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Tactile Feeling Display using Functional Electrical Stimulation

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Abstract

We proposed an electro-cutaneous display which stimulate three types of mechanoreceptors in human skin separately. We call these stimuli "tactile primary colors." Two methods are suggested. One is to use array electrodes that are properly weighted. The other is to use anodic current stimulation as well as cathodic current. We also developed experimental system and tested these methods. Qualitative results suggested that the designed stimuli succeeded in activating desired mechanoreceptors' axons.
Key words: tactile display, electrocutaneous, array electrodes, anodic stimulation, functional electrical stimulation

1. Introduction

"Tactile feeling" is a sensation produced in your skin when you touch or rub something. If we generate tactile feeling in VR(Virtual Reality) space, we can not only experience more realistic presence, but also perform more difficult tasks.

Most previous works on tactile displays [5] are variations of pin-head type, or belt type displays, which move vertically or horizontally on the skin. They are mechanical devices and have some difficulties. They are huge, difficult to fabricate, and not able to produce all kinds of cutaneous sensations.

Some other studies proposed to use electric current as a stimulus. Though fabrication became much easier, most of them lacked principle and stayed ad-hoc system, because they didn't fully understand what was happening inside skin.

Our first step is to consider mechanisms of tactile sensation. There are four types of mechanoreceptors in human skin. Meissner corpuscle (RA), Merkel cell (SAI), Ruffini ending (SAII) and Pacinian corpuscle (PC). As population of SAII is small in human finger, we only consider RA, SAI and PC from now on. In principle, if one can stimulate these mechanoreceptors separately, combinations of these stimuli should be able to produce any tactile feeling.

With this in mind, we propose a new electro-cutaneous display with three modes which stimulate RA, SAI and PC separately. We name these modes "tactile primary colors" after three primary colors (RGB) which stimulate different types of cone cells in human retina.

Second step is to consider mechanisms of electrical stimulation. We control current source distributed on skin surface and activate innervating nerve fiber indirectly. Then, activation probability can be written as a function of current source distribution on the skin. This function will be a clue for designing stimulation modes.

Two methods are presented. One is to use arrayed electrodes instead of single one. The other is to use anodic current as a stimulation, as well as cathodic current.

We also developed experimental system and tested the above methods.

2. Structure of human skin

Fig.1 is cross section of human glabrous skin(Reconstructed from [9],[14]). RA and PC are considered to perceive vibration, while SAI is said to perceive pressure. Sometimes RA and PC are considered as velocity and acceleration sensors while SAI is considered as position sensor[10]. Two characteristics are known.

- Each kind of mechanoreceptor resides in different specific depth.
- Nerve axon which is connected to each kind of mechanoreceptor has different specific diameter.

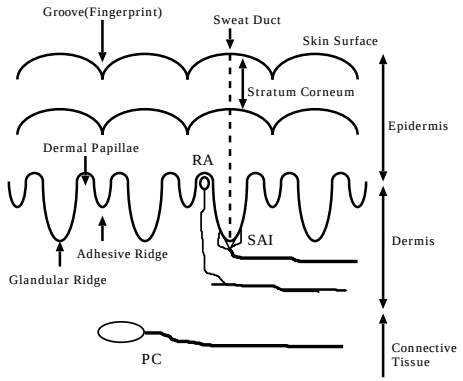

Fig.1: Cross section of human skin. RA: Meissner Corpuscle, SAI: Merkel Cell, PC: Pacinian Corpuscle

Table 1 is depth of mechanoreceptors and diameter of nerve fiber which are connected to them. Note that

Table 1: Depth of mechanoreceptors and diameter of nerve axons in human fingerpad)

	Depth (mm)	Diameter(μm)[13]
Meissner(RA)	0.7	3∼5
Merkel(SAI)	0.9	7∼12
PC(Pacinian)	2.0∼	5∼13

depths are measured at human fingerpad. It is different in other parts of the body.

Major characteristic of fingerpad skin is the thickness of stratum corneum (Fig.1). It is about 600μm in fingerpad while 15μm in other part of the body [18],[19]. Depth of dermal papillae is about 700μm and we regard it as the RA depth. We calculate SAI depth from glandular ridge height (about 200μm in fingerpad). PC resides just beneath the dermis. It's depth is about 2 to 3 mm.

