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

Effects of Electrode Design Parameters in Electro-Tactile Displays

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I. Introduction

In the fields of virtual reality and remote operations, providing users with tactile feedback is widely recognized as an essential method for enhancing immersion and improving task performance. Among the various ways to deliver such detailed feedback to the fingers, electro-tactile stimulation—where thin electrodes affixed to the skin deliver transcutaneous electrical pulses—has gained prominence. This method offers the advantage of high-density tactile presentation using ultra-thin electrodes, enabling the design of compact, lightweight, and low-power devices.

This study is part of ongoing research aimed at optimizing electrode size parameters in electro-tactile stimulation. Historically, concentric electrodes[1][2] were commonly used, but many modern systems employ matrices of miniaturized electrodes to achieve high-density placement[3][4]. In some applications, such as deep muscle stimulation, electrodes may be intentionally spaced apart[5]. In this work, however, we focus on the classical concentric design, which features a central circular electrode surrounded by a concentric ring electrode. Compared with matrix layouts, concentric electrodes may reduce spatial freedom and density as the outer ring becomes larger. However, because the electrical current pathway is enclosed by the ring electrode, the spatial offset between the stimulation site and the electrode itself is relatively small [6]. Moreover, insights gained by optimizing concentric electrodes are expected to be applicable to matrix-type electrode designs as well.

Several previous investigations have examined how electrode size relates to tactile sensation and pain thresholds [1]. Nonetheless, few studies have conducted a comprehensive examination of how changing electrode dimensions alters the quality of sensations.

Accordingly, the present research investigates how the design parameters of concentric electrodes (the diameter of the central electrode, as well as the inner and outer diameters of the annular one) affect the resulting tactile experiences, specifically, size of perceived sensation, vibration-like sensation, and pressure-like sensation. We anticipate that this work will help establish guidelines for electrode design in various application scenarios.

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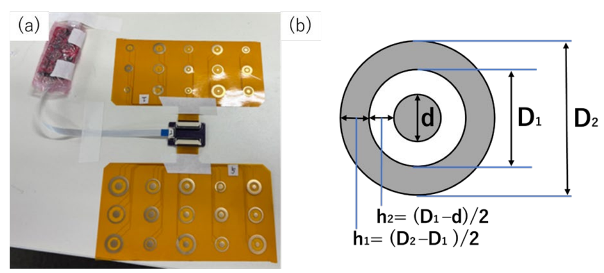
II. Methods

In this study, we designed concentric electrodes to deliver electro-tactile stimulation to the hand. Considering the typical size of adult fingertips and palms, three parameters were chosen for variation: the diameter of the central electrode (d), as well as the inner (D_1) and outer (D_2) diameters of the outer ring. Their specific levels are:

- d (central electrode): 1 to 5 mm in 1 mm increments
- D_1 (ring electrode, inner): 3 to 11 mm in 1 mm increments
- D_2 (ring electrode, outer): 5 to 15 mm in 1 mm increments

By combining these three parameters, a total of 30 distinct electrode dimensions were prepared (Figure 1.)



#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
d (mm)	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3
D_1 (mm)	3	3	5	5	7	7	4	4	6	6	8	8	5	5	7
D_2 (mm)	5	7	7	9	9	11	6	8	8	10	10	12	7	9	9
#	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
d (mm)	3	3	3	4	4	4	4	4	4	5	5	5	5	5	5
D_1 (mm)	7	9	9	6	6	8	8	10	10	7	7	9	9	11	11
D_2 (mm)	11	11	13	8	10	10	12	12	14	9	11	11	13	13	15

Figure 1. Image of electrodes, and electrode design parameters

Yem et al. have demonstrated that switching the polarity between anode and cathode can change the likelihood of eliciting “vibration-like” vs. “pressure-like” sensations, in comparison to mechanical stimulation [7]. However, in our preliminary tests, even simply altering the dimensions of concentric electrodes appeared to influence whether a vibration or pressure sensation was perceived. Since our primary goal here is to examine the effect of electrode design, we adopted only anodic stimulation—where the central electrode is the anode and the outer ring electrode is the cathode—based on the notion that anodic stimulation can enhance spatial localization. Furthermore, as summarized by Kaczmarek et al. [1], electrode size can affect the tactile sensation threshold, pain threshold, and even the ratio between these two thresholds. Accordingly, we evaluated the following five indicators.

