significant differences ($p < 0.05$) between Trial 1 and every subsequent trial following Trial 4. Comparably, for Method 2, there are significant differences ($p < 0.05$) between Trial 1 and every trial following Trial 6. Trial 1 and all trials after Trial 5 for Method 1 show significant differences ($p < 0.01$), whereas Trial 1 and all trials after Trial 7 for Method 2 show significant differences ($p < 0.01$). In Trial 6, there's a significant difference ($p < 0.05$) between the two approaches. For example, the RMSE for Method 1 drops from 0.78 N in Trial 1 to 0.68 N in Trial 6, while the RMSE for Method 2 drops from 0.82 N in Trial 1 to 0.72 N in Trial 6. The average RMSE values for Method 1 and Method 2 approach the lower level at a faster rate.

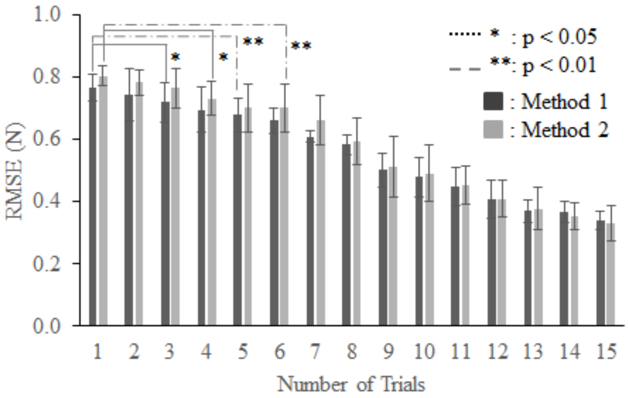
The RMSE values during the transient phase are displayed in Figure 4.9(c). Trial 1 and all trials after Trial 5 for Method 1 have significant differences ($p < 0.05$), according to a comparison of the trials, while Trial 1 and all trials after Trial 6 for Method 2 have significant differences ($p < 0.05$). Trial 1 and all trials after Trial 7 for Method 1 show significant differences ($p < 0.01$), whereas Trial 1 and all trials after Trial 9 for Method 2 show significant differences ($p < 0.01$). For instance, raw force data for one participant in Trials 1 and 15 (i.e., the final trial of the training session) for the suggested method is displayed in Fig. 4.10. There isn't a discernible difference between the two circumstances. The figure illustrates how, in Trial 15, there were less discrepancies between the measured force and the desired force than there were in Trial 1.

4.3.3.2 Task 2

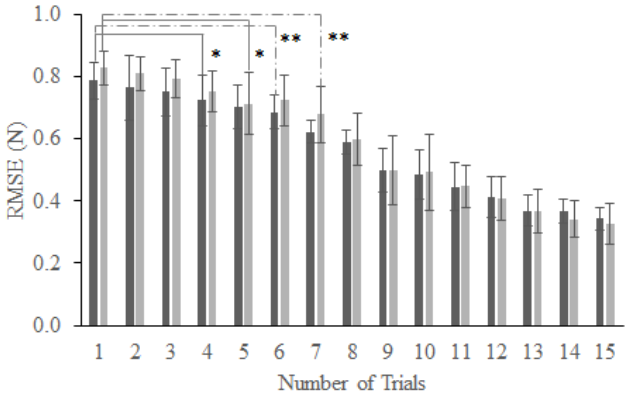
Similar to Task 1, Task 2's results are split into three parts. Task 1 and Task 2 differ in that the force magnitude is shown in different directions. Thus, the computation is divided into three parts: segment 1 (which lasts 5–15 seconds), segment 2 (15–25 seconds), and segment 3 (which lasts 25–35 seconds). It should be noted that in segments 1, 2, and 3, the participants saw the $y-$, $z+$, and $y+$ axis forces, respectively. In Task 2, the first three seconds of each segment—that is, 5–8 seconds for segment 1, 15–18 seconds for segment 2, and 25–28 seconds for segment 3—are considered the transient phase. Meanwhile, the steady phase is from 3 to 10 seconds in each segment; i.e., 8–15 seconds for segment 1, 18–25 seconds for segment 2, and 28–35 seconds segment 3. The phases are shown graphically in Fig. 4.11.

The results of segments 1, 2, and 3 are shown in Figures 4.12, 4.13, and 4.14, respectively. Overall, Method 1's performance outcomes show lower RMSE values than Method 2's, suggesting that Method 1 users perform better overall.