Mechanoreceptor axon is classified as Aβ type, which is largest in all afferent fibers in finger. Note that RA axon (4μm) is thinner than other 2 receptor axons (10μm). There are other afferent fibers such as pain, warmth, and cold. Their diameters are about 1μm. Because of this difference, electrical stimulation of Mechanoreceptor nerves are much easier than that of other afferent nerves. We will re-examine this fact in section4.

2.1. Axonal pathway

As we will see in later sections, axonal orientation and depth are the most important factors for electrical stimulation. Unfortunately, there are very few comparative works around them and we need some speculations.

RA axon branches from the superficial dermal nerves and ascend to the epidermis. Therefore, RA axon in fingerpad is perpendicular to the skin surface[14], especially near the surface.

Pathway of SAI nerve is not well known, though some drawings showed that it is horizontally oriented [12]. We temporary assume it to be horizontal. Most of PC axons are also horizontally oriented.

3. Principle of electrical nerve stimulation

In this section, we show principle of electrical stimulation. Most derivations are from [16] and [17].

First, we model nerve axon (Fig. 2)[1].We take the x axis in the direction of nerve fiber. Membrane is expressed by membrane capacitance (C_m), membrane conductance (G_m) and internal conductance(G). Let electric potential outside and inside membrane be $\Psi(x,t)$, $V(x,t)$, potential difference $V-\Psi$ be $V_m(x,t)$. What we can do is to apply $\Psi(x,t)$ and manipulate $V_m(x,t)$ indirectly.

From Kirchhoff's law, membrane current density $I_m(x,t)$ must be equal to the leak of internal current $I(x,t)$ along x direction. I_m is also the sum of current flowing C_m and G_m. Hence,

$$I_m(x,t) = -\frac{\partial I(x,t)}{\partial x} = C_m\frac{\partial V_m(x,t)}{\partial t} + G_m V_m(x,t). \quad (1)$$

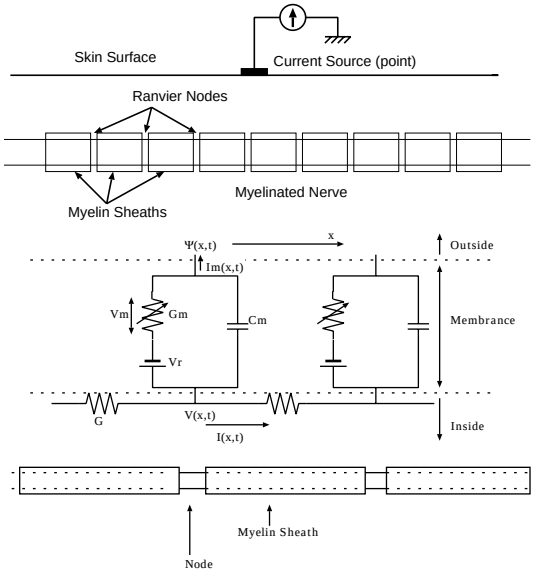

Fig.2: Electrical stimulation of nerve axon from skin surface. Cross section and equivalent circuit.

As internal current $I(x,t)$ can be expressed by internal potential gradient,

$$I(x,t) = -G\frac{\partial V}{\partial x}. \quad (2)$$

Substituting Eq(2) into Eq(1),

$$G\frac{\partial^2 V}{\partial x^2} = C_m\frac{\partial V_m(x,t)}{\partial t} + G_m V_m(x,t). \quad (3)$$

Though nonlinear property of ion channels (expressed by G_m) plays fundamental role in firing and propagation of signals[4], we assume nerve axon to be linear, time invariant system (Specifically, assume G_m to be constant). Then we can do some analysis as follows.

From now on, differential is expressed by suffix. Expressing V_m by $V-\Psi$,

$$-\lambda^2 V_{xx} + \tau V_t + V = \tau\Psi_t + \Psi \quad (4)$$

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

By taking the Fourier transform of Eq(4) with respect to x, we get

$$\lambda^2\omega^2\tilde{V} + \tau\tilde{V}_t + \tilde{V} = \tilde{\Psi} + \tau\tilde{\Psi}_t \quad (5)$$

where $\tilde{V}$ and $\tilde{\Psi}$ are the Fourier transform of V and Ψ, while ω is corresponding spacial frequency.

