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Multiple Remote Vibrotactile Noises Improve Tactile Sensitivity of the Fingertip via Stochastic Resonance

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ABSTRACT This paper proposes a method to improve the tactile sensitivity of the fingertip by placing multiple vibrators at a remote position away from the fingertip. It is known that a fingertip's tactile sensitivity improves when vibrotactile noise is applied to the fingertip or to a position away from the fingertip, such as the wrist. This is the application of stochastic resonance to the field of haptics. Preliminary experiments in this study have shown that the improvement of a fingertip's tactile sensitivity via remote vibrotactile noise depends on the propagation of the vibration on human skin. From the results of the preliminary experiments, it is expected that the larger the noise reaching the fingertip, the smaller the detectable input. Therefore, we consider that multiple vibrators at a remote position can propagate a larger noise to the fingertip and further improve the fingertip's tactile sensitivity compared to the use of only one vibrator as occurred in a previous study. Finite element analysis was performed so that the noises from multiple vibrators were properly superimposed at the fingertip. To synchronize the arrival of the noises at the fingertip from the multiple vibrators, we determined the positions of the vibrators and the time when each vibrator started generating noise. The results of a subject experiment confirmed that the proposed method significantly improved fingertip sensitivity compared to the case without SR or the case where only one vibrator was used.

INDEX TERMS Fingertip, haptic sensation, multiple remote noises, stochastic resonance.

I. INTRODUCTION

The use of stochastic resonance (SR) has been attracting attention as a method to increase tactile sensitivity and improve performance during precise work using the hands or when tactile function is degraded due to diseases such as neuropathy or aging [1]. It is known that when an optimal noise is added to a nonlinear system with a weak input, the undetected input becomes apparent and the sensitivity is improved [2]. This phenomenon is called stochastic resonance. SR is often discussed in a bistable system, i.e., a system with two stable states. For recent progress of SR, see [3], [4]. However, SR was also observed in an excitability model such as a human tactile receptor: when a certain threshold state is reached, there occurs a large excursion in the state variable, followed by a recovery to a resting state [5].

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In the SR of the excitability model, there are three necessary components: a threshold, a subthreshold input, and noise [6]. If the original input applied to the model is smaller than the threshold, the input cannot be detected. Here, when an optimal noise is added to the subthreshold input, the input exceeds the threshold and can be detected, and the period exceeding the threshold is synchronized with the original input. On the other hand, if the added noise is too large, the probability of exceeding the threshold increases, but the period is not synchronized with the original input; that is, the input is buried in the noise, and the information on the original input cannot be obtained from the output. SR is a phenomenon in which the signal is enhanced and the response is improved at a certain probability by adding noise of an optimal intensity to the subthreshold input. Collins *et al.* first applied SR to human tactile function [1]. They found that humans can detect an input when noise is added to a subthreshold input that they cannot perceive.

Thus far, many studies have applied SR to human tactile functions such as fingertips [1], [7], hands [8], and feet [6], [9]. Furthermore, it has been reported that SR improves balance control [10]–[12], control of finger force [13], [14], and motor learning using fingers [15]. Collins *et al.* found that humans can detect a subthreshold input when Gaussian noise is superimposed on the input applied to the fingertip [1]. However, considering that we perform tasks using our fingertips, it is not realistic that an input with noise superimposed is presented to the fingertips. Kurita *et al.* developed a glove-type wearable device that can improve the tactile sensitivity of a fingertip by applying white Gaussian noise to the lateral aspect of the fingertip [7]. However, for precise work using the hands, it is necessary to allow the user's hands to move as freely as possible. Therefore, it is desired that the tactile sensitivity of the fingertip can be improved even when vibrotactile noise is applied to a remote position, such as the dorsal hand or wrist away from the fingertip, that does not restrict the user's hand movement, instead of attaching a vibrator directly to the fingertip. Enders *et al.* found that the tactile sensitivity of the fingertip can be improved even when vibrotactile noise is applied to a position away from the fingertip [16]. They showed experimentally that white noise applied to the dorsal hand or wrist can improve the tactile sensitivity of the fingertip. However, the fundamental principle that remote vibrotactile noise improves the tactile sensitivity of the fingertip is still unexplained.

Preliminary experiments in this study showed that whether or not remote vibrotactile noise improves a fingertip's tactile sensitivity depends on vibration propagation on human skin. For example, we consider a case where a vibrotactile noise is applied to the wrist. This noise propagates on the skin and reaches the fingertip. Then, it has been confirmed that the noise adds to the subthreshold input presented at the fingertip, thus increasing the input until it can be detected.

From this verification of the fact, it is expected that the larger the noise reaching the fingertip, the smaller the input that can be detected. In this study, we propose a method to place multiple vibrators at a remote position away from the fingertip, such as the wrist. In the previous studies, only one vibrator is placed in a remote position. By using multiple vibrators, vibrotactile noises propagated from the vibrators are superimposed on the fingertip, so the noise at the fingertip is larger than when only one vibrator is used. As a result, it is expected that the sensitivity of the fingertip would be greater than if only one vibrator is used, thus allowing an even smaller input to be detected.

The paper is organized as follows. In Section II, we experimentally investigate the fact that remote vibrotactile noise improves the tactile sensitivity of the fingertip. In Section III, we describe a method of placing multiple vibrators at a remote position to improve the sensitivity of the fingertip. In Section IV, we explain a subject experiment to verify the effectiveness of the proposed method. In Section V, we describe the experimental results and discuss the effectiveness of the proposed method. Finally, we conclude this paper in Section VI.

II. ENHANCEMENT OF FINGERTIP TACTILE SENSITIVITY BY REMOTE VIBROTACTILE NOISE

In this section, we describe the experiments to show that remote vibrotactile noise improves a fingertip's tactile sensitivity. We confirm that the sensitivity of the fingertip improves when a sufficiently large noise reaches it, and that the sensitivity does not improve otherwise.

