An Electrotactile Display

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Abstract—An explorable electrotactile display has been constructed and tested. A thus far neglected sensation was identified and has been shown to be more useful than the more common electrotactile sensations. Exploration of the surface of the electrotactile display elicits a sensation describable as texture. Experiments have indicated that the intensity of this texture sensation is due primarily to the peak applied voltage rather than to current density as is the case for the classical electrotactile sensation. For subjects employing the texture sensation, experimental results are given for approximate thresholds and for the effect of electrode area on these thresholds. A boundary-localization measurement is offered as a measure of the usefulness of the display for textured-area presentation, and form-separation measurements are given as a measure of usefulness for line-drawing presentations. A proposed model for the mechanism producing the texture sensation is offered as a guide for future experimentation and display-engineering development.

Introduction

WE HAVE BEEN investigating electrotactile matrix displays for use as an information input to the blind. Previous work concerned with electrotactile displays has, for the most part, used rather large electrodes firmly attached to various parts of the body such as the chest, back, and arms. Our investigations have been concerned primarily with an array of fairly small electrodes, which the subjects have been able to actively search with their fingers much as they might search an array of mechanical tactile stimulators.

Stimulator Characteristics

The array consisted of small electrodes 70 mils in diameter that were spaced on 100-mil centers (Fig. 1). The maximum extent of the array was 1.0 inch wide by 1.8 inches long. The heel of the subject's hand rested on the single-return electrode. The pulses applied to the subject via the matrix of electrodes were of the bipolar rectangular type [as later shown in Figure 8(a)] from a source whose output impedance was 200 000 ohms. In all of the experiments reported here, unless otherwise noted, the pulse was symmetrical with a halfwidth of 0.60 ms, and a repetition rate of 200 pps.

In most of the experiments the subjects had control of the stimulus amplitude, and in all cases they could easily interrupt the stimuli by removing their fingers from the display.

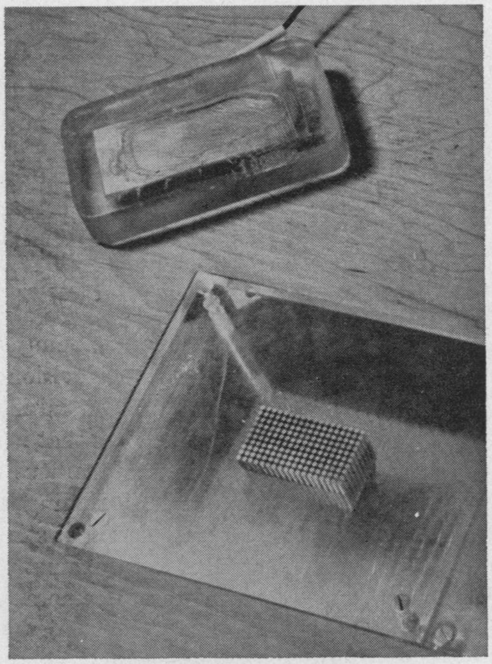

Fig. 1. Stimulator array.

Sensations Elicited

The subjects reported two distinct types of sensations. The first of these is similar to the sensation that Gibson [1] has reported when he used electrodes on the fingers; that is, that the sensations appear to be deep within the finger, indeed often concentrated in the joints, and that the sensation seems to progress up the finger, involving more of the finger as the stimulus amplitude is increased. Subjects reported that this type of sensation was relatively unpleasant and that it did not subjectively offer much information about the presentation. This sensation apparently has a mechanism more directly related to the peak stimulus current than to the voltage applied between the electrodes. A completely different sensation was experienced by most subjects when their fingers were dry and had, therefore, a high skin resistance. If the subject brushed his finger lightly over the surface, the surface appeared to acquire a texture, which could be varied by varying the stimulus parameters.[1]

This sensation bears many of the properties of an ordinary texture sensation, the most important being that it is a relatively small amplitude effect, and that it disappears in the absence of finger motion. The sensation does not seem to be at all unpleasant, and its qualities

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[1] The possibility that such a sensation existed, and its probable mechanism were suggested by Malinckrodt *et al.* [9].

can be varied quite a bit by changing either the pulse-repetition rate or the peak voltage. The mechanism for this "texture" sensation seems to be directly related to the peak stimulus voltage, not to the stimulus current. The typical peak stimulus current at the sensation threshold for the texture sensation was of the order of 50 μA, and a wide variation was noted. The peak voltages at threshold varied considerably with such circumstances as electrode size (see Experiment 2) but were generally of the same magnitude as those needed to elicit the sensations of Gibson [2] and were often lower.