Figures 4.12(a), 4.13(a), and 4.14(a), which correspond to segments 1, 2, and 3, respectively, show the outcomes of the steady phase in each segment in the completed phase. Trial 1's results are significantly different ($p < 0.05$) from all trials after Trials 6, 4, and 5 in segments 1, 2, and 3, respectively, when compared to the results of the other



(a)



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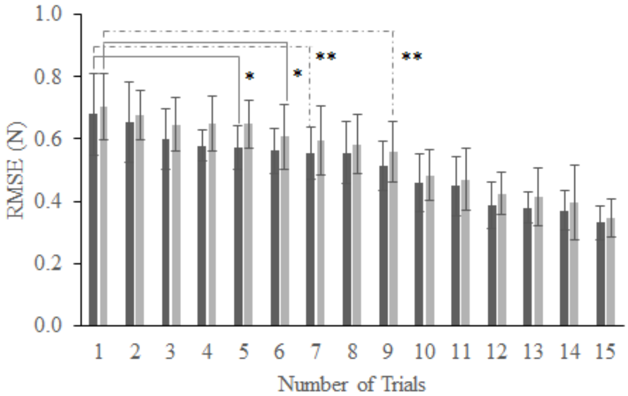
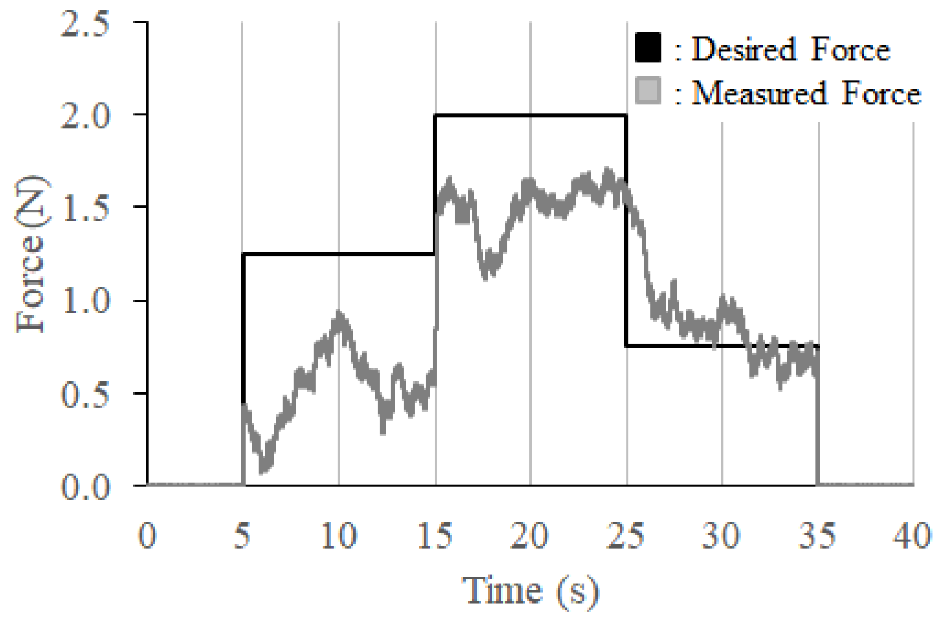


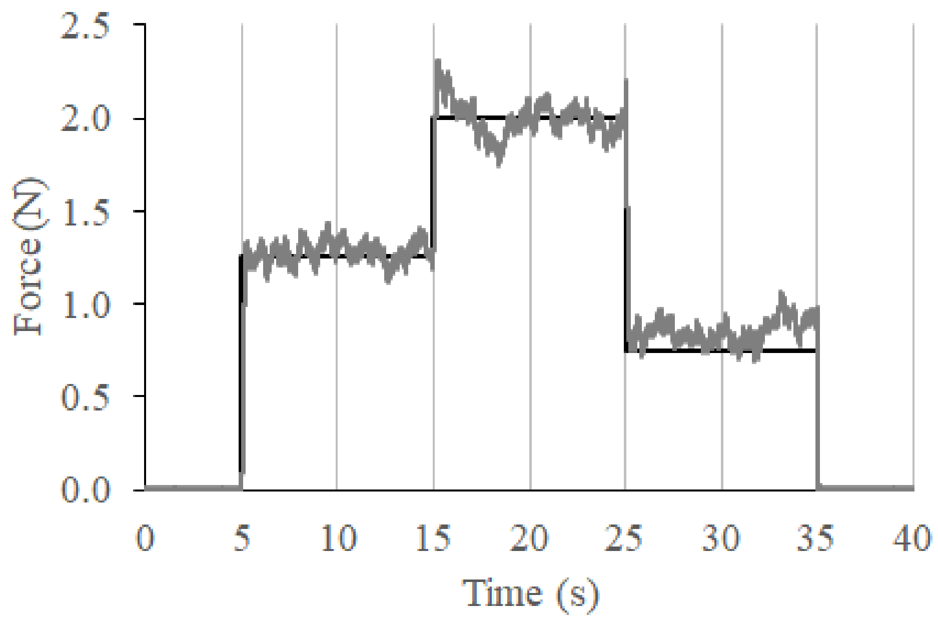
(c)

