Electro-Tactile Display with Tactile Primary Color Approach

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***Abstract*— An electro-tactile display is a tactile device that directly activates nerve fibers within the skin by electrical current from surface electrodes. It is superior to conventional mechanical devices in many respects, such as smaller size, but suffers the problem that the quality of the elicited sensation is quite ”electrical”. We focus on how to produce ”natural” tactile sensation by electro-tactile display. Our approach is to independently stimulate each type of mechanoreceptor, and combine the stimuli to produce natural tactile sensation. We call these stimuli “tactile primary colors” because they are analogous to red, green, and blue, the primary colors for vision.**

I. Introduction

Electrical stimulation is superior to conventional tactile displays in many respects. The display can be manufactured very small, thin, durable, energy efficient, and free from mechanical resonance. However, although there are quite extensive research efforts on this topic [1–3, 13, 29–32], there have been few attempts to display realistic tactile sensation with electrical stimulation. Existing electro-tactile displays could be used as “symbol displays” such as Braille, but they are still not able to convince us of the future possibilities to connect us to a realistic tactile world. Therefore, our primary motivation was to find ways to present “natural” tactile sensation through electrical stimulation.

Looking back at other sensations, a common principle is the selective stimulation of different types of receptors. In vision, primary colors are chosen so that they stimulate different types of cone cells in the retina. In auditory sensations, arguments are done primarily in a frequency domain, corresponding to different hair cells in a basilar membrane. The design of these displays made use of these characteristics to present reduced but sufficient information about the surrounding world.

In the case of tactile display, there are four types of mechanoreceptors in the human skin (Fig.1). They are the Merkel cell (SAI), Meissner corpuscle (RA), Ruffini ending (SAII), and Pacinian corpuscle (PC). As the population of SAII is small in the human finger, we only consider RA, SAI, and PC.

SAI is activated by static pressure, while RA and PC are activated by time-varying vibrations. RA and PC’s resonant frequencies are 30[Hz] and 250[Hz], respectively (Fig.2). If we could selectively stimulate these receptors, we could reconstruct any tactile sensation by combining them.

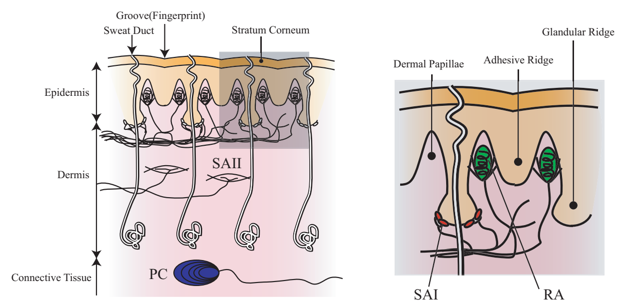

Fig. 1. Cross section of human skin. Merkel cell (SAI), Meissner corpuscle (RA), Ruffini ending (SAII), Pacinian corpuscle (PC). Reconstructed from [8, 35].

Our first goal is relatively simple: to find ways to stimulate each kind of mechanoreceptor separately (Fig.2). With this in mind, we have proposed an electro-tactile display for the fingerpad with three modes that stimulate different types of receptors. We named these stimuli “tactile primary colors” after the three primary colors in vision.

This paper is a quick review of our recent work on electro-tactile display [15–20]. In Sec.II, our selective stimulation problem is formulated and solved as an optimal control problem. In Sec.III, our designed stimuli are evaluated with psychophysical experiments. In Sec.IV, some applications that utilize the merits of the electro-tactile display are proposed.

II. Selective Stimulation

In this section, we introducing the notion of “Activating Function”, which roughly but sufficiently describes the nerve activity, in order to design an optimal stimulation technique to selectively activate each tactile afferent.

A. Activating Function

We assume that a nerve is activated when the potential difference of the nerve membrane V_m reaches a certain threshold V_{th}. Then, electrical stimulation could be recognized as a mapping problem between a current source distribution $I(x,t)$ on the skin surface and $V_m(r,t)$, where

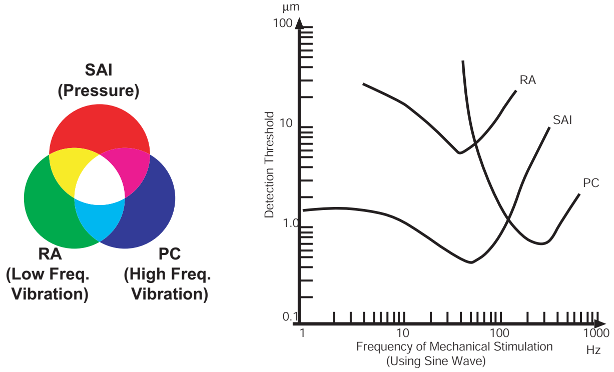

Fig. 2. Tactile primary color approach and detection threshold of SAI, RA and PC when mechanical stimulation (sine wave) is applied on the skin surface. Reconstructed from [12]

x and r are coordinates along the skin surface and nerve fiber and t represents time.

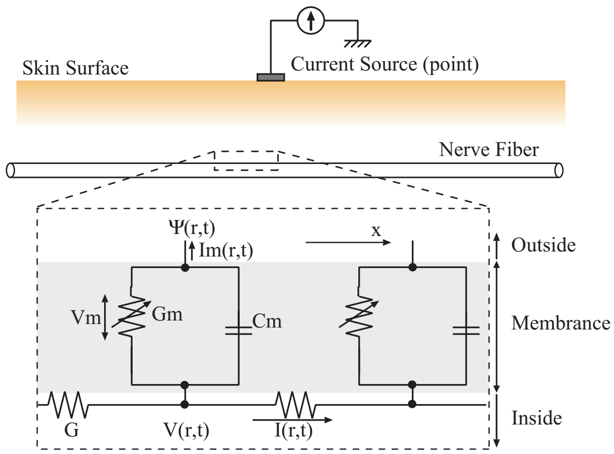

Fig. 3. Current stimulation from the skin surface and an electrical model of the nerve fiber.