The texture sensation exhibits two peculiarities, both apparently due to skin-resistance effects. The first is the need to "warm up" the finger. Subjects would typically spend 3 to 5 minutes making scanning motions over the display surface when attempting to first acquire the sensation at the beginning of a session. It is believed that this serves the dual purpose of drying the skin surface and permitting appropriate adjustment of the finger pressure. The second phenomenon was a tendency for the texture sensation to fail or become sporadic. This appears to occur on days when the subject is, for unknown reasons, unable to increase his skin resistance sufficiently.

EXPERIMENTS

Several brief experiments were performed on three subjects in order to determine in a rough manner the characteristics of such a display. First, the characteristics of the sensation itself were examined, and results are presented for the threshold of texture sensation, and the variation of that threshold with electrode area. The second group of experiments is related to a display using "textured areas" as the presentation element. This group includes measurements of the just-noticeable differences for amplitude and pulse-repetition rate and the localizability of a boundary. Finally, the applicability of the display to the presentation of point and line figures was investigated by measuring the minimum spacing needed to permit the user to determine that two such figures are distinct and not part of a larger figure.

The first two experiments presented involve threshold measurements. These thresholds were measured by detecting both the ascending and descending limits in alternate sequences until 15 pairs of values had been accumulated for each measurement. The measurements were repeated on successive sessions over a two-week period. Since the number of samples is small, these results, like those of the experiments that appear later in the paper, should be taken as indications of the range in which the actual values of the parameters measured can be expected to fall, not as accurate measurements of the parameters themselves.

Experiment 1—Texture Threshold

Table I shows the variation of the threshold of sensation over the three subjects and the range into which the thresholds fall for the texture sensation on a single-pattern presentation. The pattern used is shown in Fig. 2(a), and the surrounding electrodes were grounded. All values reported are measurements in volts of peak pulse amplitude.

TABLE I
THRESHOLD VARIATIONS

	Threshold Value (volts peak)		
Date	JD	LB	RK
November 23	25/24		
November 24			29
November 25		49	37
December 1			
December 2		31	26
December 3			
December 4	20/36	47/40	
December 5			
December 6			43/36
December 7	26		
December 14	21		
December 16		37	

A remarkably wide variation exists between subjects. It should be noted also, however, that a large variation occurs for a single subject from one session to the next.

Experiment 2—Effect of Electrode Area on Threshold

A number of threshold measurements were made in order to determine the effect of the electrode area on the threshold of touch. Over a period of two weeks and at least four sessions for each subject, measurements were made of the thresholds for five different patterns of excited electrodes. These patterns are shown in Fig. 2(b)–(f).

Measurements of each threshold were made on at least two different days and the results averaged to arrive at the result presented. The results are presented as a plot of threshold versus an area parameter, measured in units of electrode area. In Fig. 3 are shown the average results for three subjects using the texture sensation.

These results show a reduction in threshold with an increase in electrode area. This result appears to be contrary to the findings of Gibson *et al.* [2] for the previously reported electrotactile sensations. Included on the graph is a curve of the form

$$T = \frac{b}{\sqrt{A}},$$

the shape predicted in part by a model for the production of the texture sensation, which appears at the end of this paper.