FIGURE 4.9: Results of the average RMSE in Task 1. The RMSE decreases as training progresses. Error bars indicate the standard deviation while asterisks indicate the significant difference (*: $p < 0.05$ and **: $p < 0.01$). Method 1 refers to the proposed method (haptic cues with SR) while Method 2 uses haptic cues without SR.(a) Average RMSE values during the completed phase. (b) Average RMSE values during the steady phase. (c) Average RMSE values during the transient phase.

trials. In the meantime, for Method 2, significant differences ($p < 0.05$) are observed in segments 1, 2, and 3 between Trial 1 and all trials following Trials 7, 6, and 6. For



(a)



(b)

FIGURE 4.10: Raw force data of one participant in Trial 1 and Trial 15 for Task 1. The vertical axis represents the magnitude of the force while the horizontal axis represents time. The dark line shows desired force data whereas the light line shows the measured force data for the participant.

Method 1, there are significant differences ($p < 0.01$) between Trial 1 and every trial conducted after Trials 7, 6, and 6 in segments 1, 2, and 3. Nonetheless, for Method 2, notable distinctions ($p < 0.01$) are noted between Trial 1 and every trial following Trials

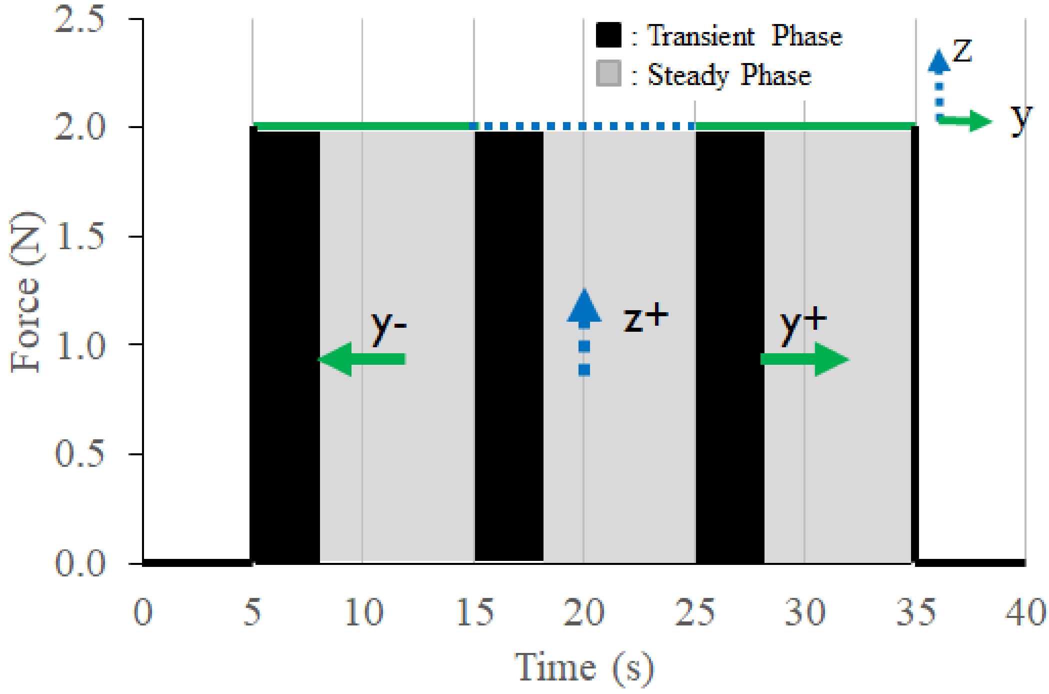


FIGURE 4.11: In task 2, there are three segments for each phase. The transient phases are presented in black whereas the gray boxes describe the steady phase. Each completed phase is the combination of the transient and steady phases in each segment.

8, 7, and 7 of segments 1, 2, and 3, in that order. A comparison between Methods 1 and 2 reveals that no trial for any segment differs from the other. Training using Method 1 tends to acquire the skill earlier than training using Method 2, according to the results (e.g., the RMSE of segment 1 decreases from 0.93 N in Trial 1 to 0.75 N in Trial 7 for Method 1, and from 0.97 N in Trial 1 to 0.85 N in Trial 7 for Method 2).