By taking Laplace transform of Eq(5) with respect to time t, we get

$$(\lambda^2\omega^2 + s\tau + 1)\bar{\tilde{V}} = (1+s\tau)\bar{\tilde{\Psi}} \quad (6)$$

where $\bar{\tilde{V}}$ and $\bar{\tilde{\Psi}}$ are the Laplace transform of $\tilde{V}$ and $\tilde{\Psi}$.

From Eq(6),

$$\bar{\tilde{V}}(s,\omega) = \frac{1+s\tau}{1+s\tau+\lambda^2\omega^2}\bar{\tilde{\Psi}}(s,\omega). \quad (7)$$

Substituting $V_m = V - \Psi$, we get

$$\bar{\tilde{V}}_m(s,\omega) = \frac{-\lambda^2\omega^2}{1+s\tau+\lambda^2\omega^2}\bar{\tilde{\Psi}}(s,\omega). \quad (8)$$

This is the basic equation which express relationship between V_m and Ψ.

Assume $\Psi(x,t)$ can be expressed by $w(t)u(x)$. Then

$$\Psi(x,t) = w(t)u(x) \quad (9)$$
$$\bar{\tilde{\Psi}}(s,\omega) = \bar{w}(s)\tilde{u}(\omega). \quad (10)$$

From now on, we consider the impulse input case, or $\bar{w}(s) = 1$.

Substituting $\bar{w}(s) = 1$ into Eq(8),

$$\bar{\tilde{V}}_m(s,\omega) = \frac{-\lambda^2\omega^2}{1+s\tau+\lambda^2\omega^2}\tilde{u}(\omega). \quad (11)$$

By inverse Laplace transform,

$$\tilde{V}_m(t,\omega) = -\frac{\lambda^2\omega^2}{\tau}\exp^{\frac{-\lambda^2\omega^2}{\tau}t}\tilde{u}(\omega). \quad (12)$$

As V_m is obviously monotonically decreasing along time, maximum value of V_m can be obtained by substituting $t = 0$.

$$\tilde{V}_m(t=0,\omega) = -\frac{\lambda^2\omega^2}{\tau}\tilde{u}(\omega). \quad (13)$$

By inverse Fourier transform,

$$V_m(t=0,x) = \frac{\lambda^2}{\tau}u_{xx}(x). \quad (14)$$

Right hand side of Eq(14) is called "activating function" (AF), or sometimes refered to as "stimulating function" [2],[3]. It is the measure of maximum membrane voltage and membrane current when impulse external stimulation is applied, and hence, good criterion to decide whether considering nerve will fire or not.

Following properties are observed.

- It is proportional to $u_{xx}(x)$, which is second spatial derivative of electric potential along fiber.
- $\frac{\lambda^2}{\tau}$ is unique property of each nerve axon.

Note that assuming nerve will fire at any point of axon, we can judge wether it will fire or not by evaluating maximum value of activating function along fiber. This argument will be repeatedly used in later sections.

4. Activating function

In this section, we observe activating function more carefully by decomposing Eq(14) into two parts.

4.1. $\frac{\lambda^2}{\tau}$

First part of activating function is $\frac{\lambda^2}{\tau}$, which is unique property of each axon.

$$\frac{\lambda^2}{\tau} = \frac{G_m}{C_m}\frac{G}{G_m} \quad (15)$$
$$= \frac{G}{C_m} \quad (16)$$

where G and C_m are internal conductance and membrane capacitance of axon with unit length.

Assume that the nerve is non-myelinated (or all part of membrane is uncovered). If axonal diameter is increased by n times, G and C_m becomes n^2 and n times bigger. Therefore, activating function is multiplied by n.

However, most mechanoreceptor fibers are myelinated (or most part is sealed and only "Ranvier node" is uncovered). In this case, when axonal diameter becomes n times bigger, C_m doesn't change because gap length of Ranvier node is constant and distance between each node is proportional to diameter. G becomes n^2times bigger and hence, activating function is multiplied by n^2.

When you compare myelinated and non-myelinated fibers with the same diameters, activating function of myelinated axon is always much bigger than that of non-myelinated one, because C_m for non-myelinated axon is typically 10^1 to 10^3 times bigger.