First, we model the nerve axon (Fig. 3) [21]. The membrane is expressed by a membrane capacitance (C_m), membrane conductance (G_m) and internal conductance(G). Let the electric potential outside and inside the membrane be $\Psi(r,t)$ and $V(r,t)$, and the potential difference $V - \Psi$ be $V_m(r,t)$. What we can do is to apply $\Psi(r,t)$ and manipulate $V_m(r,t)$ indirectly.

The relationship between $\Psi(r,t)$ and $V_m(r,t)$ is as follows [26, 27]

$$-\frac{\lambda^2}{\tau}\frac{\partial^2 V_m}{\partial r^2} + \frac{\partial V_m}{\partial t} + \frac{1}{\tau}V_m = \frac{\lambda^2}{\tau}\frac{\partial^2 \Psi}{\partial r^2} \quad (1)$$

where $\lambda = \sqrt{G/G_m}$ and $\tau = C_m/G_m$.

We can regard this equation as a kind of heat-transfer equation, where V_m is analogous to temperature, λ^2/τ is the coefficient of thermal conductivity, and $\lambda^2\partial^2\Psi/\tau\partial r^2$ is the input heat. The third term in the left-hand side does not appear in an ordinary heat-transfer equation, but can be eliminated with a simple transformation. (See Appendix A)

As we may consider the activity of the nerve membrane potential as a heat transfer equation, we can easily conclude that to raise V_m (temperature), we must apply "heat", which is the right hand-side of the equation. $\lambda^2\partial^2\Psi/\tau\partial r^2$ is the nerve specific term and $\partial^2\Psi/\partial r^2$ is called the "Activating Function"(AF) [24, 25].

$$\mathbf{AF} = \frac{\partial^2 \Psi}{\partial r^2} \quad (2)$$

Next, we calculate Ψ for a single electrode on skin surface.

For simplicity, we consider the 2D case with a uniform infinite space with pure resistance (Fig.4). The electric potential Ψ is obtained by an integral of the current density as follows:

$$\Psi(x,y) = -\int \vec{E}d\vec{R} = -\int_R i\rho dR \quad (3)$$

$$= -\int_R \frac{I}{2\pi R}\rho dR = \frac{-\rho I \log(R)}{2\pi} \quad (4)$$

where i is the current density, ρ is the resistivity, and $R = \sqrt{x^2+y^2}$ is the distance between electrode 1 and node n.

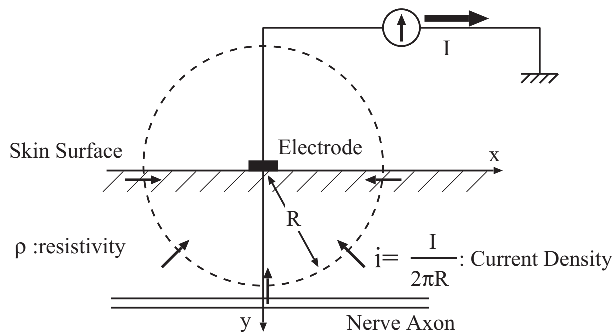

Fig. 4. Current stimulation from the skin surface. 2D single line electrode case.

Now we calculate the Activating Function (AF). If the axon lies in the x direction, since the AF is a second spatial derivative of the external membrane potential,

$$AF = \frac{\partial^2\Psi(x,y)}{\partial r^2} = \frac{\partial^2\Psi(x,y)}{\partial x^2} \propto \frac{y^2 - x^2}{(x^2+y^2)^2} \quad (5)$$

Fig.5 is the plot of Eq.5.

B. Multi-Electrode Case

Eq.5 describes the case when a single electrode is used. In general, electrodes are distributed on a skin surface, as shown in Fig.6. Let the number of electrodes be M, and the electrical current from ith electrode be I_i.

If we assume that each electrode is controlled by electrical current, not electrical potential, then the outer-membrane potential $\Psi(r,t)$ is obtained by simply superpositioning the effect from each electrode. As AF is a second time-derivative of Ψ, it is also calculated by superposition.

$$AF = \sum_{i=1}^{M}\frac{\partial^2\Psi_i}{\partial r^2} \propto \sum_{i=1}^{M} I_i AF_i, \quad (6)$$

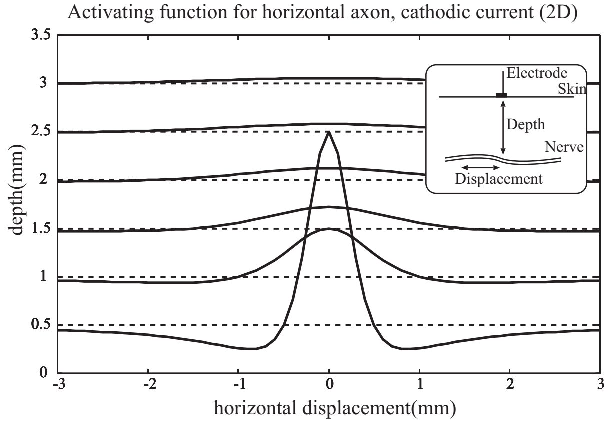

Fig. 5. Activating function for horizontal axon. Cathodic(-) single current case.

where $AF_i(r)$ is the AF derived from the unit electrical current from the ith electrode.

From Eq.6, we see that the shape of the AF is determined by the electrical current from the surface electrodes. Therefore, the design of electrical stimulation reduces to the design of emitting proper electrical current I_i from the surface electrodes. Let us introduce weight vector $\mathbf{w}$, which represents surface current distribution

$$\mathbf{w} = [I_1, I_2, \cdots I_M]^{\mathrm{T}}. \tag{7}$$

To further simplify the problem, we will discuss the case with "myelinated" nerves, which is characterized by a surrounding insulator called the myelin sheath. As almost the entire nerve membrane is insulated by the sheath, it can only be electrically accessed by the Node of Ranvier, which is a small gap between each sheath. Therefore, only these gaps need to be considered.

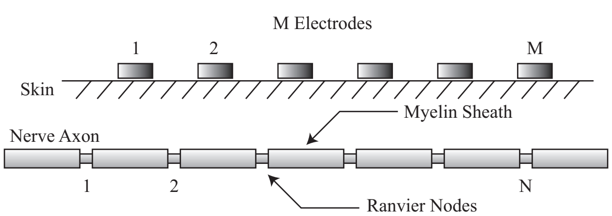

Fig. 6. Multi electrodes and myelinated nerve configuration.