Figures 4.12(b), 4.13(b), and 4.14(b), which correspond to segments 1, 2, and 3, respectively, show the outcomes of the steady phase in each segment. There are significant differences ($p < 0.05$) between Trial 1 and all trials following Trials 6, 5, and 5 in segments 1, 2, and 3, respectively, for Method 1, according to a comparison with the other trials. In the meantime, for Method 2, there are significant differences ($p < 0.05$) between Trial 1 and every trial that follows Trials 8, 6, and 7 of segments 1, 2, and 3. Additionally, for Method 1, there are noteworthy distinctions ($p < 0.01$) between Trial 1 and every trial that follows Trials 7, 8, and 7 of segments 1, 2, and 3, respectively. However, for Method 2, there are significant differences ($p < 0.01$) between Trial 1 and every trial following Trials 9, 9, and 8 of segments 1, 2, and 3, respectively. The two approaches are compared, and the results indicate that there is no discernible variation in any trial for any segment. The findings demonstrate that practicing Task 2 using Method 1 maintains a skill better than practicing Task 2 using Method 2. For example, the RMSE of segment

1 decreases for both Method 1 and Method 2, going from 0.95 N in Trial 1 to 0.78 N in Trial 7.

The transient phase results for segments 1, 2, and 3 are shown in Figures 4.12(c), 4.13(c), and 4.14(c), respectively. A comparison of the trials reveals significant differences ($p < 0.05$) for Method 1 between Trial 1 and every trial conducted after Trials 6, 5, and 5 of segments 1, 2, and 3. In the meantime, for Method 2, there are significant differences ($p < 0.05$) between Trial 1 and every trial following Trials 7, 6, and 6 of segments 1, 2, and 3. For Method 1, there are significant differences ($p < 0.01$) between Trial 1 and all subsequent trials, including Trials 7, 6, and 6 of segments 1, 2, and 3. On the other hand, for Method 2, there are significant differences ($p < 0.01$) between Trial 1 and every trial following Trials 8, 7, and 7 of segments 1, 2, and 3. A comparison between Methods 1 and 2 reveals that no trial for any segment differs from the other. Training with Method 1 is expected to produce the desired results sooner than training with Method 2, much like in the steady phase case (e.g., the RMSE of segment 1 decreases from 0.94 N in Trial 1 to 0.68 N in Trial 7 for Method 1, and from 1.00 N in Trial 1 to 0.81 N in Trial 7 for Method 2).

4.4 Discussion

4.4.1 Effect of Stochastic Resonance on Motor Training

Applying the SR effect in the majority of trials results in lower RMSE values for Tasks 1 and 2. In some trials, there was a notable distinction between the two approaches. In the steady phase of Trial 6, there is a significant difference ($p < 0.05$) between the two methods used for Task 1. Therefore, we concluded that, in comparison to using only haptic cues, the training method combining haptic cues and SR improves user performance over training sessions. According to the preliminary user study presented in section 4.2.1, SR improves the user's fingertip's haptic sensitivity even when the fingertip is in a holder. The use of SR results in haptic cues being more easily discriminated by users and a lower JND value is thus an indicator of a better force-detection capability. Adopting the suggested method improves performance outcomes because it teaches participants tasks that require a higher level of haptic sensation. Therefore, we believe that the suggested approach—adopting SR—can enhance the user's acquisition of finger-based motor skills. In the last training trial (Trial 15), the average RMSE values for Methods 1 and 2 are the same. The average RMSE values for Method 1 are declining more quickly than the average RMSE values for Method 2 are declining. When attempting to enhance performance outcomes, it is crucial to take into account

