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IMPROVEMENT OF TACTILE SENSITIVITY BY STOCHASTIC RESONANCE: APPLICATION TO VIBRATING FORCEPS

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ABSTRACT

The tactile information is crucial in the execution of precise and dexterous manipulations. The improvement of the tactile sensitivity is expected to assist tasks that require high-precision manual dexterity. In this paper, the improvement in tactile sensitivity based on stochastic resonance effect was demonstrated. A vibration actuator was attached on forceps for a minimally invasive surgery, and the improvement in tactile sensation when using the forceps was tested. The experimental results confirmed that appropriate vibration enhances the tactile sensitivity even when the vibration was transmitted via the forceps.

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 [1–4] 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, for example, in tactile [10], visual [11], hearing [12], and haptic [13] abilities. Tactile receptors that provide the sense of touch play key roles in precision tasks using fingers. The 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].

Tactile information is crucial in the execution of precise and dexterous manipulations. Our research group has been reported the concept of a sensorimotor enhancer and its initial results [19]. The ideas are to place a compact lead zirconate titanate (PZT) stack actuator at the fingertip and to keep the palmar region free. The improvement of the tactile sensitivity is expected to assist persons at work places that require high-precision manual dexterity. One of the promising applications of the sensorimotor enhancer also exists in a medical field. A minimally invasive surgery has gained popularity due to the advantages of small incisions, rapid recovery of patients, and reduction of medical costs. Here, the minimally invasive surgery requires a surgeon high tactile sensitivity and discrimination ability because he/she

Figure 1. Forceps for a minimally invasive surgery

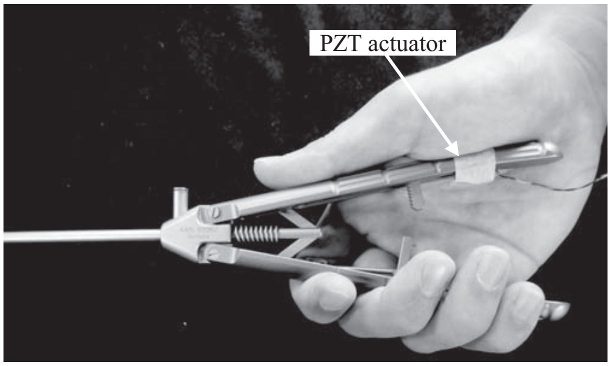


Figure 2. Developed forceps with a PZT actuator

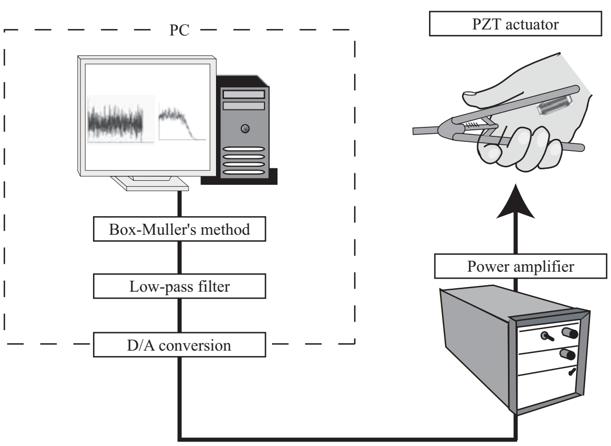


Figure 3. System configuration

cannot directly touch organs, and therefore needs to sense force information about the tissue via forceps.

In this paper, the SR effect was applied to a medical device and its initial experimental results are reported. A PZT actuator was attached on forceps for a minimally invasive surgery, and the vibration was transmitted to subject's finger via the forceps. The improvement in tactile sensation when using the forceps was confirmed through a touch test and a texture discrimination test.

PZT ACTUATOR-EQUIPED FORCEPS

In this article, the PZT actuator as a vibration source is attached on forceps, which are commonly used in a minimally invasive surgery, as shown in Fig. 1. Fig. 2 shows the developed forceps with a PZT actuator at the grip. The system configuration is shown in Fig. 3. The piezoelectric actuator generates a low-pass filtered white-noise vibration that is transmitted to tactile receptors around the grip. Taking the frequency response characteristics of the tactile mechanoreceptors into account, vibrations with a cutoff frequency of 300 [Hz] was applied. The white noise signal $X(t)$ was generated by a Box-Muller's method, which is defined by Eq. (1) with the standard deviation of $\sigma = 1.5$:

$$X(t) = \sigma\sqrt{-2\ln\alpha(t)} \cdot \sin 2\pi\beta(t) \qquad (1)$$

where α, β are the uniform pseudorandom numbers. The representatives of the generated white noise are shown in Fig. 4.