Fig.6 shows the situation. There are M electrodes and N Ranvier nodes. From the previous discussion, the AF for each Ranvier Node is calculated as follows.

$$\begin{bmatrix} AF_1 \\ AF_2 \\ \vdots \\ AF_N \end{bmatrix} = \begin{bmatrix} AF_{1,1} & \cdots & AF_{1,M} \\ \vdots & \ddots & \vdots \\ AF_{N,1} & \cdots & AF_{N,M} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_M \end{bmatrix} \tag{8}$$

$$= \mathbf{AFw} \tag{9}$$

where AF_i is the AF of the ith node and $AF_{i,j}$ is the AF generated at the ith node from a unit electrical current from the jth electrode. We call **AF** the AF matrix from now on. Note that the AF matrix is constant if the positions of electrodes and nerves are fixed.

C. Optimal Design of Selective Stimulation

Our next step is to find the optimal weight vector $\mathbf{w}$ for the selective stimulation.

The purpose of selective stimulation is simple. It is to stimulate the desired nerve fibers without stimulating undesired fibers. The simplest case is with two nerve fibers, a and b, in which fiber a should be activated, and fiber b should be suppressed.

For each nerve, the AF is calculated by Eq.8. **Recalling the assumption that the nerve will be activated when the membrane potential difference reaches its threshold, we only need to observe the maximum value of the AF to determine the nerve activities.**

Hence, the optimal selective stimulation method reduces to minimizing the maximum AF of b, while the maximum AF of a reaches the threshold. It is described as an optimization problem as follows:

$$\min_{\mathbf{w}}(\max(\mathbf{AF}_b\mathbf{w})) \tag{10}$$

$$\text{where} \quad \max(\mathbf{AF}_a\mathbf{w}) = 1 \tag{11}$$

$$\sum_{i=1}^{N} I_i = 0 \tag{12}$$

Eq.10 minimizes the maximum AF of nerve b, while Eq.11 means that the maximum AF of nerve a is 1 and Eq.12 guarantees that the sum of the electrical current is 0 to ensure safety.

The formulated problem is still difficult to solve because of the unusual condition in Eq.11. If we know at which node the nerve a is activated, Eq.11 becomes an ordinary matrix equation. Then,

$$\min_{\mathbf{w}}(\max(\mathbf{AF}_b\mathbf{w})) \tag{13}$$

$$\text{where} \quad \mathbf{AF}_{\mathbf{p}a}\mathbf{w} = 1 \tag{14}$$

$$\sum_{i=1}^{N} I_i = 0, \tag{15}$$

where $\mathbf{AF}_{\mathbf{p}a}$ is a partial matrix (vector) from $\mathbf{AF}_a$.

Eq.13 through Eq.15 is a typical linear programming problem called the min-max problem. Therefore, the problem can be solved with ordinary mathematical software.

Assignment of the location of activity does lose generality. As we do not have a general method to predict the location of activity, we must try all candidate nodes through brute force. For each candidate, we solve the optimization problem and obtain the maximum value of $\mathbf{A_b w}$. Then, for all maximum values of $\mathbf{A_b w}$, we obtain the minimum value. This is the true minimum value, and we acquire the true optimal solution at the same time.

If there are three nerves a, b, c, and we wish to stimulate only the nerve a, the problem is formulated as follows.

$$\min_{\mathbf{w}}(\max([\mathbf{AF_b}, \mathbf{AF_c}]\mathbf{w})) \quad (16)$$

$$\text{where} \quad \mathbf{AF}_a\mathbf{w} = 1 \quad (17)$$

$$\sum_{i=1}^{N} I_i = 0 \quad (18)$$

Here, matrix $[\mathbf{AF_b}, \mathbf{AF_c}]$ is the concatenated matrix of AF_b and AF_c.

D. Realization of Tactile Primary Colors with Electrical Stimulation

Finally, we design the optimal stimulation methods to selectively stimulate tactile afferents. For an optimal design, we need the nerve pathway of each nerve to calculate the AF matrix.

Unfortunately, there are very few quantitative works on nerve pathways so some assumptions are in order.

Tha RA axon branches from the superficial dermal nerves and ascends to the epidermis. Therefore, we shall first assume that the RA axon in the fingerpad is perpendicular to the skin surface [6], which is especially true near the surface.

The precise pathway of the SAI nerve is not well known, though some drawings have indicated that it is horizontally oriented [6]. We currently assume it to be horizontal.

From these observations, we model the nerve pathway as in Fig.7. We place seven electrodes at 1.0[mm] intervals. The SAI, RA and PC are located at 0.9, 0.7 and 2.0[mm] in depth. As the RA axon runs vertical to the skin surface, we arranged multiple RA axons at 1.0[mm] intervals.

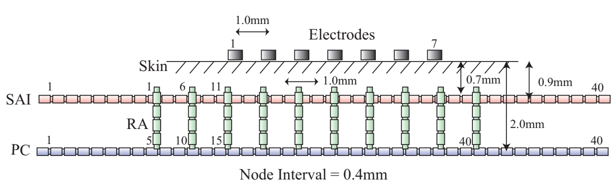

Fig. 7. Electrodes and nerve placement for the design of the Activating Function

As we saw in Eq.14, we must choose the location of activity for nerve a (stimulation nerve). In the following results, we chose a node just beneath the central electrode as an activated node.

Fig.8 shows the result of the selective stimulation of SAI, PC and RA. We shall call them "SAI mode", "PC mode" and "RA mode". The horizontal axis denotes the electrode geometry and the vertical axis is the normalized electrode weight. According to the standard notation of electrical stimulation, the positive side is cathode (-) and the negative side is anode (+). These three modes are the realization of tactile primary colors by electrical stimulation.