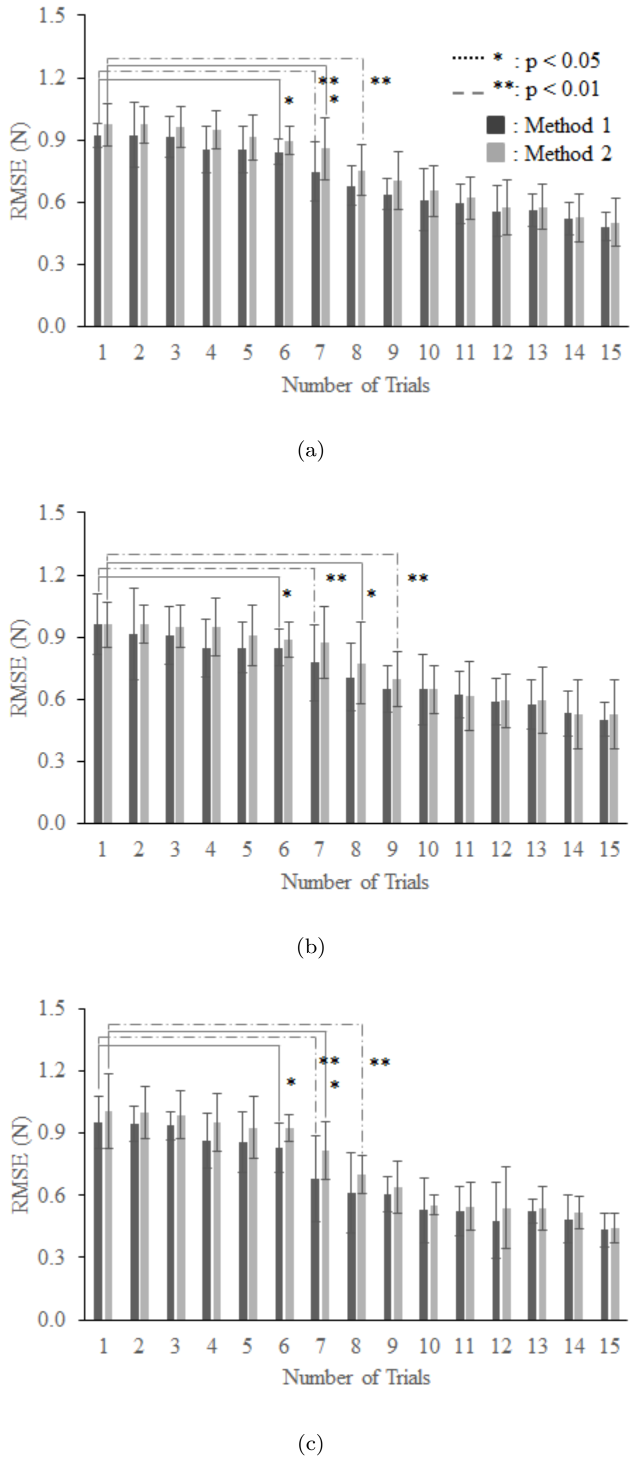
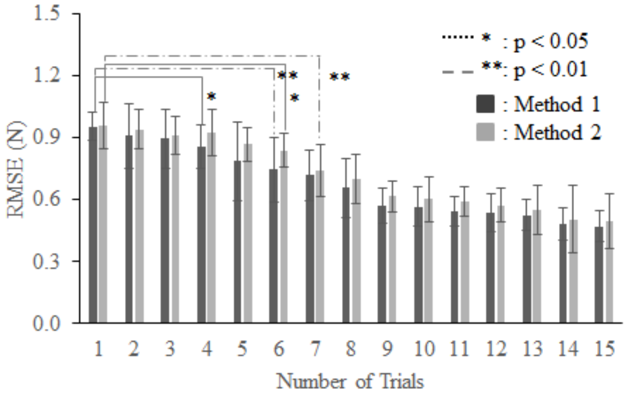
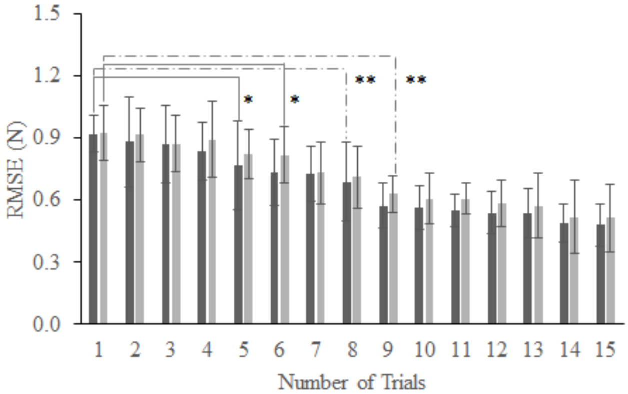


FIGURE 4.12: Results of the average RMSE values in segment 1 of Task 2. There is a decrease in the RMSE as training progresses. Error bars indicate the standard deviation while asterisks indicate the significant difference (*: $p < 0.05$ and **: $p < 0.01$). Method 1 refers to the proposed method (i.e., the use of haptic cues with SR) while Method 2 refers to the use of haptic cues without SR. (a) Average RMSE values during the completed phase. (b) Average RMSE values during the steady phase. (c) Average RMSE values during the transient phase.