EXPERIMENTS AND RESULTS

Overview of experiments

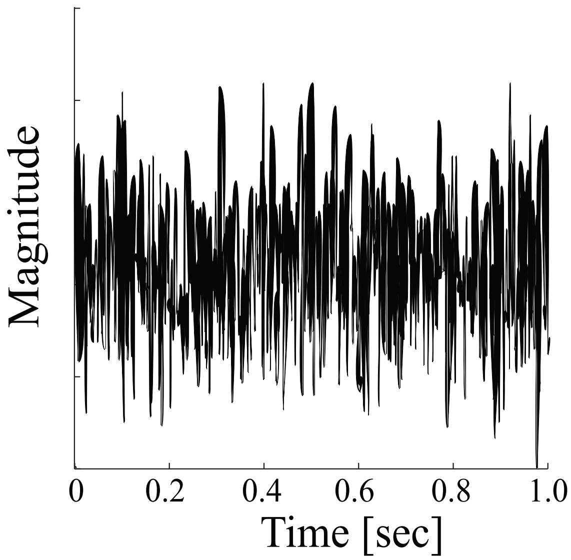
A total of two tests, i.e., one passive sensory test and one active sensory test, were conducted for 11 male healthy subjects aged 22-24 years old. The subject was asked to grasp the grip of the forceps with his dominant hand. During the experiments, the torso and the non-dominant hand of the subject were in a relaxed state to minimize unwanted movements.

Prior to the experiment, the maximum amplitude of the vibration that the subject could not feel was recorded by a method of limits. The subject was asked to report if he/she feels the vibration at the grip when the signal amplitude changes. Three ascending and descending series of stimuli were alternately applied and the average was detected. The mean detected sub-sensory amplitude of the vibration for 11 subjects was 19.15 $\pm$ SD 10.61 [μ m].

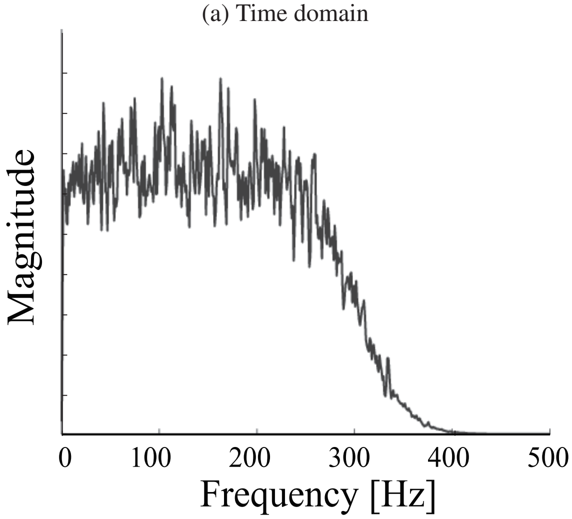
In the following experiments, no-vibration and five different amplitude conditions, i.e., 50, 75, 100, 125 and 150 [%] of the perception threshold denoted as 0.5T, 0.75T, 1.0T, 1.25T and 1.5T respectively, were conducted in a randomized order. The information about the vibration amplitude given in each task was not provided to the subjects. Before the experiment, informed consents were obtained from the subjects.

Touch test as a passive sensory test

The subject was asked to grasp the forceps and close his eyes. The hand with the forceps was placed on a table. The experimenter pressed a monofilament against an aluminum plate that is pinched at the tip of the forceps until buckling occurred. Then the experimenter held it for approximately 1.0 [sec], and removed the monofilament. Subjects were asked to report if they could feel the filament in contact. A total of 10 Semmes-Weinstein monofilaments (Touch-Test Sensory Evaluator): 0.008, 0.02, 0.04, 0.07, 0.16, 0.4, 0.6, 1.0, 1.4 and 2.0 [gf] were used under the aforementioned six conditions. Each subject performed four trials for each vibration condition, and the



