33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Development of a Spatially Transparent Electrotactile Display and Its Performance in Grip Force Control

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Abstract— **An important function for a tactile navigation system of a handheld tool, such as a surgical scalpel, is the spatial transparency of the device. This paper proposed a new tactile display that can augment touch sensation at the finger pulps without the need for a stimulator between the tool and the finger pulps. We utilized transcutaneous electrical nerve stimulation at the middle phalanx of a finger to separate the stimulated and the perceived areas. In order to verify the effects of the spatial transparency, the performances of grip force control were examined. The results indicated that the proposed display was effective in helping the user to maintain the stable control of the grip force when using a handheld tool.**

I. Introduction

RECENT advances in measurement and computer technology have been utilized to assist surgeons during complex surgical interventions. A Computer-Aided Surgery (CAS) system can be used to navigate the surgical operation based on pre-operative planning via medical images. Both visual and tactile displays are effective tools for the navigation of the manipulating force or the position of a tool [5], [8]. Although previous tactile navigations have been shown to provide intuitive information compared to the visual navigation, the usability of such a tactile device was not thoroughly discussed.

Brell et al. developed a vibrotactile feedback system to indicate the position of the tool [1]. Robineau et al. developed a navigation system for gestures occurring via the electrical stimuli of the tongue [7]. In order to navigate the manipulation of a handheld tool with the index finger and thumb, the following two kinds of usability seem to be required: (1) The tactile display should not disturb holding a tool, and (2) The coordinates of the manipulation and tactile perception should be matched (manipulation-display match). We have defined the spatial transparency as the non-existence of a device at the perceived position. The purpose of this study is to develop a spatially transparent tactile display that can augment the tactile sensation at the finger pulps without the need for a stimulator at the finger pulps (see Fig. 1).

In the previous works focusing on tactile display, mechanical stimulus on body parts [1] and electrotactile sensation caused by Transcutaneous Electrical Nerve Stimulus (TENS) [7], [4] have been utilized. However, a spatially transparent display has not yet been achieved. As for the electrotactile display, the separation between the stimulated position and the perceived position was reported [4]. Kajimoto called this phenomenon *Sensory Shift* and explained that the touch sensation appeared at a distance that was a few mm from the electrode. *Sensory Shift* was a problem in the previous pattern display, however this work aimed to extend it to achieve the spatial transparency. We examine the sufficient stimulus condition of *Sensory Shift* for tool manipulation and proposed a new tactile device.

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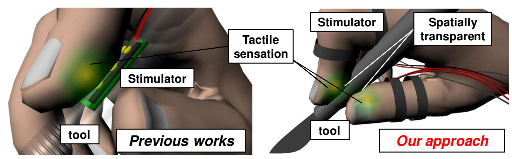


Fig. 1. Spatial transparency: In the previous work, the stimulator is placed near the thumb, which will disturb the operator. In our design the stimulator does not touch the tool.

The strategy to achieve the spatial transparency is to utilize the nerve anatomical structure and the conductivity of the skin. This paper describes the design of the spatially transparent electrotactile display and its basic performance for the CAS system. The grip force feedback system was chosen to examine the effectiveness of the proposed device.

II. Electrotactile Display using Sensory Shift

Electrotactile sensation caused by TENS has been used for neural prosthesis [6] and sensory substitution [4], [7]. *Sensory Shift* is a type of tactile illusion caused by the electrical stimulation of the common palmar digital nerves connected to the mechanoreceptors [4]. Therefore, careful observations of the anatomical structure of the nerve and the conductivity of the skin are necessary for the design of the position and waveform of the stimuli. Functional Electrical Stimulation (FES) [6] and the measurement of Sensory Nerve Conduction Velocity (SCV) [2] also utilized this strategy. However, the relationship between the stimulated and perceived positions was not revealed. In terms of tool manipulation, the design and usability of the proposed display are described below.