(a)



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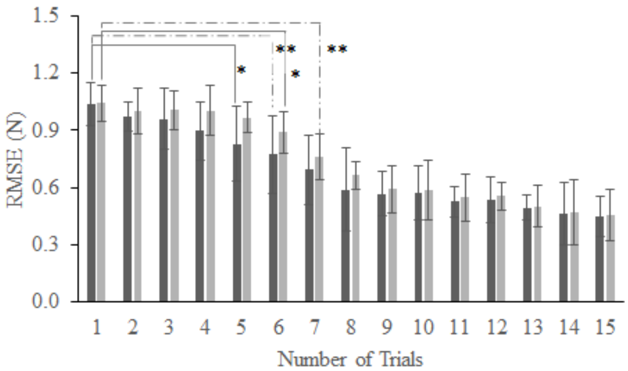
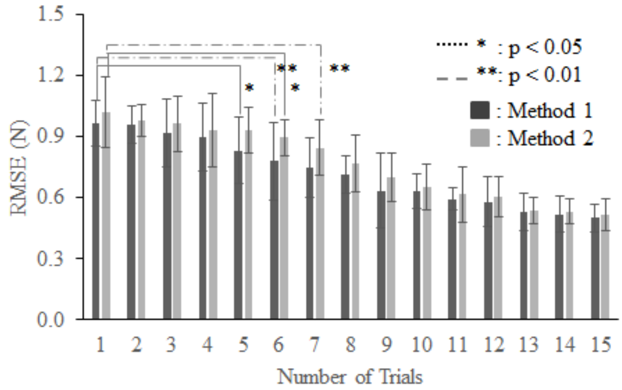


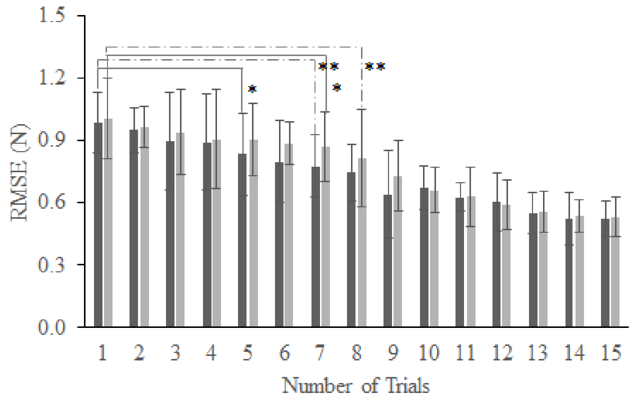
(c)

FIGURE 4.13: Results of the average RMSE values in segment 2 of Task 2. There is a decrease in the RMSE as training progresses. Error bars indicate the standard deviation while asterisks indicate the significant difference (*: $p < 0.05$ and **: $p < 0.01$). Method 1 refers to the proposed method (i.e., the use of haptic cues with SR) while Method 2 refers to the use of haptic cues without SR. (a) Average RMSE values during the completed phase. (b) Average RMSE values during the steady phase. (c) Average RMSE values during the transient phase.

alternative forms of haptic cue. Therefore, in our next work, we intend to explore various



(a)



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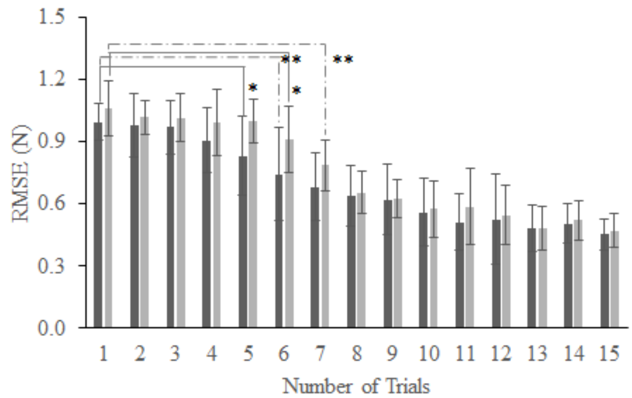

(c)

FIGURE 4.14: Results of the average RMSE values in segment 3 of Task 2. There is a decrease in the RMSE as training progresses. Error bars indicate the standard deviation while asterisks indicate the significant difference (*: $p < 0.05$ and **: $p < 0.01$). Method 1 refers to the proposed method (i.e., the use of haptic cues with SR) while Method 2 refers to the use of haptic cues without SR. (a) Average RMSE values during the completed phase. (b) Average RMSE values during the steady phase. (c) Average RMSE values during the transient phase.

kinds of haptic cue.

The impact of SR on 2D motor performance has been established by earlier research. The effect of applying Gaussian noise to the index finger to improve user performance when compensating for a force generated by a manipulandum was studied by Mendez-Balbuena *et al.* [75]. The index finger in that study received force from the manipulandum. The participants attempted to use their finger to offset the force. On the other hand, our study's noise ranged from 0 to 400 Hz, whereas the noise in [75] was between 0 and 15 Hz. Which frequency bandwidth is better for enhancing task performance is unclear. Therefore, it will be interesting to explore the ideal frequency in subsequent research.