In the development of the textured area form of the display, the primary considerations have been the ability of the subject to distinguish between textures and to locate the boundary between two areas of different textures in a situation similar to that expected in the use of an explorable display. The presentations for the experiments described below are, therefore, all based on the simultaneous presentation of two different textures on two disjoint but immediately adjacent areas of the display array. In all cases the size of an area was maintained larger than the finger pad so that the subject could feel

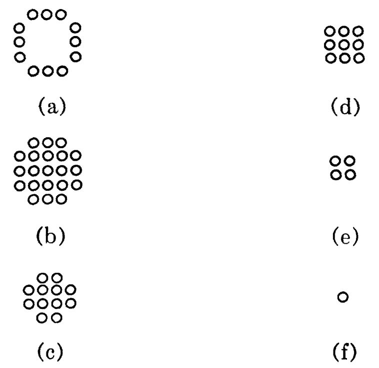

Fig. 2. Electrode patterns for threshold measurements.

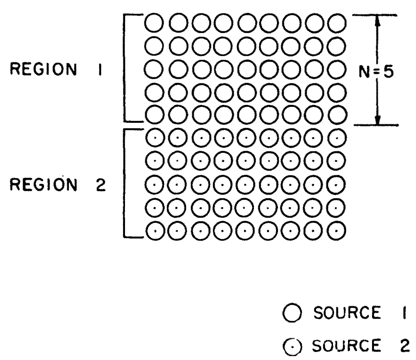

Fig. 4. Presentations for JND experiments.

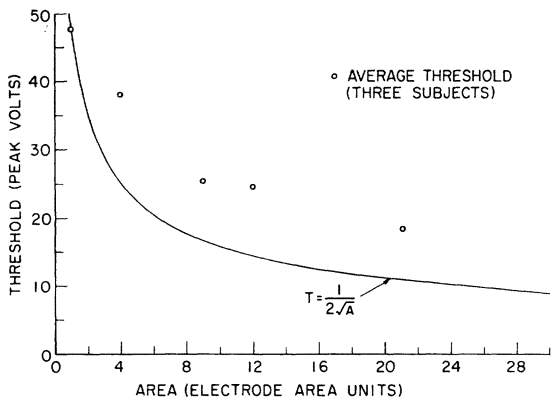

Fig. 3. Effect of area on texture threshold.

TABLE II
AMPLITUDE JUST NOTICEABLE DIFFERENCES

Level	JD	LB	RK
Near Threshold			
JND (volts)	1.20	1.32	1.77
Center (volts)	23.2	23.2	30.9
Percent	5.2	5.7	5.7
Midrange			
JND (volts)	2.24	3.17	2.35
Center (volts)	39.6	43.4	38.6
Percent	5.8	7.3	6.1
Near Maximum			
JND (volts)	3.25	5.85	6.04
Center (volts)	54.1	54.1	77.2
Percent	6.0	10.8	7.8

the textures independently if he wished. The boundary between the two areas was always a straight line, and its location was always specified along an axis perpendicular to it (Fig. 4).

Experiment 3—Just Noticeable Difference for Amplitude

This measurement was made by fixing the amplitude of one area and varying the amplitude of the other. For each measurement 100 presentations were made. In each presentation the lower area was fixed at the center amplitude and the upper area was fixed at an amplitude selected by a uniform random choice from a predetermined range. The stimuli thus differed only in amplitude and location. The experiment was performed three times, once each at 10 percent above the ascending threshold, at the "most comfortable" level selected by the subject, and at approximately 10 percent below the maximum level the subject would accept for long periods. The test was of the two-alternative-forced-choice type, the choices being "bottom is stronger" and "top is stronger."

The resulting data were treated by determining the percentage of the time the response "bottom" was given for a particular stimulus pair, and graphing the results. The reported just noticeable difference (JND) is then one half the interquartile range on that graph, or where percentages are given, the percentage that this figure represents of the center value of the same measurement (Table II).

Experiment 4—Just Noticeable Difference for Frequency

In order to determine approximately the JND for frequency, the subjects were presented with the same situation described in the previous experiment, but with stimuli that differed only in pulse-repetition rate. In all, 75 presentations were made for each measurement. In each presentation the lower area was fixed in frequency at 200 pps. Only one determination was made, and the range from which the samples were selected for the upper area was the entire useful frequency range of 100 to 1000 pps.