A. Required Usability for Handheld Tool Navigation

We focused on a handheld tool that requires the use of the index finger and thumb, such as a scalpel or a suction tube. Then, tactile augmentation at the finger pulps should be achieved without the need for a stimulator between the tool and the finger pulps. We assumed that the amount of *Sensory Shift* required to hold a tool without hindering the operation of the tool is at least 20 mm (length of the distal of a finger). Furthermore, the sensation should appear in the finger pulps. Therefore, the previously reported amount of *Sensory Shift* (i.e., about 2 mm) seems to be insufficient. Since the one-dimensional force feedback for each finger is assumed at this moment, the spatial distribution of the sensation is not considered.

B. Position of the Stimulation

As shown in Fig. 2, common palmar digital nerves connected to the mechanoreceptors run along the sides of the finger and spread like branches of a tree. The tactile augmentations at the pulps of the index finger and thumb seem to be established by stimulating the median nerve. The display performs well when the stimulator is located farther from the finger pulps. However, if the nerves near the central nerve are stimulated, stimulating only the nerves related to cutaneous sensation would be difficult. We presume that the terminal nerves from the proximal interphalangeal (PIP) joint to the fingertip are involved only in the cutaneous sensation based on the anatomical study [3]. Therefore, the stimulating position was selected to be at the middle phalanx of a finger to augment touch sensation at the finger pulps without the need for a stimulator between the tool and the finger pulps. Specifically, the electrodes are located on the sides of the finger near the common palmar digital nerves. The stimulating and ground electrodes are also arranged along the long axes of the finger to encourage *Sensory Shift*.

C. The Stimulus Wave Form

A periodic pulse wave is usually utilized in an electro-tactile display. Analytically, the parameters of the electrical stimulus related to the perceived area are the polar character and the wave height of the stimulus. A nerve axon that is connected to each kind of mechanoreceptor runs in a specific direction and depth. A horizontally oriented axon on the skin's surface can be stimulated by the cathodic current, while a vertically oriented axon can be stimulated by the anodic current [4]. We stimulate the nerve bundle rather than the individual axon of a mechanoreceptor to obtain a sufficient amount of *Sensory Shift*. This paper assumes that the nerve bundles beside the middle phalanx run along the skin's surface. Therefore, the cathodic current was utilized. The rate of the pulse used was up to 100 pulses per second (pps) with a pulse height of up to 2 mA. Because the sensory threshold varies among individuals, the wave height should be adjusted in order to produce an obvious cutaneous sensation but not pain.

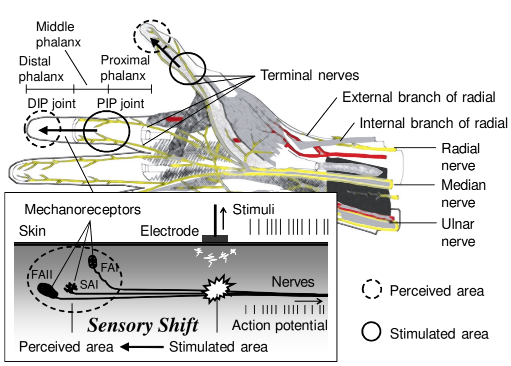
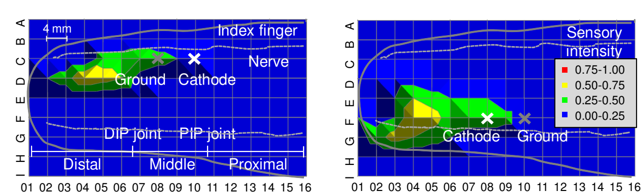


Fig. 2. Hand anatomy and *Sensory Shift*: Two main afferent nerves run along the sides of a finger. The perceived area shifts to the distal direction.

