2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Evaluation of Tactile Perception by using Simulation of Mechanoreceptor Activity via Transcutaneous Electrical Stimulation

Shunsuke Yoshimoto[1], Shunki Inoue[1], Hiroki Ohara[2,1], Yasuyoshi Asai[2],
Nobuyuki Koyama[2], Tomohiro Ota[2], and Shuichi Ino[1]

I. Introduction

Transcutaneous Electrical Stimulation (TES) has been utilized to evoke sensations in neural prostheses [1] and virtual/augmented reality applications [2]. Taking advantage of its compactness, high responsiveness, and scalability, a wide range of studies have explored TES for haptic feedback over the past decade [3]. Due to its high design flexibility, various unique stimulation methods have been proposed [4]–[6]. However, little is known about the design strategies for optimizing electrode locations and stimulation patterns.

Meanwhile, simulation studies and theoretical analysis related to TES have been conducted [7]. Kajimoto et al. proposed a primary color principle based on the mathematical model of TES [8]. Ogihara et al. developed a simulation framework to explore the optimal electrode placement for inducing electrotactile illusions on the hand using wrist-mounted electrodes [9]. These studies indicate that mathematical modeling of TES is effective for designing electrical stimuli to elicit appropriate sensations. However, understanding how mechanoreceptors at the fingertip are activated by TES remains challenging. Specifically, no attempts have been made to simulate perception using TES.

In this study, we propose a novel framework for simulating perceived area based on mechanoreceptors' activities induced by TES. Specifically, we focus on modeling the distribution of mechanoreceptors and estimating perception using an electrical nerve stimulation model. In this paper, we evaluate a simple electrode configuration through both simulation and psychophysical experiments.

II. Simulation Framework

In sensory presentation using TES, an electrical current applied via surface electrodes induces an ionic current at the nerve membrane in accordance with the potential gradient. When the ionic current exceeds a certain threshold, an action potential is generated through the function of ion channels. This action potential then propagates along the nerve axon. Typically, a series of electrical pulses is used to regulate the nerve's firing rate. As a result, the user perceives a tactile sensation corresponding to the types and locations of the mechanoreceptors connected to the activated nerves.

*Research supported by Panasonic Holdings Corporation

[1]S. Y., S. I., H. O., and S. I. with the Graduate School of Engineering, The University of Osaka, Yamadaoka 2-1, Suita-shi, Osaka, 5650871 JAPAN. e-mail:yoshimoto@mech.eng.osaka-u.ac.jp

[2]H. O., Y. A., N. K. and T. O. are with the Product Analysis Center, Panasonic Holdings Corporation, Kadoma 1048, Kadoma-shi, Osaka, 5710050 JAPAN.

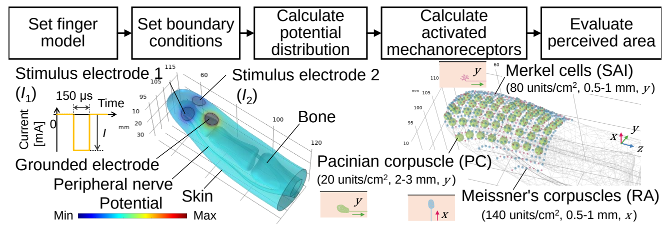

Fig. 1. A simulation framework: The model incorporates a simplified anatomical structure of the finger, along with the spatial distribution (i.e., density and depth) of three types of mechanoreceptors.

In this study, TES at the fingertip is modeled within the simulation framework illustrated in Fig. 1. First, the temporal response of the potential distribution, $\Phi(\boldsymbol{x}, t)$, is computed using the following equation:

$$\nabla \cdot \left(\sigma(\boldsymbol{x}) \nabla \Phi(\boldsymbol{x}, t) + \varepsilon(\boldsymbol{x}) \nabla \frac{\mathrm{d}\Phi(\boldsymbol{x}, t)}{\mathrm{d}t} \right) = 0, \quad (1)$$

where $\sigma(\boldsymbol{x})$ and $\varepsilon(\boldsymbol{x})$ represent the conductivity and permittivity of the tissues. This model is commonly used in the electrical modeling of biological tissues [10]. As a boundary condition, a pulse current is applied to each stimulus electrode, while the grounded electrode is set to 0 V.

