FUNDAMENTALS OF ELECTROTACTILE STIMULATION FOR SENSORY FEEDBACK FROM LIMB PROSTHETICS*†

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Summary

An electrotactile two point discrimination process was investigated as the design concept for a multichannel sensory information system compensating for loss of tactile and kinesthetic perception in upper limb prosthetics. A methodology was developed relating electrotactile two point threshold with frequency, body site, laterality, stimulation codes, pulse width, and pulse time delay. Several sensory feedback systems were developed to determine the optimal number of channels of information and optimal quantity of information per channel. A hybrid design procedure was outlined.

Introduction

Several artificial sensory augmentation systems (ASAS) have been developed in recent years to compensate for loss of function in the visual, auditory, tactile, and kinesthetic senses. These ASA systems utilize either electrical or mechanical cutaneous stimulation as the display modality, and amplitude, frequency, and pulse width as the design concepts (Bach-y-Rita, et al., 1970; Saunders, 1973; Saunders, et al., 1971; Kato, et al., 1970; Solomonow, et al., 1975; Bliss, 1967; and Prior, et al., 1976).

A great deal of progress has been made through the various ASAS's toward sensory recovery for the disabled; however, limitation in both quantity and quality of information transmission has become evident, and more complex stimulation techniques need to be sought.

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† The material in this paper reproduces and augments with more recent data the references listed Solomonow, Lyman and Freedy, 1977 and Solomonow and Lyman, 1977.

In a previous paper (Freedy, et al., 1975), a two-channel ASAS was proposed in which frequency modulated two-point discrimination was the design concept. This ASAS was to supplant fingertip pressure and elbow position sensory losses in an upper limb prosthesis. The system consisted of an electrode array attached to the stump skin, with a monophasic rectangular current pulse as the stimulus. The pulse frequency was to be related to the finger pressure, and the given electrode in the array to be related to the elbow position (Figure 1). A preliminary system was designed and tested successfully on several nonhandicapped subjects, and its potential was evident.

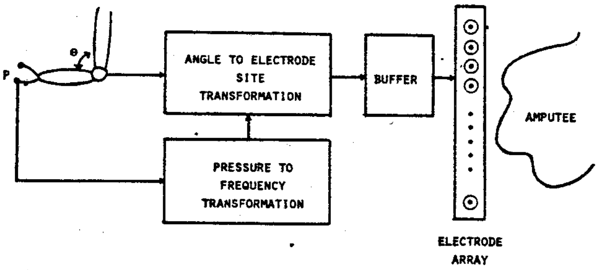

Figure 1 Proposed frequency modulated two-point discrimination artificial sensory augmentation system

In order to optimize the final design, it was necessary to know more about the response of cutaneous receptors to such stimulation codes. A search of the psycho-physiological literature indicated that most of the data that exist principally concern mechanical cutaneous stimulation (Bekesy, 1967; Weinstein, 1968; Eskildsen, 1969). No data relating specifically to electrotactile two-point discrimination were found. We then set forth to devise experimental procedures to obtain data relating two-point discrimination thresholds (TPDT) with frequency, body locus, and stimulation techniques. Some findings of these experiments are the subject of this paper.

Experimental Procedures

Since the proposed ASAS display is based on both frequency variation and proximity of placement of the electrodes, our main objective was to find how TPDT varies as a function of frequency. What are the differences in the responses at various bodily locations? Are there variations in sensitivity of the left versus the right sides of the body? Finally, would different stimulation techniques, such as spatial or temporal techniques, yield different responses?

Instrumentation

The experimental apparatus consisted of a dual channel stimulator, a micromanipulator, and two stainless steel concentric electrodes, all designed and constructed in our laboratory.

The stimulator was capable of delivering negative current pulses of 0 to 40 mA and 10 μsec to 10 msec duration at frequencies of 1 to 300 pps. In addition, the output stage could be controlled so the stimulus could be delivered to the electrodes spatially, temporally, or in a frequency on frequency mode (Figure 2).

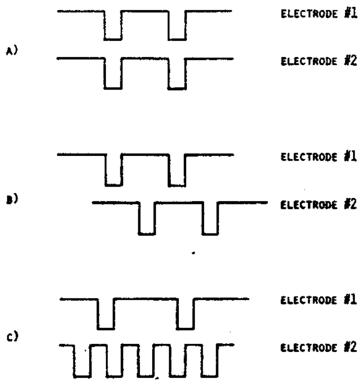

Figure 2 The three stimulus codes applied:
(A) Spatial
(B) Temporal
(C) Frequency on Frequency

F_1 = 5 pps
F_2 = C_2

In the frequency on frequency (FOF) code, one electrode was kept at 5 pps at all times, while the other electrode varied from 10 to 100 pps. The direct utilization of such a technique can be realized by keeping the reference electrode in the display at 5 pps, and letting the fingertip pressure modulate the frequency of the dynamic electrodes from 10 to 100 pps. The current amplitude could be adjusted independently for each electrode to the comfort level of the subject.