4.4.2 Study Limitations

Although the suggested method improves performance outcomes, the current study has limitations because it solely looks at the immediate effects of white-noise vibration. When the user experiences mechanical vibration, the immediate result in this scenario is an improvement in haptic perception. Enders *et al.* [18] investigated how remote vibrotactile noise improved tactile sensation at the fingertip. A Semmes-Weinstein monofilament was employed, along with two-point discrimination tests, to assess the impact of SR for one of the three vibration levels at a single, distant upper extremity location. Furthermore, they followed the same procedure during the pre- and post-test phases. That is to say, during a preliminary test, participants completed the task without any noise at all. Afterwards, they performed it at least three times with white-noise vibration, and at last, they completed it without any noise (post-test). But there was no discernible change in the outcomes between the pre- and post-test sessions. Although the task examined in [18] was not a learning task and was not tested over a large number of trials, this suggests that SR has no long-term effect. It is unknown how well the SR-based training method retains data. But the retention test is essential to the study of motor learning because it demonstrates the long-term effects of user performance. According to Schmidt et al. (2018), the test shows sustained user performance at the behavioral level. Future research will take into account the retention test results of SR in motor learning, as the current study was unable to ascertain the long-term learning improvement.

4.5 CONCLUSION

We presented a novel haptic training approach for finger-based force application learning. The suggested technique improves training performance by utilizing haptic cues and SR.

First, we performed stiffness discrimination experiments to evaluate the performance of SR in two dimensions. Then, even with the finger inside a rigid holder, we increased the user's fingertip force-detection capability by amplifying the effectiveness of using SR. Based on these findings, we conducted an experiment using a force learning task. In our study, subjects were given a mechanical white-noise vibration at the dorsal wrist along with a haptic cue while they completed force learning tasks. It is thought that SR enables participants to accurately perceive the haptic cue in our approach. In both the 1D force task and the 2D force task, our suggested method outperformed the comparison method (which only used haptic cues) in terms of RMSE values. Therefore, we believe that the suggested approach is more beneficial and efficient for learning the motor training task. In subsequent research, we will examine the white-noise vibration's frequency range after looking into how well the system performed in a retention test.

Chapter 5

CONCLUSION

5.1 Summary

A haptic perception, which is produced by the stimulation of mechanoreceptors triggered by the manual exploration of an object, is necessary for a number of daily tasks. The fingertip's extremely accurate haptic perception enables accurate perception of light touch, proprioception, and discrimination. Haptic performance in our lives tends to decline as a result of a weakening of haptic perception brought on by a degeneration of the nerve endings in the pulp of our fingers. Improving the user's fingertip haptic sensation is essential to solving this issue and achieving improved haptic performance. This thesis suggests methods for applying mechanical noise to simulate stochastic resonance in order to improve the haptic experience of the user's fingertip when utilizing one or more fingers to perform tasks. The mechanical noise is applied at a distance from the fingers.

Our primary goal is to find out how the SR effects improve the human fingertip's haptic feedback during the tasks. In order to accomplish this, we study the relationship between the tactile perception of the fingertip and the noise intensity that is transmitted from the remote noise source to the fingertip. The results demonstrate that in order to improve the user's haptic experience, the ideal noise level must be determined. We then perform a two-finger stiffness discrimination task to investigate the SR effects for the multi-finger task. The findings demonstrate that when the user is performing the multi-finger task, the SR effects can improve the haptic sensation of two fingers even when only one noise source is used. The findings demonstrate that when the user is performing the multi-finger task, the SR effects can improve the haptic sensation of two fingers even when only one noise source is used. Moreover, the location of the noise source is a significant factor in improving the user's haptic experience. Furthermore, even in tasks that require both kinesthetic and cutaneous perception, the SR effects work to improve cutaneous perception, which in turn improves overall haptic perception. The force-matching task is the last task we look at, and this is the first time the SR effects have been used to look into how effective the learning task is. Here, using a haptic training system for instruction is common in many fields. The finger-holder, on the other hand, decreases the user's cutaneous perception when manipulating a virtual object, which could result in a decrease in training performance. Applying the SR effects to the motor learning task is therefore intriguing. We present a motor learning approach with the SR effects, and the findings show that the user learns more quickly during training when noise is applied. Furthermore, the findings demonstrate that SR effects can improve haptic performance even when a user performs the fingertip-force training task with their finger in a finger holder. Finally, a summary of the key findings and recommendations for future research directions wrap up the thesis.