A. SENSORY THRESHOLD OF THE FINGERTIP FOR SINUSOIDAL VIBRATION

1) METHOD

In this experiment, the fingertip sensory threshold for sinusoidal vibration is measured when white Gaussian noise is applied to the wrist or forearm (a position about 200 mm from the wrist in the forearm direction). Here, note that many studies have been conducted to improve the tactile sensitivity of fingertips by using white Gaussian noise ([1], [7], [15], [16], and others), and we have already described this fact in the introduction. According to these results, we used white Gaussian noise as the noise in this paper. Fig. 1 shows an overview of the experimental environment. A voice coil actuator (Haptuator Planar, Tactile Labs, Montreal, Canada) for applying sinusoidal vibration was attached to the index fingertip, and a piezoelectric actuator (APA400M, Cedrat Technologies, Meylan, France) for presenting white Gaussian noise for SR was attached to the wrist or forearm. Each vibrator was fixed to the subject using a hook and loop (Velcro) tape.

First, the subject's sensory threshold at the wrist and forearm for white Gaussian noise is examined. Then, the fingertip sensory threshold for sinusoidal vibration is measured with and without SR. Six healthy subjects (mean age $\pm$ SD: 23.8 $\pm$ 0.69 years, all males) participated in this experiment, where SD indicates standard deviation. All participants understood and consented to the experimental protocol approved by The Ethics Committee, Graduate School of Engineering, Kyoto University (No. 201707).

First, we measured the subject's sensory threshold at the wrist and forearm for white Gaussian noise. Considering the frequency characteristics of the tactile receptors on the human fingertips, we selected white Gaussian noise with a frequency band of 0 – 300 Hz. There are four known types of tactile receptors on human fingertips, each with different frequency characteristics [17]. In other words, the frequency with the highest sensitivity differs for each receptor. Therefore, we decided to use 0 – 300 Hz white Gaussian noise, which included all of the most sensitive frequencies of the four types of tactile receptors. White Gaussian noise was obtained by applying a low-pass filter with a cutoff frequency of 300 Hz to $f(t)$ generated using the Box-Muller method expressed by the following equation [18]:

$$f(t) = \sigma \sqrt{-2 \ln U_1(t)} \sin\left(2\pi U_2(t)\right), \quad (1)$$

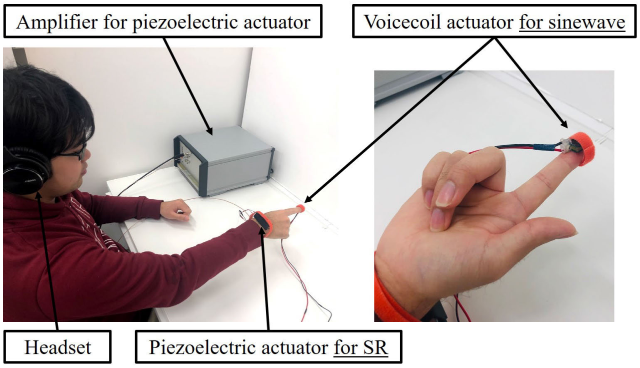

FIGURE 1. **Experimental environment for measurement of sensory threshold for sinusoidal vibration.**

where $U_1(t)$ and $U_2(t)$ are independent random variables on the interval (0, 1), σ is the noise intensity, and t is time.

The sensory threshold was measured using the up-down method [19]. Additionally, the subjects wore passive noise-canceling headsets to avoid hearing the vibration actuator. The subject's sensory thresholds for the white Gaussian noise at the wrist and forearm obtained here are T_{wrist} and T_{forearm}, respectively.

Next, we measured the fingertip sensory threshold for sinusoidal vibration with and without SR. The frequency of the sinusoidal vibration applied to the fingertip was set to 100 Hz. In the case of vibration with SR, white Gaussian noise with 0.6 T_{wrist} and 0.6 T_{forearm} was applied to the wrist and forearm, respectively. Here, note that the noise with 0.6 T means that the noise intensity is 60 % of the sensory threshold T. The following are known to be true, depending on the task: [15], [22]: 1) applying noise with an intensity of less than 1.0 T to the wrist significantly improves the tactile sensitivity of the fingertip compared to when no noise is applied; 2) on the other hand, the tactile sensitivity of the fingertip does not improve when noise with an intensity of 1.0 T or higher is applied to the wrist; and 3) the tactile sensitivity of the fingertip is highest at 0.6 T. Therefore, in this experiment 0.6 T is chosen as the condition when using SR. The experiments were performed under three conditions: without SR, when vibrotactile noise was applied to the wrist, and when vibrotactile noise was applied to the forearm. The order of these conditions was random. The fingertip sensory threshold for sinusoidal vibration was also measured using the up-down method.

2) RESULTS

Fig. 2 shows the experimental results. The horizontal axis indicates the SR condition while the vertical axis shows the subject's fingertip sensory threshold for sinusoidal vibration, which is the smallest amplitude of sinusoidal vibration that the subject could detect at the fingertip. Therefore, a small value indicates that a smaller vibration was detected; that is, the sensitivity was high. In addition, the T-topped error bars show the standard deviation for each value. We carried out a two-tailed paired t-test. There was a significant difference

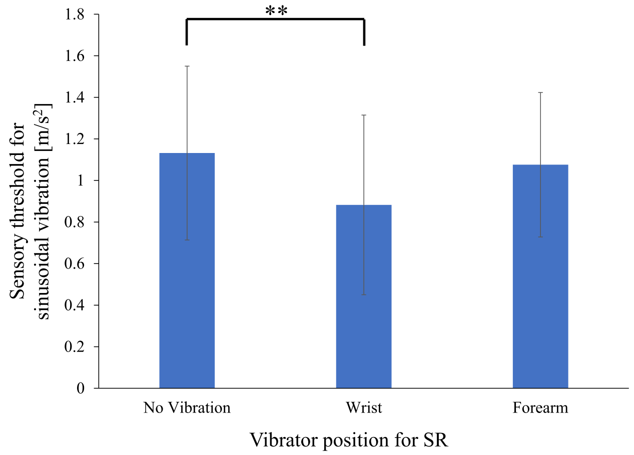

FIGURE 2. **Sensory threshold for sinusoidal vibration with SR (Wrist, Forearm) and without SR (No vibration). In the Wrist and Forearm applications, noise was applied to those respective parts. A statistically significant difference was observed between Wrist case and No vibration case ("∗∗" means $p < 0.01$).**

between the Wrist case and the No-vibration case ($t = 5.05$, DOF $= 5, p = 0.004$), and there was no significant difference between the Forearm case and the No-vibration case ($t = 0.72$, DOF $= 5, p = 0.502$).