As mentioned in section2, axonal diameters of mechanoreceptors are about 10^1 times bigger than other afferent fibers (pain, warmth, cold, etc). Furthermore, mechanoreceptor axon is myelinated while other afferents are non-myelinated. In conclusion, activating function of mechanoreceptors are much bigger than that of other afferents so that we can selectively stimulate mechanoreceptor nerves easily.

4.2. $u_{xx}(x)$

Second part of activating function is second derivative of electric potential along axon. Electric potential is generated by input current from skin surface. Therefore, activating function should be expressed by current source distribution on the surface.

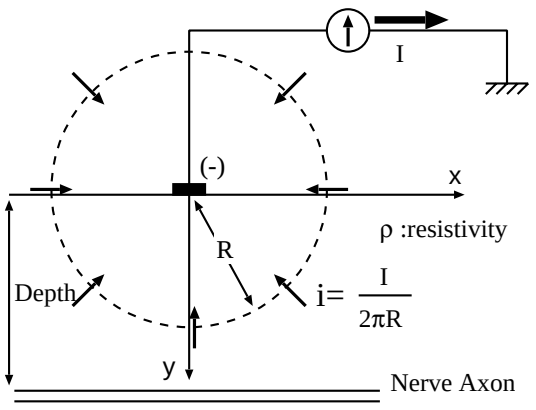

Fig.3: Current stimulation from skin surface. 2D, single line electrode case

First we consider single line electrode with cathodic current I(Fig.3). For simplicity, we assume uniform infinite space. Take x axis parallel to skin surface and y axis in the direction of skin depth. Letting the electrode coordinate be origin, current density i at (x,y) is expressed as

$$i(x,y) = \frac{I}{2\pi R}, \tag{17}$$

where $R = \sqrt{x^2+y^2}$ is distance from electrode. Electric potential Ψ at (x,y) is

$$\begin{aligned} \Psi(x,y) &= -\int \vec{E} d\vec{R} && (18)\\ &= -\int_R i\rho dR && (19)\\ &= -\int_R \frac{I}{2\pi R}\rho dR && (20) \end{aligned}$$

where ρ is resistivity.

Assuming that electric potential of infinite distance is 0, we get

$$\Psi(x,y) = \frac{-\rho I \log(R)}{2\pi}. \tag{21}$$

Now we will calculate activating function (AF). If the axon lies in x direction,

$$\begin{aligned} AF &\propto \frac{\partial^2 \Psi(x,y)}{\partial x^2} && (22)\\ &\propto \frac{y^2-x^2}{(x^2+y^2)^2}. && (23) \end{aligned}$$

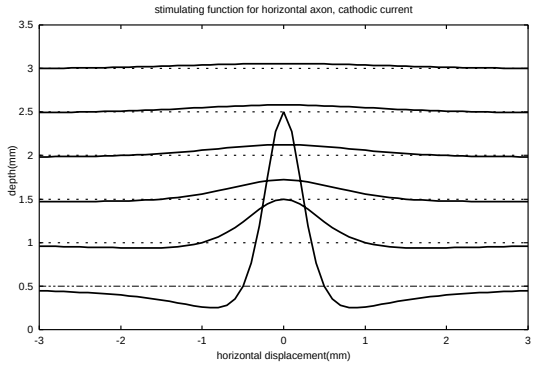

Fig.4: Activating function for horizontal axon. Cathodic (-) single current case.

Fig.4 is the plot of Eq(23). Following two things are observed.

- Activating function takes the maximum value when $x = 0$. It is directly under electrode. As $AF_{x=0} \propto 1/y^2$, it decreases in inverse proportion to square of axon depth y. It means shallower part of nerve is easier to stimulate.
- This is the activating function for horizontal axon, cathodic single current case. Therefore, if current becomes anodic(+), plot will be reversed and activating function will have minus value. This is the reason why most previous works on functional electrical stimulation used cathodic current as stimulus.

