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An Artificial Arm/Hand System with a Haptic Sensory Function Using Electric Stimulation of Peripheral Sensory Nerve Fibers

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***Abstract*— We are currently developing an artificial arm/hand system which is capable of sensing stimuli and then transferring these stimuli to users as somatic sensations. Presently, we are evoking the virtual somatic sensations by electrically stimulating a sensory nerve fiber which innervates a single mechanoreceptor unit at the target area; this is done using a tungsten microelectrode that was percutaneously inserted into the use's peripheral nerve (a microstimulation method). The artificial arm/hand system is composed of a robot hand equipped with a pressure sensor system on its fingers. The sensor system detects mechanical stimuli, which are transferred to the user by means of the microstimulation method so that the user experiences the stimuli as the corresponding somatic sensations. In trials, the system worked satisfactorily and there was a good correlation between the pressure applied to the pressure sensors on the robot fingers and the subjective intensities of the evoked pressure sensations.**

I. INTRODUCTION

The most important thing for artificial arm/hand systems is that the users of the system are able to control the movement of the system precisely in accordance with their intention. However, a sensory function is also very important for the precise control of the artificial arm/hand movements. Although many trials have been conducted in order to give sensory information to the users, most have presented the users with different stimuli than the original (e.g. vibration or auditory stimuli), and the quality of sensation that is obtained using such an approach is far from 'real' and 'vivid'. The goal of our study is to develop an artificial arm/hand system which is capable of sensing stimuli and then transferring the stimuli to users as somatic sensations. In this system, we evoke the virtual sensations by electrically stimulating a sensory nerve fiber which innervates a single mechanoreceptor unit at the target area using a tungsten microelectrode that was percutaneously inserted into the user's peripheral nerve (a micro-stimulation method). Users of the system can feel as if they are in touch with, or otherwise sensing the stimuli with their own natural hands.

II. MATERIALS AND METHODS

A. *Generation of Virtual Sensation Using Microneurography/Microstimulation Technique*

The idea to generate virtual sensation is as follows. Mainly four types of mechanoreceptors are present in the human glabrous skin. Among them Merkel discs and Ruffini endings detect deviations of the skin and in particular, the signals from the Merkel discs evoke pressure/touch sensations when they are transferred to the sensory field of the brain. Therefore, if an appropriate electrical stimulation is supplied to a (single) peripheral nerve fiber which comes from a Merkel disc (correspond to a slowly adapting type I (SA-I) mechanoreceptor unit) and if the same afferent signal (the same series of pulses) can be generated to the nerve fiber as is generated when the actual corresponding mechanoreceptor unit is stimulated physically, the same somatic (pressure) sensation that is evoked when the actual corresponding mechanoreceptor unit is stimulated physically would be evoked in the user [1].

In order to verify this idea, we conducted experiments to transfer mechanical stimuli that are given to the robot hand to the subject as pressure sensations. We used a microneurography technique [2] that was developed by Hagbarth and Vallbo in Sweden in the late 1960's [3]. The technique consists of directly inserting a tungsten microelectrode percutaneously into a peripheral nerve so that the signal of the nerve fiber attached to the tip of the electrode can be measured.

Figure 1. Experiment using microneurography

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Microstimulation of the nerve fiber, but not recording of the signal of the nerve fiber can be performed with the same microelectrode. The diameter of the shaft of the tungsten needle electrode we used was around 125 μm and the shaft was coated with an electric insulator (epoxy resin), and the diameter of the tip of the electrode where the electric insulator had been peeled off as a recording site was around 1-5 μm. When the recording site (tip of the electrode) is properly attached to only one nerve fiber, it is possible to record nerve signals only from that fiber and it is also possible to stimulate the single nerve fiber electrically. The biggest advantage of the microneurography/microstimulation method is that the technique is minimally invasive and experiment can be performed on subjects who are awake. Although great many researches which uses microneurography have been performed [4-6] and excellent results have been achieved in the field of basic neural science, there have been far fewer studies on microstimulation. . .

B. Experimental Procedure

First, we inserted the microelectrode into the median nerve of the subject at the forearm, and fixed the electrode so that signals of a nerve fiber from a single mechanoreceptor unit (SA-I mechanoreceptor unit) could be measured (Fig.1). Then we identified the location of the receptive field by confirming whether nerve signals were generated in accordance with a pressure applied to the skin by pushing the skin. (Here, we monitored the nerve signals using an oscilloscope and also auditory sounds.) Then, we gave various magnitudes of pressure to the receptive field of the SA-I mechanoreceptor unit using a bar-shaped load-cell and recorded the value of the impressed pressure and the output neural signals and analyzed the relationship between these two factors.