The same spatial presentation was used as in Experiment 3, and again the subject was permitted as much time as he wanted to make a decision. Decision times averaged about 10 seconds for all subjects. The presentation amplitude was set at the subject's most comfortable level, and the amplitudes of the two areas were identical. No attempt was made, however, to correct for the effect of pulse-repetition rate on the subjective strength, and so the stimuli were subjectively the same strength only when the frequencies were identical.

The subjects were asked to designate which of the two areas was "coarser," a term that had come into common use to designate frequency-based texture differences. The resulting data were treated as in Experiment 3 (Table III).

The results are consistent with their reports in other situations, though the JND appears to be somewhat larger than might have been hoped for.

TABLE III
Frequency Just Noticeable Differences

Subject	JND	Percentage
JD	76 pps	38.0
LB	83 pps	41.5
RK	77 pps	38.5

Center frequency is 200 pps.

The remaining three experiments in the textured-area group were performed with the same stimulus arrangement. In each case, two areas of the same form used in the JND experiments were used, but with the location of the transition from one stimulus region to the other variable. In each case, the stimuli remained constant throughout the experiment. Each measurement represents 50 presentations. Each presentation had a number N of rows of pins in the upper-electrode group connected to one source, and the remainder of the pins in the array connected to a second source.

The subject was permitted to explore the display for an unlimited period of time but was requested to respond quickly. He was asked to specify the number of rows in the upper area. The resulting data were, in each case, analyzed to derive the mean and variance of the localization error in one dimension.

Experiment 5—Area-Boundary Localizations

The boundary between an "on" and an "off" or grounded area was explored at three amplitudes, threshold plus 10 percent, twice that value, and at the level preferred by the subject as "best." In each case, the upper portion of the array was excited with a standard pulse and the lower region of the array was grounded.

The results are presented in Table IV. Decision times were on the order of 30 seconds.

Subject RK reported having difficulty maintaining the sensation on the day these data were taken, and his skin resistance was abnormally low. It is presumed that this is the reason for the large variance that his results exhibit.

Experiment 6—Amplitude Boundary

In order to obtain an initial measurement of the ability of a subject to locate the boundary between two areas excited by signals that were identical except for differing amplitudes, an experiment was performed using the results of Experiment 3. Using the same stimuli as in the "best amplitude" case of that experiment, with the amplitudes differing by 2 times the measured JND, the procedure of Experiment 5 was repeated.

At this level of difference all of the subjects felt that the difference in amplitudes was easily detectable. Any smaller difference, however, would elicit complaints that the difference was not always clear. Those subjects utilizing the texture sensation reported that unlike the situation of the previous experiment that provided a distinct boundary, the boundary in this case was more like an indistinct region than like a sharp transition. This remained true even for very large amplitude differences, only disappearing when the border was emphasized by grounding a row of pins. No experiment was performed to test this technique.

TABLE IV
Area-Boundary Localization

		JD	LB	RK
Near threshold				
Error	mean*	0.16	0.74	−1.86
	variance†	0.14	1.09	2.02
	amplitude‡	22.9	24.3	15.4
Twice threshold				
Error	mean	0.19	0.21	−1.58
	variance	0.38	0.25	2.48
	amplitude	45.7	48.5	30.8
Preferred amplitude				
Error	mean	0.20	0.04	−1.94
	variance	0.16	0.47	1.96
	amplitude	27.0	26.7	23.1

* Means are in tenths of inches.
† Variances are in hundredths of square inches.
‡ Amplitudes are in volts.

The results appear in Table V. The amplitude values used are recorded as well as the mean and variance of the errors. As might be expected, these results show a somewhat larger variance than the previous experiment, but it is not excessively large.

Experiment 7—Frequency Boundary

The previous boundary-localization experiment was also carried out with a 2-JND difference in frequency. The procedures were the same as was the method of data analysis. In this case, the frequencies and amplitude were taken from the results of the frequency JND experiment.

