Electro-tactile Display: Principle and Hardware

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Abstract An electro-tactile (electrocutaneous) display is a tactile display that directly activates sensory nerves in the skin by electrical current supplied from an electrode on the skin surface. Compared with a mechanical tactile display that is typically composed of vibrating pins, the electro-tactile display has several merits, such as thinness and mechanical robustness. However, there remain several issues to be solved, such as stabilization. Furthermore, the development of the electro-tactile display requires certain knowledge of electrical circuits. The present paper thus serves as an introduction to research on electro-tactile displays. We start by explaining the principle of electrical nerve stimulation, introducing how the spatial distribution of the electrical current source affects stimulation using the notion of the activating function, and discuss temporal parameters (i.e., pulse width and pulse height) using a simplified nerve model and introducing the strength–duration curve. A typical hardware design, including a voltage-to-current converter circuit and a switching circuit is then introduced, and the electrode fabrication process and necessity of a conductive gel layer are discussed. Finally, the issue of sensation stabilization is treated with possible solutions.

Keywords: Activating Function, Chronaxie, Electrocutaneous, Electro-tactile display, Rheobase, Strength-Duration Curve

1. Introduction

An electro-tactile (electrocutaneous) display is a tactile display that directly activates sensory nerves in the skin with electrical current from an electrode on the skin surface [1][2]. Compared with a mechanical tactile display that is typically composed of vibrating pins, the electro-tactile display has several merits such as thinness, deformability, low weight, low energy consumption, and mechanical robustness. Its applications include welfare devices for the visually handicapped, virtual reality and telexistence, and touch panels with haptic feedback (Figure 1) [3][4][5][6][7][8].

Several issues relating to the electro-tactile display remain to be solved; e.g., a method of rendering natural tactile sensation needs to be developed, pain felt by the user needs to be minimized, and the strength of the sensation needs to be stabilized.

Furthermore, the development of an electro-tactile display requires certain knowledge of electrical circuits.

Against the background described above, this paper serves as an introduction to research on electro-tactile displays. We first explain the principles of electrical stimulation and typical hardware design. We then go on to discuss current issues relating to the electro-tactile display and their possible solutions.

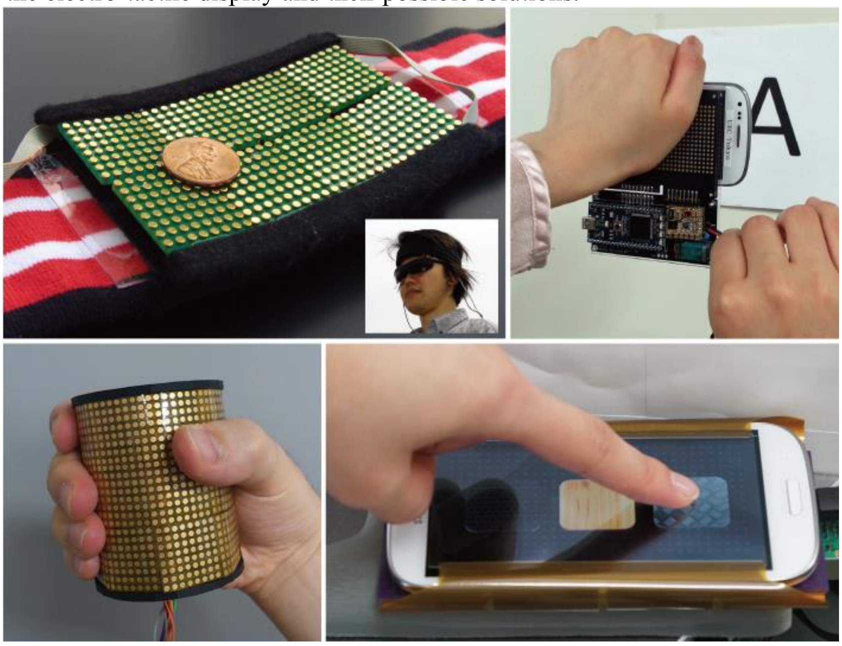

Figure 1 Applications of the electro-tactile display. (Top left) Forehead stimulation for a tactile–vision substitution system (TVSS) [1]. (Top right) TVSS of palm type [4]. (Bottom left) Cylindrical type for virtual-reality application [5]. (Bottom right) Touch-panel type using transparent electrodes [6].

2. Principle of stimulation

The electro-tactile display activates sensory nerves under the skin with surface electrical current. We first introduce how the spatial distribution of the electrical current source (i.e., electrode placement and polarity) affects stimulation using an activating function, and then discuss temporal parameters (i.e., pulse width and pulse height).

2.1. Activating Function

When electric potential is distributed along the outer membrane of a nerve, the nerve is depolarized and activated. This model was first described by McNeal [9], and its use led to the precise modeling and simulation of electrical nerve stimulation. As the model considers the dynamical change of nerve membrane conductance and cannot be used to easily grasp general trends, we introduce Rattay's simple model

[10] that sets nerve electric parameters constant and assumes that the nerve is activated when the nerve membrane potential reaches a certain threshold.

Figure 2 is a schematic of electrodes, skin, and a nerve and the electrical representation of the system. The nerve is composed of a membrane and internal medium. The system is discretized so that one unit is composed of a membrane with conductance G_m and capacitance C_m and an internal medium with conductance G_a. This discretization matches reality when the nerve is myelinated (i.e., the nerve is insulated by a myelin sheath and is only accessible through small gaps in the sheath).