It has been reported that the relation between the strength of the force (or deviation) impressed to the mechanoreceptor and the rate (repetition frequency) of the spikes generated in the nerve fiber concerned fit Stevens' law, and our results showed reasonable agreement with the law as well [7].

C. Microstimulation

Next, we gave a train of electric stimulations to the same nerve fiber using the same microelectrode with various rates of repetitive frequency. Then we confirmed the area where the virtual sensation was evoked (projected area) and evaluated the magnitude of the evoked pressure sensation quantitatively.

The evaluation of the evoked pressure sensation magnitude was done as follows. When the virtual sensation was evoked by electric stimulation, subjects described the intensity of the generated pressure sensation using the contra-lateral hand in the following manner. He/she pushed a load cell (if possible with the same part of the hand as that of the projected field) and adjusted the pushing force so that the virtual pressure sensation generated by the electric stimulation become equal to the pressure sensation generated by pushing the load cell with the subject's own finger actually.

As a single electrical input pulse for the stimulation, we used a biphasic square-wave pulse for 250 μs. The amplitude of the electric stimulation (electric current) was gradually raised from 0 and was fixed at around 1.2-1.5 times the level of the threshold value (the current at which the subject first felt a sensation). We found that relationship between the frequency of the electric stimulation to the nerve fiber and the subjective magnitude of the evoked pressure sensation also met Stevens' law as well. However, our results suggested that the two relationships (applied pressure vs. repetition frequency of generated spikes, and generated pressure sensation vs. repetition frequency of electric stimulation) did not coincide with each other.

D. Robot Hand and Pressure Sensing System

A humanoid robot hand system (TMS52, Kawabuchi Co. LTD.) and a commercially available pressure sensing system (Finger TPS system, PPS systems Co.) were used in this study. The sensor probe had a flexible fingerstall shape and there was an electrostatic volume type pressure sensor (Fig. 2).

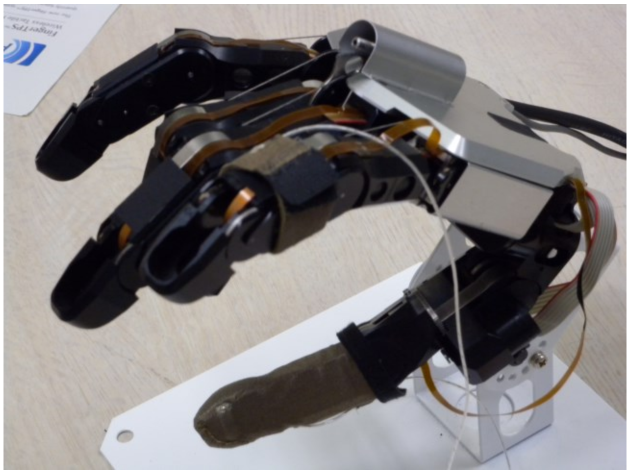

Figure 2. Robot hand used in the experiments and Finger TPS sensor (placed on the 1st thumb)

E. Modulation of the Physical Stimuli Impressed to the Robot Hand to the Pressure Sensation of the Subject

After confirming the projected area of the attached nerve fiber, we covered the same area of the robot hand with the Finger TPS system, and applied pressure to the pressure sensor which was covering the robot hand. (The applied pressure could be detected by the Finger TPS system and was modulated to the frequency of electrical pulses; the sensory nerve fiber from the SA-I mechanoreceptor unit at the corresponding projected area was then stimulated by the electrical pulses. The repetition frequency of the output electrical pulse train was determined in accordance with the strength of the pressure by the following equation:

$$f = \alpha \times P$$

where f is repetition frequency of the electrical pulse train used for stimulation (Hz), P is the pressure measured by the Finger TPS system (N) and α is a coefficient and was varied from 10 to 50 in accordance with the characteristics between impressed pressure and firing rate of each SA-I mechanoreceptor unit.

Quantitative evaluation of the evoked pressure sensation was conducted in the same manner as was mentioned in Sec. **II**.*C* Microstimulation.

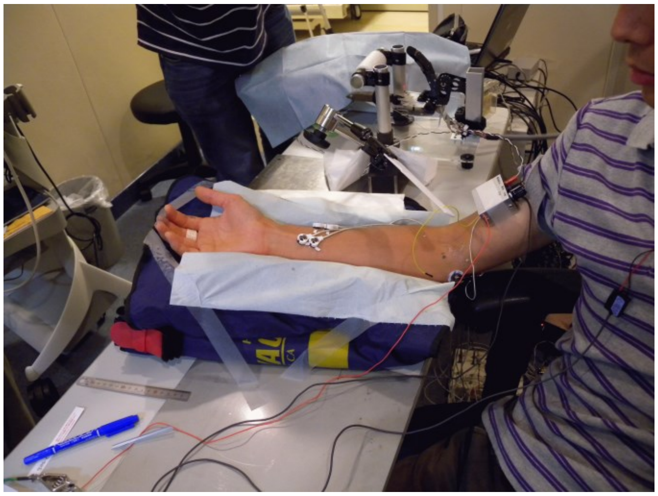

Figure 3. Experimental set up to convey physical pressure stimuli impressed to the artificial arm/hand system to the users as a corresponding pressure sensation by electrically stimulating the sensory nerve fiber.

