Receptive Field Characteristics Under Electrotactile Stimulation of the Fingertip

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***Abstract*— Skin on human fingertips has high concentrations of mechanoreceptors, which are used to provide fine resolution tactile representations of our environment. Here we explore the ability to discriminate electrotactile stimulation at four sites on the fingertip. Electrical stimulation was delivered to arrays of electrodes centered on the index fingertip (volar aspect). Accuracy of discrimination was tested by examining electrode size, inter-electrode spacing, and stimulation frequency as primary factors. Electrical stimulation was delivered at 2 mA with the pulse width modulated to be at (or above) perceptual threshold at 25 Hz and 75 Hz and an average pulse width of 1.03 ms (+/- 0.70 ms standard deviation). Discrimination of the stimulated locations under this stimulation paradigm was significantly above chance level in all cases. Subjects' ability to discriminate stimulus location was not significantly influenced by electrode size or stimulation frequency when considered as separate factors. However, increased electrode spacing significantly increased subjects' ability to discriminate the location of the stimulated electrode. Further analysis revealed that errors were only significantly reduced along the medial-lateral direction with increasing inter-electrode spacing. These results suggest that the electrotactile stimulus localization on the fingertip has some directional dependency, in addition to its dependency on inter-electrode spacing. The neural mechanisms underlying this phenomenon are discussed in relation to electrical stimulus transduction characteristics of tactile mechanoreceptors.**

***Index Terms*—Electrocutaneous, Nerve stimulation, Mechanoreceptors, Sensory aids, Sensory suubstitutsion, Touch.**

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I. Introduction

THROUGH the normal mechanisms of touch, we receive information about shape, size, weight, texture, and mechanical vibration. This rich signal allows us to interact with our environment in intricate ways to perform complex tasks. We have difficulty executing these tasks when this information is compromised or lost, e.g. working through thick gloves, telerobotics, or due to neural impairment. This difficulty arises due to poor mechanical stimulation and/or reduced capability of the peripheral or central nervous system to detect or process mechanical stimuli. An alternative way to elicit tactile sensations is by exciting the underlying afferent fibers electrically [1]-[3]. One of the goals of research in electrical stimulation of tactile afferents is to replace or augment sensation associated with mechanical stimuli. However, attainment of this objective depends on the extent to which electrical stimulation can match signals normally carried by afferent fibers serving the mechanoreceptors. This, in turn, would allow us to interact with virtual environments, detect feedback while performing telerobotic tasks, or evaluate neural deficits associated with sensory recovery after skin grafts, carpal tunnel surgery, vibrotactile injury, or other repetitive movement injuries. However more research is needed to further understand the type and quality of information that can be transferred through electrotactile stimulation.

In general, the conduction of electrical current through tissues (skin, epidermis, and dermis) that intervene between the electrode and afferent fibers can accurately be modeled [4-6]. Less well understood, however, is the impact of anatomical anisotropy or irregularity on the mechanisms of electrical stimulation of receptive fields on the fingertips. On the volar aspect of the fingertip, mechanoception is largely isotropic; that is, the resolution is not dependent on the location of applied mechanical stimuli [7]. We have recently confirmed this finding for mechanical stimulation for stimuli above a certain level (0.2 g von Frey Hairs at 5mm spacing) [8]. Electrotactile receptive fields are fundamentally different from mechanical receptive fields in that electrotactile receptive fields are determined by the electric field's ability to depolarize an afferent fiber underneath or near an electrode, whereas mechanical receptive fields are determined by physical perturbation of the mechanoreceptor. Electric field strength is determined by the current/voltage of the electrical signal/source, the distance from the electrical source, and the impedance of the intervening tissue. For a given electric field strength, the amount of depolarization that an afferent fiber will undergo depends on the fiber's diameter and orientation with respect to the electric field [9].