The results show that the sensitivity of the fingertip was significantly improved when white Gaussian noise with 0.6 T_{wrist} was applied to the wrist compared to the case without SR (No vibration). However, it can be seen that the sensitivity did not improve when the noise was applied to the forearm. From these results, we expect that when noise was applied to the wrist, stochastic resonance appeared and the sensitivity improved because a sufficiently large noise reached the fingertip. On the other hand, it is considered that, when noise was applied to the forearm, a sufficiently large noise did not reach the fingertip, so stochastic resonance did not appear and sensitivity did not improve. In the next experiment, we measure the noise propagating to the fingertip in order to investigate the hypothesis mentioned above.

B. NOISE PROPAGATING TO THE FINGERTIP

1) METHOD

In this experiment, the noise propagating to the fingertip is measured using a polyvinylidene fluoride (PVDF) film when the white Gaussian noise used in the first experiment is applied to the wrist or forearm. We used the same method in [20] to measure the noise at the fingertip using a PVDF film. Fig. 3 shows an overview of the experiment. A piezoelectric actuator (APA400M, Cedrat Technologies) for presenting white Gaussian noise was attached to the wrist or forearm, and PVDF film (LDT1-028K, TE Connectivity, Schaffhausen, Switzerland) was wound around the index fingertip with a skin adhesive. We measured the acceleration of the fingertip skin in the normal direction when white Gaussian noise with 0.6 T_{wrist} or 0.6 T_{forearm} was applied to the wrist or forearm, respectively.

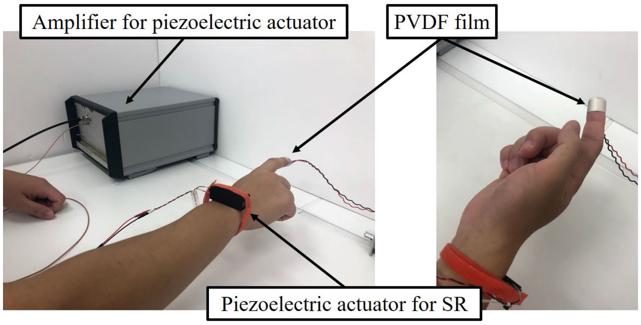

FIGURE 3. Experimental environment for measuring noise at the fingertip with PVDF film.

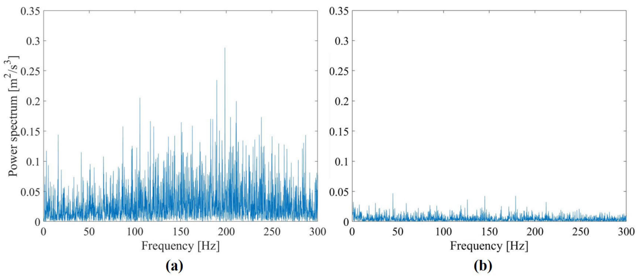

FIGURE 4. Power spectrum of the noise at the fingertip when white Gaussian noise is applied to (a) wrist or (b) forearm.

2) RESULTS

Fig. 4 shows the results of the experiment. The horizontal axis indicates frequency, and the vertical axis indicates the power spectrum of the noise propagating to the fingertip from the wrist or forearm.

The experimental results show that when white Gaussian noise was applied to the forearm, a sufficiently large noise did not reach the fingertip, unlike the case where the noise was applied to the wrist. It is known that the number of tactile receptors decreases as the distance from the fingertip increases, which means the tactile sensitivity decreases [21]. Therefore, the sensory threshold at the forearm for white Gaussian noise (T_{forearm}) is larger than the sensory threshold at the wrist (T_{wrist}). Then, the white Gaussian noise applied to the forearm (0.6 T_{forearm}) was larger than the noise applied to the wrist (0.6 T_{wrist}). However, since the distance from the forearm to the fingertip was long, the noise was attenuated and a sufficiently large noise did not reach the fingertip. It is considered that the sensitivity of the fingertip did not improve as shown in Fig. 2 because the noise propagating to the fingertip was small when the noise was applied to the forearm.

C. DISCUSSION

The present results confirmed that the tactile sensitivity of the fingertip improves when a sufficiently large noise reaches the fingertip but does not improve otherwise, as shown in Figs. 2 and 4. Therefore, from the result showing that the intensity of the noise propagating to the fingertip determines the appearance of stochastic resonance, we can conclude that remote vibrotactile noise improves the tactile sensitivity of the fingertip by the propagation of vibration on human skin. In other words, the noise propagated from the remote position appears to detect the subthreshold input presented to the fingertip.

In addition, the improvement of the index finger's tactile sensitivity for sinusoidal vibration was confirmed, but the improvement of the sensitivity of other fingers or of the palm can be expected by applying noise to the wrist. The noise propagating to the middle finger was also measured using PVDF film in the same way as described above, and it was confirmed that the noise with the same intensity as the index finger reached the middle finger. Thus, the advantage of adding noise to remote positions is that it can also improve the tactile sensitivity of all five fingers or the palm in addition to the known advantage mentioned in [16], [22], which allows the user to move their hand as freely as possible.

III. PROPOSED METHOD TO IMPROVE TACTILE SENSITIVITY AT THE FINGERTIP USING MULTIPLE REMOTE NOISES

A. BACKGROUND

From Section II, we found that when noise is applied to a remote position such as the wrist, it propagates to the fingertip and adds to the subthreshold input at the fingertip, so that the input can be detected. Based on this principle, we can expect that the larger the noise reaching the fingertip, the smaller the detectable input. Therefore, white Gaussian noise with an intensity of 0.6 T was used in the subject experiment in Section II, but if a larger noise, such as 1.0 T or 1.5 T, is applied, the noise reaching the fingertip also increases, so it may be possible to detect an even smaller input. However, it is known that the sensitivity of the fingertip does not always improve even if a noise larger than 1.0 T is applied [15], [22]. This seems to be a matter of human attention rather than SR principle. Since T represents the subject's sensory threshold for white Gaussian noise, when white Gaussian noise with 1.0 T or more is applied, the subject perceives the vibrotactile noise itself at the wrist, for example. While performing the task of detecting a weak input below the sensory threshold at the fingertip, all subjects felt the vibrotactile noise in another part. Thus, it is considered that noise with 1.0 T or more did not improve the tactile sensitivity of the fingertip, though a larger noise should have propagated to the finger.