Stimulation of the electrical nerve involves changing the membrane voltage difference V_m by changing the external membrane potential Ψ. The stimulation can be represented by a simple control system, with input Ψ and output V_m. Hereafter, we consider the relationship between input and output.

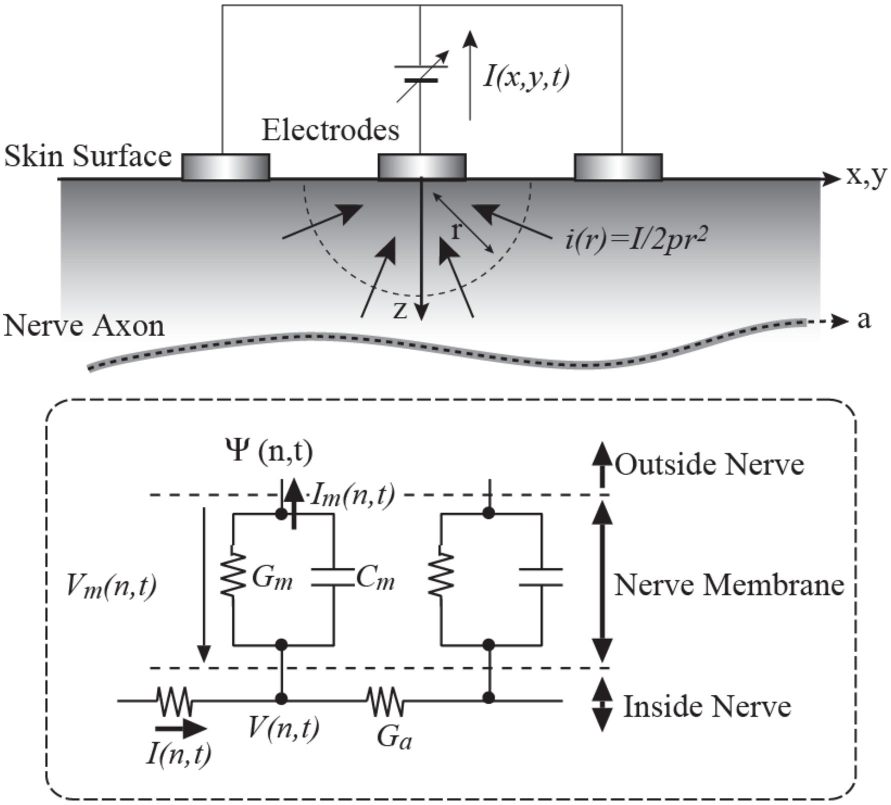

Figure 2 Electrical representation of electrical stimulation. Electrical current I from the skin surface generates a potential distribution. The potential distribution Ψ along the nerve axon generates membrane current I_m, resulting in a membrane voltage difference V_m. G_m: membrane conductance, C_m: membrane capacitance, G_a: internal conductance.

Denoting the membrane current through the nth partition as I_m(n), the internal current as I_a(n), and potentials inside and outside the partition as V_a(n) and Ψ(n), it follows that

$$V_m(n) = V(n) - \Psi(n)\,, \tag{1}$$

$$I_m(n) = G_m V_m(n) + C_m \dot{V}_m(n)\,, \tag{2}$$

$$I_m(n) = I(n) - I(n+1)\,, \tag{3}$$

$$G_a(V(n+1) - V(n)) = -I(n+1)\,. \tag{4}$$

From (3) and (4), it follows that

$$I_m(n) = G_a(V(n+1) - 2V(n) + V(n-1))\,. \tag{5}$$

From (2) and (5), it follows that

$$G_a(V(n+1) - 2V(n) + V(n-1)) = G_m V_m(n) + C_m \dot{V}_m(n)\,. \tag{6}$$

Substituting (1) into (6) yields

$$\begin{aligned} &C_m \dot{V}_m(n) + G_m V_m(n) - G_a(V_m(n+1) - 2V_m(n) + V_m(n-1)) \\ &= G_a(\Psi(n+1) - 2\Psi(n) + \Psi(n-1)) \end{aligned}\,. \tag{7}$$

As the term on the right and the third term on the left are spatial second-order differentials, rearranging the constant values yields

$$-G_a \frac{d^2}{dx^2} V_m + C_m \frac{d}{dt} V_m + G_m V_m = G_a \frac{d^2}{dx^2} \Psi\,. \tag{8}$$

This is a kind of one-dimensional heat transfer equation, where V_m can be regarded as temperature, the right hand side as input heat, and the third term on the left as heat radiation. As the purpose of electrical stimulation is to raise V_m (temperature) above a certain threshold, the right hand side (input heat) directly relates to the strength of the electrical stimulation. This term, a second-order spatial differential of the external membrane potential, is called the activating function [10].

The external membrane potential Ψ is formed by the distribution of electrical current. For example, let us consider the case when the electrical current is generated by a single point current source as in Figure 2, and the medium is uniform. In this case, the equipotential surface is a hemisphere, and the potential distribution can be obtained by integrating current density along distance r from the current source [9]. In the case of multiple electrodes, if all electrodes are current-controlled, we can obtain the potential distribution by the superposition of potentials from each electrode.

