Wearable Sensorimotor Enhancer for a Fingertip based on Stochastic Resonance

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Abstract— **This paper reports the initial experimental results of a wearable sensorimotor enhancer for a fingertip. A short-time exposure of tactile receptors to sub-sensory white-noise vibration is known to improve the tactile sensitivity. This phenomenon, called "noise-enhanced tactile sensation" or stochastic resonance (SR) in the somatosensory system, is expected to enhance the sense of touch when white-noise vibration is applied to a fingertip, and thereby improve associated motor skills. A prototype sensorimotor enhancer has been developed in this research. This wearable device is to stimulate tactile receptors by applying vibration from a compact lead zirconate titanate (PZT) piezoelectric stack actuator attached at the radial side of the fingertip. This design keeps the palmar region free and maintains the wearer's manipulability. Sensory and motor tests have been conducted for health subjects to confirm the efficacy of the device. Statistical significance has been observed in most of the tests.**

I. Introduction

Stochastic Resonance (SR) is known to improve the sensitivity of a nonlinear system to weak periodic or aperiodic stimuli in the presence of non-zero level of noise. SR has been observed in a variety of physical systems [1], [2], [3], [4] including biological systems, such as in mechanoreceptors of crayfish [5], cutaneous mechanoreceptors of rats and toads [6], [7], and neurons [8]. It has also been reported that the sensitivity of somatosensory receptors can be improved by a short-time exposure to sub-sensory white-noise vibration [9], [10] in visual [11], hearing [12], and haptic [13] abilities. Tactile receptors that provide the sense of touch play key roles in precision tasks using fingers. SR effect in tactile sensation has also been examined and confirmed in feet [14], [15], hands and fingers [16], [17]. More importantly, this "noise-enhanced tactile sensation" based on SR is known to improve some of the motor skills [18].

The development of a wearable device for a fingertip is expected to assist persons at work places that require high-precision manual dexterity; however, to the authors' knowledge, there is no SR device that is wearable and attachable to a fingertip to date. One of the hurdles may be the lack of a compact actuator with an effective attachment mechanism. In the past studies, a relatively large actuator was placed on the object's side [16], [17], or a haptic device with actuators was used [19]; however, these approaches greatly limit practical applications and cannot be applied to the manipulation of general objects. To maintain the manipulability of fingers, no device should be directly attached to the palmar sides of fingertips (i.e., finger pulps) since humans mainly use these regions to manipulate an object.

This paper proposes a novel, wearable orthopedic device, named "sensorimotor enhancer," that enhances tactile sensitivity of fingertips and thereby improves motor performances. The features of this wearable device are: 1) a piezoelectric stack actuator is used for generating high-frequency vibration in a compact body, and 2) the manipulability of a finger is maintained by attaching the actuator at the lateral side of a fingertip and keeping the palmar region free. To validate the efficiency of the proposed sensorimotor enhancer, several sensory and motor tests have been conducted for healthy adult subjects. To confirm the enhancement of tactile sensitivity, (a) two-point discrimination test, (b) single-point touch test, and (c) texture discrimination test using sandpapers were conducted. Also, to investigate the improvement of motor performance, (d) submaximal force generation test and (e) grasping test were conducted. Most of the tests observed statistical significance.

II. Sensorimotor enhancer

The concept of the sensorimotor enhancer is shown in Fig. 1. The ideas are to place a compact lead zirconate titanate (PZT) piezoelectric stack actuator at the radial side of the fingertip and to keep the palmar region free. The actuator with a strain amplification mechanism is small and light-weight with high-speed and high-force generation [20], [21]. The piezoelectric actuator generates white-noise vibration that is transmitted to tactile receptors around the finger pulp.

The prototype sensorimotor enhancer is shown in Fig. 2. A latex finger cap was used for the device whose palmar side was cut open so that the palmar side of the fingertip could directly contact with an object. Reference commands to the linear amplifier of the piezoelectric actuator were generated by a LabView program. In this study, low-pass filtered white-nose vibration with a cutoff frequency of 300 Hz was applied as shown in Fig. 3. Amplitudes of the noise (i.e., reference voltages to the linear amplifier) were determined based on a threshold amplitude of each subject.

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Y. Kurita expresses his gratitude to Japan Science and Technology Agency (JST) – National Science Foundation (NSF) Strategic International Cooperative Program.