Two concentric electrodes, 6.55 mm outside diameter with a 3.275 mm cathode, were made of stainless steel with a ring of PVC insulating the inside from the outside electrodes. The electrodes were then mounted on a micromanipulator designed for accuracy of 0.01 mm, and capacitively coupled to the stimulator.

For the temporal code, the phase shift of the two pulse trains could be varied independently of frequency between 0^o to 180^o, which corresponds to the appropriate time delay depending on the frequency under consideration.

Protocol

TPDT tests were made at eleven body locations for each frequency and each stimulus mode. The skin location under consideration was prepared with a water dampened sponge to facilitate stimulus current conduction, and to give consistency to the measurements. At the outset of a series of readings, the center to center electrode distance was set at 20 to 25 mm to assure a clear separation of signals. Light pressure was applied to the electrodes to ensure good skin contact, and the stimulus strength to the first electrode raised slowly up to pain threshold, and then backed up slightly to the comfortable range, just below pain. The same process was repeated independently with the second electrode to insure equal amplitude of perceived stimulus. The electrodes were then slowly brought closer together to the point where the subject reported a single stimulus. This was defined as the two-point discrimination threshold (TPDT), and was recorded.

In order to estimate the accuracy and repeatability of the TPDT, three measurements at the most sensitive frequency (F_m) were taken for the spatial code.

The above procedure was repeated for frequencies of 5 to 100 pps, and for each of the following body locations: fingertip, palm, forearm, upper arm, shoulder, chest, back, belly, thigh, calf, and sole.

The whole procedure was repeated for spatial temporal, and frequency on frequency techniques.

In order to eliminate consistent error due to learning, a 20 minute period prior to the experiment was dedicated to familiarizing the subject with the sensation of TPDT without data being taken. The order of the stimulus codes applied was varied from individual to individual (an equal number of subjects followed the order of spatial, temporal, and frequency on frequency; temporal, frequency on frequency and spatial; and frequency on frequency, spatial and temporal, respectively). This procedure further eliminated the effect of learning on the data.

A second group of subjects was tested for the effect of pulse width and pulse phase shift on the TPDT. The above procedure was, therefore, retested for frequencies of 5 to 100 pps at pulse widths of 10 μs, 100 μs, and 1 ms, and phase shifts of 0^o (spatial code), 45^o, 90^o, 135^o, and 180^o (temporal code).

Subjects

Twenty-nine subjects were tested, of whom 15 were females and 14 were males. Most subjects were drawn from a freshman psychology class, and their ages ranged from 18 to 27, with an average of 20 years.

Data

In general, for the three stimulation coding techniques employed (spatial, temporal, and frequency on frequency), the TPDT exhibited a characteristic V-shaped curve over the frequency range of 0 - 100 pps, as shown in Figure 3.

Definitions

For brevity, the following definitions were established:

MTPDT: Minimum TPDT. The absolute lowest value of TPDT over the frequency range 0 - 100 pps.

F_m: Minimum frequency. The frequency at MTPDT.

SBW: Sensitive bandwidth. The frequency range measured for which TPDT stayed below the line MTPDT + 1 mm.

Typical Plots

Data collected in the light of the questions posed earlier in the paper resulted in the following typical behavior of TPDT threshold as a

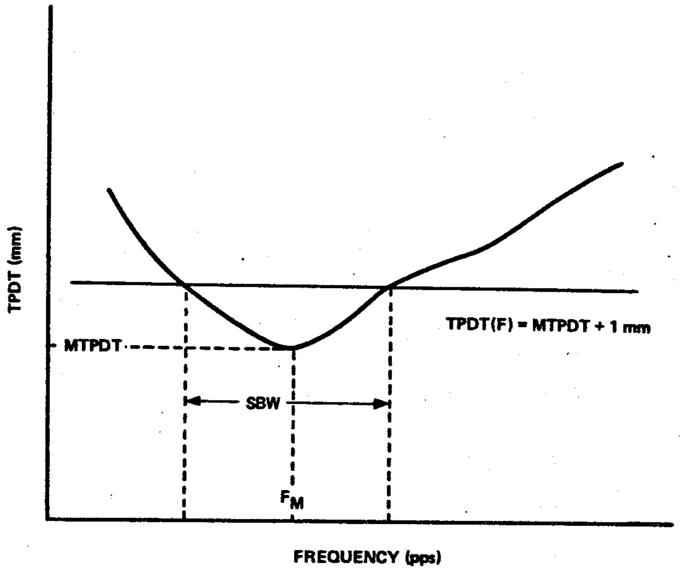

Figure 3 Typical form curve for each code in the range 0-100 pps

function of frequency for the three stimulation codes, for various body sites, for contralateral body parts, and for variations in F_m. A typical plot of TPDT versus frequency for the spatial, temporal, and frequency on frequency (FOF) stimulation modes presented in the palm is shown in Figure 4.