There are two types of fiber bundles located underneath the surface of the skin. In general, type I fibers are located more superficially (0.08 mm below the fingertip surface) and will, for a given transcutaneous stimulus, experience stronger electric fields than type II fibers, which tend to lie deeper beneath the skin surface (0.2 mm) [10]. Type I fibers are associated with Meissner and Merkel corpuscles, these mechanoreceptors are densely packed and have small receptive fields, resulting in high mechanical spatial resolution. Type II fibers are associated with Ruffini endings and Pacinian corpuscles; these are less densely packed and have larger receptive fields which results in lower mechanical spatial resolution. Both of these fiber types can vary in diameter from 6 – 12 microns. Though these fibers are known to vary in size there is no known characteristic distribution between fiber diameter and termination (mechanoreceptor) or type. Because of the variances in anatomical arrangement, fiber diameter, and impedance under the skin surface, it remains unknown whether the volar aspect of the fingertip has isotropic resolution for electrotactile stimulation.

A number of studies have measured the skin's ability to transfer electrical stimuli to mechanoreceptors and their fibers by delivering either pulsed voltage across or, more commonly, regulated current through the skin surface [5]-[7], [11]-[18]. Pulse width is an important characteristic in determining the amount of charge that is delivered to the skin. It also affects sensation of the electrical stimulation. The frequency of stimulation may also play a role in discriminating the location of a signal [18]-[21].

We designed a series of studies to explore the perceptual resolution of electrotactile stimulation and determine the parameters that influence electrotactile receptive fields of the fingertip. The aim of this study was to determine the effect of electrode size, spacing, and frequency of stimulation on the ability to discriminate the location of electrotactile stimulation on the fingertip. We quantified subjects' ability to determine which of four locations on the fingertip were stimulated in a forced choice protocol. In this protocol we tested several combinations of factor levels to determine which factors were the most influential. As the space between electrodes is increased, there is greater separation (or less overlap) between the electric fields underneath the electrodes. We therefore hypothesized that the percentage of correctly discriminated stimulus sites would increase as a function of distance between the stimulation sites. For a given inter-electrode distance, as electrode size decreases, there is more space between the electric fields underlying the electrodes; this should increase one's ability to discriminate the location of electrotactile stimuli. We therefore hypothesized that the discrimination of each electrically stimulated site would be greater than chance-level and that, as the electrodes became smaller, discrimination of stimulus location would increase. Stimulating the afferent fibers at firing rates that are comparable to vibrational firing rates may have an impact on the ability to discriminate the location of the stimulation site. Previous research indicates that higher frequency stimulation might improve electrotactile resolution [18]-[21]. We hypothesized that detection of stimulus location would be higher at 75 Hz than 25 Hz.

II. Methods

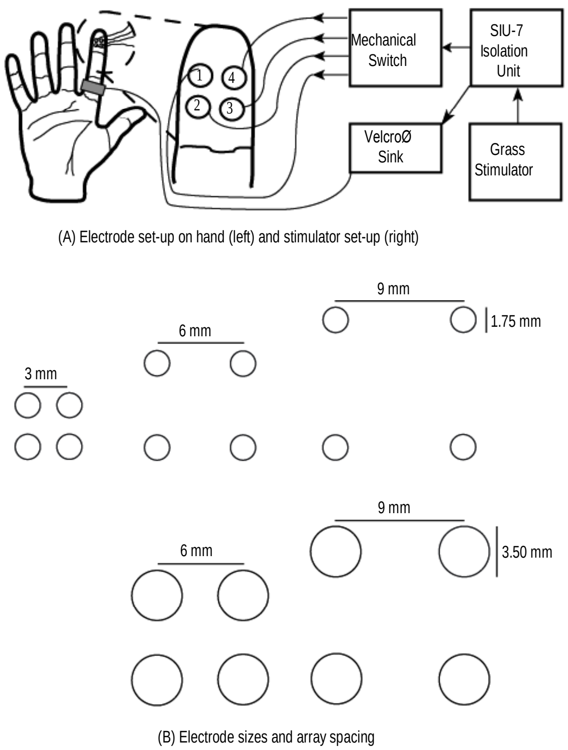
A. Subjects

All subjects (n = 5) were right handed (0.69±13; Edinburg Inventory [22]) students or faculty from Arizona State University. Subjects gave their informed consent prior to each recording session; and had no known sensory impairments or neurological conditions. Experimental procedures were approved by the Arizona State University Institutional Review Board and were in accordance with the Declaration of Helsinki.