Second, we define the distribution of mechanoreceptors and consider the terminal nerves connected to them. Since Ruffini endings are difficult to activate [8], we focus on Meissner's corpuscles (RA), Merkel cells (SAI), and Pacinian corpuscles (PC). The reference values for mechanoreceptor distribution are shown in Fig. 1. Next, the activated mechanoreceptors are evaluated using the input term of the axon cable equation [8] as follows:

$$\tau \frac{\partial V_{\mathrm{m}}(\boldsymbol{x}_{\mathrm{r}}, t)}{\partial t} - \lambda \frac{\partial^2 V_{\mathrm{m}}(\boldsymbol{x}_{\mathrm{r}}, t)}{\partial r^2} + V_{\mathrm{m}}(\boldsymbol{x}_{\mathrm{r}}, t) = \lambda \frac{\partial^2 \Phi_{\mathrm{e}}(\boldsymbol{x}_{\mathrm{r}}, t)}{\partial r^2}, \quad (2)$$

where $V_{\mathrm{m}}(\boldsymbol{x}_{\mathrm{r}}, t)$ represents the membrane potential, $\Phi_{\mathrm{e}}(\boldsymbol{x}_{\mathrm{r}}, t)$ is extracelluer potential, r denotes the direction of the axon, and τ and λ are parameters associated with the conductance and capacitance of the membrane. While calculating the membrane potential is ideal for evaluating nerve activation, the activation likelihood can be estimated more simply using the activating function (AF), $\partial^2 \Phi_{\mathrm{e}}(\boldsymbol{x}_{\mathrm{r}}, t)/\partial r^2$, as an approximation of mechanoreceptor activation.

Finally, the perceived area is estimated by calculating the area of the convex hull including all activated mechanoreceptors. Since the number of activated mechanoreceptors changes with the activation level (threshold of the AF), we calculate the average area to quantify the perceived area.

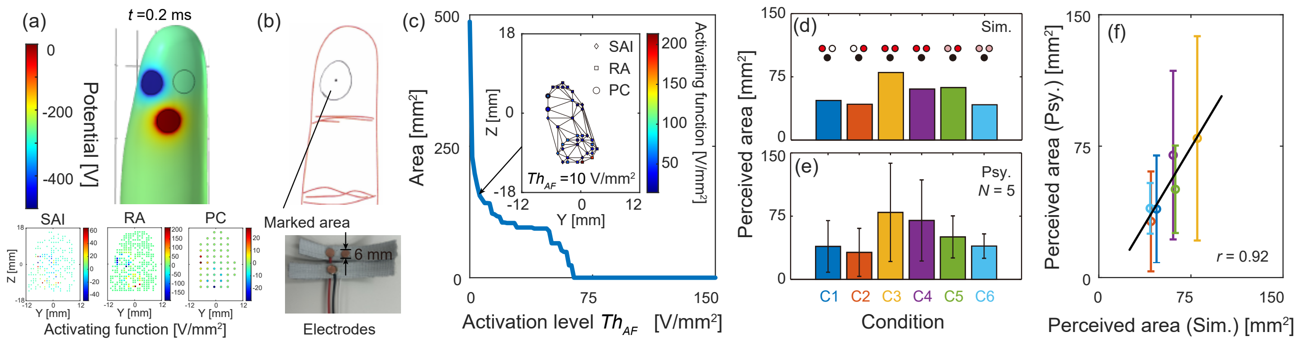

Fig. 2. Simulations and experimental results: (a) Calculated potential distribution and activating functions for each mechanoreceptor under Condition 1. (b) Perception induced by actual electrical stimuli, represented by marked areas on a finger illustration. This approach is similar to the one used in [9]. (c) Calculated area versus activation level, showing activated mechanoreceptors at 10 V/mm^2. (d) Simulated areas for six different stimulus conditions. (e) Perceived area determined through a psychophysical study. (f) Correlation of perceived areas between the simulation and psychophysical studies.

III. Experiments

We conducted both simulation and psychophysical experiments to validate the proposed framework. As an initial step, we simplified the experimental setup by: (1) using two stimulus electrodes and one ground electrode as an example configulation, and (2) evaluating the perceived area instead of conducting a quantitative assessment of the sensation.