Figure 5 shows the TPDT versus frequency plot for five body locations of the dominant side of the subject.

In Figure 6, the TPDT versus frequency curves of five individuals are superimposed to show differences in F_m from subject to subject.

Variations in TPDT versus frequency patterns from dominant to contralateral palms of the same individual are given in Figure 7.

The response of the TPDT versus frequency for three pulse widths and two stimulation codes is shown in Figure 8. Variations of TPDT as a function of frequency for five values of phase shift in the temporal code is shown in Figure 9.

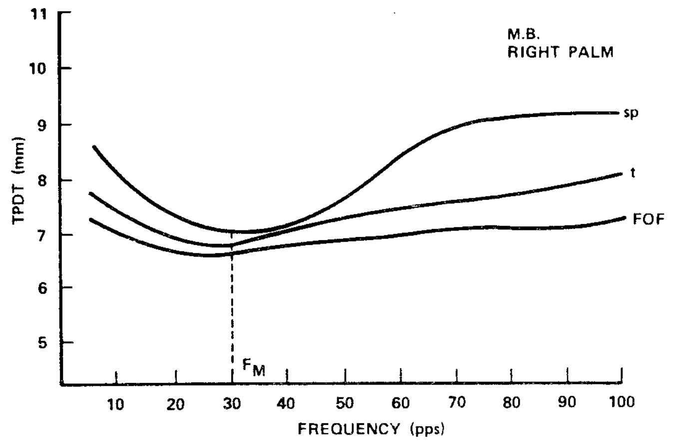

Figure 4 TPDT versus frequency plots for spatial, temporal, and frequency on frequency stimulation codes

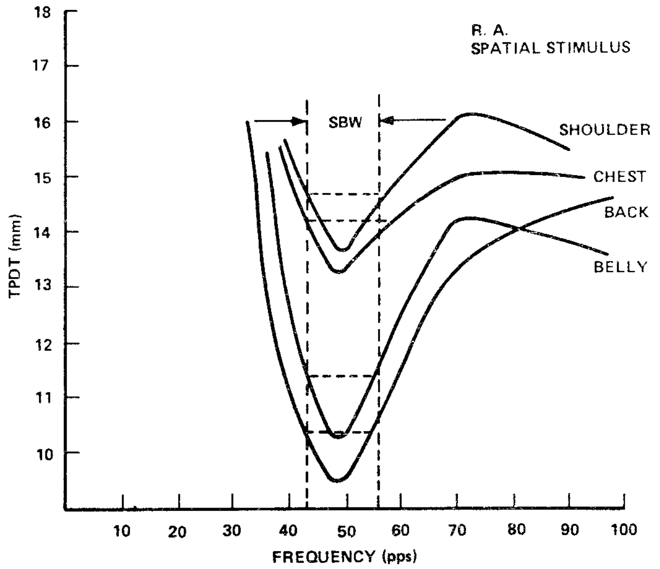

Figure 5 TPDT versus frequency plots for various body sites of the same individual

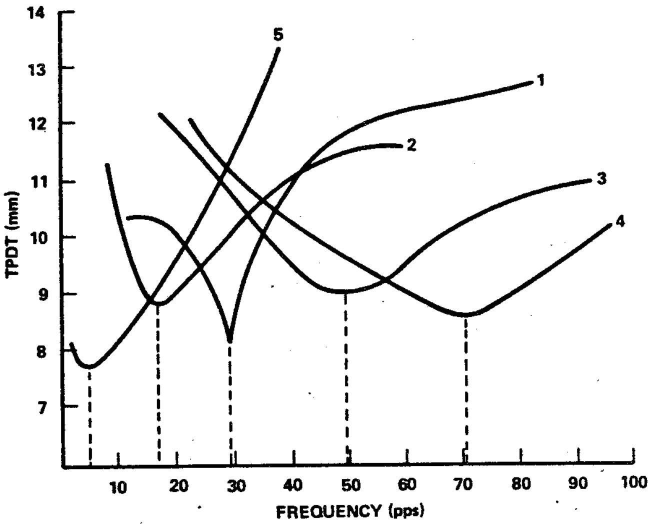

Figure 6 TPDT versus frequency plots for five subjects showing variation in F_m and MTPDT at the palm