The results appear as Table VI. With the notable exception of the results of JD, which show small variance, these results are similar to those of the amplitude-boundary experiment. The subjects again reported that the boundary was not a distinct thing, but rather an indistinct region between two areas of distinctly different texture.

Experiment 8—Form-Separation Measurements

The last group of measurements to be presented are related to point-and-line presentations. In each of the measurements given below the subject was presented with two figures whose separation was variable. The figures were all simple points and lines. The unexcited areas of the display were connected to ground. The subjects were premitted to select the amplitude that they felt most comfortable with, much as they would in using a point-and-line display.

The subject was informed of the shape of the pattern, and was allowed to adjust the amplitude to a comfortable level. He was then instructed to report either that he could feel two distinct forms or that they were merged. It was impressed on the subject that a report of "separate"

TABLE V

Two Area-Transition Localization—Amplitude Differences*

Subject	Center Amplitude (volts)	Error Mean†	Error Variance‡
JD	39.6	−0.166	1.47
LB	43.4	−0.024	1.56
RK	38.6	0.106	1.88

* Localization of the boundary between two areas whose excitation differs by two JND's in amplitude.

† Mean error is measured in tenths of inches.

‡ Error variance is measured in hundredths of square inches.

TABLE VI

Two Area-Transition Localization—Frequency Differences*

Subject	Amplitude (volts)	Error Mean†	Error Variance‡
JD	39.6	0.71	0.078
LB	43.4	0.311	2.70
RK	38.6	0.74	3.67

* Localization of the boundary between two areas whose excitation differs by two JND's in frequency.

† Mean error is measured in tenths of an inch.

‡ Error variance is measured in hundredths of a square inch.

was to be given only if they were felt to be separate, not if they "might" be separate.

The data collected have been organized to show the percentage of responses "separate" that were elicited for each number of grounded pins separating the two figures, and an average over the subject set is also given. Since the measurement is relatively coarse, due to the constraint of pin size in the available electrode array, the results are given in tabular form. Each set of results represents 75 presentations to each subject with separation distances ranging from 0 to 5 pins. The presentations were made in a random order, with no attempt to constrain the response time. Response times averaged about 10 seconds.

The patterns are shown in Fig. 5, and the corresponding results as Tables VII–IX. Note that the measurement given X is the number of unexcited electrodes between figures. Therefore, the minimum distance between electrode segments that are excited is $0.1X + 0.03$ inch.

Proposed Mechanism and Model for Texture Sensation

The mechanism that we propose is that an electrically induced variation in the vertical force between the subject's skin surface and the display electrode is converted by the friction mechanism into a variation in the lateral force (tangential to the skin surface) as the subject passes his finger across the electrode. This variation in lateral force then causes motions of the portions of skin in contact with the surface over the electrode to vary about the relatively constant motion of the whole finger. The re-

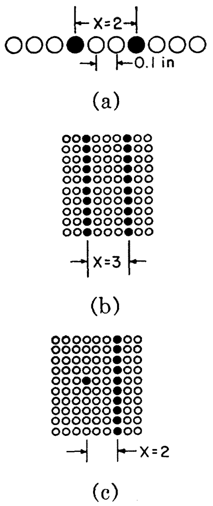

Fig. 5. Presentations for form-separation test.

TABLE VII

Separation of Two Points

Separation X (in point spacings)	Subject Responses (percent) RK	LB	JD	Average
0	0	0	8.3	2.7
1	0	16.6	0	5.5
2	12.5	33.3	58	34.6
3	97	88.2	94	93.1
4	100	100	100	100
5	100	100	100	100

Necessary separation is 3 points.

TABLE VIII

Separation of Two Lines

Separation X (in point spacings)	Subject Responses (percent) RK	LB	JD	Average
0	0	0	0	0
1	0	0	0	0
2	16.6	68.6	42	42.4
3	91	100	94	95
4	100	100	100	100
5	100	100	100	100

Necessary separation is 3 points.