B. PROPOSED METHOD

Based on the above background, aiming to further improve tactile sensitivity and performance, we consider applying multiple white Gaussian noises with intensities less than the threshold from multiple vibrators. If the intensity of white Gaussian noise is less than the threshold, humans do not feel the noise at the positions where the vibrators are placed. We thus expect that, since the vibrotactile noises propagated from the multiple vibrators are superimposed on the fingertip, the noise at the fingertip will increase and the sensitivity will improve; that is, even smaller inputs can be detected.

However, since the vibrotactile noises are presented from different positions, there are differences in the time for the noises from various positions to reach the fingertip even if noises with the same waveform are applied. Thus, the use of multiple vibrators does not always increase the noise at the fingertip because the noises do not arrive at the fingertip at the same time. Furthermore, depending on the position of the vibrators and the noise intensity, humans may feel the vibrotactile noise at unexpected positions. Therefore, we will develop a simple 3D finite element hand model with reference to the study by Wu *et al.* [23], and observe the behavior of vibration propagation on human skin by conducting finite element analysis. By properly determining the positions of the vibrators and the time when each vibrator starts generating noise through the simulation, we aim to synchronize the arrival of the noises at the fingertip and thus increase the noise compared to using only one vibrator.

C. 3D FINITE ELEMENT HAND MODEL

To determine the positions of the vibrators and the time when each vibrator starts generating noise, we developed a simple 3D finite element hand model consisting of a finger (assuming the index finger), a hand, and a wrist as shown in Fig. 5. Further, Fig. 6 shows a finger cross section. The finger, the hand, and the wrist are composed of four elements: outer skin, inner skin, subcutaneous tissues, and bone. The size of each component, the physical properties, and the hand size are based on related studies [23]–[25].

D. SIMULATION

We consider applying white Gaussian noises with exactly the same waveform from different positions. Because the distance from each position to the fingertip differs, the time required for the vibrotactile noise to reach the fingertip also differs. These differences in the arrival times of the noises are filled by shifting the time at which each vibrator starts generating noise. Then, we aim to propagate the resulting larger noise to the fingertip than when using only one vibrator.

We have decided to place multiple (two) vibrators, one at the upper part of the wrist and the other at the lower. This time, we consider using multiple vibrators to increase the noise at the index finger, but it is necessary to consider the possibility of expanding to multiple fingers in the future. This is because, as described in Section II, the biggest advantage of applying vibrotactile noise to a remote position like a wrist is that remote vibrotactile noise can improve the tactile sensitivity of all five fingers without attaching a vibrator to each finger. Therefore, it is not effective if the noise is increased only at the index finger when using multiple vibrators. Then, in this study, the positions of two vibrators were set at the upper and lower parts of the wrist. Since the difference in distance from the upper and lower parts of the wrist to the finger pad does not change significantly for each finger, we consider that if the arrival time of the noises is adjusted at the index finger, the noise can be increased at the other four fingers.

First, the noise of the fingertip is calculated when white Gaussian noise is applied independently to the upper and lower parts of the wrist, as shown in Fig. 7. Next, from these results, considering the differences in arrival times of the vibrotactile noise, the time at which one of the two vibrators starts generating noise shifts, so that the arrival of the noise is adjusted at the fingertip. Finally, we obtain the noise at the fingertip when white Gaussian noise is applied to both the upper and lower parts of the wrist, and confirm that the noise at the fingertip is larger than it is when using only one vibrator.

The position where the white Gaussian noise was applied was shifted 20 mm from the wrist joint toward the forearm, and the noise intensity was set to $0.6\,T$. We set the frequency band of white Gaussian noise to 0 – 300 Hz, as shown in Section II. The simulation time was set to 0.1 s, considering it was not necessary to perform a long simulation because the objective was to observe the differences in the arrival times of the noise. It is known that 0 – 300 Hz white Gaussian noise applied to the wrist can reach the fingertip even if the noise lasts only 0.1 s [26]. As shown in Fig. 8, the bones at the end of the wrist and the fingertip were completely constrained as boundary conditions. The simulations were performed using the commercially available FE software package Abaqus (Dassault Systemes, Vélizy-Villacoublay, France).

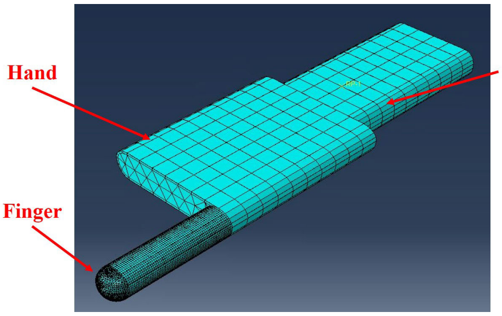

FIGURE 5. 3D finite element hand model.

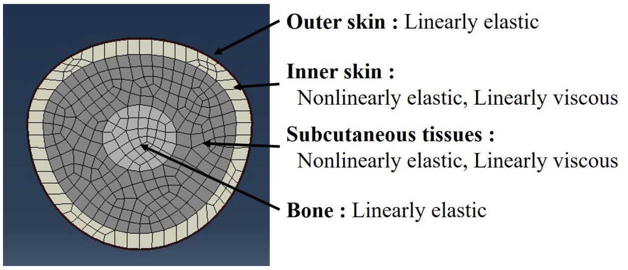

FIGURE 6. Cross section of the finger.

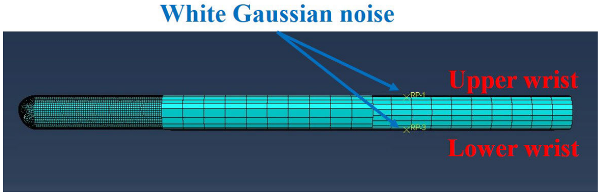

FIGURE 7. Sideview of 3D finite element hand model.