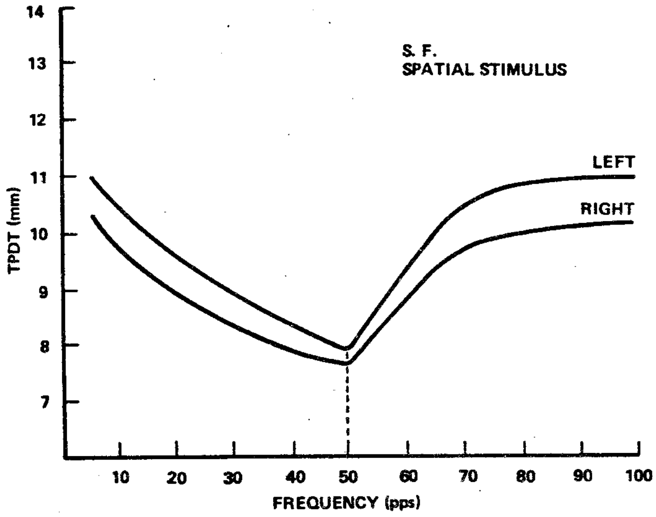

Figure 7 TPDT versus frequency plots for right and left palms of one subject

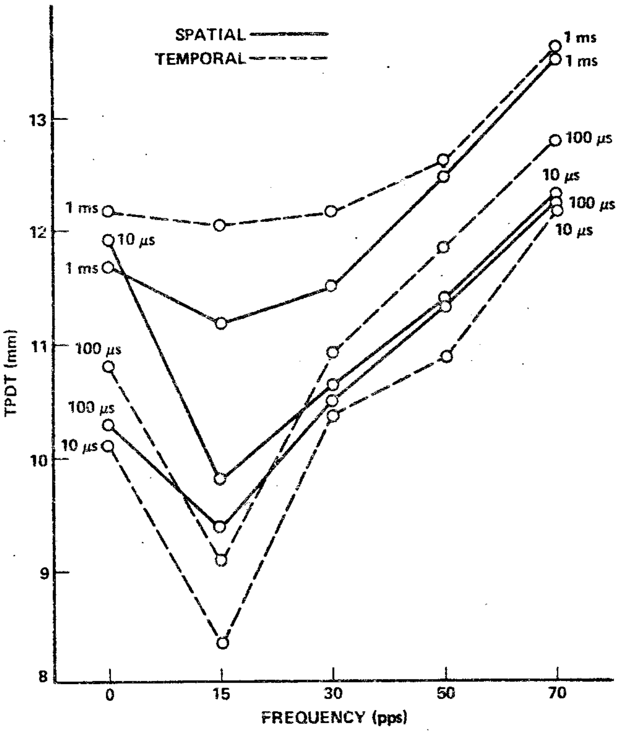

Figure 8 Typical TPDT versus frequency plot for three pulse widths in the spatial and temporal codes

Results

The direct goal of these experiments was to obtain data to aid in the definition of a set of specifications for the design of an electrotactile display. Since the design concept for the display consists of electrode-interdistance and frequency variation, the variables of interest here are the TPDT, bandwidth, and their relationships. Comparison of the three stimulation techniques is in order for optimal design.

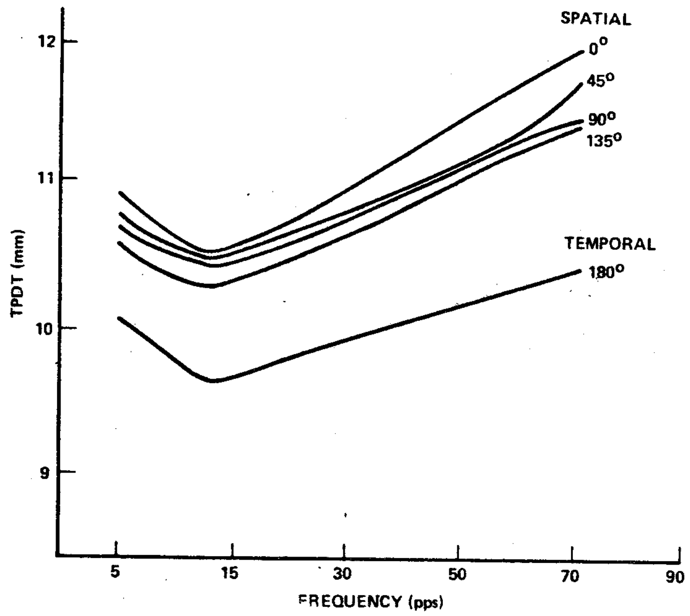

Figure 9 Typical TPDT versus frequency plot for phase shifts of 0° to 180° range

Since TPDT varies with frequency, and also possesses a frequency where TPDT is at the absolute minimum, an arbitrary definition of bandwidth was set at the frequency limits of the straight line, TPDT (f) = MTPDT + 1 mm, superimposed on the three TPDT versus f curves for three stimulation codes. We assume, then, that we are willing to sacrifice interelectrode distance for larger frequency variation range. Two channels of information will thus exist.