B. Experimental Tasks

Subjects wore an electrode array on the volar aspect of their right index finger and were stimulated at an amplitude of approximately 2 mA. Five electrode arrays were used during the experimental series. The electrodes were located 3, 6, and 9 mm apart, center-to-center, with two electrode sizes, 1.75 and 3.5 mm diameter electrodes (3.5 mm diameter were not used at a 3 mm spacing as they would have overlapped, see Fig. 1a). The pulse width was modulated so that each subject could accurately and consistently detect the presence of the electrotactile stimuli. The shortest detectable pulse width through two sets of 10 consecutive stimulations was used for experimental trials. Pulse widths used in the experiment varied from 0.25 ms to 3.00 ms across all subjects and experimental conditions (an average of 1.03 +/- 0.70 ms). There were smaller variations in pulse width between the four stimulation sites for each subject in each experimental condition. During experimental trials, each subject was instructed to keep their hand comfortably supinated with fingers slightly extended. The subject's view of their hand was occluded during the entire block of trials. Subjects were provided a schematic of the electrode location for reference. A forced choice paradigm was used to report stimulus location. During the experiments each subject was instructed to verbally report the site of the stimulus on the finger pad among the four possible locations each time a stimulus train was presented (Fig. 1a).

The disks of the electrodes used to stimulate the fingertip were made from 316L stainless-steel shim stock (1/1000 in. thickness, Lyon Industries, South Elgin, IL). These disks were spot welded to polyvinylchloride coated, stainless-steel wire (AS 361, Cooner Wire, Chatsworth, CA). The electrodes were fixed to transparent adhesive tape by pulling the wires through the tape, thereby adhering the disks to the adhesive side of the tape. Electrode cream (Genuine



(A) Electrode set-up on hand (left) and stimulator set-up (right)

(B) Electrode sizes and array spacing

Fig. 1. Diagram of stimulator connections and electrode set-up. (A) Electrode arrays are mounted to the central (flattest) portion of the volar aspect of each subject's right (dominant) hand. When stimulated, these electrodes act as current sources. The stimulating current is anodic. (B) During the experimental trials five electrode arrays were used. The electrodes were one of two sizes, either 1.75 mm or 3.5 mm in diameter. The electrodes are arranged into a two-by-two array with inter-electrode spacings of 3, 6, or 9 mm.

Grass EC2TM Electrode Cream, Astro-Med, Inc., Grass Instrument Division, W. Warwick, RI, USA) was carefully applied only to the area under each electrode in order to lower the skin impedance and provide a uniform interface between the fingertip and electrode. Each stimulation electrode acted as a monopolar source electrode, and a dampened Velcro band finger electrode (J+J Engineering, Poulsbo, WA) was placed around the proximal phalange of the same finger as the reference electrode (Fig. 1a).

Electrical stimuli were delivered to the electrode arrays in experimental blocks (each site was stimulated 24 times in a pseudo-random sequence). Each experimental block lasted between ten and fifteen minutes, with approximately five minutes devoted to setup and calibration of the electrical stimulation. Subjects underwent ten experimental blocks during one session; one for each combination of electrode size, spacing, and stimulation frequency (Fig. 1b). The experimental blocks were presented in a counterbalanced order across the subject population. Before each block of trials, subjects underwent two practice stimulation sets where they were told the number of the site being stimulated.

C. Electrical Stimulation

We delivered anodic (positive) stimuli to the index finger pad of each subject, using monopolar electrodes, to quantify the extent to which subjects could discriminate the spatial location of each stimulus. Electrical stimulation was produced by a Grass S48 stimulator (Astro-Med, Inc., Grass Instrument Division). A photoelectric stimulus isolation unit (model SIU7, Astro-Med, Inc., Grass Instrument Division) was used to convert the stimulator's voltage output to current. During each trial a regular half-rectified square wave was delivered with current amplitude of 2 mA. These stimuli were not charge balanced. The pulse width was set to the pulse width threshold that was longest among the four stimulation sites. Both 25 and 75 Hz stimulation frequencies were used to stimulate for 5-7 seconds. Trials were usually stopped before the 7 second mark because the subjects had already reported the perceived site of the stimulation. After each response by the subject stimulation was switched to the next site where this process was repeated.