5.2 Future Works

In this thesis, the goal is to enhance the haptic sensation of the fingertip, which is related to several tasks in our daily life. We first aim to investigate how the SR effects enhance the haptic sensation of the human fingertip while performing the tasks. To achieve this purpose, we investigate the relationship between the noise intensity propagated from the remote noise source to the fingertip and fingertip tactile perception. The outcomes show that it is necessary to define the optimal noise level in order to enhance the user's haptic sensation. Next, we examine the SR effects for the multi-finger task by conducting a two-finger stiffness discrimination task. The results show that the SR effects can enhance the haptic sensation of two fingers even using a single noise source while the user performs the multi-finger task. Furthermore, the position of the noise source also plays an important role in increasing the haptic performance of the user. Moreover, the SR effects aim to enhance the cutaneous perception, which results in the overall haptic perception being enhanced even if the task requires both kinesthetic and cutaneous perception. In the final step, we consider the force-matching task, and the SR effects had never been applied to investigate the effectiveness of the learning task. Here, training through a haptic training system is ubiquitous in several fields. However, the finger-holder, which is used to manipulate a virtual object, reduces the user's cutaneous perception, which might lead to a reduction in training performance. Thus, it is interesting to apply the SR effects to the motor learning task. We propose a motor learning method with the SR effects, and the results reveal that the training performance when the noise is applied to the user has a faster learning process. Moreover, the results present the SR effects can enhance the haptic performance even if the user's finger is in the finger-holder while performing the fingertip-force training task. Finally, the thesis is concluded by summarizing the main findings and highlighting future research directions.

In chapter 2, we investigated the possible remote SR mechanism by the investigation of the propagated noise and the user haptic performance while performing the task. However, there is no theoretical evidence of the remote SR mechanism. Therefore, it is interesting to realize the formula of the remote SR mechanism.

In chapter 3, we examine the SR effects for the multi-finger task by conducting a two-finger stiffness discrimination task. It is interesting to explore the other frequency range, not only a low-pass filter at 300 Hz. For example, the other frequency ranges that rely on the mechanoreceptor characteristics. This might be have a different effect from the low-pass filter at 300 Hz. Furtheremore, it is interesting to realize how to select the optimal position by realizing the mathematical formulation.

Finally, in chapter 4, we consider the force-matching task, and the SR effects had never been applied to investigate the effectiveness of the learning task. It is interesting to investigate the performance in a retention test and then explore the other frequency range of white-noise, which might have the different result from the low-pass filter at 300 Hz.

Appendix A

A.1 Publications Related to the Dissertation

A.1.1 Journal Papers

1. Chamnongthai, K., Endo, T., Matsuno, F., Fujimoto, K., & Kosaka, M. (2020). Two-dimensional Fingertip Force Training with Improved Haptic Sensation via Stochastic Resonance. IEEE Transactions on Human-Machine Systems, 50(6), 593-603.
2. Chamnongthai, K., Endo, T., & Matsuno, F. (2023). Two-finger Stiffness Discrimination of a Virtual Object with Haptic Sensation Enhancement via the Stochastic Resonance Effect. Displays, 78, 102429.
3. Chamnongthai, K., Endo, T., & Matsuno, F. (2024). Two-finger Stiffness Discrimination with the Stochastic Resonance Effect. ACM Transactions on Applied Perception. ACM Transactions on Applied Perception, 21(2), Article 6, 1–17.

A.1.2 International Conference Papers

1. Chamnongthai, K., Endo, T., Nisar, S., Matsuno, F., Fujimoto, K., & Kosaka, M. (2019, July). Fingertip force learning with enhanced haptic sensation using stochastic resonance. In 2019 IEEE World Haptics Conference (WHC) (pp. 539-544). IEEE.
2. Chamnongthai, K., Endo, T., Ikemura, S., & Matsuno, F. (2020, September). Stiffness Discrimination by Two Fingers with Stochastic Resonance. In Haptics: Science, Technology, Applications: 12th
International Conference, EuroHaptics 2020, Leiden, The Netherlands, September 6–9, 2020, Proceedings 12 (pp. 497-505). Springer International Publishing.

A.1.3 Domestic Conference Papers

1. Chamnongthai, K., Endo, T., & Matsuno, F. (2021, March). Enhancement of Haptic Sensation on Dominant and Non-dominant Hands for Stiffness Discrimination Task by Stochastic Resonance. Proc. of the 7th IEEJ international workshop on Sensing, Actuation, Motion Control, and Optimization (SAMCON2021) 202-205

A.2 Publications not Related to the Dissertation

A.2.1 Journal Papers

1. Endo, T., Kim D. H. & Chamnongthai, K. (2023). Enhancing Fingertip Tactile Sensitivity by Vibrotactile Noise and Cooling Skin Temperature Effect. IEEE Transactions on Haptics, 16(3), 391-399

List of Figures

List of Tables

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