(a) Time domain



(b) Frequency domain

Figure 4. Generated band-limited white noise

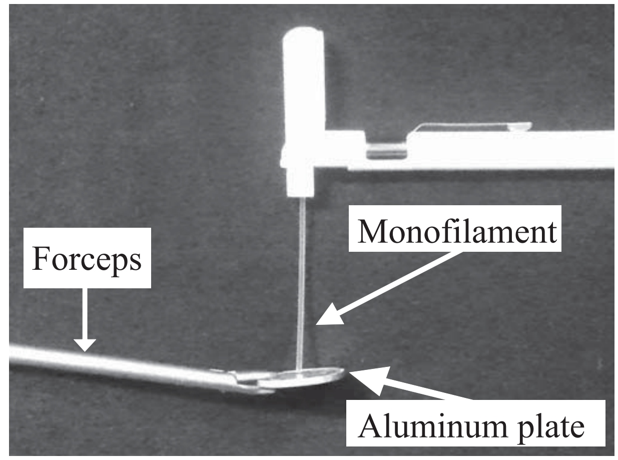


Figure 5. Touch test

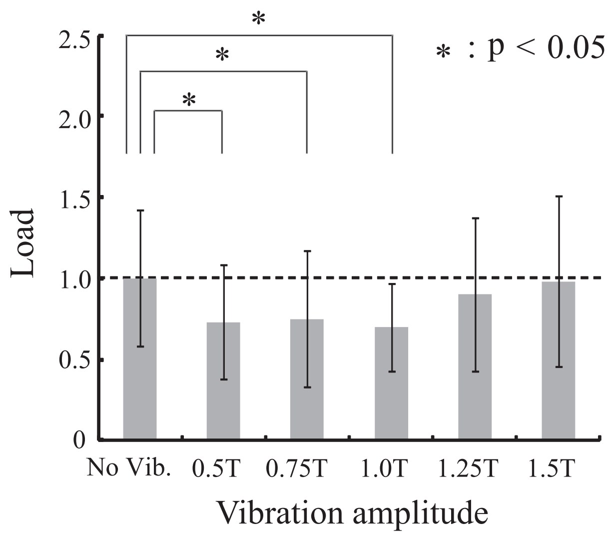


Figure 6. Experimental result of the touch test

mean was recorded as the minimal load the subject can sense. The overview of the experiment is shown in Fig. 5.

The experimental results are shown in Fig. 6. The horizontal axis indicates the vibration amplitude and the vertical axis indicates the normalized mean minimal load. The load was normalized against the results in the no-vibration (No vib.) case. A smaller mean load indicates better tactile sensitivity.

Texture discrimination test as an active sensory test

The subject was asked to grasp the forceps and the hand with the forceps was placed on a table. In this experiment, four sandpapers with CAMI grit sizes of #150, #180, #240 and #320 were used as shown in Fig. 7. All sandpapers were glued on one side of a plastic board. On another board, a test piece of a sandpaper was attached whose grit size was chosen from the four sandpaper types. The test piece board was covered during the experiment so that subjects could not see the test piece but allowed to touch it by the tip of the forceps. The subject was asked to select sandpaper out of four types that he thought had the same texture as the test piece as shown in Fig. 8. Each subject performed three trials for each vibration condition.

The experimental results are shown in Fig. 9. The horizontal axis indicates the vibration amplitude, and the vertical axis indicates the mean correct ratio. A higher correct ratio indicates better tactile sensitivity.