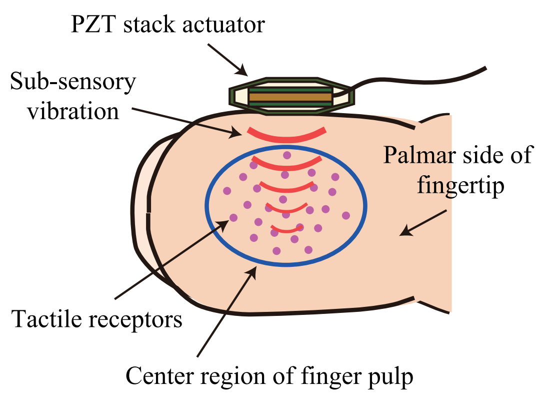


Fig. 1. Concept of the sensorimotor enhancer

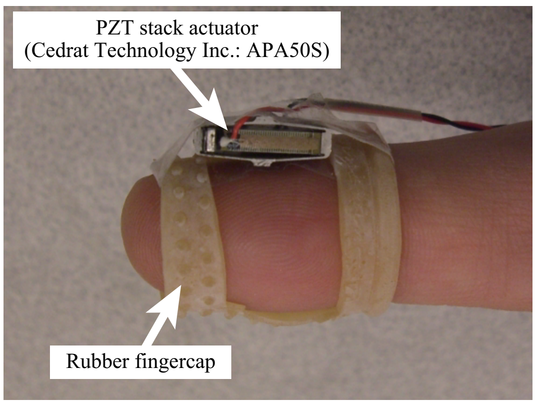
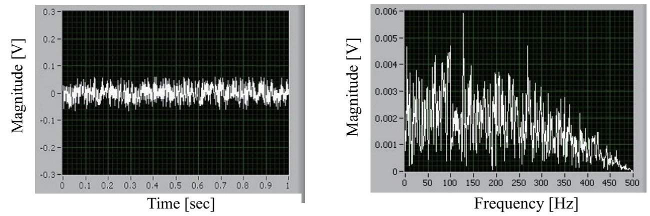


Fig. 2. Prototype sensorimotor enhancer

III. Vibration Transmissibility Characteristics of a Fingertip

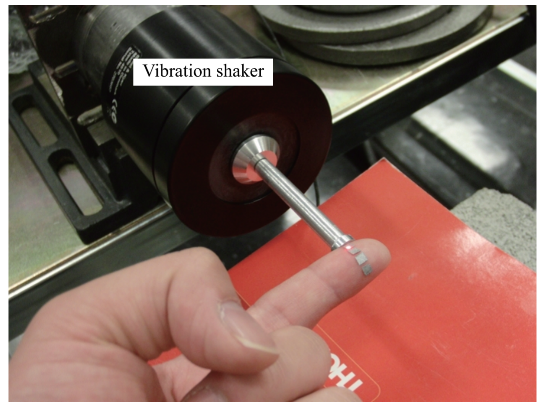
The proposed sensorimotor enhancer applies band-limited white-noise from the radial side of the fingertip. It is expected that the vibration applied from the actuator is attenuated by the viscoelasticity of skin and subcutaneous tissue of a fingertip. Preliminary experiments were conducted to investigate the vibration transmissibility characteristics of a fingertip. The experimental setup is shown in Fig. 4(a). One end of a vibration shaker was pressed against the lateral side of the fingertip, and a sinusoidal vibration was applied. As shown in Fig. 4(b), a laser doppler vibrometer measured induced displacements at five measurement points at the interval of 2 [mm] on the finger pulp.

The input frequency was swept from 10 to 300 Hz to obtain the characteristics of the transmission of the vibration. The gain and phase characteristics from points #1 to #4 were normalized by that of the Base point. The obtained results are shown in Fig. 5(a) and (b). As can be observed in the graph, the vibration applied from the Base point attenuates; the amplitude becomes progressively smaller and the delay becomes larger for points farther from the Base point. However, it should be noted that the attenuation of the amplitude at Point 2 (i.e., the region of interest) does not fall below -20 dB. This observation implies that the application of vibration from the radial side of the fingertip can successfully stimulate tactile receptors by taking this attenuation into account. This justifies the design concept of the sensorimotor enhancer.