D. Data Analysis

Data analysis was performed using MATLAB® (The MathWorks Inc., Novi, MI). Correct response percentages were computed for stimuli delivered to each site. Incorrect responses were classified by their location relative to the stimulated site. We defined 'proximal-distal errors', 'medial-lateral errors', and 'diagonal errors' depending on the orientation of the reported and actual stimulation sites. We performed analyses of variance (ANOVA) tests utilizing a blocked factorial model. Design–Expert® (Stat-Ease Inc., Minneapolis, MN) was used to create this model and analyze the data. The model was blocked by subject and analyzed the effects of electrode size, electrode spacing, and frequency of stimulation. When a significant main effect or interaction was found it was reported and Fisher Least Significant Difference (Fisher LSD) tests were used to compare means when necessary. The alpha value of $p < 0.05$ was used for all comparisons, unless otherwise noted.

III. Results

The perception of electrotactile stimulation was slightly different for each subject in this experiment. Subjects most commonly reported tactile experiences similar to vibration, light buzzing, and pulsing underneath or adjacent to the stimulating electrodes. Above threshold, all of these sensations were slightly electrical in nature, as if induced by a small diameter, needle like, electric probe. As pulse width was increased, apparent probe size increased and the electrical sensation increased in magnitude. Subjects reported similar sensations, though no two reported exactly the same experience. This was expected as threshold derives from a combination of perception and skin impedance, which are different for each subject [3], [4], [6]. The range of stimulated pulse widths was large (0.25-3.00 ms) across subjects and experimental conditions, but with a tight distribution (1.03 +/- 0.70 ms). For an individual subject the stimulation pulse widths varied very little across trials and conditions. Accurate discrimination of location of electrotactile stimuli varied for all subjects across the various experimental conditions. Though each subject performed differently under different conditions, no subject performed statistically different from any other under the same electrotactile conditions.

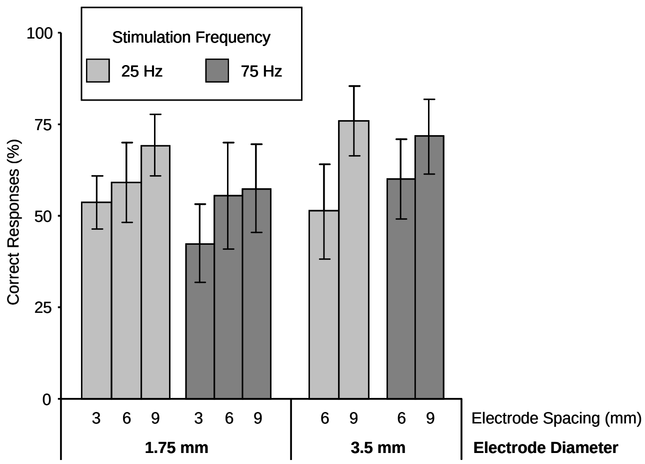


Fig. 2. Chart of percentage correct responses for electrode size, inter-electrode spacing, and frequency of stimulation. Half-rectified, anodic square-wave pulses of varying pulse width (1.03 +/-0.70 ms) duration were used for the electrical stimulation. Percentages indicate mean percentage correct responses across all subjects and trials. Error bars indicate standard error.

The experimental results were mixed with respect to the stated hypotheses of this study. Electrical discriminability was above chance level (25 %, Fig. 2) for all subjects and electrical arrays. Stimulation frequency did not have a significant effect on the ability to correctly identify the location of the stimulus (Fig. 2). Specifically, the trend of discrimination accuracy as a function of electrode diameter and spacing was similar when using 25 and 75 Hz frequency of stimulation. Therefore, analysis on the effects of electrode spacing and size was performed on data pooled across both frequencies.

The percentage of correct stimulus localization was not significantly affected when considering electrode size as a factor ($p > 0.05$, Figs. 2 and 3). However, electrode spacing