Figure 3 shows the activating function produced by cathodic (negative) current from a single electrode. Here we assume that the nerve runs parallel to the skin surface, and the second-order differential is taken horizontally. We observe the following characteristics.

- For the nerve that runs parallel to the skin surface, there is a positive activating function in the case of cathodic current. This means that the nerve can be depolarized and activated.
- The activating function decreases as the nerve goes deeper. This means that deeper nerves are more difficult to activate.

The first characteristic is the reason why cathodic current stimulation is normally applied. We note that if the nerve runs perpendicular to the skin surface, the second spatial differential along the nerve takes a negative value, and we choose anodic (positive) stimulation. We address this topic in section 2.3.

The second characteristic holds true not only in the case of a single electrode but also in the case of multiple electrodes. In other words, we cannot form a “local peak” of the activating function “inside” the tissue. This interesting limitation can be understood from the previously introduced analogy. No distribution of heaters can generate a local peak in temperature if the medium obeys the heat transfer equation.

However, it does not necessarily follow that selective activation of a deeper nerve is impossible. For example, as we will see in section 2.2, thicker nerves are easier to activate, allowing the selective activation of deeper nerves if the deeper nerves are thicker.

The above discussion is for the case of a single electrode, assuming ground at infinity. In practical situation, concentric electrodes comprising a central stimulating electrode and peripheral ground electrode are used (Figure 4). In this case, the ground is anodic (i.e., electrical current flows from the electrode). Considering the superposition of the activating function for each electrode, the activating function from peripheral ground electrode partly cancels the activating function from the central stimulating electrode. This results in confinement of the stimulation to a small and shallow region.

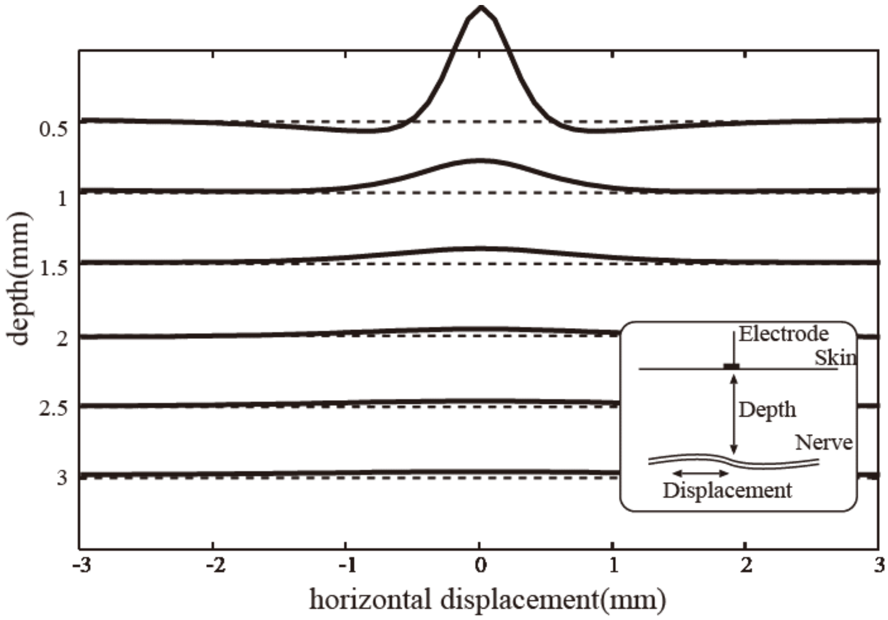

Figure 3 Activating function of cathodic current from a single electrode, assuming the nerve runs parallel to the skin surface.

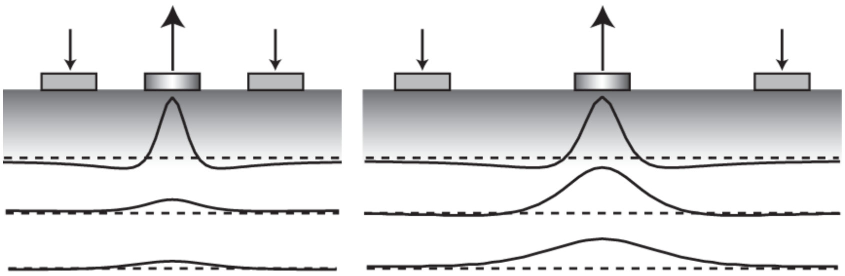

Figure 4 Relationship between the activating function and the diameter of the concentric electrode. A larger inter-electrode distance results in greater and deeper stimulation.

2.2. Strength–Duration Curve

The activating function introduced in section 2.1 provides insight into the spatial design of electrical stimulation, such as the design of the electrode size and polarity. We also need to consider the temporal design; i.e., the waveform. While there have been several studies on the optimal waveform, especially in the field of electrical muscle stimulation. We simply consider a rectangular wave and two parameters: the pulse height and pulse width.

We consider a simplified model of a nerve as in Figure 5. The nerve is represented by internal conductance G_a, membrane conductance G_m, and membrane capacitance C_m. As the electrical current from the surface electrode is converted to a potential distribution, the input to this model is voltage Ψ. The purpose of electrical stimulation is to raise V_m above a certain threshold by operating Ψ.