D. Preliminary Experiment

The amount of *Sensory Shift* at the index finger was measured in order to confirm the sufficient conditions for the tactile augmentation of a handheld tool. In the experiment, 10 different stimulating positions were selected. The two electrodes (i.e., each 4 mm in diameter) were fixed with a band for each trial. The cathode electrode was placed at an 8 mm distantce from the other for the ground. The pulse width and the pulse rate were 200 μs 10 pps, respectively, and the pulse height was decided for each subject. Subjects turned the volume up from zero in order to the set pulse height and answered the perceived position with the two-phased sensory intensity, i.e., weak and strong for each stimulating position. A grid illustration of the index finger is utilized for the answer (see Fig. 3). The 9 participants in the study were volunteers whose ages ranged from 22 to 25. The representative results of the average intensity are shown in Fig. 3. The cells were colored according to the average perceived tactile intensities. This paper defined the amount of *Sensory Shift* as the distance from the stimulating electrode to the position of the maximum sensory intensity. As shown in Fig. 4, the average amounts of *Sensory Shift* were calculated for each stimulated position.

In Fig. 3, we could visually observe the TENS at the middle phalanx causing *Sensory Shift*. Because the density of the mechanoreceptors is largest at the finger pulps, the largest sensory intensity seems to appear at the finger pulps. The amount of *Sensory Shift* is large when the stimulating position is near the afferent nerve axon (see Fig. 4). As we



(a) (b)

Fig. 3. Results of perceived area (average among the all subjects): The unit of each grid is 4 mm. (a) The stimulated position is at C10. (b) The stimulated position is at F8.

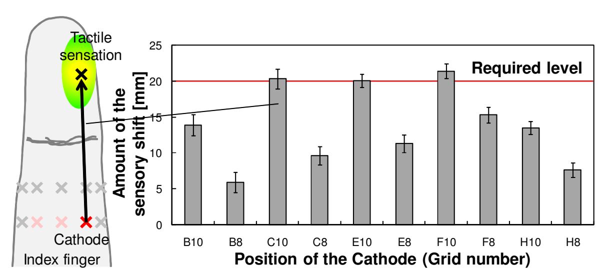


Fig. 4. The averaged amounts of *Sensory Shift*: The vertical bar represents the standard variation. The colored positions of the electrodes were effective.

mentioned previously, the required amount of *Sensory Shift* is at least 20 mm. Therefore, the results showed that the cathodic current stimulation at the middle phalanx, especially on each side of the finger (C10 and F10 in Fig. 4), was effective in terms of causing *Sensory Shift*. The effects were also confirmed in the thumb.

III. Performance in the Grip Force Control

The performance of the tactile display was tested by using the tactile feedback system which allows users to maintain the desired grip force with the index finger and thumb.

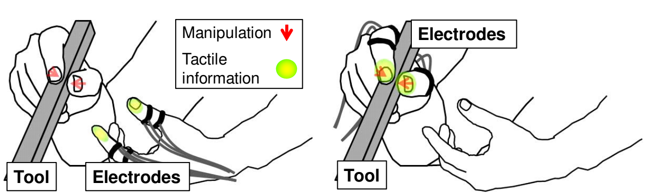
A. The Objective of the Experiment

The same task is compared in the two different displayed positions in order to verify the performance of the proposed tactile display for grip force control. In the **manipulation-display mismatch** condition, the tactile display was attached to the other finger, as shown in Fig. 5(a). Fig. 5(b) shows the case of **manipulation-display match** condition which is achieved due to the spatial transparency. The evaluation barometers of the force control are the error, the stability (fluctuation), the overshoot, and the response time in terms of the control system. The time to reach the steady state was decided at 10 seconds. The stability was defined as the variance of the error in this paper. The response time was defined as the time to reach 90 % of the desired force. If the barometers for the manipulation-display match conditions are significantly smaller than in the mismatch conditions, the effect of the proposed display is recognized.