A. Simulation Study

A finger model, consisting of skin, bone, nerve, and three electrodes, is shown in Fig. 1. We set six current pairs, e.g., (I_1, I_2) =(-1,0), (0,-1), (-1,-1), (-1,-0.5), (-0.5,-1,), (-0.5,-0.5) mA. The potential distribution and the perceived area were calculated using COMSOL Multiphysics and MATLAB, respectively. Examples of the potential distribution, activation level of each mechanoreceptor, and the estimated perceived area versus activation level are shown in Fig. 2(a)(c).

B. Psychophysical Study

An electrotactile display developed in [4], along with electrode bands (Fig. 2(b)), was used. We prepared six stimulus conditions similar to those in the simulation study, though the absolute current values were adjusted for each participant. The participants were instructed to place the electrodes on their left index fingertips and adjust the maximum current intensity according to their perception. In each trial, the selected stimulus (100 pps) was presented, and participants were asked to mark the perceived area (see Fig. 2(b)). These steps were repeated three times across six randomized conditions. The stimuli were paused between trials.

This experiment was conducted with the approval of the Ethics Review Committee of the graduate school of Engineering, the University of Osaka (6-6-1). Five healthy participants (22.8$\pm$1.2) gave informed consent.

C. Result and discussion

The experimental results are presented in Fig. 2(d)–(f). These results indicate that the perceived area is influenced by both the amount of stimulus current and the location of the stimulus electrodes. Additionally, asymmetry between the two stimulus electrodes is observed due to the uneven shape of the finger. As shown in Fig. 2(f), a comparison between the simulation and psychophysical data reveals a strong correlation in the perceived area ($r = 0.92$). This finding supports the potential of the proposed framework for evaluating perceived area. However, this study did not account for individual differences in stimulus adjustment, as well as the effects of mechanoreceptor types and nerve bundles. Future work will address these factors, explore the evaluation of more complex perceived areas, and investigate various stimulus conditions.

IV. Conclusion

A simulation framework for evaluating the perceived area in TES, based on activated mechanoreceptors, was proposed. The experimental results showed a strong correlation of the perceived areas between the simulation and psychopysical studies. Further consideration of biological factors could lead to a more efficient design of electrotactile interfaces.

References

[1] P. D. Marasco *et al.*, "Neurorobotic fusion of prosthetic touch, kinesthesia, and movement in bionic upper limbs promotes intrinsic brain behaviors," *Sci. Robot.*, vol. 6, no. 58, p. eabf3368, 2021.

[2] W. Lin *et al.*, "Super-resolution wearable electrotactile rendering system," *Sci. Adv.*, vol. 8, no. 36, p. eabp8738, 2022.

[3] P. Kourtesis *et al.*, "Electrotactile feedback applications for hand and arm interactions: A systematic review, meta-analysis, and future directions," *IEEE Tran. Haptics*, vol. 15, no. 3, pp. 479–496, 2022.

[4] S. Yoshimoto *et al.*, "Material roughness modulation via electrotactile augmentation," *IEEE Tran. Haptics*, vol. 8, no. 2, pp. 199–208, 2015.

[5] C. Jiang *et al.*, "Designing unobtrusive modulated electrotactile feedback on fingertip edge to assist blind and low vision (blv) people in comprehending charts," in *Proc. ACM CHI*, 2024, pp. 1–20.

[6] S.-Y. Teng *et al.*, "Haptic permeability: Adding holes to tactile devices improves dexterity," in *Proc. ACM CHI*, 2024, pp. 1–12.

[7] G. Valle *et al.*, "Biomimetic computer-to-brain communication enhancing naturalistic touch sensations via peripheral nerve stimulation," *Nat. Commun.*, vol. 15, no. 1, p. 1151, 2024.

[8] H. Kajimoto *et al.*, "Tactile feeling display using functional electrical stimulation," in *Proc. ICAT*, vol. 133, 1999.

[9] S. Ogihara *et al.*, "Multi surface electrodes nerve bundles stimulation on the wrist: Modified location of tactile sensation on the palm," *IEEE Access*, vol. 11, pp. 13 794–13 809, 2023.

[10] S. Romeni *et al.*, "Tutorial: a computational framework for the design and optimization of peripheral neural interfaces," *Nat. Proto.*, vol. 15, no. 10, pp. 3129–3153, 2020.