Eq(23) is for the case when current source distribution is $I\delta(x)$. In general, it is distributed on the skin surface. Hence,

$$AF(x,y) \propto \int I(x') \frac{y^2-(x-x')^2}{((x-x')^2+y^2)^2} dx'. \tag{24}$$

For arrayed electrodes case(Fig.5),

$$AF(x,y) \propto \sum_{i=1}^{M} I_i \frac{y^2-(x-x_i)^2}{((x-x_i)^2+y^2)^2}, \tag{25}$$

where I_i the current from ith electrode, M the number of electrodes and x_i the coordinate of ith electrode.

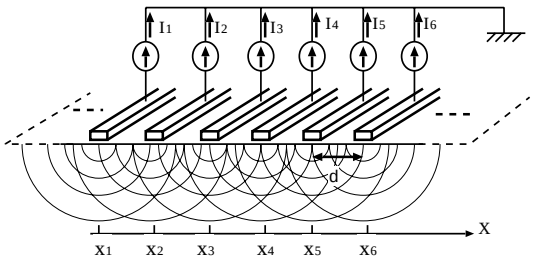

Fig.5: 1-D arrayed electrodes

5. Three stimulation modes, or "tactile primary colors"

As discussed before, if we can stimulate SAI, RA and PC separately, combinations of these stimuli, or "tactile primary colors" should be able to produce any cutaneous sensation. We call each of these colors "RA mode", "SAI mode" and "PC mode". From now on, utilizing activating function introduced in section4we show how to create such modes.

5.1. RA mode by anodic current

First we consider RA mode, which stimulate RA axon uniquely. The fact that direction of RA axon is perpendicular to skin surface changes the activating function dramatically (Fig.6).

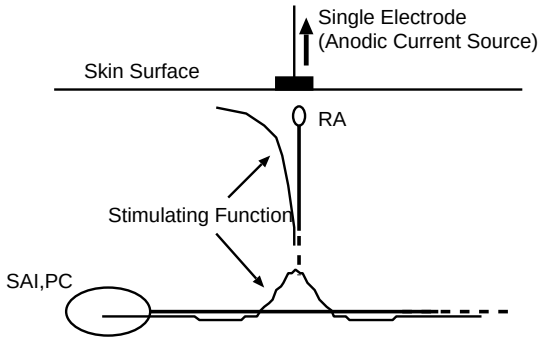

Fig.6: Cathodic current stimulation. Activating function of horizontal axon is positive while that of vertical axon is negative.

As discussed in section4.activating function is second spatial derivative of electric potential along fiber. Therefore, AF of horizontally oriented axon is d^2V/dx^2 while that of vertical axon is d^2V/dy^2. From Gauss's law,

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0 \tag{26}$$

for space where no electric charge flows out. Therefore,

$$\frac{d^2V}{dy^2} = -\frac{d^2V}{dx^2} \tag{27}$$

always holds true. Hence ordinary cathodic current can't stimulate vertically oriented nerve axon such as RA, because activating function takes negative value.

Now we will use anodic (positive) current as stimulus. Then electric potential is reversed so that activating function is reversed (Fig.7). In this case only vertically oriented nerve axon is stimulated while horizontally oriented axon is suppressed. This is the principle of RA mode.

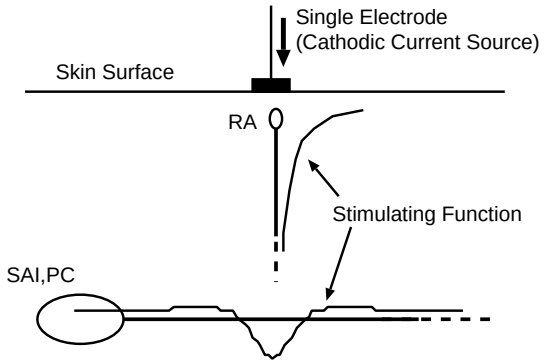

Fig.7: Anodic current stimulation. Activating function is reversed and only vertical axon is stimulated.

Kaczmarek[6] has reported that in his experiment, he observed that anodic pulse, as well as cathodic one seemed to evoke some kind of sensation. Though he was not aware at that time, we suppose he was stimulating RA axon.

5.2. SAI mode by weighted array electrodes

Second, we consider SAI mode, which stimulate SAI afferent fiber uniquely. SAI and PC fibers are horizontally oriented. Thought RA axon is also horizontal in deep dermal region (Fig.1), we don't need to consider it because diameter of RA axon fiber is about half of that of PC and SAI(Table1) and hence, activating function is one-fourth at the same depth (as we discussed in section5.). We utilize the fact that SAI axon resides in shallower part than PC axon.