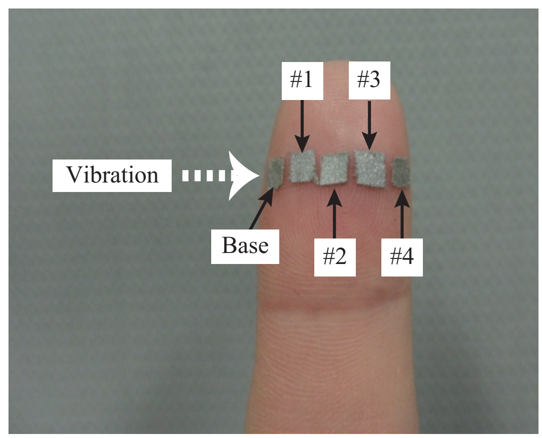


(a) Time-series data (b) Frequency spectrum

Fig. 3. Reference commands to the piezoelectric actuator: Band-limited white noise with a cutoff frequency of 300 Hz



(a) Overview of the experiment



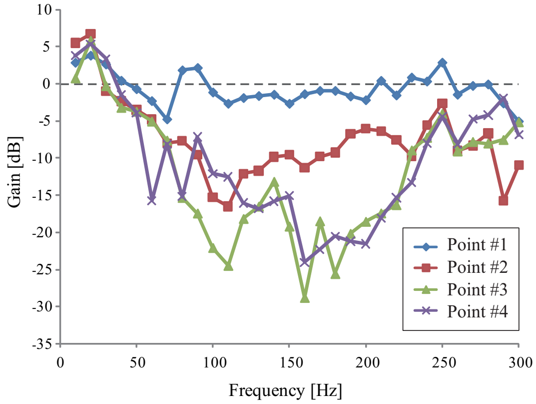
(b) Measurement points

Fig. 4. Measurement of vibration transmissibility characteristics

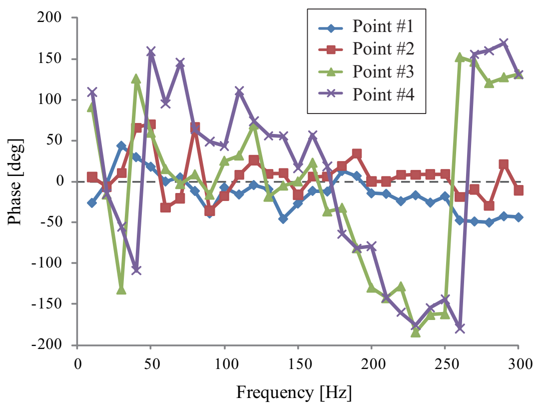
IV. Experiments

A. Overview of experiments

A total of five tests were conducted for healthy subjects including three sensory tests and two motor tests. The sensorimotor enhancer was attached to subject's non-dominant index finger. The non-dominant hand was placed on a desk with the palmer surface upward. During the experiments, the torso and the dominant hand of the subject were in a relaxed state to minimize unwanted movement.



(a) Gain



(b) Phase

Fig. 5. Vibration transmissibility characteristics of fingertip

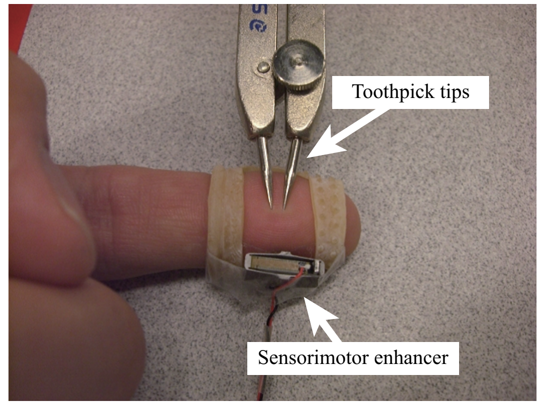


Fig. 6. Two-point discrimination test

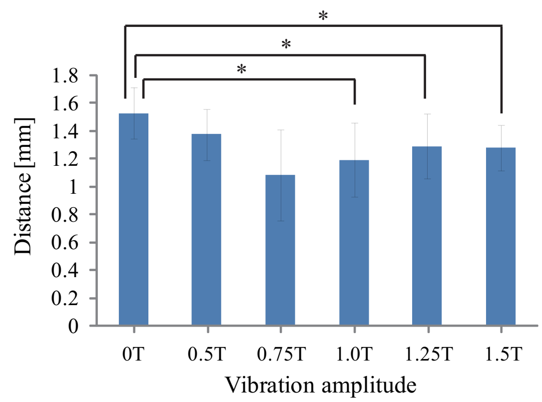


Fig. 7. Results of two-point test: Discriminable distances for conditions 0.5T $\sim$ 1.5T were smaller than that of the no-vibration case (0T). Statistically significant differences were observed for 1.0T $\sim$ 1.5T ($*$ means $p < 0.05$).