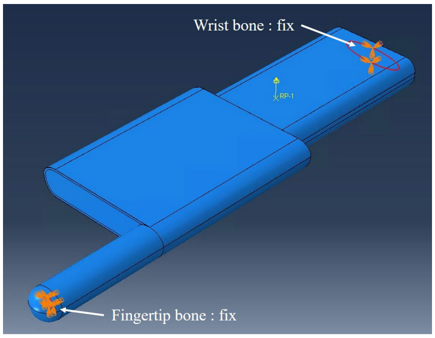

FIGURE 8. Boundary conditions of 3D finite element hand model.

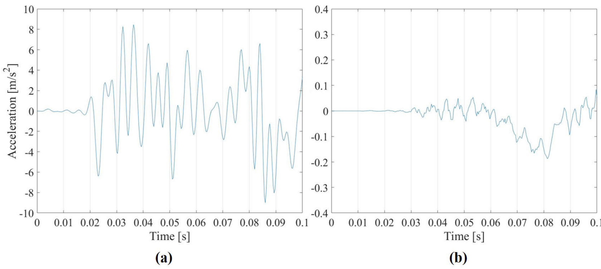

FIGURE 9. Comparison of (a) white Gaussian noise applied to the upper wrist and (b) the noise at the index fingertip.

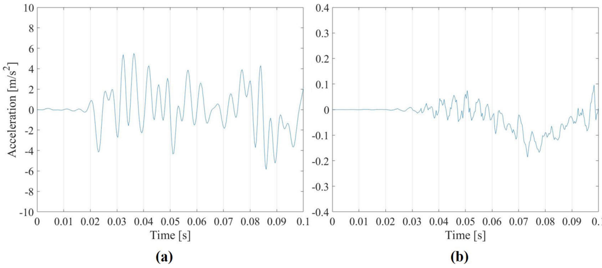

FIGURE 10. Comparison of (a) white Gaussian noise applied to the lower wrist and (b) the noise at the index fingertip.

E. RESULTS

1) APPLYING WHITE GAUSSIAN NOISE ONLY TO THE UPPER WRIST

Figure 9 (b) shows the noise at the fingertip when white Gaussian noise with 0.6 $T_{\text{upper wrist}}$ expressed by Fig. 9 (a) is applied only to the upper wrist.

2) APPLYING WHITE GAUSSIAN NOISE ONLY TO THE LOWER WRIST

Figure 10 (b) shows the noise at the fingertip when white Gaussian noise with 0.6 $T_{\text{lower wrist}}$ expressed by Fig. 10 (a) is applied only to the lower wrist.

It can be seen that the amplitude of white Gaussian noise applied to the upper wrist is larger than that of the noise applied to the lower wrist, as shown in Fig. 9 (a) and Fig. 10 (a). This is because the sensory threshold at the upper wrist for white Gaussian noise ($T_{\text{upper wrist}}$) was larger than that at the lower wrist ($T_{\text{lower wrist}}$). This time, the noise at the finger pad was calculated, so the noise from the lower wrist arrived earlier than the noise from the upper wrist as shown in Fig. 9 (b) and Fig. 10 (b). Therefore, in order to synchronize the arrival times of the noises, the vibrator at the lower wrist should start generating noise slightly after the vibrator at the upper wrist does so.

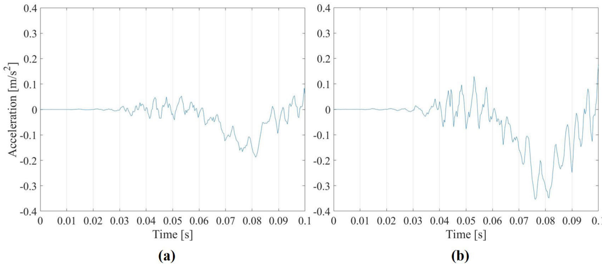

FIGURE 11. Comparison of the noise at the index fingertip between (a) using one vibrator and (b) using two vibrators.

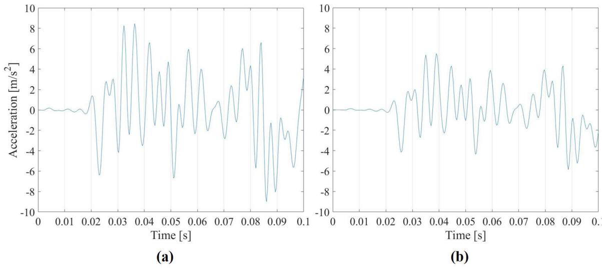

FIGURE 12. White-Gaussian-noise vibration applied to (a) the upper wrist and (b) the lower wrist.

3) APPLYING WHITE GAUSSIAN NOISE TO BOTH THE UPPER AND LOWER PARTS OF THE WRIST

Figure 11 (b) shows the noise at the fingertip when white Gaussian noise with 0.6 $T_{\text{upper wrist}}$ expressed by Fig. 12 (a) is applied to the upper wrist and white Gaussian noise with 0.6 $T_{\text{lower wrist}}$ expressed by Fig. 12 (b) is applied to the lower wrist. Note that Fig. 12 (b) slightly delays the white Gaussian noise shown in Fig. 10 (a), taking into account the difference in the arrival times of the noises.

Figure 11 shows that the use of multiple vibrators can propagate a larger noise to the fingertip than when using only one vibrator by properly designing the positions of the vibrators and the time when each vibrator starts generating noise. Therefore, it is expected that stochastic resonance will be more likely to occur because the noise propagated to the fingertip is larger by using multiple vibrators, thus enabling the detection of even smaller inputs.

F. MEASUREMENT OF NOISE PROPAGATING TO THE FINGERTIP WHEN USING MULTIPLE VIBRATORS

Here, by using a PVDF film, we check whether the vibrotactile noise propagated to the fingertip is larger when using multiple vibrators than when using only one vibrator. The positions of the vibrators and the time when each vibrator starts generating noise were the same as in the simulation.