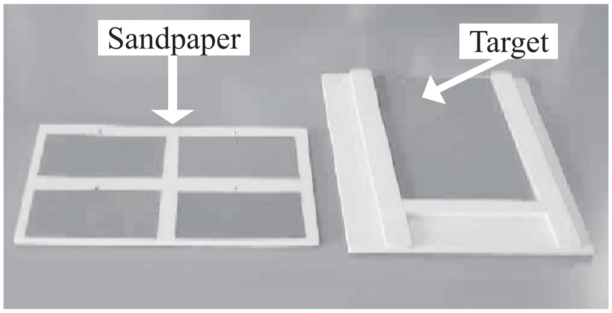


Figure 7. Sandpapers used in the experiment

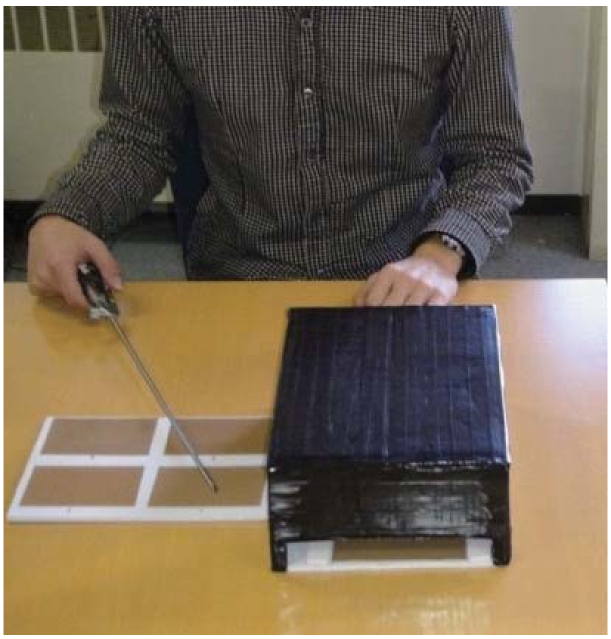


Figure 8. Overview of the experiment

DISCUSSION

In the touch test, the results show that the minimal loads in all the controlled cases were smaller than that in the no-vibration case. A one-way analysis of variance (ANOVA) detected a significant main effect of the vibration amplitude ($p < 0.01$). As a result of the post-hoc Dunnett test shown in Table 1, the significant differences against the no-vibration case were observed for the cases of 0.5T, 0.75T and 1.0T ($p < 0.05$).

In the texture discrimination test, the results show that the mean correct ratios for 0.75T, 1.0T, 1.25T and 1.5T cases tend to be higher than that of the nominal (no-vibration) case. ANOVA detected a significant main effect of the vibration amplitude ($p < 0.01$). As a result of the post-hoc Dunnett test shown in Table 2, the significant differences against the no-vibration case were observed for the 0.75T ($p < 0.05$) case.

Overall, the experimental results confirmed that the application of appropriate vibrations enhanced the tactile sensitivity even when using the forceps. These results support past studies that investigated the SR effect on the improvement of tactile sensation [16, 17, 19]. The experimental results imply that the proposed forceps can be used in practical surgical situations where a high sensitivity of touch is required. Our previous study [19] also suggests a possibility that the improvement of the tactile sensitivity due to the SR effect could also improve the motor performance. Although further investigation is necessary to discuss the improvement in surgical skills, the application of the SR effect to a medical device is expected to assist surgeons in a minimally invasive surgery.

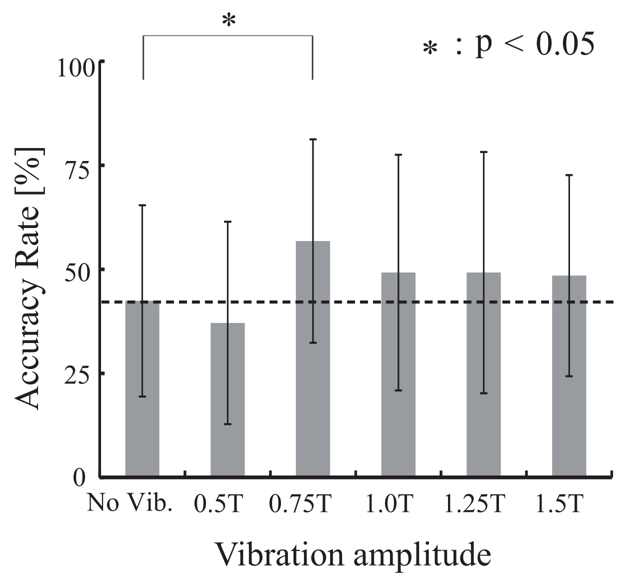


Figure 9. Experimental result of the texture discirimination test

Condition	T statistics	p value
No Vib. - 0.5T	2.8719	0.0097
No Vib. - 0.75T	2.6950	0.0161
No Vib. - 1.0T	3.1749	0.0039
No Vib. - 1.25T	1.0360	0.3982
No Vib. - 1.5T	0.2053	0.7650

Table 1. Result of the Dunnett test

Condition	T statistics	p value
No Vib. - 0.5T	0.8409	0.9759
No Vib. - 0.75T	-2.2825	0.0463
No Vib. - 1.0T	-1.0812	0.3782
No Vib. - 1.25T	-1.0812	0.3782
No Vib. - 1.5T	-0.9611	0.4325

Table 2. Result of the Dunnett test of the texture discrimination test

CONCLUSION

This paper presented the concept of a medical application of stochastic resonance. A PZT actuator, which generated low-pass filtered white noise, was attached on the grip of the forceps and the appropriate amplitude of the vibration was applied to the subject's hand via the forceps. Passive and active sensory tests were conducted to confirm the improvement of tactile sensitivity. The experimental results suggest the usefulness of the application of SR to a medical device.

Future work includes the experiments at more realistic situations of the minimally invasive surgery, such as exploring body tissue and searching abnormal tumor. Force information obtained via the forceps is fundamental to understand the situation in the body. Because medical doctors are required to touch the tissue via forceps and to indirectly sense force-related information from the body organ, the improvement of the tactile sensation would be helpful. We also plan to evaluate the surgical performance when using the proposed forceps.

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