Prior to the experiments, threshold of vibration perception (i.e., threshold input voltage) was sought for each subject. In the following experiments, a total of 6 amplitudes were applied: 0, 50, 75, 100, 125 and 150 [%] of the threshold value denoted as T. No vibration was applied for the 0T condition. Vibrations with the six different amplitudes were applied in a randomized order.

B. *Sensory tests*

Sensory tests consist of three tests: (a) two-point discrimination test, (b) single-point touch test, and (c) texture discrimination test.

1) Two-point discrimination test: A total of eight healthy subjects participated in the experiment. The sensorimotor enhancer was attached to subject's non-dominant index finger and the subject was asked to close his/her eyes. The hand was placed on a table. The experimenter gently pressed two sharp points of a divider against the subject's fingertip as shown in Fig. 6. Subjects were asked to report if they could reliably distinguish two points in contact. Various distances between the two points were tested with an interval of 0.5 [mm] under the aforementioned six different vibrations. One trial took 90 seconds with 30 seconds of rest between trials. Each subject performed 2 trials for each vibration condition.

The experimental results are shown in Fig. 7. The horizontal axis indicates the vibration amplitude with respect to the threshold vibration T. The vertical axis indicates the minimum distance that the subjects could distinguish; a smaller distance indicates better tactile sensitivity. The results show that the mean distances for all the five controlled cases were smaller than that of the nominal (i.e., 0T) case, which shows the improvement of the tactile sensitivity. In particular, statistically significant differences ($p < 0.05$) were observed for cases 1.0T, 1.25T, and 1.5T.

2) One-point touch test: A total of eight healthy subjects participated in the experiment. The sensorimotor enhancer was attached to subject's non-dominant index finger and the subject was asked to close his/her eyes. The hand was placed on a table. The experimenter pressed a monofilament against the subject's fingertip until buckling occurred, held it for approximately 1.0 [sec], and removed. Subjects were asked to report if they could feel a filament in contact. A total of 5 monofilaments: 0.008, 0.02, 0.04, 0.07, and 0.1 [g] were used under the aforementioned six conditions. Each subject performed 2 trials for each vibration condition. Each trial took 60 seconds with 30 seconds of rest between trials. The overview of the experiment is shown in Fig. 8.

The experimental results are shown in Fig. 9. The horizontal axis indicates the vibration amplitude with respect to the threshold vibration T. The vertical axis indicates the mean

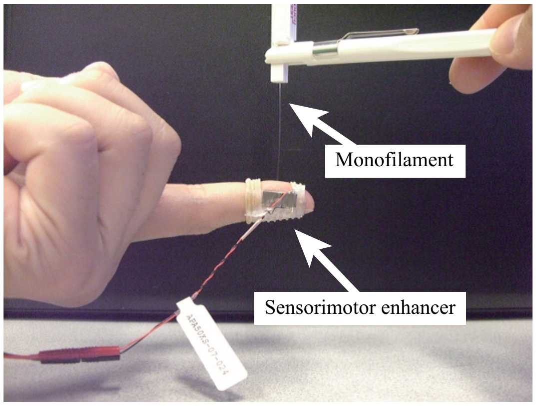


Fig. 8. One-point touch test

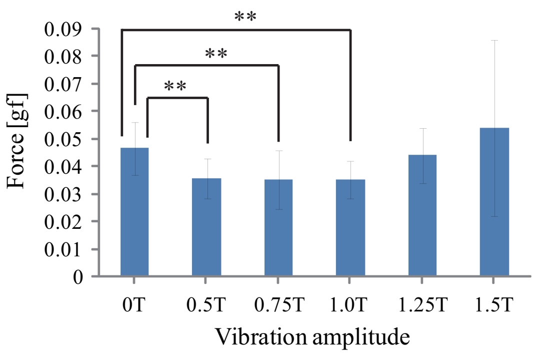


Fig. 9. Results of one-point test: Perceivable forces for 0.5T $\sim$ 1.25T were smaller than that of the no-vibration case (0T). Statistically significant differences were observed for 0.5T $\sim$ 1.0T ($**$ means $p < 0.01$).