Figure 13 shows the results of the experiment. The horizontal axis indicates frequency, and the vertical axis indicates the power spectrum of the noise propagating to the fingertip

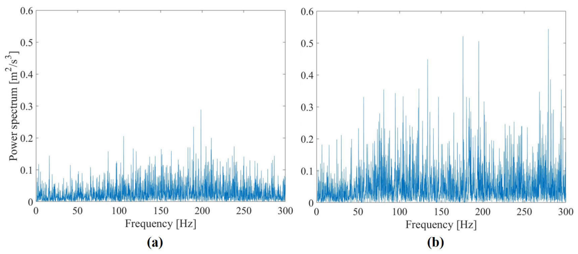

FIGURE 13. Comparison of power spectrum of the noise at the fingertip between (a) using one vibrator and (b) using two vibrators. (a) : Applying white Gaussian noise with an intensity of 0.6 $T_{\text{wrist upper}}$ only to the upper wrist, (b) : Applying white Gaussian noise with an intensity of 0.6 $T_{\text{wrist upper}}$ and 0.6 $T_{\text{wrist lower}}$ to the upper and lower parts of the wrist, respectively.

when using only one vibrator (Fig. 13 (a)) or two vibrators (Fig. 13 (b)). This result shows that multiple vibrators can propagate a larger noise to the fingertip than only one vibrator.

Through the finite element analysis and the measurement with PVDF film, we can confirm that multiple vibrators can propagate a larger noise to the fingertip than only one vibrator if the positions of the vibrators and the time when each vibrator starts generating the noise are properly arranged. Therefore, it is expected that stochastic resonance will be more likely to occur by using multiple vibrators, and it will be possible to detect even smaller inputs and thus to further improve performance.

IV. EXPERIMENTS USING THE PROPOSED METHOD

Now we verify the effectiveness of SR using multiple vibrators through a subject experiment.

The task of the subject experiment was a texture discrimination task that calculates the ratio of sandpaper grade identification. In this experiment, we aim to improve the ratio of correct sandpaper grade identification by using multiple (two) vibrators compared to without SR or using one vibrator.

Figure 14 shows an overview of the experiment. Piezoelectric actuators (APA400M, Cedrat Technologies) for presenting white Gaussian noise for SR were attached to the upper and lower parts of the wrist, respectively, using hooks and loop tape. There were six grades of sandpaper (#120, #150, #180, #220, #240, #280) as shown in Fig. 15. Eight healthy subjects (mean age ± SD: 23.6 ± 1.22 years, all males) participated in this study. All participants understood and consented to the experimental protocol approved by The Ethics Committee, Graduate School of Engineering, Kyoto University (No. 201707).

First, we measured the subject's sensory threshold at the upper and lower parts of the wrist for 0 – 300 Hz white Gaussian noise. The sensory threshold was measured using the method described in Section II. The subject's sensory threshold at the upper and lower parts of the wrist for white Gaussian noise obtained here are $T_{\text{upper wrist}}$ and $T_{\text{lower wrist}}$, respectively.

Next, using the subject's sensory threshold for white Gaussian noise, the ratio of sandpaper identification was measured

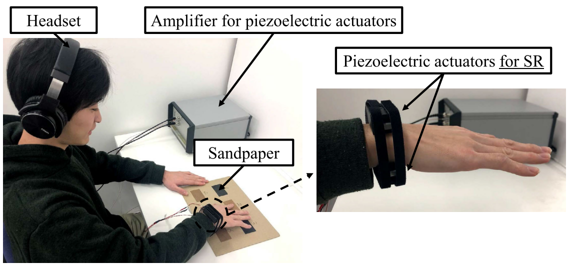

FIGURE 14. Experimental environment for the texture discrimination test.

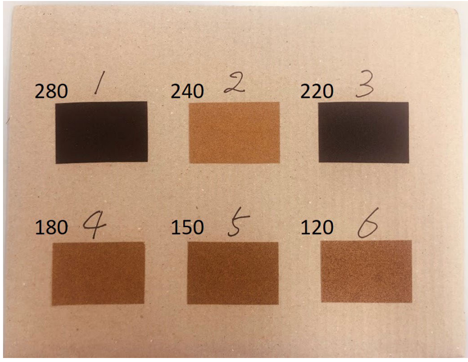

FIGURE 15. Sandpaper grades used in the texture discrimination test: numbers indicate U.S. CAMI grit sizes.

under three conditions: without SR, with SR by one vibrator, and with SR by two vibrators. In the case of "with SR by one vibrator", white Gaussian noise with an intensity of 0.6 $T_{\text{upper wrist}}$ was applied to the upper wrist. In the case of "with SR by two vibrators", white Gaussian noise with an intensity of 0.6 $T_{\text{upper wrist}}$ was applied to the upper wrist and white Gaussian noise with an intensity 0.6 $T_{\text{lower wrist}}$ was applied to the lower wrist. The noise to the lower wrist began slightly after that to the upper wrist, as in the simulation.

The procedure of the subject experiment is explained. First, the experimenter randomly presented one of the six sandpaper grades to the subject as a test sandpaper. At this time, the subject was asked to wear an eye mask so that they could not see the sandpaper. Next, the subject temporarily removed the eye mask and then touched the six sandpaper grades shown in Fig. 15. Finally, the subject selected the same sandpaper as the test sandpaper from the six grades and the ratio of correct sandpaper identification was recorded. The subject was allowed to repeatedly touch the test sandpaper as needed before answering, and the subject touched the sandpaper using the index finger. This was performed four times for each sandpaper grade under the three SR conditions mentioned above. The order of the presented sandpaper and that of the three conditions were randomized.