Qualitative explanation of these results is as follows. Comparing the SAI mode and PC mode, the SAI mode is characterized by a central cathodic weight and a neighboring anodic weight, while the PC mode is characterized

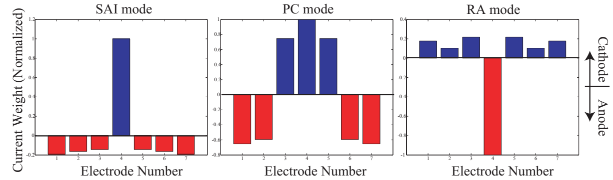

Fig. 8. Optimal design of Activating Function. (Left) SAI mode. (Middle) PC mode. (Right) RA mode. The horizontal axis denotes the electrode geometry, and the vertical axis is the normalized electrode weight.

by a broadened cathodic weight. The difference between these two types of receptors is depth within the skin.

If we add anodic current around a central cathodic current, the AF approaches zero in the deeper part, so we can stably stimulate a shallower region (Fig.9(a)). On the contrary, if we add cathodic current around central cathodic current, the size of the electrode virtually increases. Therefore, the rate of convergence decreases, and a deeper region can also be stimulated (Fig.9(b)). We call these selective stimulation schemes "depth-selective stimulation" (Fig.9).

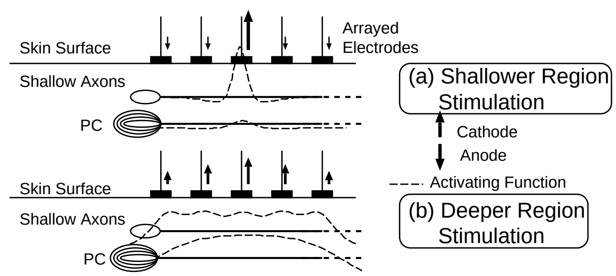

Fig. 9. Depth-selective stimulation by weighted-array electrodes. (a)Shallower-region stimulation. (b)Deeper-region stimulation. Activating Function is shown for each

Comparing the SAI mode and the RA mode, the polarity is reversed. The difference between these two types of receptors is the orientation of nerves. Our assumption was that the SAI nerve lies horizontal to the skin surface, while the RA nerve runs perpendicular to the skin.

Remember that the AF is a second spatial derivative of the outer membrane potential along the nerve fiber. The AF of horizontally oriented axons is $d^2\Psi/dx^2$, but that of vertical axons is $d^2\Psi/dy^2$.

From Gauss's law($\Delta\psi = 0$), $d^2\Psi/dy^2 = -d^2\Psi/dx^2$ always holds true. Therefore, horizontal and vertical axons can be separately stimulated by changing the polarity of the electrodes. We call these two pairs of selective stimulation schemes "orientation-selective stimulation" (Fig.10).

III. Psychophysical Experiment

In this section, the proposed selective stimulation methods are evaluated both qualitatively and quantitatively.

A. Experiment System

We constructed an experimental system shown in Fig. 11. Multiplying one channel high-speed wave signal by eight channel low speed weight signals, we obtained eight

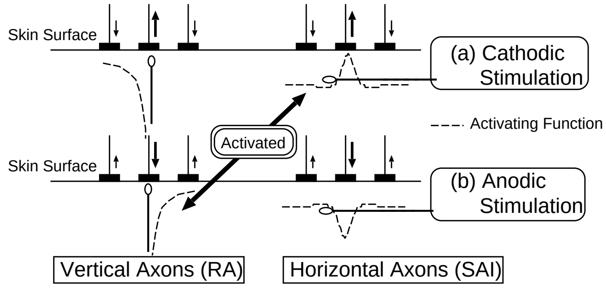

Fig. 10. Orientation-selective stimulation. (a)Cathodic-current stimulation. (b)Anodic-current stimulation. Activating Function is drawn.

synchronized waves. V-I converters were used to convert them to current stimuli. Subjects put their fingers on an array of electrodes. As the sum of the array weight is 0, we do not need an additional ground electrode to release current.

Arrays were composed of eight line electrodes that were equally spaced. The distance between each electrode was 1.0[mm] and the electrode size was 0.5[mm] $\times$ 10[mm]. Electrical current from the central electrode ranged from 0 to 2.0[mA], which is controlled by the subject using keyboard. The current pulse width was fixed to 200[μs].

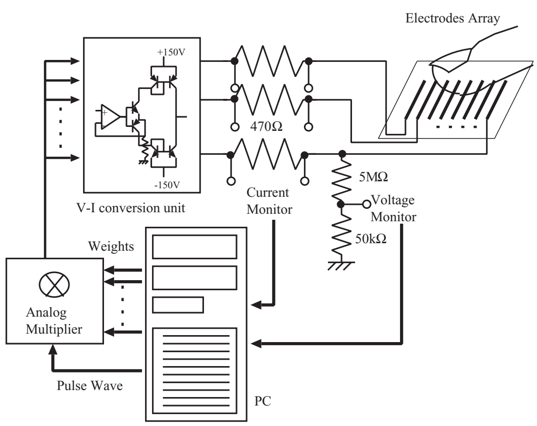

Fig. 11. System configuration [17].

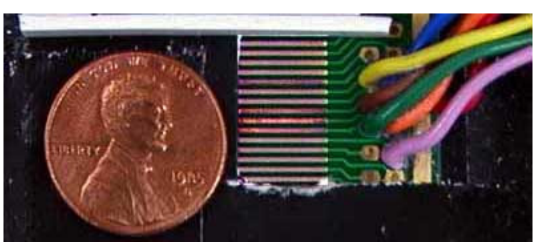

Fig. 12. 1D array of electrodes.

B. Qualitative Evaluation

During the experiment, some qualitative phenomena were found that seem to support our hypothesis that each mode is stimulating the desired mechanoreceptor's fibers.

1) Pressure sensation in SAI mode: In SAI mode, when current was gradually increased from 0, the sensation changed as follows.

- At 0.2mA, a tiny tremoring sensation occurred.
- At 0.4mA, the subject felt pressure in the shape of the central electrode. As we used line electrodes, it was like touching a knife-edge.
- At 0.6mA, a new sensation of vibration was evoked, as well as pressure.
- More than 1.0mA current induced stronger vibratory sensation and the pressure sensation was masked.