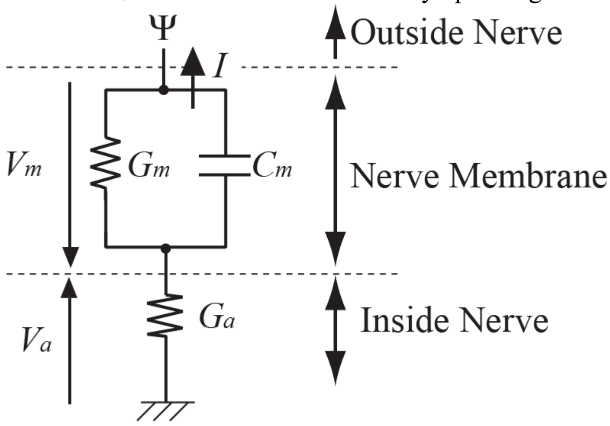

Figure 5 Simplified model of electrical nerve stimulation.

First, we set the differential equation

$$V_m = V_a - \Psi\,, \tag{9}$$

$$I = G_m V_m + C_m \dot{V}_m = -G_a V_a\,. \tag{10}$$

Substituting (9) into (10) yields

$$V_m = -\frac{G_m V_m + C_m \dot{V}_m}{G_a} - \Psi\,. \tag{11}$$

The Laplace transform of (11) gives

$$\tilde{V}_m = -\frac{G_a}{C_m}\left(\frac{1}{s + \dfrac{G_a + G_m}{C_m}}\right)\tilde{\Psi}\,. \tag{12}$$

We now consider a step input $-V$ (cathodic stimulation):

$$\Psi(t) = \begin{cases} 0 & (t < 0) \\ -V & (t \geq 0) \end{cases}. \tag{13}$$

Substituting the Laplace transform of (13) into (12) and taking the inverse Laplace transform gives

$$V_m = \frac{G_a}{G_a + G_m}\left(1 - \exp\left(-\frac{G_a + G_m}{C_m}t\right)\right)V \quad (t \geq 0)\,. \tag{14}$$

This is the step response of the membrane voltage difference, as in Figure 6.

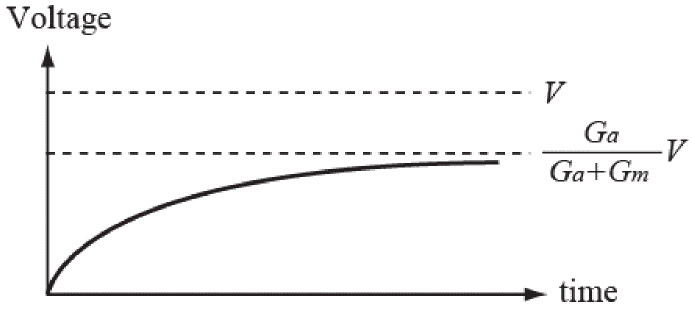

Figure 6 Step response of the membrane voltage difference

Hereafter, we set $b = G_a / (G_a + G_m)$ and $a = (G_a + G_m) / C_m$. The converging value of the step response is written as bV.

Normally, the electrical stimulation is composed of a finite pulse, not an infinite step function. Let the pulse width be denoted T. The condition in which the membrane voltage difference reaches the threshold V_{th} is

$$V_{th} \leq V_m = b(1 - \exp(-aT))V \ . \tag{15}$$

We thus find the important relationship between pulse width T and pulse height V for which the nerve is only just stimulated:

$$V = \frac{1}{b} \frac{V_{th}}{1 - \exp(-aT)} \ . \tag{16}$$

Figure 7 shows this relationship, referred to as the strength–duration curve.

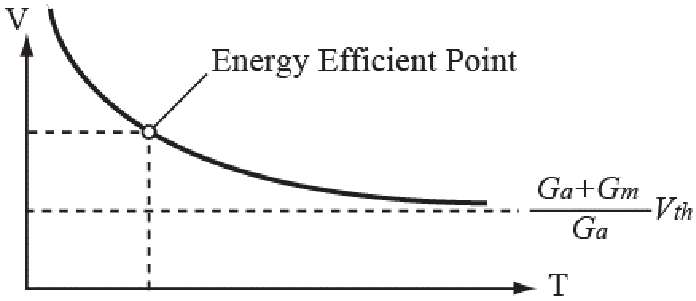

Figure 7 Strength–duration curve showing the relationship between the pulse width and pulse height when the nerve is only just stimulated.

We observe a near inversely proportional relationship between the threshold pulse height and pulse width. This is natural considering that the system is basically supplying an electrical charge to the membrane capacitance, and a larger current results in faster charging.

However, the expression in (16) it is not exactly inversely proportional. For example, we require a certain pulse height when the pulse width is infinite. This value, called the rheobase [13], is calculated as

$$\lim_{T\to\infty}\frac{1}{b}\frac{V_{th}}{1-\exp(-aT)}=\frac{V_{th}}{b}\ . \tag{17}$$

2.2.1. Nerve Thickness and Threshold

Let us consider the relationship between the nerve thickness and ease of stimulation. Considering the relationships between the nerve diameter and nerve parameters G_a, C_m and G_m, as the membrane thickness does not change, G_a is proportional to the cross-sectional area (i.e. proportional to the square of the diameter) of the nerve and C_m and G_m are proportional to the perimeter (i.e., proportional to the diameter) of the nerve. Therefore, as the nerve thickens, V_m in (14) rises more rapidly. A thick nerve thus has a lower threshold than a thin nerve, especially when the pulse is narrow. This difference diminishes as the pulse width increases.