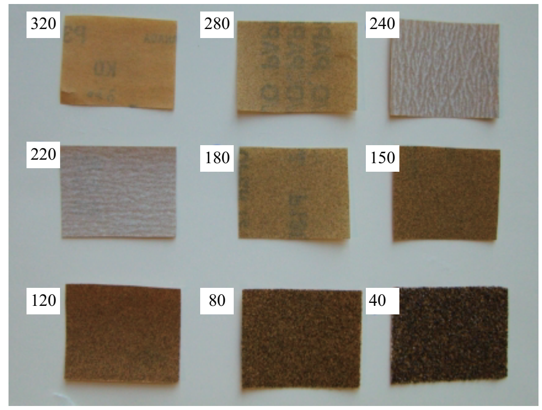


Fig. 10. Sandpapers used in texture discrimination test: Numbers indicate US CAMI grit sizes.

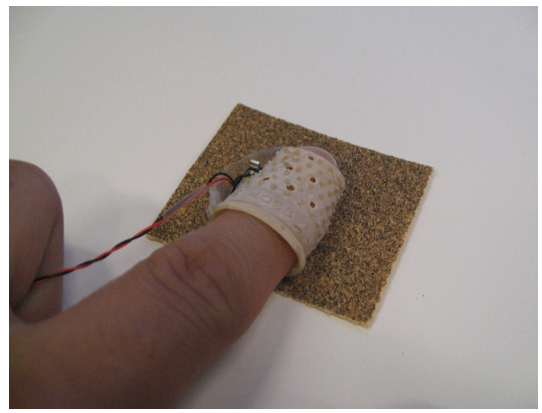


Fig. 11. Discrimination of sandpaper texture

minimum force that the subjects could feel the contact of a monofilament. A smaller mean force indicates better tactile sensitivity. The results show that the mean forces for four out of five controlled cases except 1.5T were smaller than that of the nominal (i.e., 0T) case. In particular, statistically significant differences ($p < 0.01$) were observed for three controlled conditions (0.5T, 0.75T, 1.0T).

3) Texture discrimination test: A total of five healthy subjects participated in the experiment. The sensorimotor enhancer was attached to subject's non-dominant fingertip. In this experiment, sandpapers with CAMI grit sizes of #40, #80, #120, #150, #180, #220, #240, #280, and #320 were used as shown in Fig. 12. All of these sandpapers were glued on one side of a plastic board which was provided to subjects. On the other side of the board, a test piece of sandpaper was attached whose grit size was randomly chosen from the nine sandpaper types. Subjects were not allowed to see this sandpaper but allowed to touch it. The subject was asked to select sandpaper out of nine types which he/she thought had the same texture as the one attached on the other side. Each subject performed 2 trials for each vibration condition. Each trial took 60 seconds with 30 seconds of rest between trials.

The experimental results are shown in Fig. 12. The horizontal axis indicates the vibration amplitude with respect to the threshold vibration T, and the vertical axis indicates the correct ratio. A higher correct ratio indicates better tactile sensitivity.

As can be observed in Fig. 12, the mean correct ratios for all of the controlled cases tend to be higher than that of the nominal (no-vibration) case. Unfortunately, statistical significance was not observed due to the large standard deviation. Future work will further investigate the efficacy by increasing the number of subjects.

C. Motor skill tests

1) Submaximal force generation test: A total of eight healthy subjects participated in the experiment. The sensorimotor enhancer was attached to subject's non-dominant index finger. The subject was asked to place the fingertip on a force transducer as shown in Fig. 13. Prior to the experiment, the subject's maximum voluntary contraction force (MVC) was recorded. The subject was instructed to exert 15[%], 30[%] and 50[%] of MVC respectively as precise as possible without visual feedback. Each subject performed 2 trials for each vibration condition. Each trial took 60 seconds with 30 seconds of rest between trials.