Stimulation pulse frequency varied from 10 to 200[Hz], but the above observationwas not influenced by frequency. This result supported our hypothesis that our SAI mode selectively stimulated SAI receptors, because SAI is responsible for pressure sensation [11, 12, 23, 34].

Vibratory sensation evoked after pressure might have been caused by RA and PC receptors. The result suggests that the range of current amplitude in which SAI is selectively stimulated is quite narrow.

2) Sensation of soft material in SAI mode: When pressure sensation was stably presented in SAI mode, the subject felt a hard bump. When the subject moved his or her finger up and down slightly, the feeling of bump suddenly changed to that of a soft elastic rod (Fig.13). This qualitative change was quite dramatic, and some subjects expressed that the electrode moved down like a push button.

This phenomenon is explained as follows. Many works on nerve information coding have suggested that the SAI cell encodes pressure through firing frequency [12]. If one touches a hard object, the finger motion directly affects the pressure inside the skin, so that the firing frequency changes. On the contrary, if one touches a soft material, the finger motion doesn't affect pressure as much and hence, firing frequency does not change.

In our case, we did not change the stimulating frequency during finger motion. Therefore, the subject perceived that the touched object was made of soft material.

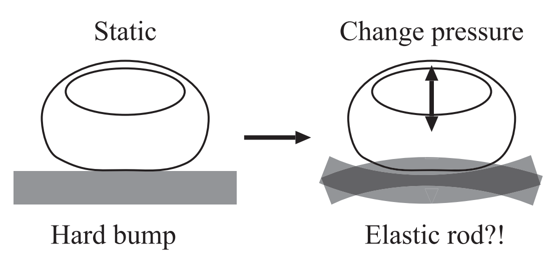

Fig. 13. SAI mode experiment. Subject felt a hard bump at first, but upon moving the finger slightly up and down, it changed dramatically to an elastic rod, even though contacting area did not change.

3) Vibratory sensation in RA mode: In RA mode, the subject felt a stable vibratory sensation. When the pulse frequency was less than 100 [Hz], the elicited sensation was quite similar to that of touching a vibrating speaker cone. This result supported our hypothesis that our RA mode selectively stimulated RA receptors, since RA is responsible for vibratory sensation.

4) Sensation shift phenomenon in PC mode: In PC mode, one interesting phenomenon was observed. The subject felt pure vibration, and the sensation was elicited not just on the central electrode, but always shifted 1-3 [mm] with respect to the fingertip (Fig.14).

This phenomenon reminds us of the fact that the current doesn't stimulate the mechanoreceptor itself, but rather stimulates the nerve axon that is connected to the receptor. However, our brain mistakes the receptor at the tip of the axon as activated, which would explain the sensation shift phenomenon. Since the Pacinian corpuscle resides in a deeper region than other receptors, this sensation shift became easier to observe.

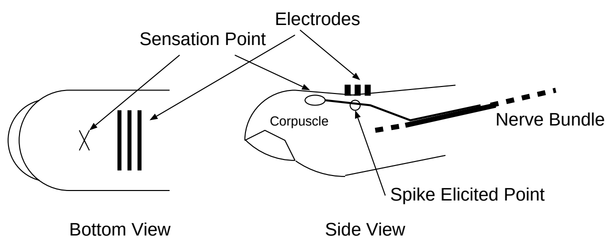

Fig. 14. Sensation shift phenomenon. Though the nerve axon is stimulated, the evoked sensation point is shifted 1-3 [mm] along the fingertip.

5) Focused Sensation by Anodic Stimulation: Let us examine the sensation shift phenomenon more deeply. As we have seen in Sec.II-D, cathodic current activates nerve axons parallel to the skin surface (Fig.15 Left). Therefore, there is always some "gap" between the stimulation point (nerve axon) and the sensation point(mechanoreceptor). Accumulation of this gap results in blurred, or unfocused sensation. As conventional electrical stimulation always used cathodic current, its resolution was significantly lower than that of mechanical stimulation [9, 10].

On the contrary, as we have seen in Sec.III-B.5, if we apply anodic current, we can selectively stimulate "vertical" nerves (Fig.15 Right). Although there is still a gap between the stimulation point and the sensation point, the gap is vertical, so its influence on the sensation is negligible. As a result, an acute tactile image should be obtained. This anodic stimulation was already introduced as the RA mode. Kaczmarek has observed that an anodic pulse generated more acute sensation than cathodic stimulation [14]. Note that this phenomenon was observed only at the fingertip, where the RA nerve runs perpendicular to the skin surface.

C. Selectivity Evaluation Between Vibration Sensitive Receptors

The following is a quantitative evaluation of selective stimulation through psychophysical experiment. Here we treated two types of vibration sensitive receptors, RA and PC.

RA reacts to low frequency vibration (20-70[Hz]), with a resonant frequency of about 30[Hz]. PC reacts to high

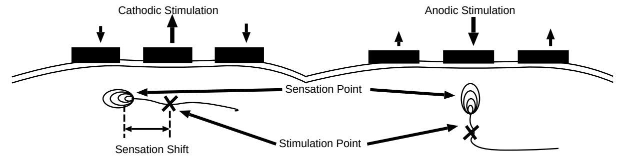

Fig. 15. Gap between stimulation point and mechanoreceptor. (Left) Cathodic stimulation. (Right) Anodic stimulation, or RA mode [18]

frequency vibration (60-800[Hz]), with a resonant frequency of about 250[Hz] (Fig.2). Previous psychophysical experiments showed that in all frequency ranges, about a 20% frequency difference could be discriminated.

In mechanical vibration, nerves that are connected to the receptors generate electrical pulses at the same frequency as the vibration [35]. Therefore, we supposed tha conversely, if electrical pulses are applied, participants should perceive the pulse train as mechanical vibration with the same frequency, which should result in the same frequency discrimination threshold.

First, we measured the frequency discrimination threshold in RA mode with a constant method.