This is one reason why stimulation with a narrower pulse is generally preferred in electro-tactile display, as pain-related nerves are thinner than mechanoreceptor-related nerves. When we consider myelinated nerves, most of the nerve membrane is covered by insulator and the changes in C_m and G_m are more suppressed, leading to much easier stimulation of thicker nerves [11][12].

2.2.2. Optimal Pulse Width

There might be several criteria used to decide the optimal pulse width, such as lower pain sensation or robustness against variations in skin conditions. Here we consider energy consumption as the most basic criterion for optimal electrical stimulation. This leads not only to lower energy stimulation but also to lower pain stimulation, since one cause of pain during electrical stimulation is Joule heat.

We regard energy E to be proportional to V^2T:

$$E\propto V^2T\propto\left(\frac{1}{1-\exp(-aT)}\right)^2T\ . \tag{18}$$

We set the right-hand side as $F(T)$. Differentiating $F(T)$, we obtain the optimal pulse width T_{optim} that achieves minimum energy, and by substituting T_{optim} into (16), we obtain the required pulse height V_{optim}. Numerically obtaining these values, we find the optimal pulse height is 1.4 times the rheobase that we introduced in section 2.2.

The above calculation is derived from the simplified nerve model. However, in the field of electrical stimulation, the relationship between the pulse width and pulse height is generally fitted using an inversely proportional function with an offset:

$$V=c+d/T\ . \tag{19}$$

This modeling does not have a solid physical background. However, with this simple function, the minimum required pulse height is c (rheobase) and the optimal pulse height for minimizing energy V^2T is obtained as

$$E \propto V^2 T \propto (c + d / T)^2 T \,, \qquad (20)$$

$$\frac{\partial E}{\partial T} \propto (c + d / T)(c - d / T). \qquad (21)$$

From (21), the optimal pulse width becomes $T = d / c,$ and the optimal pulse height is $2c$ (twice the rheobase). The required pulse width for minimizing energy is called chronaxie and is an important parameter for electrical stimulation. The chronaxie differs for different types of nerves, and ranges from 0.35 to 1.17 ms for sensory nerves in arms [13].

The above discussion only dealt with the optimization of energy for a single nerve. However, as mentioned before, there are numerous possible criteria for optimality. As we discussed in section 2.2.1, a thick nerve is easier to stimulate than a thin nerve, and this tendency becomes clearer when the pulse is narrower. To avoid pain sensation from the activities of thin pain nerves, the electro-tactile display uses a shorter pulse, generally ranging from 50 μs to 200 μs [8]. The pulse height differs for different pulse widths and electrode sizes. When using electrodes with a diameter of 1 mm, the pulse height is approximately 1 mA to 10 mA.

2.3. Cathodic and Anodic Stimulation

As mentioned in section 2.1, electrical stimulation generally uses cathodic current for stimulation. This means that electrical current enters the skin at the ground electrode, and exits the skin at the stimulating electrode.

There are some cases that anodic (positive) current plays an important role. Kaczmarek discovered that, in the case of fingertip electrical stimulation, the anodic current stimulation has a much lower threshold than the cathodic current [14]. Kajimoto mentioned the possibility of selectively stimulating different types of nerves using different polarities. He further discussed the possibility of achieving any kind of tactile sensation by combining receptor selective stimulations, in what is referred to as the tactile primary color approach [16].

There are two possible reasons why anodic current stimulation is effective in electro-tactile display, although cathodic stimulation is used in general electrical nerve stimulation. The first reason is that, in electro-tactile stimulation, the nerve terminal is close to the electrode, and the simple assumption of an infinitely long nerve fiber does not hold true. The other reason is that the nerves may not run parallel to the skin surface. Physiological studies have revealed that the nerve terminal of Meissner’s corpuscle runs perpendicular to the skin surface. This seems to explain the fact that anodic stimulation mostly generates vibratory sensation, which is the role of Meissner’s corpuscle.

The anodic stimulation has another merit. In an ordinary cathodic stimulation, the sensation elicited point does not coincide with the stimulation point because the sensation is elicited at the mechanoreceptor (i.e., nerve terminal) whereas the electrical stimulation is conducted at the midpoint of the nerve (Figure 8, left). In electro-tactile display, this “sensation shift” is a critical issue. Although we stimulate the finger pad, we feel the sensation at the fingertip, and it is thus not possible to realize a high-resolution tactile display. In contrast, anodic stimulation does not generate this kind of spatial gap, since it activates the nerve terminal or vertically oriented nerves as discussed above (Figure 8, right).

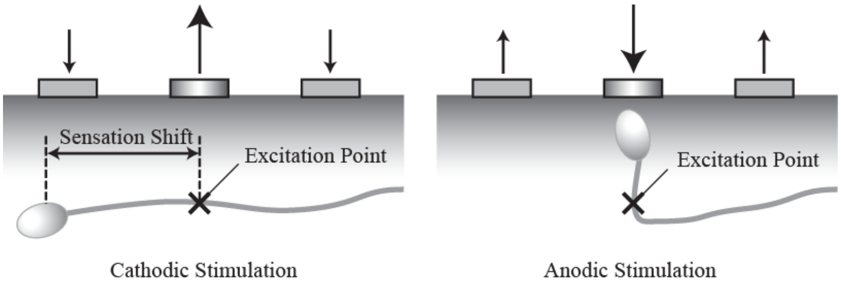

Figure 8 (Left) Cathodic stimulation. (Right) Anodic stimulation. The anodic stimulation generates a spatially confined sensation because it activates the nerve terminal or vertically oriented nerves.