Fig. 14 shows the experimental results. The horizontal axis indicates the vibration amplitude with respect to the threshold T. The vertical axis indicates the absolute error [% MVC] between the desired force and the measured force. Absolute errors were normalized by the MVC of each subject. A

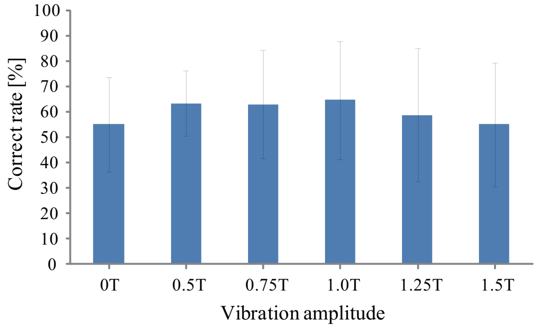


Fig. 12. Results of texture discrimination test: Mean correct ratios for 0.5T $\sim$ 1.25T were higher than that of the no-vibration case (0T).

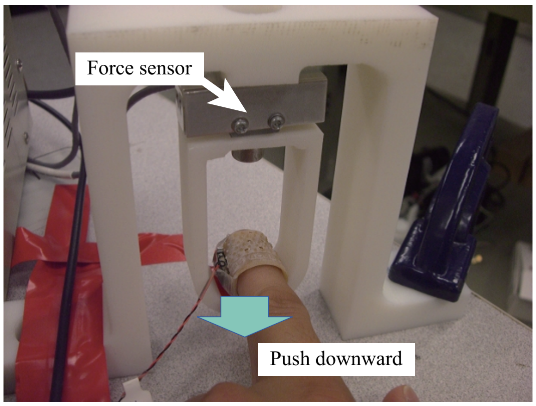
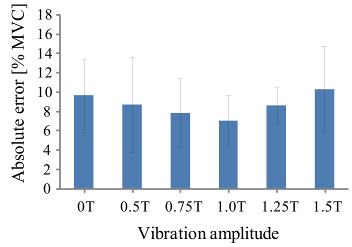
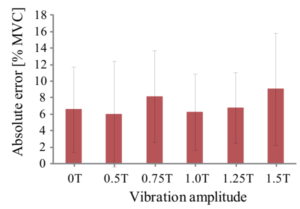


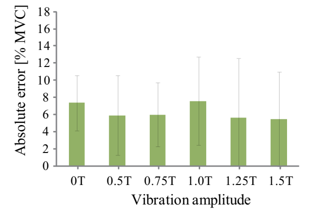
Fig. 13. Submaximal force generation test



(a) 15 % MVC



(b) 30 % MVC



(c) 50 % MVC

Fig. 14. Results of submaximal force generation test: The absolute errors for 0.5T $\sim$ 1.25T (15 % MVC), 0.5T, 1.0T, 1.25T (30 % MVC), and 0.5T, 0.75T, 1.25T, 1.5T (50 % MVC) were smaller than that of the no-vibration case (0T).

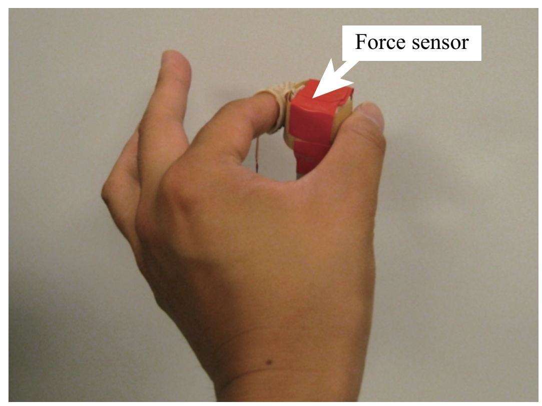


Fig. 15. Grasping test

smaller absolute error indicates higher accuracy in exerting force. Regarding the average values, an effect of vibration at the lowest intensity (i.e., 15% MVC) can be observed in the mean values but not at higher intensities (i.e., 30% and 50% MVC). Statistical significance was not observed due to the large standard deviation in this experiment. Future work will further investigate the significance by increasing the number of subjects.

2) Grasping test: A total of five healthy subjects participated in the experiment. The sensorimotor enhancer was attached to subject's non-dominant fingertip. As shown in Fig. 15, the subject was asked to pinch and hold an object whose weight is 140 [g] for 3 seconds with as small force as possible without slip. The object was covered with a plain printer paper. The object was equipped with a force sensor so that the grasping force between the index finger and thumb was recorded. Each subject performed 2 trials for each vibration condition. Each trial took 60 seconds with 30 seconds of rest between trials.