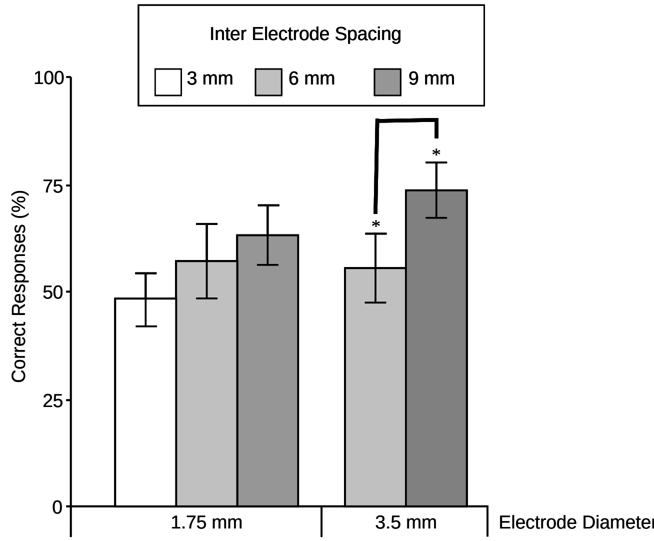


Fig. 3. Chart of percentage correct responses for electrode size and inter-electrode spacing. Stimulation frequencies were combined due to lack of significance. Percentages indicate mean percentage correct responses across all subjects and trials. Error bars indicate standard error. * indicates significance at the $\alpha < 0.05$ level.

had a significant effect on accuracy ($p < 0.05$; Fig. 3). Further examination of the data revealed that only one type of error was significantly reduced as the electrode spacing increased (medial-lateral error, $p < 0.05$; Fig. 4 and Table 1). This result was somewhat surprising. We expected that *all* error types would decrease as the inter-electrode spacing increased. In fact, this reasoning led us to hypothesize that the largest decrease in error would occur for diagonal errors, since this metric would be most affected by increasing inter-electrode spacing. However, we did not observe this trend as diagonal errors were not affected by electrode spacing ($p > 0.05$, Fig.

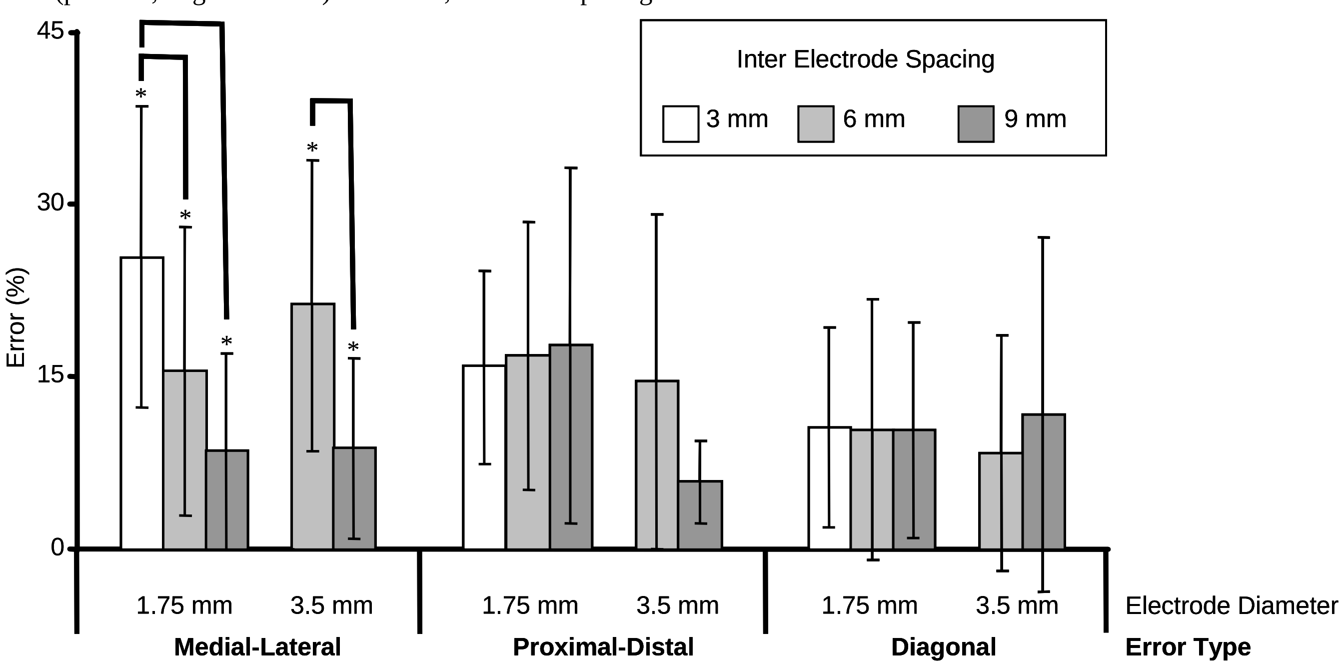


Fig. 4. Chart of percentage error for various error types, electrode sizes, and inter-electrode spacing. Percentages indicate mean percentage correct responses across all subjects and trials. Error bars indicate standard error. * indicates significance at the $\alpha < 0.05$ level.