B. Grip Force Feedback System

Fig. 6 illustrates the overview of the system. The grip force according to the manipulation was measured by a pressure sensor and utilized as input for the feedback model for each finger. The tactile display will be based on the calculated feedback force. The feedback force is represented by the pulse rate because the intensity of the electrotactile sensation can be linearly controlled by the pulse rate [9]. The feedback force is presented while the applied force is over the desired force. Therefore, the display augments the virtual force according to the excessive force. Users should apply the force and keep the force they have applied at the moment of feeling the virtual force to apply the desired force. Numerically, the augmented force $f_{\mathrm{vi}}(t)$ is represented by the following equations. ($\mathrm{i} = 1,2$: index finger and thumb)

$$f_{\mathrm{vi}}(t) = \begin{cases} 0 & f_{\mathrm{i}}(t) \leq F_{d\mathrm{i}} \\ \alpha\left(f_{\mathrm{i}}(t) - F_{d\mathrm{i}}\right) & \text{otherwise} \end{cases} \quad (1)$$



(a) (b)

Fig. 5. Experimental conditions: (a) Manipulation-display mismatch condition. (b) Manipulation-display match condition.

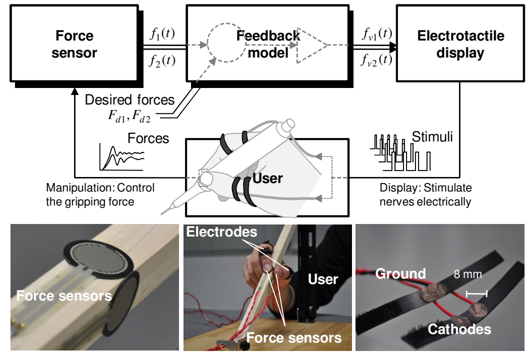


Fig. 6. Experimental system: The artificial tactile sensation is fed back according to the finger pressure.

Where $f_{\mathrm{i}}(t)$ is the applied force, α is the feedback gain, and $F_{d\mathrm{i}}$ is the desired force.

C. Experimental Setup

Users gripped the square log using the index finger and the thumb and individually stabilized the forces at the desired force for each based on the tactile feedbacks. The grip forces were sampled at 100 Hz by using the piezoelectric force sensors, which were calibrated by using the gravity force of a weight. As shown in Fig. 5, the left index finger and thumb were chosen as the manipulation-display mismatch condition to compare to the match condition (right hand). The desired forces, i.e., 0.5, 2, and 6 N, were chosen for each to obtain enough deference, making 9 combinations and a total of18 trials. The subjects were informed how to control the force based on the tactile feedback before each experiment. In the experiment, the subjects were asked to keep pressing the force sensors attached to the 15 mm squared log on the table with their index finger and thumb while resting their elbows on the table. The desired forces were randomly chosen for each condition, and the applied forces were recorded for 30 seconds, which was a sufficient period for the forces to settle. As for the stimulus parameter, the amount of force is directly related to the pulse rate below the pulse rate 100 pps. In practice, the gain, α, for each model is adjusted to focus on the range of the desired force (i.e., 0.005, 0.02, or 06). The stimulating and ground electrodes were redesigned as shown in Fig. 6.

D. Participants

Nine subjects ranging in age from 22 to 25 participated in the experiments. The subjects wore the electrodes at the target fingers and adjusted the amounts of the current at the beginning of the experiment. The amount of the current that causes appropriate touch sensation at the finger pulp was individually adjusted. Note that each current volume for the electrodes should be the same sensed level by adjusting the pulse height. The subjects were allowed to practice the manipulation a few times to get accustomed to the system at the beginning of the experiment. The manipulation was operated using the right hand while in a sitting posture.