Fig.8 is activating function of SAI and PC when single cathodic current is used. As SAI is shallower than PC, activating function of SAI is bigger than PC so that we can stimulate SAI separately. Furthermore, If we use arrayed electrodes, We can make activating function of SAI much bigger while suppressing that of PC.

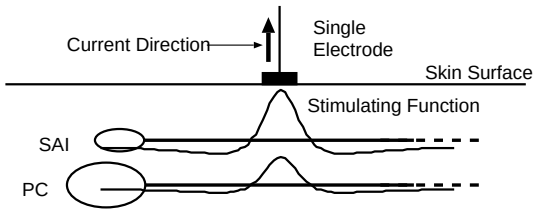

Fig.8: Merkel and Pacini stimulation by single electrode.

Adding anodic current around central cathodic current, attenuation of activating function becomes faster so that we can stably stimulate only SAI (Fig.9). This is the principle of SAI mode. Note that in this case, "array" is not used to express pixels (which is the case of many previous electrocutaneous displays), but as a kind of beamformer which form required activating function at required depth.

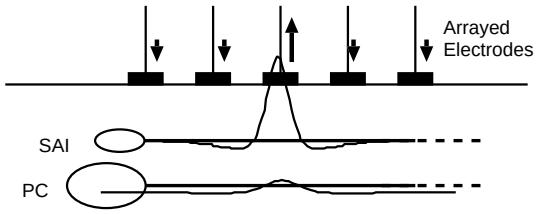

Fig.9: SAI stimulation by arrayed electrodes.

5.3. PC mode by weighted array electrodes

Last one is PC mode. As PC resides deeper than SAI, and axon diameter of PC is about the same as SAI, we can't stimulate PC separately because activating function of PC has smaller maximum value than that of SAI.

Proof of the above argument is as follows.

$$\begin{aligned}
\frac{\partial^2 AF}{\partial x^2} + \frac{\partial^2 AF}{\partial y^2} &\propto \frac{\partial^2}{\partial x^2}\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2}{\partial y^2}\frac{\partial^2 V}{\partial x^2} && (28)\\
&= \frac{\partial^2}{\partial x^2}\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2}{\partial x^2}\frac{\partial^2 V}{\partial y^2} && (29)\\
&= \frac{\partial^2}{\partial x^2}\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) && (30)\\
&= 0 && (31)
\end{aligned}$$

where AF represents activating function for horizontally oriented axon. Last equation is obtained by using Gauss's law (Eq(26)). Therefore, activating function itself is harmonic function. Let depth of SAI and PC be y_1 and y_2. $y_1 > y_2$ because PC resides deeper than SAI. If you set $y = y_1$ as a boundary and consider $y <= y_1$ region, "principle of maximum value" for harmonic function states that

Harmonic function is a function which satisfy Laplace equation.

the activating function takes maximum and minimum value only on the boundary. Therefore, activating function of SAI takes larger maximum value than that of PC.

However, we can stimulate PC, at least as good as SAI by using arrayed electrodes.

Contrary to SAI mode, we add cathodic current stimulation around central cathodic current, so that electrode size becomes virtually bigger. Then, attenuation of activating function becomes slower and PC will have as big activating function as SAI (Fig.10). This is the principle of PC mode.

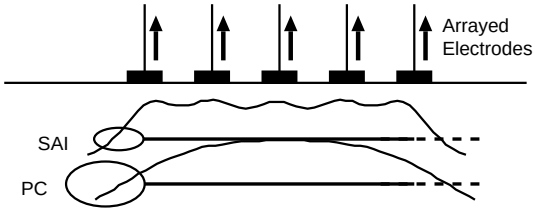

Fig.10: Pacini stimulation by arrayed electrodes.

In Pacinian mode, Merkel is also stimulated. However, in some physiological papers, it was shown that SAI always fires when PC fires, at least to the extent that frequency of mechanical stimulation is less than 200Hz[12]. Therefore, for the present, we think it can be called Pacinian mode.