Four participants, three males and one female between 25 and 35 years old, were asked to place their finger on the conventional concentric electrodes. The central electrode was 1.0[mm] in diameter, and the inner diameter of the outer electrode was 6.0[mm]. Frequencies of standard stimulation were 15, 30, 45, 60 and 75[Hz]. The comparison frequency ranged from 0.5 to 2.0 times the standard frequency. For each stimulation pair, subjects were asked to answer which frequency was higher (forced choice) 10 times. After fitting the answer rate with the cumulative density function, we acquired a 75% discrimination threshold. To save experiment time, for some standard frequencies, comparison frequencies ranged from 1.0 to 2.0 times the standard frequency, and only upper thresholds were obtained.

The pulse amplitude was about 2.4[mA], and the pulse width was 0.2[ms]. During the experiment, subjects controlled pulse amplitude freely so that the elicited sensation was always clear.

Results are shown in Fig.16. For frequencies of 15[Hz] through 45[Hz], the threshold was lower than 20%, which is quite similar to mechanical stimulation. However, at 60[Hz], the threshold suddenly increased and at 75[Hz], the threshold reached 0.7, which means that subjects could not interpret 130[Hz] stimulation to be higher than 75[Hz].

This puzzling result is explained by assuming that the RA is selectively stimulated. Remember that in mechanical stimulation, 15[Hz] through 45[Hz] are the frequencies where only RA, not PC is activated (Fig.2). Therefore, there is no difference between mechanical and electrical stimulation from the receptor's viewpoint. However, from 60[Hz] or more, the PC is also activated in mechanical stimulation. At that frequency, it is quite natural to conclude that we discern frequency by observing the activity ratio of both the RA and PC.

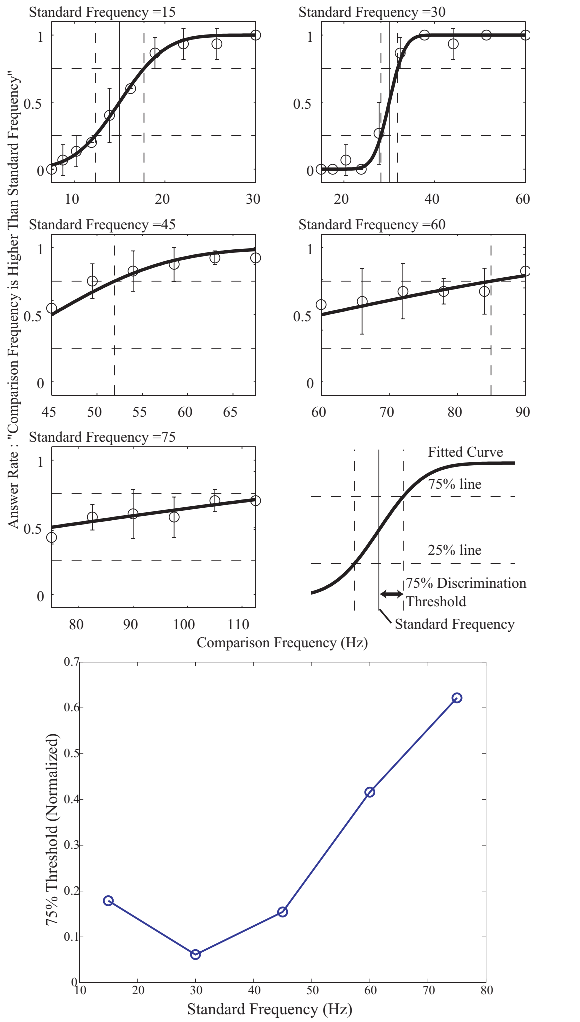

Fig. 16. (Top) Frequency discrimination test result with constant method in RA mode electrical stimulation. (Bottom)75% discrimination threshold.

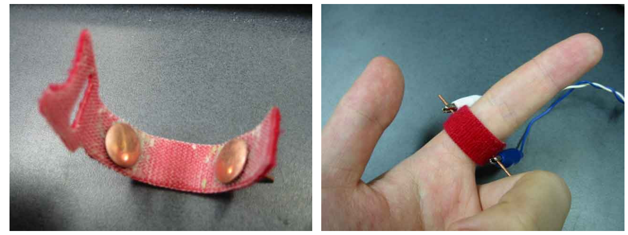

Fig. 17. Ring electrode to stimulate all nerves in the finger

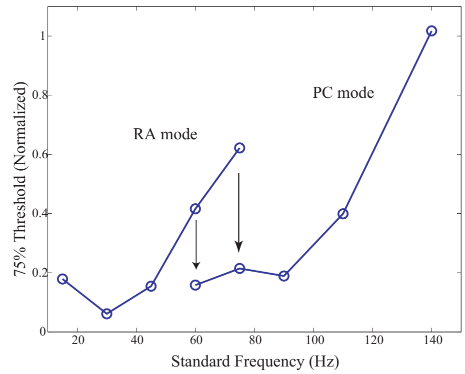

Fig. 18. 75% discrimination threshold of PC mode. Results of RA mode are also shown.

However, in RA mode electrical stimulation, we assumed that only RA corpuscles are activated even at high frequency. This situation should never happen in mechanical stimulation. Hence, the participants could not discern the frequency of the stimulation. From another viewpoint, this result supported our hypothesis that RA mode selectively stimulated RA receptors.

1) Verification of the hypothesis by deep tissue stimulation: If the above-mentioned rationale is true, the frequency discrimination threshold should decrease if we also stimulate the PC. This is achieved in PC mode, which was performed by using a larger electrode. Fig.17 shows the large electrode we used to stimulate all nerves in the finger.

The result is shown in Fig.18. The discrimination threshold from 60[Hz] to 90 [Hz] decreased dramatically, which supported our hypothesis that the PC was not stimulated in RA mode.

However, at more than 100[Hz], the discrimination threshold of PC mode increased. This result is also explained by comparing mechanical and electrical stimulation. For mechanical stimulation, at higher than 100[Hz], the PC is much more activated than the RA (Fig.2). However, in electrical stimulation, the RA are always more activated than the PC because the RA resides in a shallower region, resulting in a misinterpretation of the stimulation frequency.

IV. Application

In this section, after presenting basic extensions of electro-tactile display, we show two practical applications, the electric mouse and SmartTouch.