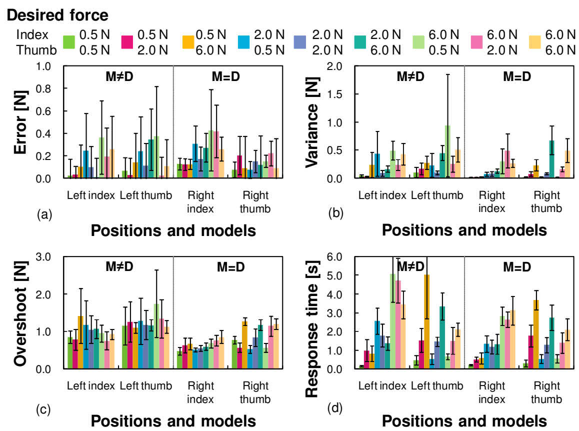


Fig. 7. The averaged barometers in case of two fingers control (The vertical var represents the standard variation): M=D represents manipulation-display match condition. (a) error, (b) variance, (c) overshoot, and (d) response time.

E. Results and Discussion

The four barometers of the force control were obtained (see Fig. 7). The force control in the index finger was easier to identify than in the thumb due to the tool posture. Therefore, the metrics had different values for corresponding pairs of forces. Most errors showed no significant difference between the manipulation-display match and mismatch conditions based on one-way Analysis Of Variance (ANOVA). On the other hand, the variances were significantly small in the manipulation-display match condition except for the cases of the desired forces (i.e., index/thumb) 2/6 N and 6/2 N ($F(1,8)=1.15, 0.97, p<0.05$). The overshoots were significantly smaller in the match condition than the mismatch condition except for the cases of the desired forces 0.5/6 N ($F(1,8)=2.09$, $p<0.05$). This paper discusses the following three important performances.

(A) Fig. 7 (a) indicates that subjects can keep the force around the desired force within a certain margin of error. The error was mainly affected by the feedback gain regardless of the presented position. Therefore, larger desired force deteriorated the stability. This characteristic is usually confirmed in a simple proportional feedback. This performance can be improved by using PID control. **(B)** As shown in Fig. 7 (b), the variances were significantly smaller in the manipulation-display match condition as compared to the mismatch condition. The difference is thought to come from the users' interpretation of the feedback information for the manipulating position. In the match condition, users seem to be able to intuitively understand the correspondence and rapidly respond. Consequently, the better results regarding the variance were seen in the match condition. **(C)** Fig. 7 (b) indicates the tendency noted in**(B)**, which is quite noticeable in the case of the smaller desired force in particular. Additionally, the larger desired forces result in a negative effect in the variance. The results suggest that the augmented touch sensation is affected by the real touch sensation according to the manipulation. A real touch sensation of a the large intensity seems to eclipse the virtual augmented sensation. In other words, the great difference between the desired and the augmented forces decreases the performance of the system. Therefore, the sensory intensity should be set as the same level of the desired force.

Finally, possible applications are discussed. The spatially transparent electrotactile display is expected to be used to maintain small grip forces. Specifically, the system would perform well in the exclusion or retraction of tissue in surgery. In this application, the desired grip forces according to the tool manipulation should be obtained in advance. The feedback gain should be adjusted to allow the augmented force to be as much as the desired force. Although the proposed system is not applicable to every tool, the system seemed to be valid for the basic control of a tool held with the index finger and the thumb.

IV. Conclusion

A spatially transparent electrotactile display for tactile augmentation was proposed. Effective spatial transparency was achieved by the TENS at the middle phalanx of a finger. As an evaluation of the performance for grip force control, a tactile feedback system was constructed. The results of the grip force control indicated that the manipulation-display match feedback is significantly effective in terms of ensuring the stability as compared to manipulation-display mismatch feedback. Then, we concluded that the spatially transparent electrotactile display had effective usability in a grip force control system. Furthermore, the results also suggested that the proposed tactile display is expected to become a new navigation device for a CAS system.

Acknowledgments

This work was supported in part by the Global COE Program "*in silico* medicine" at Osaka University. Ethics approval for this research was granted by the Ethics Committee of Engineering Science in Osaka University.

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