6. Design and fabrication

We constructed experimental system shown in Fig. 11. Multiplying 1 channel high speed bi-phasic signal by eight channel low speed weight signals, we got synchronized eight waves. V-I converters were used to change them to current stimuli. Subject put his finger on arrayed electrodes while he wore metal ring which was connected to ground.

Arrays were composed of eight line electrodes which were equally spaced. Distance between each electrode is 1mm and electrode size is 0.5mm × 10mm.

For safety, some restrictions were imposed. First, maximum current which flows from one electrode was limited to 2mA. Second, sum of the eight weights was set to 0 so that current was confined locally. Third, time average of bi-phasic pulse was also set to 0 so that electric charge didn't accumulate on the skin.

Fig. 12 is the waveform of high speed bi-phasic signal. Though it seems negative (cathodic) pulse, you can change it to positive (anodic) pulse by multiplying negative weight. Main pulse duration was fixed to 200 μs tentatively.

6.1. Obtaining array weights

In section 5, we saw the principles of three stimulation modes. To obtain actual array weights, we must solve optimization problems. Tentative restrictions are as follows.

- Distance between each array is fixed.

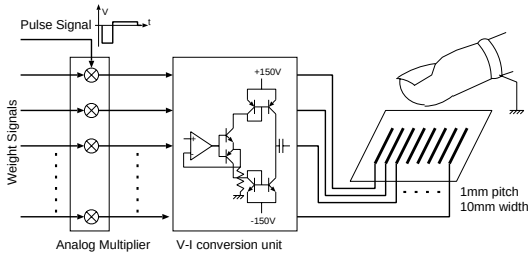

Fig.11: System configuration.

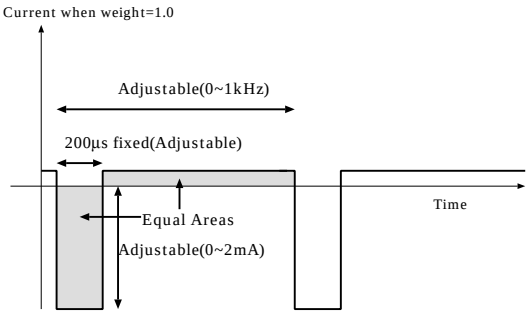

Fig.12: Waveform of input pulse.

- Sum of array weights is 0, as discussed before.

Optimization problems are as follows.
For RA mode:

$$\min_{\vec{w}} \frac{\max_{x,y}(AF_{PC}, AF_{SAI})}{\max_{x,y}(AF_{RA})} \text{ subject to } \sum w_i = 0 \tag{32}$$

where AF_{RA}, AF_{SAI} and AF_{PC} are activating functions of RA, SAI and PC, while $\vec{w}$ is the weighting vector to obtain.

Numerator and denominator of Eq(32) are maximum values of PC, SAI and RA activating function along axon. x and y take the coordinates where axons exist. Eq(32) tries to suppress maximum values of AF for PC and SAI while preserving that of RA, and hence stimulate only RA fiber.

In the same manner, for SAI mode:

$$\min_{\vec{w}} \frac{\max_{x,y}(AF_{PC}, AF_{RA})}{\max_{x,y}(AF_{SAI})} \tag{33}$$

and for PC mode:

$$\min_{\vec{w}} \frac{\max_{x,y}(AF_{RA}, AF_{SAI})}{\max_{x,y}(AF_{PC})} \tag{34}$$

are the optimization problems. Solving these problems numerically, we obtain optimized array weights.

7. Experimental result and discussion

During experiment, some qualitative phenomena are found. They seem to support that each mode is stimulating desired mechenoreceptor's fibers.

7.1. Sensation shift phenomenon in PC mode

In PC mode, current was set to zero at first and gradually increased by subject himself. One interesting phenomenon was observed. The subject felt vibration, and the point of sensation was not just below the electrodes but always 1-3 mm shifted to fingertip direction (Fig. 13).

It convinces us of the fact that the current doesn't stimulate mechanoreceptor itself, but stimulates axon (which was connected to the receptor), which coincides with our previous assumption.