A. Scanning

In mechanical tactile displays with matrix pins, a surface can easily be represented by the simultaneous movement of pins. However, in our electrocutaneous display, the situation is complicated by the interference of the current between electrodes.

Therefore, we employed a method of time-division scanning, as shown in Fig.19(Top). Each electrode takes the following three states: cathode, anode and insulated. Note that numerous electrodes are used simultaneously to present a single point stimulus.

Fig.19(Middle) and (Bottom) show the simple switching circuit to realize the three states. Each electrode is connected to two switch pairs, the top switch and bottom switch. If the top switch is on and the bottom switch is off, the electrode works as anode. If the top switch is off and the bottom switch is on, it works as cathode. If both switches are off, the electrode is insulated. Finally, if both switches are on, the whole system is short-circuited and unnecessary accumulated electric charge is released [33].

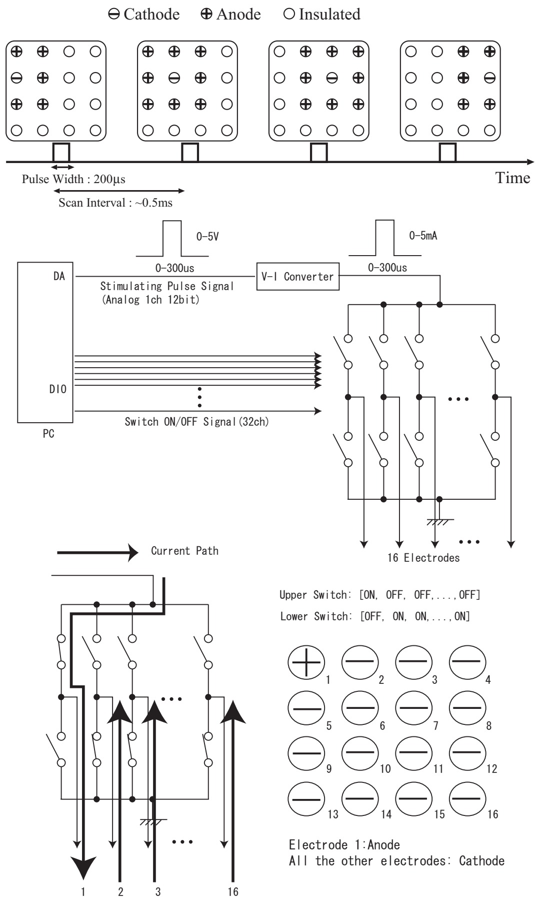

Fig. 19. Scanning mechanism. (Top) Scanning procedure in SAI mode. Each electrode takes the following three states: cathode, anode and insulated. (Middle) Simple switching circuits to realize three states for each electrode. (Bottom) Example of switch state and current path.

B. Force Feedback

One critical problem to solve in electro-tactile display is the unstable relationship between the amount of current and the generated sensation. This problem has two aspects. One is that the amount of generated sensation changes over time due to deviation in electrical impedance. Many previous works dealt with this problem. One successful result was obtained by Tachi [32], who suggested using energy (current times voltage) as a control parameter.

The other aspect of this problem is more serious. A sudden change of sensation gives an invasive impression, or even fear. This is a typical phenomenon in electrical stimulation.

Why do we feel ”invaded” by electrical, but not mechanical stimulation? In mechanical stimulation, we receive the same amount of pain or more if the object we touch is sharp, such as a needle or razor, but people are never shocked by them.

Furthermore, we handle such objects in daily life. This implies that we have a skill to control the amount of skin sensation through force application. However, in the case of electrical stimulation, the skin sensation is unrelated to force, so although people might not be harmed by the mild amount of electricity, they are often shocked by a sudden and unexpected sensation from simply touching the stimulation source.

Therefore, our solution is as follows: by setting a force sensor (load cell) under the electrodes, we measure the finger pressure. The applied pulse height or width is set as a monotonically increasing function (possibly linear, or logarithmic) of this pressure. We can therefore control the amount of sensation by regulating finger pressure.

C. Electric Mouse

The first application is an electric mouse, in which electrodes are mounted on an ordinary mouse interface (Fig.20). 64 electrodes with 1.0[mm] in diameter, 2.0[mm] interval are arranged to cover the index finger. A force sensor under the electrode array measures finger pressure.

According to the mouse motion, the stimulation pattern is changed so that the subject feels the existence of a stationary object under the skin. Stimulation frequency is set as a function of mouse speed, so that the spatial frequency of the virtual surface, or so-called ”texture” is presented.

Fig. 20. Electric Mouse. 64electrodes, 2.0mm interval.(Top) Whole view (Bottom Left) Front view. (Bottom Right) Load cell to measure finger pressure.

D. SmartTouch:A new interface to touch the real world

The second application is named SmartTouch, which is a new tactile interface to enhance tactile sensation.

The interface is essentially composed of a tactile display and a sensor, both mounted on the skin. When contacting an object, information acquired by the sensor is translated into tactile sensation by a tactile display. Thus, the person not only can make physical contact with the object, but also

”touch” surface information of any modality. SmartTouch ultimately serves as a new functional layer of the skin (Fig.21).

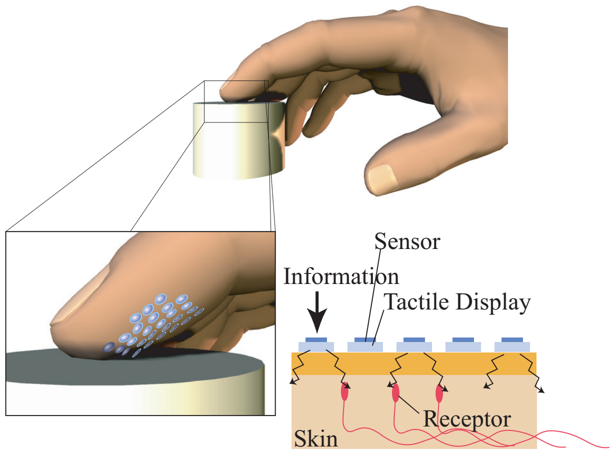

Fig. 21. SmartTouch: A new functional layer of the skin composed of a sensor and a tactile display [16].