3. Hardware

The electro-tactile display is composed of electrical components, including a PC (personal computer) for pattern generation, microprocessor for high-speed pulse control, D/A (digital to analog) converter, V/I (voltage-current) converter if the display employs current-controlled stimulation, switching circuit, and electrodes (Figure 9).

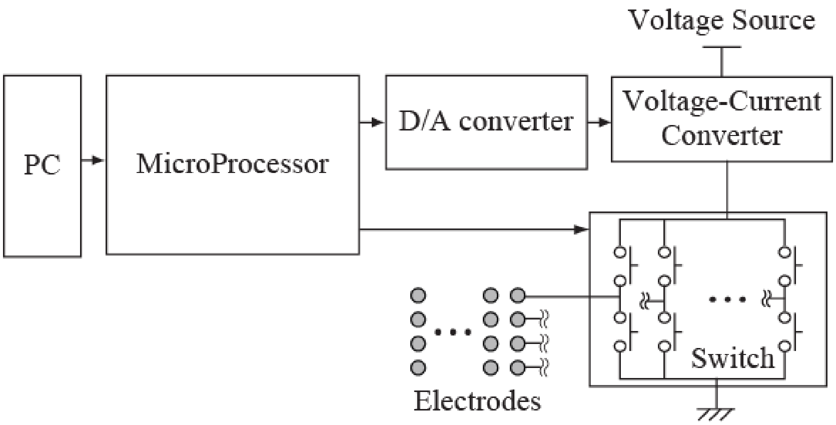

Figure 9 Typical system architecture of an electro-tactile display.

3.1. Voltage–Current Conversion

There are two main designs of the electro-tactile display circuit. One employs voltage regulation [15] and the other current regulation [3][4][7][8]. The voltage-controlled electrical circuit is simpler, but safety issues such as a short circuit between the electrodes and greater electrical current due to sweat must be handled. As the situation of the electro-tactile display is characterized by a frequent change in the contact condition, current control is mainly used.

Figure 10 is an example of the voltage–current conversion design. The design is composed of a converter circuit and current mirror circuit that allows high-voltage driving. V_{in} is added to V_+ of the operation amplifier, the amplifier output voltage, which is applied to the gate of field-effect transistor Q_1. Electrical current I_1 flows and a voltage is generated at R_1, which is fed back to V_- of the operational amplifier. According to the principle of virtual ground, $V_+ = V_-$, which gives $I = Vin/R_1$. In other words, input voltage is converted to current.

The current mirror circuit works as follows. The electrical current passing through field-effect transistor Q_1 is supplied by PNP transistor Q_1. As the base of PNP transistors Q_2 and Q_3 are connected, the transistors have the same base voltage. As the base–emitter voltage of the transistor is almost constant, the emitter voltages Q_2 and Q_3 are almost the same. Therefore, for electrical current I_2 at R_2 and I_3 at R_3, $I_2R_2 = I_3R_3$ holds true. This means that electrical current is amplified by R_2/R_3. We can also drive the load with high voltage V_s, which is critically important to electro-tactile display.

In an ordinary electro-tactile display, the pulse width is around 50 to 200 μs, and the pulse height is approximately 1 to 10 mA. The resistance parameters are thus designed to output maximum current of around 10 mA. The resistance of a fingertip is approximately 50 kΩ for an electrode having a diameter of 1 mm and current pulse of 5 mA, and the voltage source V_s thus needs to be at least 250 V. To compensate for impedance variation of the skin, a voltage of approximately 350 V is desirable.

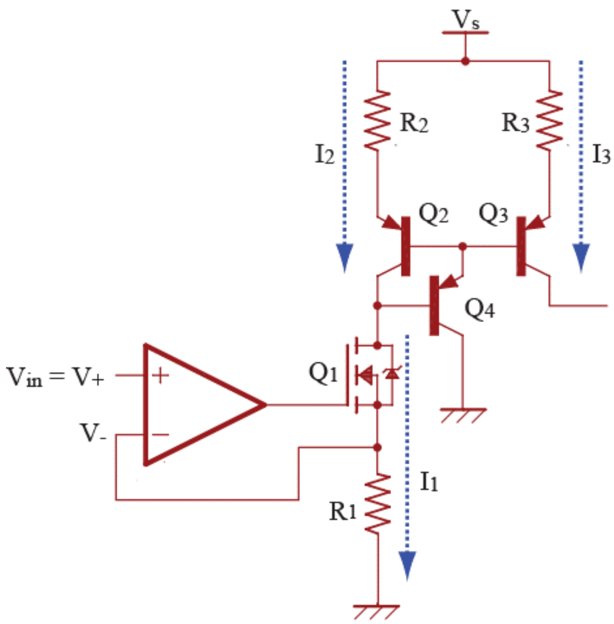

Figure 10 Voltage–current conversion design composed of a converter and current mirror.

3.2. Switching Using Half-bridges

When driving numerous electrodes, it is impractical to prepare the same number of current sources as electrodes. A switching circuit is thus required to stimulate one electrode at a time and scan the electrodes. Such a method was first presented for cochlea implants [17][18].