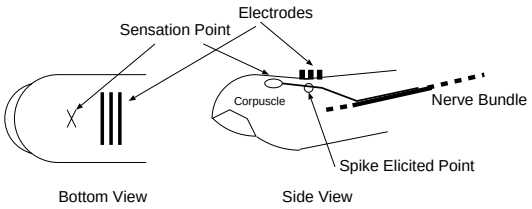

Fig.13: Sensation shift phenomenon. Though nerve axon is stimulated, evoked sensation point is 1-3 mm shifted to fingertip direction

7.2. Pressure sensation in SAI mode

In SAI mode, when current was gradually increased from 0, sensation changed as follows.

- At 0.2mA (cathodic current of central electrode), very tiny tremble sensation occurred.
- At 0.4mA, subject felt pressure in the shape of central electrode. As we used line electrodes, it was like touching knife-edge.
- At 0.6mA, new sensation of vibration was evoked, as well as pressure.

Stimulating frequency was always 200Hz. It is reasonable that SAI mode evoked pressure sensation, because many previous works [7],[8],[11],[12] suggested that Merkel cell senses pressure.

Vibratory sensation evoked after pressure might have been caused by PC stimulation, because SAI and PC are the same cathodic stimulation.

7.3. Sensation of soft material in SAI mode

As mentioned before, when pressure sensation was stably presented in SAI mode, subject felt knife-edge shaped pressure. Then, he was asked to move his finger up and down slightly while contact area didn't change so much. At this instance, feeling of knife-edge suddenly changed to soft elastic rod (Fig.14).

It is explained as follows. Many works on nerve information coding suggested that Merkel cell changes pressure to firing frequency [12]. Now, assume if one touches hard object. Then one's finger movement directly affects pressure inside skin, so that firing frequency changes. On the other hand, if one touches soft material, though one's finger moves up and down, finger pressure doesn't change so much and hence, firing frequency doesn't change. In our case, we didn't change stimulating frequency while moving finger. Therefore, subject's brain guessed that it was soft material. This is the reason why subject felt "soft material" feeling.

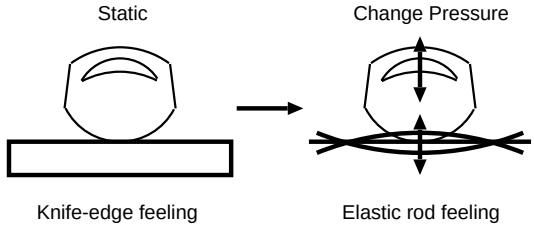

Fig.14: SAI mode experiment. Subject felt knife-edge at first, but when he slightly moves his finger up and down, it changed dramatically to elastic rod though contacting area didn't change.

7.4. Vibratory sensation in RA mode

In RA mode, subject felt vibration and that sensation was quite stable. If the pulse frequency was less than 100 Hz, generated sensation was quite the same as touching vibrating speaker cone. However, if the frequency was higher than 200Hz, subject received strange feeling which was quite uncomfortable.

It may be explained as follows. We were stimulating RA axon. RA is known to respond to low-frequency mechanical vibration (20-70Hz) [12] and at that range, firing frequency is the same as vibration frequency. Therefore in our case, subject felt vibratory sensation of the same frequency as electrical stimulation. However, stimulation of RA by more than 200Hz was unnatural situation, which lead to uncomfortable feeling.

We stated in section 2.1, that direction of SAI axon is not exactly known but temporary assumed to be horizontal. If it is vertically oriented, it should also fire in RA mode, because RA mode stimulate vertically oriented axons. However, in this experiment, the subject only felt vibration and pressure sensation was not generated. This fact seems to support our assumption. The other possibility is that pressure sensation might have been masked by vibratory sensation. In either case, we can say that RA stimulation mode is made.

8. Conclusion

We proposed a new electro-cutaneous display with three modes which stimulate RA, SAI and PC separately. We introduced "activating function" as a measure for nerve activation. Using this function, we designed current source distribution on skin surface for three modes.

For RA mode, we used anodic current to stimulate only vertically oriented axon. For SAI and PC modes, we used array electrodes which are properly weighted.

We also constructed experimental system. In the experiment we found three phenomena. Sensation shift in

PC mode, Pressure feeling in SAI mode and Vibratory feeling in RA mode. These phenomena suggested that our designed "primary colors" succeeded in stimulating desired mechanoreceptors.

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