Before we treat the data further, it is relevant to point out the following. To establish the superiority in discrimination of a given body location, a direct measurement comparison of MTPDT will suffice. In general analysis, however, a relative measure of discrimination, such as normalized MTPDT, would be an advantage. Such normalization will also prove to be advantageous from the standpoint of equipment limitations. For safety, we avoided the introduction of tissue damaging high current densities by setting the electrode size at 6.55 mm o.d. In order to allow for this equipment limitation and permit generalization of data in this study, normalization of the MTPDT should be done using the minimum interelectrode distance of 6.55 mm.

The normalized MTPDT is therefore introduced by the relationship

$$G = 6.55/\text{MTPDT},$$

where G = normalized gain ratio, 6.55 = minimum interelectrode distance (center to center), MTPDT = minimum two point discrimination threshold.

Furthermore, a relative index of discrimination effectiveness is necessary to assess superiority of a given stimulation code. Such an index should incorporate the two variables to be optimized in the electrotactile display design: MTPDT and SBW. The product gain (G) and the sensitivity bandwidth (SBW) is assigned as the sensitivity index (SI). Thus,

$$SI = G \cdot SBW$$

or

$$SI = (6.55/\text{MTPDT})\ SBW$$

The sensitivity index (SI) is therefore normalized, and will allow objective statistical evaluation without taking equipment limitations as a variable.

Body Sites

Superiority of a given body location for attachment of the electrodes was approached from the standpoint of the optimal amount of information transfer in terms of electrodes per square centimeter of skin or bits per square centimeter. In order to determine the most effective and appropriate attachment place for the electrotactile display, the average MTPDT's for the spatial code were compared for 11 sites, and were rank ordered (Table I).

TABLE I

Location	MTPDT (mm)	Order (1 - 11)
Fingertip	7.25	1
Palm	7.73	3
Forearm	8.93	4
Upper Arm	9.48	7
Shoulder	9.17	6
Chest	10.23	11
Back	9.79	9
Belly	9.78	8
Thigh	9.88	10
Calf	9.06	5
Sole	7.67	2

The separation of the average MTPDT into three groups (the arm, leg, and trunk) reveals that a discrimination gradient exists in the arm and leg, where the two-point discrimination is most sensitive in peripheral body sites, such as the fingertips and soles. The gradient steadily increases when approaching the trunk. No conclusive evidence was observed as to the existence of this gradient within the trunk itself. Figure 10 shows the increase in MTPDT for the arm and leg as the trunk is approached.

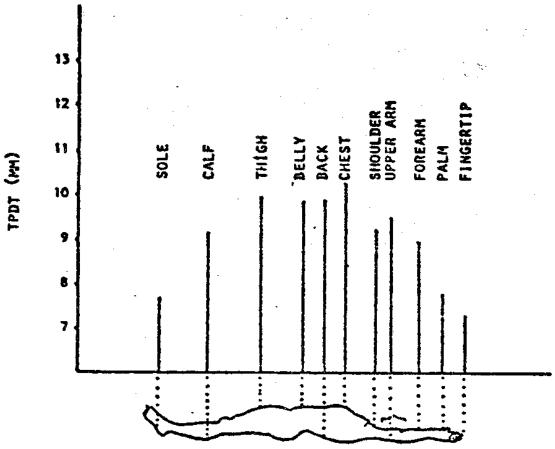

Figure 10 Two point electrocutaneous discrimination threshold for different body sites

These data agree with Weinstein (1968), who used two thin metal rods to map TPDT of the body. It is not surprising to find that the hand and sole are the most sensitive parts of the body when we consider the large areas that represent the hand and the sole in the sensory cortex, and compare them with the smaller areas provided for the trunk.

It is clear that the most appropriate location for a clinically useful display is somewhat limited; i.e., for hand amputation, only forearm and above are available for display attachment. The choice of display location is thus subject to particular disability conditions and convenience of harnessing the stimulators.

Repeatability

TPDT reading accuracy and possible error for three sequential trials for the spatial code at right and left palms were analyzed. The analysis centered on the comment made by most subjects concerning the superior clarity and distinction of the TPDT on the nondominant palm compared with the dominant palm.