Figure 11 shows a schematic circuit diagram. Each electrode is connected to the current source and ground with switches. Such a pair of switches is called a half-bridge, because it is half of the typical bridge circuit used to drive a motor. When the electrode is connected to the current source, it becomes an anode. When it is connected to ground, it becomes a cathode. To achieve anodic stimulation, one electrode is connected to the current source and all other electrodes are connected to ground. This is electrically equivalent to anodic stimulation using a concentric electrode. Conversely, when one electrode is connected to the ground and all others are connected to the current source, cathodic stimulation using a concentric electrode is achieved. In other words, cathodic and anodic stimulation can be achieved using the same circuit.

If the two switches are off, the electrode is insulated, and such an arrangement might be used to realize a concentric electrode with a different diameter. If the two switches are on, there is a short circuit, which might be used to release unnecessary electric charge.

A high-voltage photo coupler is typically used as a switch. A multi-channel switching integrated circuit for driving a microelectromechanical system is also commonly employed.

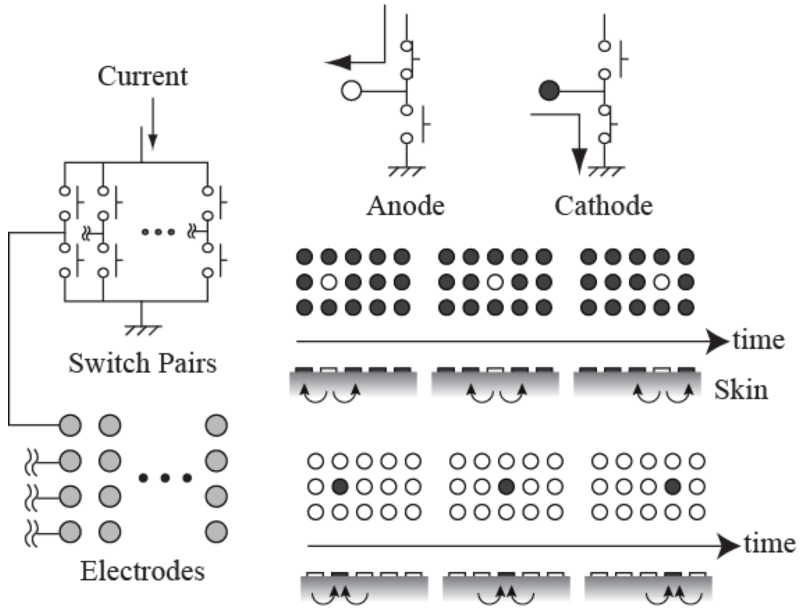

Figure 11 Scanning stimulation using a switching circuit. A pair of switches changes the state of electrodes between anode and cathode. The spatial pattern is obtained by temporal scanning.

3.3. Electrode and Gel

In the measurement of the myoelectric signal, the material of the electrode directly affects the accuracy of measurement, and an Ag-AgCl electrode is commonly used. In contrast, for an electro-tactile display, the material of the electrode does not directly affect the elicited sensation, and materials that can prevent rust, such as stainless steel, carbon, and gold as a coating, are used. When numerous electrodes are needed, an electronic substrate can be fabricated, including the application of a gold coating as part of the fabrication process. Additionally, a flexible substrate can be used to achieve deformable or curved-surface electrodes [5].

Figure 12 (left) shows the structure of the electrode when an electronic substrate is fabricated. The wiring is on the other side of the substrate to prevent the risk of leaking current.

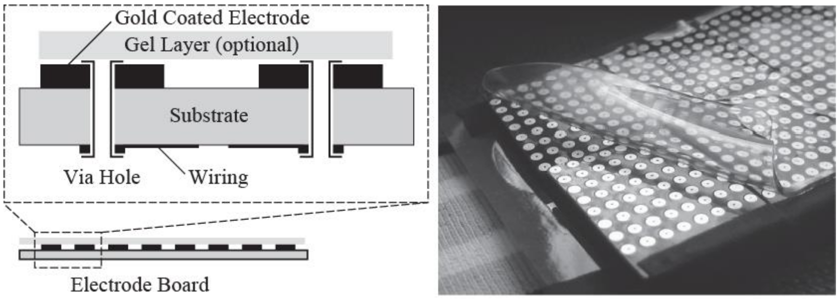

Figure 12 Electrode structure and conductive gel. The electrode surface is gold coated and the wiring is on the other side of the substrate. The conductive gel works as a diffuser.

For the measurement of a myoelectric signal or for muscle electrical stimulation, conductive paste is commonly used to stabilize contact. Conductive paste is also effective in the case of the electro-tactile display but only when the electrode is large. When the electrodes are densely distributed and the gap between electrodes is 1–2 mm, the electrical current from the stimulating electrode only passes the conductive paste layer and reaches the surrounding electrode, without penetrating the skin. Therefore, for a typical electro-tactile display for the fingertip that uses tens of electrodes spaced at intervals of 2–3 mm, conductive paste is not used and the electrode is in direct contact with the skin.