Table I. Fisher Least Squared Differences for Electrode Diameters and Error Types.

	Error Type	Medial-Lateral	Proximal-Distal	Diagonal
1.75mm electrodes	3mm vs. 6mm	0.0243	0.8617	0.9637
	3mm vs. 9mm	0.0006	0.7540	0.9637
	6mm vs. 9mm	0.1081	0.8891	1.0000
3.5mm electrodes	6mm vs. 9mm	0.0140	0.0558	0.3834

4). Similarly, there was no significant effect of electrode spacing on proximal-distal errors ($p > 0.05$, Fig. 4).

IV. Discussion

The rationale for this investigation was to examine important factors that contribute to electrotactile resolution. Specifically, we focused on the extent to which electrode size, spacing, and stimulation frequency affect the ability to localize an electrical stimulus applied to the volar aspect of the fingertip. Neither electrode size nor stimulation frequency were significant factors in the subjects' ability to determine the location of the electrical stimulus. In contrast, electrode spacing did have significant influence on electrotactile resolution and the type of error made.

We expected that smaller electrodes would be more easily distinguished: as electrode size decreases for a particular inter-electrode spacing, the electric fields become smaller and thus, with less overlap, should be more easily distinguished. Electrotactile stimulation will excite a volume of tissue related to the diameter of the electrode. In this case it is likely that the diameters were not different enough to see an effect of electrode size. As electrodes get smaller it is more likely that they can elicit excitation of individual afferent fibers as they leave mechanoreceptors before they aggregate into fiber bundles. However, with both the size of the electrodes used here and the associated currents and pulse widths this probably was not achieved.

Stimulation frequency did not significantly affect subjects' abilities to discriminate location of electrotactile stimuli. Stimulation frequencies of 25 Hz and 75 Hz were chosen to reflect afferent firing rates similar to mechanical vibration. To avoid crossing the vibratory/pressure threshold 75 Hz was chosen to represent the upper bound [18]. The lower stimulation frequency of 25 Hz was chosen to attempt to capture the population average for the minimum two-point discrimination threshold [25]. Though subjects reported the electrotactile sensations as feeling 'vibratory' in most cases, neither of the stimulation frequencies gave an advantage in localizing the electrotactile source signal.

To more carefully consider the influence of electrode spacing, we examined the relationship between correct determination of stimulation site and the types of errors that occurred during incorrect responses. We expected that these errors would be a function of inter-electrode spacing, i.e., we hypothesized that the percent of incorrect responses for all error types would *decrease* as the space between each electrode was *increased*. This was not the case. The distance between the electrodes in the proximal-distal and medial-lateral directions was always less than the distance between the electrodes in the diagonal direction due to the square-packed array, thus we expected to see fewer diagonal errors than the other two possible error types. By the same logic we also expected to see these diagonal errors decrease further with increasing inter-electrode space than the other error types because of the larger distance between these stimulation sites. While fewer diagonal errors were observed than other types of errors for a given inter-electrode spacing, diagonal error did not decrease as a function of increasing inter-electrode distance. This result might be explained by subjects reaching a minimum error level. It is likely that subjects will always make some errors in the identification of stimulus location, as they do in mechanical stimulation [8], some of which will occur along the diagonal direction. This phenomenon will be at a minimum level if the space between stimulation sites, in any direction, is sufficiently large.

In the square-packed array electrode configuration used in this study, the inter-electrode spacing in the proximal-distal and medial-lateral directions is equivalent. Assuming the ability to isotropically resolve *electrotactile* stimuli, as is true for mechanical stimuli, one would expect a statistically significant difference in the frequency of errors made in the proximal-distal and medial-lateral directions as the space between electrodes increased. However, a significant effect of electrode spacing was not observed in the proximal-distal direction (Fig. 4). Specifically, as the space between the electrodes was increased, significantly fewer errors were made along the medial-lateral direction, while the number of errors made along the proximal-distal direction did not significantly change. A possible explanation for the lack of a decrease in proximal-distal (and diagonal) errors is that these errors had already reached a systematic minimum, beyond which they could not further decrease. We speculate that this differential effect of inter-electrode spacing on error type may be caused by stimulating a large number of afferent fibers lying along the proximal-distal direction. This, in turn, could lead to an increase in the number of instances where the location of a stimulus may evoke sensation on a site lying in the proximal-distal direction relative to the stimulated site.