Table II summarizes the average deviations observed in three sequential measurements for all subjects, as well as the average variation range (i.e., difference between highest and lowest reading).

TPDT analysis showed that all the above subjects demonstrated lower TPDT over the frequency range of 0 - 100 with the dominant arm. This suggests that, although the dominant side is superior as far as threshold value is concerned, the contralateral side is more accurate and distinction is better for determination of the exact threshold occurrence. The subjective comments made by the subjects (noted above) support such an hypothesis. No explanation, however, can be given for these somewhat puzzling findings at this time.

Minimum Frequency (F_m)

The F_m as seen in Figures 4 and 5 is constant for all body sites for the three stimulation codes. In addition, the F_m is variable from person to person, as seen in Figure 6. The distribution of the F_m for the 29 subjects tested is shown in the histogram of Figure 11.

TABLE II

	Average deviations (mm)	Average deviation range (mm)*
Dominant palm	0.132	0.318
Nondominant palm	0.0772	0.20

*Note: Largest range was 0.62mm; smallest range was 0.03 mm.

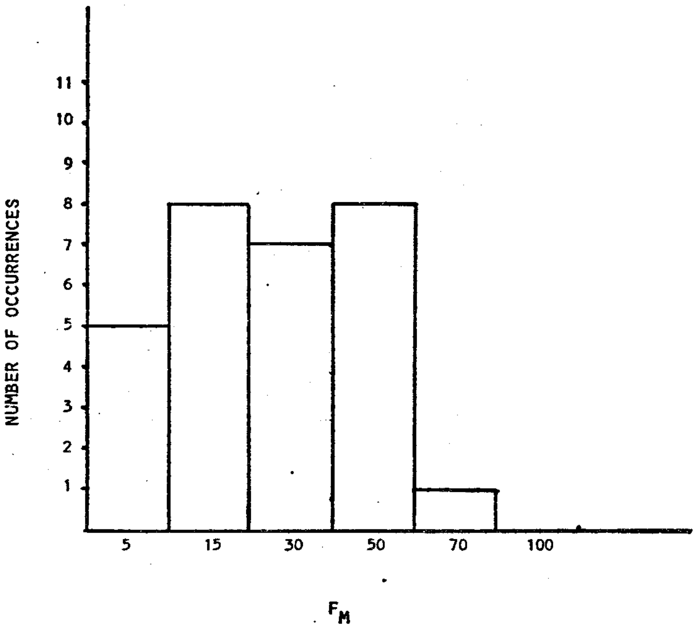

Figure 11 Distribution of Occurrence of F_m

It should be noted that, because of the experimental procedures, only six TPDT measurement points were taken over the frequency range 0 - 100 pps, and it may be possible for an individual to have an F_m at frequencies between data points. With this in mind, the histogram should be regarded as a distribution pattern, rather than an absolute distribution. It can be seen, nevertheless, that most of the subject's F_m's fall within frequencies of 0 - 50 pps rather equally, with no particular concentration about a given frequency. No subject had an F_m of over 70, and most subjects reported vague or unclear TPDT at such high frequencies. In fact, several subjects were not able to indicate the TPDT at 100 pps, which is in agreement with the data obtained by Prior (1972).

It may be concluded at this time that the F_m is distributed randomly over 0 - 50 pps. Additional subject testing is required to determine whether a normal distribution exists for the F_m. In addition, the subjects were asked at the end of each data set at what frequency the TPDT was most easy and obvious to determine; nearly all subjects indicated that it was their own F_m.

Laterality

The MTPDT, as well as the SBW, were considered here in establishing the superiority in discrimination of the dominant body side. Table III indicates the differences in average MTPDT and in average SBW for spatial, temporal, and frequency on frequency stimulation codes, as well as the associated sensitivity index (SI) for the dominant and contralateral palms.

TABLE III

	MTPDT(mm)			SBW(pps)			SI		
	SP	T	FOF	SP	T	FOF	SP	T	FOF
Dominant side	7.73	7.03	6.79	52.2	71.82	88.0	45.35	68.11	85.49
Contralateral side	8.09	7.23	6.94	51.0	67.36	77.36	43.21	62.2	73.94

It is clear that the dominant side has better discrimination capability as well as larger bandwidth than the contralateral side. It is also worth noting that although the SBW is constant for all body sites of a given individual on one side, the dominant body side possesses larger SBW than its contralateral part (Table III).

Comparison of Stimulation Codes

Table IV shows the average SI of each of the stimulation codes: spatial, temporal, and frequency on frequency.