The experimental results are shown in Fig. 16. The horizontal axis indicates the vibration amplitude and the vertical axis indicates the recorded grasping force. The grasping force is the average from 1 to 2 [sec] in each measurement period. A smaller force indicates a better motor performance in terms of pinch grasping. Improvements in motor performance were observed for all of the controlled cases. In particular, statistically significant differences were observed for cases 0.5T ($p < 0.05$) and 0.75T ($p < 0.01$).

V. Discussion

Overall, the sensing ability tests confirmed that the application of appropriate vibrations enhanced the tactile sensitivity of the fingertip. These results support past studies that investigated the SR effect on the improvement of tactile sensation [16], [17]. The texture discrimination test implies that the sensorimotor enhancer may be used for some practical applications that require a high sense of touch, e.g., manual surface finishing or design of personal digital products. The motor skill tests suggest a possibility that the improvement of the tactile sensitivity could improve the motor performance.

Some of the experimental results indicate that not only sub-sensory amplitudes (0.5T $\sim$ 1.0T) but also over-sensory amplitudes (1.25T and 1.5T) improved some of the sensorimotor functions. It should be noted that the amplitude of vibration at a particular region (e.g., center region) of the fingertip can be less than 1.0T even an over-sensory

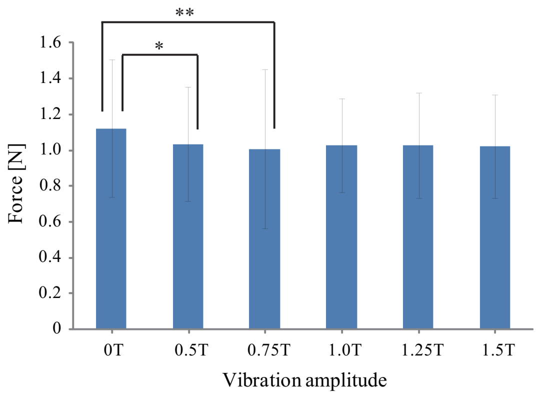


Fig. 16. Results of grasping test: Grasping forces for all of the controlled cases were smaller than that of the no-vibration case (0T). Statistically significant differences were observed for 0.5T ($p < 0.05$) and 0.75T ($p < 0.01$).

amplitude is applied from the lateral side of the fingertip. As discussed in Section III, the viscoelasticity of the fingertip attenuates the applied vibration.

In this paper, only one vibration source was attached at the radial side of the fingertip. However, several difference designs can be considered. For example, actuators can be attached at both the radial and ulnar sides. In addition, an actuator could be mounted on the fingernail so that the fingernail could transmit the applied vibration effectively behaving as a "speaker cone." Future design of the device will optimize the design as well as the amplitude and frequency characteristics of vibration by taking into account the transmissibility characteristics of the fingertip.

VI. Conclusion

This paper reported the initial experimental results of the wearable sensorimotor enhancer for a fingertip. The wearable device was designed to stimulate tactile receptors by using a compact piezoelectric actuator attached at the radial side of the fingertip. This design keeps the palmar region free and maintains the wearer's manipulability. Sensory and motor tests were conducted for health subjects to confirm the efficacy of the device. Statistical significance was observed in most of the tests.

The sensorimotor enhancer is expected to assist persons at work places that require high-precision manual dexterity, including laboratory work with miniature objects, neural surgery, texture design of products, and precise manual assembly. Special gloves with these devices embedded around the fingertips would improve the handling performances of workers in cold environment who will have dampened fingertip sensitivity with thick gloves. Furthermore, the continuation of this research may lead to the development of a novel orthopedic device that helps persons with incomplete peripheral neuropathy resume their daily activities and work.

Future work includes more investigation into the physiological aspects of this approach, optimization of the design of the device, and experiments for persons with incomplete peripheral neuropathy. Findings may be applicable to the design and analysis of haptic interfaces. Investigating the influence of a long term exposure of vibrations is also included in our future experiments.

VII. Acknowledgments

The authors wish to thank for Maxi Hertanto, Danielle Martin, Morgan Hunter, Kazuki Namima, Muhammad Salman, and Dr. Karim Sabra for their support in the experiments.

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