Mechanical stimulation of the fingertip excites the mechanoreceptive end organs of these fibers. The mechanoreceptive organs are spatially arranged so that their overlap allows isotropic resolution [7], [23]-[26]. While axons leading to Meisnner's corpuscles are oriented along the proximal-distal direction, afferents serving Merkel's disks and Pacinian corpuscles are arranged more along the medial-lateral direction and "…mingle with one another in an apparently random manner [27]". As inter-electrode spacing is decreased, there is a higher likelihood of stimulating fiber collaterals that arise from adjacent fiber bundles. This increase in probability of firing of adjacent fiber bundles would lead to increased errors along the medial-lateral direction but would not have as much of an effect on the errors made along the proximal-distal direction as inter-electrode distance is decreased. As such, our result may be explained by the spatial bias caused by bundling of the afferent fibers in the proximal-distal direction. Electrotactile resolution on the fingertip is therefore not isotropic, i.e. electrotactile resolution is dependent on the directionally dependent.

It appears that one's ability to resolve electrotactile stimuli is not a simple function of electrode size, electrode spacing, or frequency of stimulation. Instead, other factors including the relationship between the mechanical receptive fields and the electrotactile receptive fields need to be considered. When considering this relationship, we found that the ability to discriminate electrotactile stimuli on the fingertip significantly improved along the medial-lateral direction with increasing distance between electrodes but not along the proximal-distal direction. Further investigation is needed to uncover how to maximize or match electrotactile resolution to that of tactile resolution. Specifically, electrical signal properties need to be investigated to achieve discrimination that would more closely resemble that of mechanical stimulation. These may include signals of even smaller pulse widths; smaller electrodes, to allow for more electrodes to be placed into an array; and more complex patterns of anodic/cathodic (source/sink) stimulation. Additionally, examination of the effects of stimulation of deep fibers, superficial fibers, and their associated receptive fields in isolation may be important to maximize electrotactile resolution.

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References

[1] G. B. Rollman, "Electrocutaneous stimulation," in *Proceedings of the Conference of Cutaneous Communications Systems and Devices*, F. A. Gerald, Ed. Psychonomic Society, 1973, pp. 38-51.

[2] A. Y. Szeto, R. R. Riso, "Sensory feedback using electrical stimulation of the tactile sense," in: *Rehabilitation Engineering*, R. V. Smith, J.H. Leslie Jr. Eds. Boca Raton Florida, CRC Press, 1990, pp. 29-78.

[3] A. Y. Szeto, F. A. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering," *IEEE Trans. Biomed. Eng.*, vol. 29, pp. 300-308, April 1982.

[4] D. Panescu, J. G. Webster, R. A. Strabucker, "A Nonlinear Finite Element Model of the Electrode-Electrolyte-Skin System," *IEEE Trans. Biomed. Eng.*, vol. 41, pp. 681-687, July 1994.

[5] F. Rattay and M. Aberham," Modeling Axon Membranes for Functional Electrical Stimulation," *IEEE Trans. Biomed. Eng.*, vol. 40, pp. 1201-1209, December 1993.

[6] E. N. Warman, W. M. Grill, D. Durand, "Modeling the Effects of Electric Fields on Nerve Fibers: Determination of Excitation Threshold," *IEEE Trans. Biomed. Eng.*, vol. 39, pp. 1244-1254, December 1992.

[7] S. Weinstein, "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality," in: *The Skin Senses*, D. R. Kenshalo Ed., Springfield, IL, C. C. Thomas, 1968, 195-222.

[8] L. R. Bobich, J. P. Warren, J. D. Sweeney, S. I. Helms Tillery, M. Santello, "Spatial Localization of Electrotactile Stimuli on the Fingertip in Humans," *Somatosensory and Motor Research*, vol. 24, pp. 179-188, April 2007.