V. RESULTS AND DISCUSSION

Figure 16 shows the experimental results. The horizontal axis indicates the SR condition, and the vertical axis indicates the ratio of correct sandpaper grade identification. Therefore, a high value indicates that the subject could identify the sandpapers more accurately. In addition, the T-topped error bars

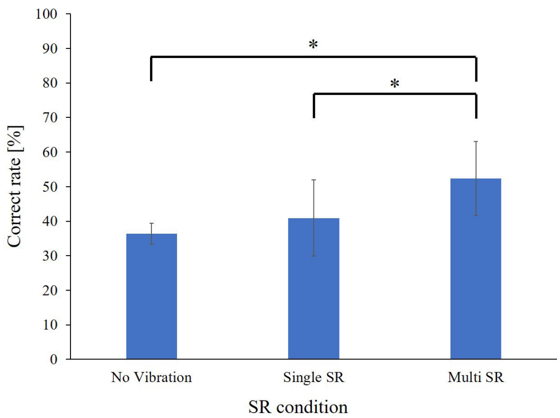

FIGURE 16. **Comparison of the ratio of correct sandpaper grade identification. Single SR means noise was applied only to the upper wrist. Multi SR means the noise was applied to both the upper and lower parts of the wrist. Statistically significant differences were observed between the No vibration and Multi SR and between the Single SR and Multi SR cases ("*" means $p < 0.05$).**

show the standard deviation for each value. One-way ANOVA showed a significant main effect from the SR conditions ($F(2, 21) = 3.47$, $p = 0.0061$). The result of Tukey's test revealed significant differences between the "without SR (No vibration)" case and the "with SR by two vibrators (Multi SR)" case ($p < 0.05$), and between the "with SR by one vibrator (Single SR)" case and the "with SR by two vibrators (Multi SR)" case ($p < 0.05$).

The results show that the ratio of correct sandpaper identification was significantly improved in the proposed method "with SR by two vibrators" compared to "without SR" and "with SR by one vibrator". On the other hand, in this experiment, no significant difference was observed between "without SR" and "with SR by one vibrator". It is considered that recognizing the difference in the frequency of skin vibration generated at the fingertip when tracing the surface of a grade of sandpaper greatly contributes to the identification of the sandpaper. The periodic input applied to the fingertip is small when tracing the surface of the fine sandpaper with small protrusions, as used in this experiment. Therefore, it was difficult to identify the grade of sandpaper in the case of "without SR" or "with SR by one vibrator" where the noise propagating to the fingertip was small. On the other hand, in the proposed method "SR with two vibrators", a sufficiently large noise reached the fingertip, and the probability that the periodic input exceeds the sensory threshold increased, so the subject could detect the input and identify the sandpaper grades more accurately.

From the results of the subject experiment, we can confirm the effectiveness of the proposed method, in which multiple vibrators are placed at remote positions. A comparison cannot be made because the grades of sandpaper differed, but a similar subject experiment was also performed in a previous study [7]. The ratio of correct sandpaper identification in the case of the proposed method "SR with two vibrators" in this study is slightly lower than the ratio in the case where one vibrator is attached to the lateral aspect of the fingertip in the previous study. This is because it was more difficult to correctly identify the grades of sandpaper in this study than in the previous study. Therefore, if the experiment is performed with the same grades of sandpaper used in the previous study, the same ratio may be obtained by the proposed method. In addition, in the previous study, a vibrator is attached to the side of the index finger to apply noise, so we can expect the sensitivity of only the index finger to improve. However, in the proposed method the vibrators are placed at remote positions, so the same sensitivity improvement can be expected not only for the index finger but also for other fingers.

On the other hand, the studies [16], [22] have been investigated the tactile sensitivity at the fingertips to the noise intensity at the wrist. These results are task-dependent, but it has been shown that noise greater than 0.6T on the wrist reduces the tactile sensitivity at the fingertips. In addition, the result [16] shows that the tactile sensitivity at the fingertip is reduced even when noise smaller than 0.6T is applied at the wrist. Thus, the results caused by SR has a non-monotonic behavior with respect to the noise intensity. That is, for smaller noise or larger noise, the sensitivity results caused by SR are worse than those under moderate noise conditions. Here, note that we did not examine non-monotonic behavior because it is outside this study's scope. However, we think that our proposed method has this behavior. This investigation is considered to be an issue for the future.

VI. CONCLUSION

This paper proposed a method to improve a fingertip's tactile sensitivity by placing multiple vibrators at a remote position away from the fingertip. First, we experimentally examined why remote vibrotactile noise improves the tactile sensitivity of the fingertip. When white Gaussian noise was applied to the wrist, the sensitivity of the fingertip for sinusoidal vibration improved. At this time, it was confirmed that noise applied to the wrist propagated on the human skin and reached the fingertip. On the other hand, it was also found that sensitivity did not improve if a sufficiently large noise did not reach the fingertip. Therefore, from the result that the intensity of the noise propagating to the fingertip determines the appearance of stochastic resonance, we can conclude that remote vibrotactile noise improves the tactile sensitivity of the fingertip based on vibration propagation on human skin.

Based on this investigation, we expected that the larger the noise reaching the fingertip, the smaller the input that can be detected. In this study, we proposed a method to place multiple vibrators at a remote position away from the fingertip, such as the wrist. First, we conducted a finite element analysis to properly superimpose the noises from multiple vibrators at the fingertip. In order to synchronize the arrival of the noises at the fingertip, we determined the positions of the vibrators and the time when each vibrator started generating noise. As a result, by using multiple vibrators, the noise at the fingertip became larger than when using only one vibrator. We then conducted a subject experiment to verify the effectiveness of the proposed method. The results of that experiment confirmed that the use of multiple vibrators significantly improved fingertip sensitivity compared to the case of without SR or the case where only one vibrator was used.

In the future, it will be necessary to adapt the proposed method to specific tasks using multiple fingers, not only the index finger. In addition, we plan to examine the frequency band and type of noise for SR in order to further improve the tactile sensitivity of the fingertip. On the other hand, we believe that the amount of improvement in the tactile sensitivity of the fingertip depends on the sensory threshold at the fingertip. Thus, the relationship between the improvement of the fingertip's tactile sensitivity by our proposed method and the fingertip's sensory threshold should be investigated in the future.

REFERENCES

[1] J. J. Collins, T. T. Imhoff, and P. Grigg, "Noise-mediated enhancements and decrements in human tactile sensation," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 56, no. 1, pp. 923–926, Jul. 1997.

[2] R. Benzi, A. Sutera, and A. Vulpiani, "The mechanism of stochastic resonance," *J. Phys. A Math. Gen.*, vol. 14, no. 11, pp. 453–457, 1981.