TABLE IV

	Sensitivity Index		
	Spatial	Temporal	FOF
Dominant side	45.35	68.11	85.49
Contralateral side	43.21	62.2	73.94

Considering that an SI value of 100 pps is the maximum possible, the temporal stimulation code shows an improvement over the spatial code of 22.76 and 18.99% for the dominant and contralateral sides, respectively. The FOF code shows improvement over the spatial code of 40.14 and 30.73% for dominant and contralateral sides, respectively, or 17.38 and 11.74% over the temporal code for dominant and contralateral sides, respectively.

It follows, therefore, that the FOF stimulation code is the superior code, whereas the temporal and spatial stimulation codes are secondary and tertiary, respectively, in effectiveness. Most subjects also made the subjective comment indicating FOF as the code at which TPDT was most distinct. The superiority of the FOF is compounded due both th gross reduction in the MTPDT and to appreciable flattening of the curve, so larger frequency bandwidth is allowed. Table III shows the average MTPDT for the left and right palms for the three stimulation codes.

Sensitive Bandwidth (SBW)

Three subjects were tested for constancy of SBW at several body sites. Figure 5 shows the SBW calculations for the right side of one subject. The SBW seems to be constant over all body sites of one side of a given individual ±5 pps. Therefore, if the SBW for one body site is known, the SBW of all body sites of the same side of the same person can be predicted without further measurements.

Table V summarizes the average SBW for the spatial, temporal, and FOF stimulus codes for the dominant and contralateral body sites.

TABLE V

	Sensitivity bandwidth (pps)		
	Spatial	Temporal	FOF
Dominant side	52.2	71.82	88.0
Contralateral side	51.0	67.36	77.36

Two features of interest are observed in Table V. The first is that, although it has been established that the SBW is constant for all locations of one body side, the SBW of the contralateral side is somewhat smaller. The difference between contralateral sides increases from 1.2 to 4.46%, and 10.7% for the spatial, temporal, and FOF stimulation codes, respectively.

The second feature of interest is the increase in the SBW for the different stimulation codes. An increase of 19.2% is observed from the spatial to the temporal codes, and 16.18% from the temporal to the FOF code.

The applications of such results appear to include the advantage of electrotactile displays on the dominant body side and the use of the FOF as the stimulation code for which frequency information coding will gain a larger range.

It should be noted that some of the contributing factors for the average ±5 pps possible error for one body site to another of the same side of an individual are the frequency intervals for which data were recorded, and the accuracy of the curve drawn from such data. Smaller intervals, say every 10 pps, would probably result in reduction of SBW error from ±5 pps.

Pulse Width

From the standpoint of interelectrode distance optimization, the effect of stimulus pulse width on the TPDT is examined and represented in Figure 12. For the spatial code, the superiority of the 100 μs pulse width over 10 μs and 1 ms is apparent and consists of an improvement of 4.2% and 12.5%, respectively.

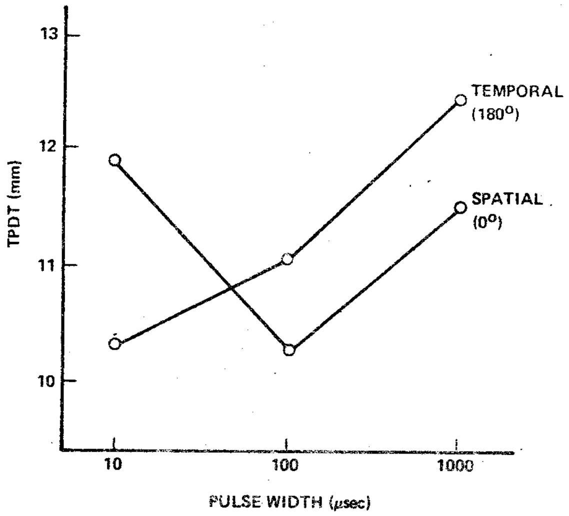

Figure 12 Average TPDT versus pulse width for spatial and temporal codes

The most striking feature from Figure 12, however, is the observed superiority of the 10 µs pulse width for temporal stimulation compared to the 100 µsec observed for the spatial code.

This indicates that the appropriate pulse width for electrotactile stimulation is 10 – 100 µs, for optimal TPDT in the spatial and temporal codes. In specific, 10 µs should be employed when using the temporal code, while 100 µs is to be employed for spatial stimulation.

Phase Shift

The typical response of the TPDT as a function of frequency for several pulse time delays (or as the corresponding phase shift since it does not depend on frequency in the considered range) was shown in Figure 9. Representing the data in a continuous curve relating TPDT to phase shift is shown in Figure 13.