1. Sensation threshold (mA)
2. Pain threshold (mA)
3. Perceived diameter of stimulated area: Participants were asked to select which of nine printed circles (with diameters ranging from 3 mm to 11 mm) most closely matched their subjective sense of the stimulated area.
4. Vibration-like sensation: Rated on a seven-point scale (0 = not noticeable at all, 7 = distinctly noticeable).
5. Pressure-like sensation: Rated on a seven-point scale (0 = not noticeable at all, 7 = distinctly noticeable).

The electrical stimulation device used in this study is based on a previous developed one [4]. Throughout the experiment, the outer ring electrode acted as ground, while the central electrode delivered unipolar anodic pulses, with 75 µs width at 100 Hz. One second stimulation was followed by one second rest, letting the participants easy to perceive the stimuli.

Participants applied the tip of their left index finger. They incrementally adjusted the pulse amplitude until reaching their sensation threshold and then the pain threshold, reporting each value. The stimulus was then set to a midpoint current between the two thresholds. At this level, participants evaluated the perceived diameter of the stimulated area, vibration-like level, and pressure-like level.

Each of the 30 electrodes was tested once in this manner, with randomized order. The number of stimulations per electrode was limited to one to avoid fatigue. Eight participants (22–36, seven male and one female) took part in the study. This study was approved by the ethics committee of the University of Electro-Communications.

III. Results and Discussions

We treated three concentric electrode parameters as independent variables: the center electrode diameter d (1 to 5 mm), the width of the outer ring h_1 ($(D_2$-$D_1)/2$; 1 or 2 mm), and the gap h_2 between central and outer electrodes ($(D_1$-$d)/2$; 1 to 3 mm). The five tactile metrics described earlier were taken as dependent variables. A multiple linear regression (MLR) analysis was then conducted using Python's statsmodels api, focusing on how each dimension affects perceived sensation—specifically, whether each parameter exerts a positive or negative influence and whether that effect is statistically significant ($p < 0.05$).

TABLE I. presents representative outcomes of the MLR analysis. For ease of interpretation, only the coefficient of determination (R^2), the regression coefficients (coef), and the corresponding p-values are reported.

TABLE I. Result of Multiple Linear Regression Analysis

	D		h_1		H_2		R^2
	coef	P val.	coef	P val.	coef	P val.	
Sensation threshold	**-0.124**	0.000	-0.034	0.725	**-0.425**	0.000	0.214
Pain threshold	-0.062	0.171	-0.054	0.675	**-0.757**	0.000	0.289
Perceived size	**0.657**	0.000	**0.412**	0.045	**0.484**	0.000	0.301
Vibration	0.142	0.066	**0.427**	0.051	**0.483**	0.000	0.079
Pressure	**0.204**	0.009	0.143	0.514	**0.288**	0.032	0.049

Based on items with $p < 0.05$ (highlighted by red text), the following trends emerged:

- Increasing h_2 lowers both the sensation and pain thresholds. In addition, participants reported stronger vibration-like and pressure-like sensations, although the current amplitude was set to midpoint of the two thresholds.
- Increasing h_1 slightly enhances the perceived vibration, although the effect appears modest.
- Increasing d decreases the sensation threshold without substantially lowering the pain threshold. It also increases the pressure-like sensation, but has limited impact on the vibration-like sensation.
- Perceived diameter of the stimulated area tends to grow when h_2, h_1, or d is increased, with d showing a particularly pronounced effect.

Next, we calculated the ratio of the pain threshold to the sensation threshold (P / S) across all conditions. A larger P / S value indicates that a weak stimulus can be perceived as tactile yet induces relatively little pain, and often regarded as an indicator of stimulation stability [1]. Although no formal statistical analysis was conducted, we observed the highest P / S value at $(d, h_1, h_2) = (2, 1, 1)$. This suggests that such an electrode configuration may offer a distinctly perceivable tactile sensation at the fingertip while minimizing discomfort.

The results show that increasing h_1 and h_2 enhances vibration-like sensations, aligning with previous findings [2] that a larger stimulated area can activate both superficial Meissner corpuscles and deeper Pacinian corpuscles. Meanwhile, increasing d intensifies pressure-like sensations, possibly because the broader current distribution stimulates a larger area of Merkel cells, generating a sense of pressure.

Further work is needed to refine experimental design (e.g., controlling the pressing force) and to expand the number of participants. Such efforts will help define more robust guidelines for designing electrodes with broad applicability.

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