When the same electrodes are attached to another part of the body such as the forehead or forearm, a strong pain sensation is sometimes elicited, whereas it is not observed in the case of the fingertip. This difference is presumably due to the difference in skin structure. The fingertip has a stratum corneum layer that is approximately 0.6 mm thick and most nerve fibers are below this layer. This thick layer works as a dissipation layer for electrical current. In contrast, other parts of the body have a stratum corneum layer that is a few tens of μm thick [19]. Therefore, local current concentration can sometimes stimulate thin nerves before activating thick nerves, which results in a pain sensation before a tactile sensation.

One way to prevent the issue described above is to use a conductive gel layer that has conductance equivalent to that of skin [1]. In contrast to commonly used conductive paste, this gel layer has a much higher volume resistance, and its thickness allows current dissipation, as in the case of the stratum corneum of the finger pad.

4. Stabilization

While there are numerous merits to the electro-tactile display such as its small size, thin dimension, low cost, energy efficiency and durability, the variability of the elicited sensation has hindered its practical use.

This variability is a result of two problems. First, temporal changes occur when the contact conditions are altered by sweat and motion (Figure 13, top). Sweat alters the amount of sensation, while abrupt motion of the skin generates an electric shock sensation, sometimes perceived as an itchy feeling.

Second, spatial effects contribute to variability (Figure 13, bottom). The threshold for tactile sensation (the absolute threshold) is close to the pain threshold [8]. Furthermore, there is substantial spatial variation in the threshold between different electrodes. Thus, if hundreds of electrodes are used, and the stimulating currents are the same, it is practically impossible to exceed the absolute threshold at all electrodes without also exceeding the pain threshold at some. This problem is specific to the case of numerous electrodes, where the user cannot adjust the volume for each electrode.

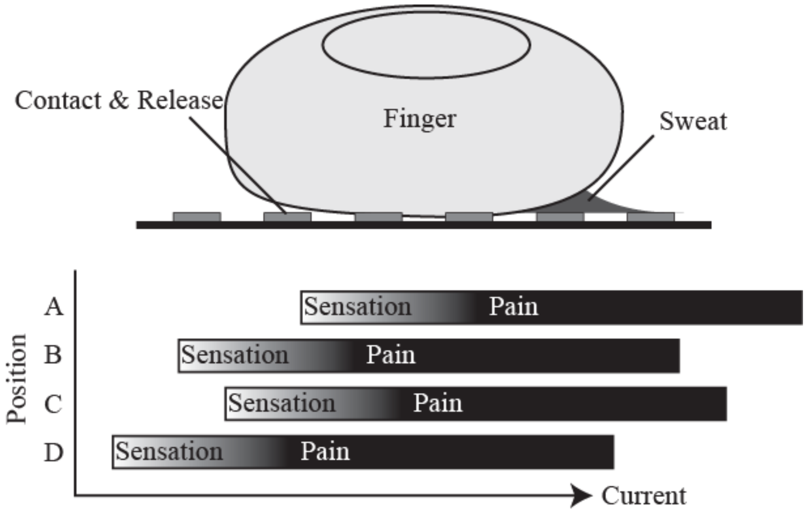

Figure 13 Two factors contributing to the sensation variability of electro-tactile displays. (Top) Temporal changes caused by sweat and contact. (Bottom) Spatial variation of thresholds.

Several solutions aimed at stabilizing the sensations generated by electro-tactile displays have been proposed. These can be classified into three categories as follows.

4.1. Explicit Feedback by the User

One practical solution is to adjust the stimulation in response to the user's explicit feedback [20]. A pressure sensor is placed under the electrode, and the electrical current is controlled by the sensor value. This simple method is effective for one finger and might be applied to the multi-touch situation if a multi-touch sensor is used, but requires the user to control each finger pressure independently.

4.2. Expansion of the Dynamic Range

Solutions in the first category aim to increase the difference between the absolute and pain thresholds. Collins [8] found that using a smaller pulse width (20–50 μs) was effective, while Polleto and van Doren [21] suggested applying a low-level pulse before the main pulse. Kaczmarek et al. [22] optimized several parameters, such as the number of pulses per burst, to obtain the maximal dynamic range. These methods represent important advances, but their effectiveness is limited.

4.3. Impedance Feedback

Solutions in the second category measure the electrical impedance of the skin and use the value to control the pulse. The voltage regulation and current regulation that we described in section 3.1 can be regarded as an analog way of achieving impedance feedback in some way. At least, these analog circuit methods provide different strategies for dealing with impedance fluctuations.

To approach the problem in a more general way, it is necessary to construct a measurement–stimulation control loop, such that an electrode can be used for both stimulation and measurement. Tachi et al. [23][24] regulated the pulse width, on the basis that perceived strength is related to input energy (current × voltage × pulse width). Watanabe et al. [25] reported a correlation between the skin resistance and absolute threshold, and Gregory, Xi and Shen [26] applied a similar technique to fingertips. Additionally, Kajimoto realized impedance feedback with a very fast feedback loop [27].

5. Conclusion

Intending to serve as an introduction to research on electro-tactile display, this paper summarized necessary knowledge of the principles of electrical stimulation, hardware design, and current solutions to the problem of stabilization. A search of the literature did not find a derivation of the strength–duration curve from a simple nerve model, and the result presented in section 2.2.2 might therefore have certain novelty.

There are many issues relating to the practical use of electro-tactile displays to be solved, but the electro-tactile display has many merits such as its size, cost, energy efficiency and durability. It is hoped that this paper provides the knowledge required by researchers to participate in the attractive research field of electro-tactile displays.

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