[3] Z. Qiao, Y. Lei, and N. Li, "Applications of stochastic resonance to machinery fault detection: A review and tutorial," *Mech. Syst. Signal Process.*, vol. 122, pp. 502–536, May 2019.

[4] L. Zhang and A. Song, "Realizing reliable logical stochastic resonance under colored noise by adding periodic force," *Phys. A, Stat. Mech. Appl.*, vol. 503, pp. 958–968, Aug. 2018.

[5] A. Longtin, "Stochastic resonance in neuron models," *J. Stat. Phys.*, vol. 70, nos. 1–2, pp. 309–327, Jan. 1993.

[6] C. Wells, L. M. Ward, R. Chua, and J. T. Inglis, "Touch noise increases vibrotactile sensitivity in old and young," *Psychol. Sci.*, vol. 16, no. 4, pp. 313–320, Apr. 2005.

[7] Y. Kurita, M. Shinohara, and J. Ueda, "Wearable sensorimotor enhancer for fingertip based on stochastic resonance effect," *IEEE Trans. Human-Machine Syst.*, vol. 43, no. 3, pp. 333–337, May 2013.

[8] P. Hur, Y.-H. Wan, and N. Jin Seo, "Investigating the role of vibrotactile noise in early response to perturbation," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 6, pp. 1628–1633, Jun. 2014.

[9] L. Khaodhiar, J. B. Niemi, R. Earnest, C. Lima, J. D. Harry, and A. Veves, "Enhancing sensation in diabetic neuropathic foot with mechanical noise," *Diabetes Care*, vol. 26, no. 12, pp. 3280–3283, Dec. 2003.

[10] A. Priplata, J. Niemi, M. Salen, J. Harry, L. A. Lipsitz, and J. J. Collins, "Noise-enhanced human balance control," *Phys. Rev. Lett.*, vol. 89, no. 23, Nov. 2002, Art. no. 238101.

[11] S. E. Ross, B. L. Arnold, J. T. Blackburn, C. N. Brown, and K. M. Guskiewicz, "Enhanced balance associated with coordination training with stochastic resonance stimulation in subjects with functional ankle instability: An experimental trial," *J. Neuroengi. Rehabil.*, vol. 4, no. 1, p. 47, Dec. 2007.

[12] O. White, J. Babič, C. Trenado, L. Johannsen, and N. Goswami, "The promise of stochastic resonance in falls prevention," *Frontiers Physiol.*, vol. 9, p. 1865, Jan. 2019.

[13] C. M. Germer, L. S. Moreira, and L. A. Elias, "Sinusoidal vibrotactile stimulation differentially improves force steadiness depending on contraction intensity," *Med. Biol. Eng. Comput.*, vol. 57, no. 8, pp. 1813–1822, Aug. 2019.

[14] I.-S. Hwang, C.-L. Hu, Z.-R. Yang, Y.-T. Lin, and Y.-C. Chen, "Improving precision force control with low-frequency error amplification feedback: Behavioral and neurophysiological mechanisms," *Frontiers Physiol.*, vol. 10, p. 131, Feb. 2019.

[15] K. Chamnongthai, T. Endo, F. Matsuno, K. Fujimoto, and M. Kosaka, "Two-dimensional fingertip force training with improved haptic sensation via stochastic resonance," *IEEE Trans. Human-Machine Syst.*, vol. 50, no. 6, pp. 593–603, Dec. 2020.

[16] L. R. Enders, P. Hur, M. J. Johnson, and N. Seo, "Remote vibrotactile noise improves light touch sensation in stroke survivors' fingertips via stochastic resonance," *J. Neuroengin. Rehabil.*, vol. 10, no. 1, p. 105, 2013.

[17] S. J. Bolanowski, G. A. Gescheider, R. T. Verrillo, and C. M. Checkosky, "Four channels mediate the mechanical aspects of touch," *J. Acoust. Soc. Amer.*, vol. 84, no. 5, pp. 1680–1694, Nov. 1988.

[18] G. E. P. Box and M. E. Muller, "A note on the generation of random normal deviates," *Ann. Math. Statist.*, vol. 29, no. 2, pp. 610–611, Jun. 1958.

[19] W. J. Dixon, "The Up-and-Down method for small samples," *J. Amer. Stat. Assoc.*, vol. 60, no. 312, pp. 967–978, Dec. 1965.

[20] Y. Tanaka, D. Phuong Nguyen, T. Fukuda, and A. Sano, "Wearable skin vibration sensor using a PVDF film," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2015, pp. 146–151.

[21] R. S. Johansson and Å. B. Vallbo, "Tactile sensory coding in the glabrous skin of the human hand," *Trends Neurosci.*, vol. 6, no. 1, pp. 27–32, Jan. 1983.

[22] K. Lakshminarayanan, A. W. Lauer, V. Ramakrishnan, J. G. Webster, and N. J. Seo, "Application of vibration to wrist and hand skin affects fingertip tactile sensation," *Physiol. Rep.*, vol. 3, no. 7, e12465, 2015.

[23] J. Z. Wu, D. E. Welcome, and R. G. Dong, "Three-dimensional finite element simulations of the mechanical response of the fingertip to static and dynamic compressions," *Comput. Methods Biomech. Biomed. Engin.*, vol. 9, no. 1, pp. 55–63, 2006.

[24] S. Shimawaki and N. Sakai, "Quasi-static deformation analysis of a human finger using a three-dimensional finite element model constructed from CT images," *J. Environ. Eng.*, vol. 2, no. 1, pp. 56–63, 2007.

[25] M. Kawai. *2012: AIST Japanese Hand Dimensional Data*. [Online]. Available: https://unit.aist.go.jp/hiri/dhrg/ja/dhdb/hand/index.html

[26] L. R. Manfredi, A. T. Baker, D. O. Elias, J. F. Dammann, III, M. C. Zielinski, V. S. Polashock, and S. J. Bensmaia, "The effect of surface wave propagation on neural responses to vibration in primate glabrous skin," *PLoS ONE*, vol. 7, no. 2, 2012, Art. no. e31203.

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