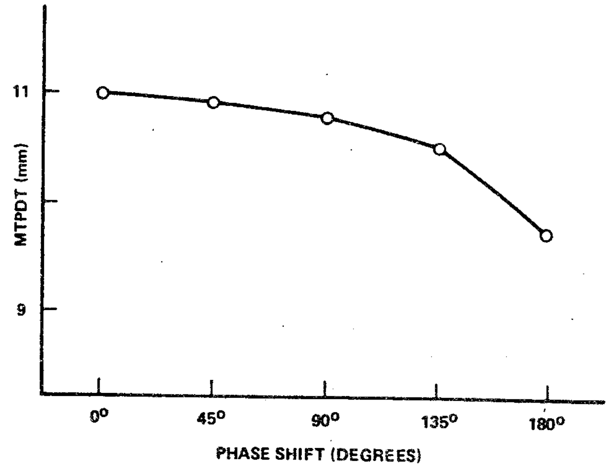

Figure 13 Average MTPDT versus phase shift

It seems that a monotonic improvement of the TPDT is present for phase shifts of 0 - 135 , while a drastic, nearly step improvement is associated with the 180 phase shift. In addition, the curves of the various phase shifts demonstrate the consistency of the F_m for all codes, as was shown earlier. When we reconsider Figure 12, we can state that an interaction of pulse width and phase shift is present, and that further studies are required in order to define such interactions.

Conclusions

Based on the data analyzed above, the following tentative conclusions are postulated regarding TPDT, stimulation codes, frequency, response of various body sites, and laterality:

1) TPDT varies as a function of frequency over the range 0- 100 pps for all three codes.
2) An absolute minimum TPDT (MTPDT) occurs for each individual at a different specific frequency F_m. This is true for all three stimulation codes considered.
3) The value of MTPDT is different for various body sites, but its frequency F_m is the same for all sites of the same individual.
4) The minimum frequency F_m is different from person to person; i.e., different individuals have different F_m's. The F_m also is the same for the same person for the three stimulation codes considered.
5) The MTPDT for a given body site is different for different individuals (see Figure 6).
6) The MTPDT at the extremities follows a specific pattern, in which peripheral sites, such as fingertip and sole, are the most sensitive; the sensitivity gradually decreases as electrodes are moved toward the trunk. No specific pattern was apparent for the MTPDT at sites on the trunk.
7) The dominant body side displays lower TPDT over the frequency range considered relative to the nondominant (contralateral) side.
8) The clarity and distinction of TPDT is superior at the nondominant body side.
9) The sensitive bandwidth (SBW) differs among individuals, but is constant for all body sites of one side of the same individual. The SBW is lower for the nondominant side. SBW also improves for spatial, temporal, and FOF, respectively, with FOF code resulting in the largest SBW.
10) The TPDT is improved when the stimulus code varies from spatial to temporal and FOF, respectively. The FOF code results in the lowest TPDT values over the complete frequency range considered.
11) The subjective sensation of the individual regarding frequency at which most comfortable TPDT occurs coincides with its minimal frequency F_m.

12) The clarity and distinction of TPDT at the nondominant side is also supported by the individual's judgment.
13) The TPDT is a function of pulse width with absolute sensitivity at a specific pulse width corresponding to a given stimulation code.
14) The most effective pulse width resulting in absolute minimum TPDT is 100 µs and 10 µs for the spatial and temporal codes, respectively.
15) The TPDT is also a function of phase shift (or the corresponding time delay) with absolute minimum TPDT at 180° phase shift.
16) Phase shifts in the range of 0 - 135° result in a small improvement in the TPDT response, while the 180° phase shift represents a rather large improvement.
17) The F_m of an individual is constant and independent of pulse width and pulse time delay in addition to stimulation codes, laterality and body site.

In summary, it has been shown that the ability to discriminate two-point electrotactile stimulus is principally a function of frequency. Furthermore, there is an absolute minimum two-point discrimination threshold (MTPDT) for a specific frequency, F_m. The variations of F_m for different individuals are evident, as well as the MTPDT. The MTPDT is also variable for different bodily locations, but the minimum frequency F_m is constant for the individual.

Three stimulation codes were tested for possible application to electrotactile displays. It was shown by defining a new measure, the sensitivity index (SI) (which incorporates frequency bandwidth and TPDT as variables), that the best stimulation code for two electrodes is frequency on frequency, with temporal and spatial codes following second and third, respectively.

As for applying the above data, several display configurations would be feasible. For example, a single array is sufficient to deliver two separate information channels. Other applications, such as visual substitution (Bach-y-Rita, et al., 1970), could be greatly optimized with respect to number of electrodes per square centimeter of skin by an electrode matrix at constant frequency. Utilizing the sensitivity index, visual substitutions could be expanded into a new dimension, where given the SBW, variations in stimulus frequency could indicate light intensity (e.g., high frequency corresponds to intense light conditions, low frequency to lower light intensities).

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