TABLE IX

Separation of a Point from a Line

Separation X (in point spacings)	Subject Responses (percent) RK	LB	JD	Average
0	17	0	0	5.5
1	83	33	0	39
2	91	98	100	96.5
3	100	100	100	100
4	100	100	100	100
5	100	100	100	100

Necessary separation is 2 points.

quired variation in vertical force is assumed to be generated by electric-charge accumulations in the subject's finger and on the electrode surface.

The following symbols will be used in the discussion.

$f_v(t)$	The vertical component of force (pounds) between the skin and the electrode.
$\Delta G(t)$	The variation with time of any function $G(t)$ about its average value (in the units of $G(t)$).
F_v	The force (pounds) applied by the subject in the vertical direction. (It is assumed to be essentially constant).
μ	The coefficient of friction for the skin-display surface pair.
$f_t = \mu f_v$	The total tangential force (pounds) in steady-state finger motion.
Z_m	The mechanical stiffness, in pounds per inch, of the skin in the direction tangential to the skin surface.[2]
$x(t)$	The position (inches) of the local skin surface with respect to a coordinate frame fixed to the finger.
T_i	The thickness (inches) of insulator layer i.
ϵ_i	The dielectric constant of insulator layer i.
$\hat{T}_i = T_i/s_i$	The effective thickness (inches) of material i.
A	The area of skin contact with the electrode.
C	The capacitance (farads) of the skin surface in contact with the electrode.
$v(t)$	The instantaneous voltage applied to the subject.
V_j	The peak voltage applied in the jth experimental case.

s (subscript) applies to the subject's skin.
p (subscript) applies to the plastic insulator.
$\epsilon_0 = 8.854 \times 10^{-12} f/m$ is the permittivity of free space.

The pertinent forces are shown in Fig. 6. Mathematically, this system can be described as follows:

$$f_v = F_v + \Delta f_v$$

$$f_t = u\, f_v$$

$$\Delta f_t = u\, \Delta f_v$$

$$\Delta x(t) = \Delta f_t(t)/Z_m.$$

We wish to show that $\Delta x(t)$ is of the same magnitude as the motion required for mechanical stimulation of the skin in a tangential direction, at frequencies near the pulse frequency used to elicit the texture sensation. The values measured for mechanical thresholds in the tangential direction are similar to those for vertical motion, and about 10 microns (about 4×10^{-4} in) peak-to-peak displacement [3], [5], [6].

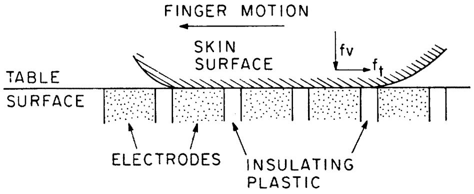

Fig. 6. Applicable forces.

The value of mechanical impedance in the tangential direction has been measured as about 0.48 lb/in [3], [4].[3] It is not practical to directly measure the coefficient of friction, as it depends on a great many factors including applied finger pressure, atmospheric humidity, and individual skin factors, especially perspiration. However, subjects indicate a coefficient μ, for the finger in contact with the dry electrode, of the order of 1, with a maximum variation in that judgment of less than a factor of 3 in either direction. This value was the result of simply asking the subjects to estimate the ratio of horizontal to vertical force in their finger motions. We would, therefore, expect to require a vertical-force variation on the order of 2×10^{-4} lb, peak to peak.

The electrical model used, in the form of a pair of closely spaced parallel plates of the same slice, is shown in Fig. 7. The electrically induced force between the two "plates" and the capacitance of the system are given by

$$\Delta f_v = \frac{\epsilon_0 A[v(t)]^2}{2(\hat{T}_x + \hat{T}_p)^2}$$

$$C = \frac{\epsilon_0 A}{\hat{T}_s + \hat{T}_p}\,.$$

In order to extract the parameters of this model, in particular the skin thickness, an experiment was performed. It consisted of measuring the threshold of sensation for each of three conditions.

The active electrode consisted of the entire right half of the display array, much larger than the subject's finger tip. This was done three times in scrambled order, and the results averaged to yield the values given in Table X. Note that only one subject was used to derive these values.