III. RESULTS

With the developed system, we found that the user experienced physical pressure stimuli that were applied to the robot hand as pressure sensations of a magnitude corresponding to having touched the object with his/her own hand. Fig. 4 and Fig.5 show examples of the results. The upper graph shows the changes with respect to time in the force with which the Finger TPS system was pressed measured by the Finger TPS sensor system itself, and the lower graph shows the changes with respect to time in the subjective intensity of the pressure sensation generated by the electrical stimulation of the SA-I mechanoreceptor unit with the repetition frequency in accordance with the impressed pressure value of the upper graph. The middle graph of the Fig.5 shows the train of the electrical pulses used to stimulate the nerve fiber of interest. As can be seen from these two graphs, changes in the subjective magnitude of the pressure sensation and those in the pressure applied to the Finger TPS system showed a very similar tendency, indicating that the user can successfully experience the pressure stimuli as the corresponding somatic sensations with the same intensity.

IV. DISCUSSION AND CONCLUSION

The system worked satisfactorily and showed there was a good possibility that the system could give sensory functions to an artificial hand/arm system. In addition, this technique is able to be applied for the development of a sensory prosthetic system capable of substituting for sensory functions that have been lost due to injury or diseases of peripheral nervous system [8]. However, an interfacing system using percutaneously inserted microelectrodes is not suitable for clinical use, because the needle electrode is fixed only by the resistance between the inserted electrode and the surrounding tissues, and it is very difficult to fix the inserted electrodes for a long time. Therefore, development of a multichannel microelectrode that is capable of connecting each nerve fiber with an electrical signal line from external devices is indispensable so as to enable actual clinical use.

In summary, our artificial arm/hand system was able to convey the physical stimuli impressed to it to the users by electrically stimulating the sensory nerve fiber with a frequency corresponding to the magnitude of the impressed stimuli, which produced the same somatic sensation as the original stimuli, and with the corresponding magnitude.

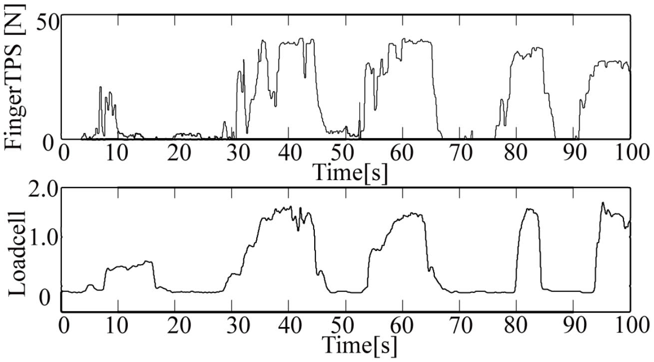

Figure 4. Changes with respect to time in the force with which the finger TPS system is pressed (upper graph). Changes with respect to time in the subjective intensity of the pressure sensation generated by the electrical stimulation of the SA-I mechanoreceptor unit with the repetition frequency in accordance with the impressed pressure value of the upper graph (lower graph)

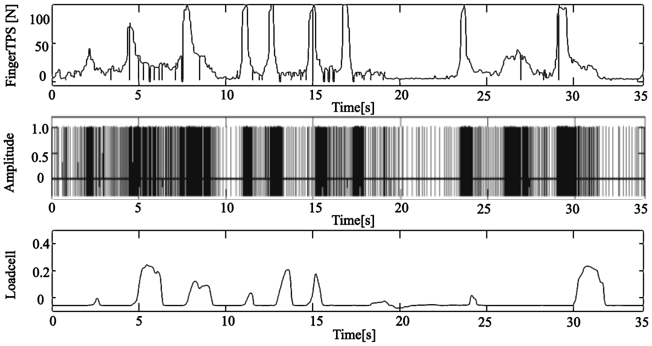

Figure 5. The results of other subject. The same tendency is observed. Changes with respect to time with which the Finger TPS system is pressed (upper graph). Changes with respect to time in the electric stimulation pulse train (middle graph). Changes with respect to time in the subjective intensity of the pressure sensation generated by the electrical stimulation of the SA-I mechanoreceptor unit with the repetition frequency in accordance with the impressed pressure value of the upper graph (lower graph)

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