Fig.22 depicts one realization of SmartTouch. It is composed of three layers. The first layer has electrodes on the front side of a thin plate, the second has optical sensors on the reverse side of the plate, and the third is a thin force sensor between the other two layers.

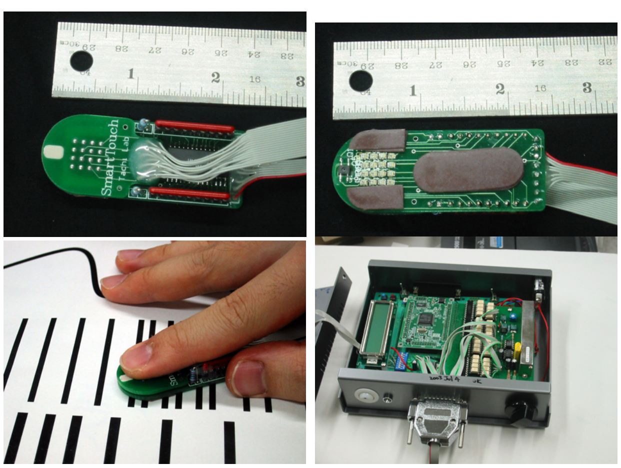

Fig. 22. One realization of SmartTouch with optical sensors. (Left Top)Electrodes on top surface. (Right Top)Optical Sensors on bottom surface. (Left Bottom) Usage. (Right Bottom) Electrical Circuit.

Visual images captured by the sensor are translated into tactile information, and displayed through electrical stimulation. As the system facilitates the recognition of printed materials through tactile sense, it could be applied as a Braille display for the visually impaired. The total thickness of the system is 5.0[mm].

There have been extensive research efforts on visual-to-tactile conversion systems. Bliss [4, 5] has developed the first converter system, while Collins [7] employed electrical and mechanical stimulation at the skin of the back. The representative commercial product Optacon [28] was developed in 1960s using a video camera and a matrix of vibrating pins. However, their aim was for a visually impaired person to read printed material, but not to ”augment” the real world. Specifically, in their system, the participant must have a video camera in one hand and tactile information is displayed onto the other hand. On the contrary, in our system, the optical sensor and the tactile display are located at practically the same place, and work in combination as a new skin ”receptor”.

Our goal for SmartTouch is to achieve a very thin display and sensor directly mounted on the skin to serve as a new functional layer so that the system can be worn as an unconscious daily interface. If we could “print” electrodes on the skin directly by using conductive ink or a disposable tattoo, we could reduce the thickness of the display to virtually zero.

V. Conclusion and Future Work

In this paper, we showed the basic principles of electro-tactile display and its typical application.

In Sec.II, after introducing the notion of Activating Function, selective stimulation was formulated as a linear programming problem, which gave us an optimal weight pattern of electrodes. Tactile primary colors with electro-tactile display were designed using thie method, named RA mode, SAI mode and PC mode.

In Sec.III, the designed tactile primary colors were evaluated through psychophysical experiments. The generated sensations in each mode agreed well with our hypothesis that the desired mechanoreceptor’s nerves are selectively activated. We showed one quantitative evaluation of RA mode using a frequency discrimination test. Of course, if direct measurement of nerve activity is possible, it would be the most direct evidence of selective stimulation. We are currently exploring this possibility [22].

In Sec.IV, we showed some applications. Until now, there were only two types of applications for tactile display. One is a Braille system for the visually impaired, and the other is a haptic device that adds realism to the virtual world by obtaining tactile textures. What we try to emphasize with SmartTouch is that when sensor and tactile displays are combined, tactile display may be used to augment the real world.

We also showed the fundamental limitation of electro-tactile displays, which is caused by the fact that we cannot selectively stimulate PC, which resides in the deeper tissue, because the shallow part is inevitably co-activated. This limitation was observed as the limitation of frequency perception, in which pulses with more than 100[Hz] were not interpreted correctly. This limitation was already reported in the 1970’s [31], although there has never been an explanation based on receptor activity.

To overcome this limitation, we are considering a hybrid method of applying mechanical and electrical stimulation simultaneously. Mechanical stimulation aims to selectively stimulate PCs, while electrical stimulation targets RA corpuscles. Selective stimulation of the PC with a mechanical vibrator is not so difficult, because the PC has the highest resonant frequency (about 250[Hz]) of all receptors. At the same time, the density of PC's in the skin is relatively low. Therefore, the only requirement for PC selective stimulation is to fabricate a sparse mechanical vibrator matrix and vibrate it at high frequency. On the contrary, the RA is densely populated (1[mm-2]), and the fabrication of an appropriately dense display with electrodes is far more practical than using mechanical stimulators.

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APPENDIX

A. Understanding nerve activity as a heat transfer function

The basic heat transfer equation is

$$\frac{\partial u}{\partial t} = \kappa \frac{\partial^2 u}{\partial x^2}. \tag{19}$$

We now transform Eq.1 to Eq. 19. Introducing variable W

$$V_\mathrm{m} = \exp(-\frac{t}{\tau})W, \tag{20}$$

Temporal and spatial differential of V_m is represented as

$$\frac{\partial V_\mathrm{m}}{\partial t} = -\frac{t}{\tau}\exp(-\frac{t}{\tau})W + \exp(-\frac{t}{\tau})\frac{\partial W}{\partial t} \tag{21}$$

$$\frac{\partial^2 V_\mathrm{m}}{\partial x^2} = \exp(-\frac{t}{\tau})\frac{\partial^2 W}{\partial x^2}. \tag{22}$$

Substituting into Eq. 1, we obtain

$$\exp(-\frac{t}{\tau})(-\frac{\lambda^2}{\tau}\frac{\partial^2 W}{\partial x^2} + \frac{\partial W}{\partial t}) = \frac{\lambda^2}{\tau}\frac{\partial^2 \mathbf{\Psi}}{\partial x^2}. \tag{23}$$

If there is no stimulation, the right-hand side vanishes. Therefore,

$$\frac{\partial W}{\partial t} = \frac{\lambda^2}{\tau}\frac{\partial^2 W}{\partial x^2}. \tag{24}$$

This is the ordinary heat-transfer equation.