[9] R. Plonsey and R. C. Barr, *Bioelectricity A Quantative Approach (Second Edition)*, New York, NY, Kluwer Academic/Plenum Publishers, 2000.

[10] Z. Halata, *The Mechanoreceptors of the Mammalian Skin Ultrastructure and Morphological Classification*, New York, NY, Springer-Verlag, 1975.

[11] A. Higashiyama & G. B. Rollman, "Perceived locus and intensity of electrocutaneous stimulation," *IEEE Trans. Biomed. Eng.*, vol. 38, pp. 679-686, July 1991.

[12] K. A. Kaczmarek & S. J. Hasse, "Pattern identification and perceived stimulus quality as a function of stimulation waveform on a fingertip-scanned electrotactile display," *IEEE Trans. Neural Systems and Rehab. Eng.*, vol. 11, pp. 9-16, January 2003.

[13] K. A. Kaczmarek & S. J. Hasse, "Pattern identification as a function of stimulation current on a fingertip-scanned electrotactile display," *IEEE Trans. Neural Systems and Rehab. Eng.*, vol. 11, pp. 269-275, March 2003.

[14] K. A. Kaczmarek, "Electrotactile adaptation on the abdomen: preliminary results," *IEEE Trans. Rehab. Eng.*, vol. 8, pp. 499-505, April 2000.

[15] K. A. Kaczmarek, M. E. Tyler, A. J. Brisben, & K. O. Johnson, "The afferent neural response to electrotactile stimuli: preliminary results," *IEEE Trans. Rehab. Eng.*, vol. 8, pp. 268-270, February 2000.

[16] K. A. Kaczmarek, M. E. Tyler, P. Bach-y-Rita, "Electrotactile haptic display on the fingertips: Preliminary results," in: *Engineering in Medicine and Biology Society, Engineering Advances: New Opportunities for Biomedical Engineers*, Proceedings of the 16th Annual International Conference of the IEEE, vol. 2, pp. 940-941, 1994.

[17] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, pp. 1- 16, January 1991.

[18] J. Ochoa and E. Torebjork, "Sensations Evoked by Intraneural Microstimulation of Single Mechanoreceptor Units Innervating the Human Hand," *J. Phys.*, vol. 342, pp. 633-643, September 1983.

[19] M. Solomonow, L. Raplee, J. Lyman, "Electrotactile Two-Point Discrimination as a Function of Frequency, Pulse Width, and Pulse Time-Delay," *Annals Biomed. Eng.*, vol. 6, pp. 117-125, February 1978.

[20] M. Solomonow, J. Lyman, A. Freedy, "Electrotactile Two-Point Discrimination as a Function of Frequency, Body Site, Laterality, and Stimulation Codes," *Annals Biomed. Eng.*, vol. 5, pp. 47-60, January 1977.

[21] A. Y. Szeto and G. R. Farrenkopf, "Optimization of Single Electrode Tactile Codes," *Annals Biomed. Eng.*, vol. 20, pp. 647-665, June 1992.

[22] R. C. Oldfield, "Assessment and Analysis of Handedness – Edinburgh Inventory," *Neuropsychologia*, vol. 9, pp. 97-113, January 1971.

[23] R. S. Johansson and A. B. Valbo, "Detection of tactile stimuli. Thresholds of afferent units related to psychophysical thresholds in the human hand," *J. Phys.*, vol. 297, pp. 405-422, December 1979.

[24] A. Y. Szeto, "Relationship between pulse rate and pulse width for a constant-intensity level of electrocutaneous stimulation," *Annals Biomed. Eng.*, vol. 13, pp. 373-383, May 1985.

[25] H. E. Wheat, A. W. Goodwin, & A. S. Browning, "Tactile resolution: peripheral neural mechanisms underlying the human capacity to determine positions of objects contacting the fingerpad," *J. Neurosci.*, vol. 15, pp. 5582-5595, August 1995.

[26] F. A. Saunders, "Information transmission across the skin: High-resolution tactile sensory aids for the deaf and blind," *Int. J. Neurosci.*, vol. 19, pp. 21-28, 1983.

[27] N. Cauna and G. Mannan, "Organization and Development of the Preterminal Nerve Pattern in the Palmar Digital Tissues of Man," *J. Computational Neurology*, vol. 117, pp. 308-327, March 1961.