These values were measured on only one subject, and only one day. While variations in the specific voltage values do occur, the same calculated values were ob-

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[2] It has been shown [3], [4] that the mechanical impedance of the skin, for small relative displacements, is essentially a spring in nature, with a constant stiffness in the range of displacements encountered in these experiments.

[3] This value was not measured on the finger pads. It was measured for small excursions (less than 6 mils) and we can expect that the skin of the finger pad is not significantly stiffer over small excursions than the skin of the upper arm where the measurement was made. Franke's measurements unfortunately do not apply directly because of the large areas of contact and large excursions involved, though they indirectly support the figure given [4].

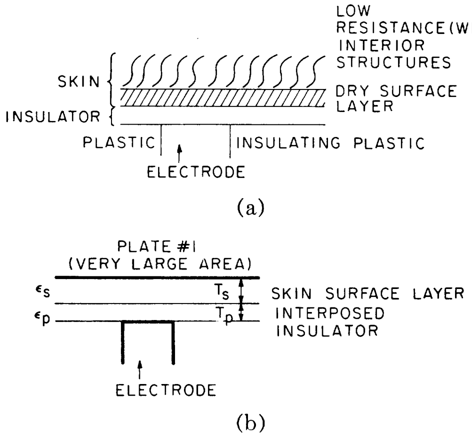

Fig. 7. Electrical model.

TABLE X

Condition	Average Peak Voltage at Threshold (volts)
No insulator	17
0.5-mil insulator	73
1.0-mil insulator	110

tained with another subject.[4] It should be noted that these figures also reflect a large difference in the coefficient of friction between the insulated and uninsulated cases, so that the insulated and uninsulated cases cannot be directly compared.

The insulator used was polyvinylidene chloride (Dow Saran); its pertinent properties are shown in Table XI.

In the experimental situation there is a return electrode under the palm of the same hand in addition to the contact at the fingertip. The results of other experiments, not reported here, indicate that this electrode is usually quite wet from perspiration, and can thus be neglected when compared to the dry fingertip contact. Skin resistances measured in this experimental situation on the order of 2×10^6 ohms with no interposed insulator and dry finger electrodes, and 5000–10 000 ohms with both electrodes wet. No measurable current flows with the insulator between the finger and the electrode.

It has been assumed that the tangential-force variation on the skin is the same at all three threshold measurements shown in Table X. The voltage pulse train applied to the user's finger is shown in Fig. 8(a). The assumption is made that the time constant (RC product) of the skin is much smaller than the voltage pulsewidth, in order to guarantee the rectangular shape of the force pulse.

The variation in tangential force is thus just the peak value of the electrically produced force, or

$$\Delta f_{ti} = \frac{\epsilon_0 A (v_{\max})^2}{2(\hat{T}_s + \hat{T}_p)^2} \mu_i ,$$

TABLE XI

PROPERTIES OF THE INSULATOR

Dielectric constant	3.5–5.5 (approximately 4.5 at 200 Hz)
Dielectric strength	350 V/mil
Resistivity	> 10^{14} Ω·cm

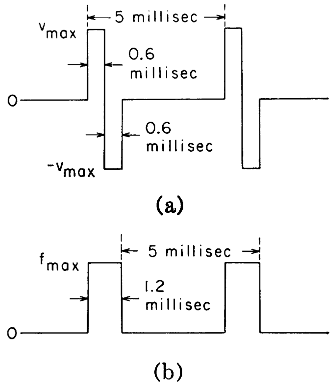

Fig. 8. Voltage and pulse waveforms.

giving

$$\mu_1 \frac{\epsilon_0 A (v_{1\,\max})^2}{2(\hat{T}_s + \hat{T}_{p_1})^2} = \mu_2 \frac{\epsilon_0 A (v_{2\,\max})^2}{2(\hat{T}_s + \hat{T}_{p_2})^2} = \mu_3 \frac{\epsilon_0 A (v_{3\,\max})^2}{2(\hat{T}_s + \hat{T}_{p_3})^2} .$$

Manipulation of the force functions for the two insulated cases, noting that $\hat{T}_{p_3} = 2\hat{T}_{p_2}$ and $\mu_2 = \mu_3$, can be made to give

$$\hat{T}_s = \hat{T}_p \frac{(2V_2 - V_3)}{(V_3 - V_2)} .$$

For each 0.50×10^{-3} inch of physical thickness, the insulating material used has an effective thickness of

$$\hat{T}_p = 0.111 \times 10^{-3} \text{ in} = \hat{T}_{p_2}.$$

This gives an effective thickness of the dry surface skin layer to be

$$\hat{T}_s = 0.108 \times 10^{-3} \text{ in.}$$

The variation in vertical force generated by the model, using this value of skin thickness and the threshold voltage measured for the no-insulator case of the experiment is

$$\Delta f_v = 93.3 \times 10^{-6} \text{ lb per electrode point.}$$

Since the voltages needed to elicit sensation become extremely high for single-electrode presentations, the experiment used here was performed using an array of active electrodes much larger than the finger pad. This fact makes it difficult, however, to determine the actual contact area being used by the subject. The result is, therefore, reported in terms of the force per electrode area, which is 3.846×10^{-3} in. It is estimated that the maximum possible contact area is about 5 points, and the minimum about 1 point.

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[4] Skin thicknesses computed using the model change considerably, but calculated forces do not.

This value of force does not, of course, take into account the surface coefficient of friction. However, unless the subjects have consistently and repeatedly overestimated the coefficient of friction, the resultant tangential force would be greater than the expected force needed to cause sensation by the proposed mechanism.

Earlier it was assumed that the RC time constant for the skin was small compared to the pulsewidth. To show that this is true, we calculate the value of this surface capacitor as

$$C = \frac{\epsilon_0 A}{\hat{T}}$$

$$C = 8.56 \text{ pF per point electrode.}$$

Thus, the maximum value of capacitance is about 45 pF, and the corresponding RC product, using the skin resistance for the case of two wet electrodes, becomes 45×10^{-8} second. This value is clearly much smaller than the pulsewidth of 10^{-3} second. Thus, we can expect the full effect of the rectangular force pulse.

CONCLUSION

The existence of a texture effect produced by an electrical stimulator has been demonstrated. We have presented a justification for a model of this effect in which a physical motion of the skin is caused by the potential difference between the electrode and the interior side of the skin. The texture effect has been clearly distinguished from the usual type of electrical stimulation by noting a direct dependence of the perceived stimulus intensity and the applied voltage rather than the usual result of the stimulus intensity being a function of the applied current. Indeed, the use of an insulator between the electrode and skin produces no apparent change in the perceptual qualities of the texture effect, while the resulting current is several orders of magnitude lower than that normally required to elicit electrotactile sensations. An explorable tactile display has been built that utilizes this effect, and the results of preliminary experiments indicate that a person can resolve details presented by this electrotactile display.

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A Survey of the Mechanical Characteristics of Skin and Tissue in Response to Vibratory Stimulation

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***Abstract*—The possibility that the mechanical characteristics of skin and tissues may influence physiological and psychophysical measurements of tactile sensitivity is considered. A survey of selected literature indicating how certain mechanical characteristics of skin and tissue vary as a function of changes in variables known to influence physiological and psychophysical measurements of the tactile system is presented.**

Finally, certain physiological and psychophysical studies in which the physical properties of the area stimulated may have influenced the results are mentioned.

THE RESPONSE of the human body to mechanical vibration has long been an area of interest for the Air Force. The Air Force became particularly interested in this field with the advent of jet engines and power plants that generate intense sound fields. The possibility of physiological damage from the absorption of vibrations in the environment and from direct contact of the human with vibrating machinery (e.g., in the of the pilot) had to be evaluated. For these purposes it became necessary to obtain quantitative measures of the physical behavior of the body surface and tissues in response to mechanical vibratory energy.

The majority of the data the author wishes to discuss

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