Electrotactile and Vibrotactile Displays for Sensory Substitution Systems

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***Abstract*—Sensory substitution systems provide their users with environmental information through a human sensory channel (eye, ear, or skin) different from that normally used, or with the information processed in some useful way. We review the methods used to present visual, auditory, and modified tactile information to the skin. First, we discuss present and potential future applications of sensory substitution, including tactile vision substitution (TVS), tactile auditory substitution, and remote tactile sensing or feedback (teletouch). Next, we review the relevant sensory physiology of the skin, including both the mechanisms of normal touch and the mechanisms and sensations associated with electrical stimulation of the skin using surface electrodes (electrotactile (also called electrocutaneous) stimulation). We briefly summarize the information-processing ability of the tactile sense and its relevance to sensory substitution. Finally, we discuss the limitations of current tactile display technologies and suggest areas requiring further research for sensory substitution systems to become more practical.**

I. Introduction

A. Purpose

In this paper, we summarize the technology developed by many investigators for presenting information to the skin by electrical and mechanical stimulation. We examine limitations of present displays for sensory substitution systems and propose topics for future research to overcome some of these limitations.

B. Definitions

A *biphasic* current pulse has a positive and a negative current phase of equal duration and magnitude for a zero net dc current. The literature is inconsistent in the use of the terms monophasic and biphasic. Biphasic is used elsewhere to refer to any waveform with positive and negative phases. We will use the restricted definition above.

A *coaxial* (also called *concentric* or *annular*) electrode consists of an active center electrode insulated from a larger annular surrounding dispersive electrode for the return current path.

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Electrotactile (also called *electrocutaneous*) stimulation evokes tactile (touch) sensations within the skin at the location of the electrode by passing a local electric current through the skin.

A *monophasic* current pulse has a single positive or negative current phase. A train of such pulses may or may not have a zero net dc current.

Sensory substitution is the use of one human sense to receive information normally received by another sense. For the sense of touch, sensory substitution may also be the use of one area of skin to receive tactile information normally received at another location.

Spatial integration occurs when a skin tactile receptor or neuron sums a stimulus over some area of the skin.

Slowly-varying tactile stimulation is a slow local mechanical deformation of the skin that varies the deformation amplitude directly rather than the amplitude of a fixed frequency of vibration. This is "normal touch" for grasping objects, etc.

Telepresence consists primarily of visual, auditory, thermal, proprioceptive, and tactile feedback to a person from a remote location.

Teleproprioception is feedback of position and joint torques on a remote gripper to a human operator.

Teletouch is feedback of tactile (spatial force) patterns from a remotely grasped object to a person's skin.

Temporal integration occurs when a skin tactile receptor or neuron (or its CNS connection) sums a stimulus over time.

Vibrotactile stimulation evokes tactile sensations using mechanical vibration of the skin, typically at frequencies of 10–500 Hz.

II. Tactile Display Applications

This section provides some examples of the types of tactile displays used in experimental and commercial sensory substitution systems. For a broader overview of available devices, we refer the reader to reviews on systems for visual substitution [5], [26], auditory substitution [93], [112], [123], and other applications [28], [89], [96], [106], [129], [128].

A. Single-Element Display

A single stimulation point can present information to the skin by variations in intensity, frequency, or both.

The source information could be temporally varying. For example, Leder *et al.* [73] describe the evaluation of an auditory prosthesis (sensory substitution system) in which the sound intensity as sensed by a microphone varies the vibration intensity of a vibrator strapped to the chest. Goldstein and Proctor [48] describe a similar device.

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The source information might also vary spatially. Szeto *et al.* [127] discuss the evaluation of their system in which either the frequency or the amplitude of a single electrotactile stimulus could be controlled by the elbow angle in a below-the-shoulder arm prosthesis.

B. One-Dimensional Display

A row of two or more stimulation points presents spatial information more naturally (dimensionally more like normal touch) than a single-element display. For example, a variant of the prosthetic example above stimulates one of five electrodes in a line depending on the shoulder angle [98]. This voluntary shoulder position controls a functional neuromuscular stimulation orthosis for restoration of hand grasp to quadriplegic spinal-injured patients. Szeto and Chung [124] and Szeto and Lyman [125] earlier found that such a one-dimensional code was superior to frequency or intensity modulation of a single electrode when a subject was asked to position a joystick based on the electrotactile sensation. Mann and Reimers [79] describe a one-dimensional vibrotactile display of the elbow angle of a prosthetic arm. Sandstrom [103] developed an ultrasonic ranging device for the blind which displays the distance to the nearest object on a linear array of vibrators along the finger. The compact vibrators are modified dot-matrix-printhead mechanisms.

Even the display of temporal information may be enhanced by spatially spreading it over several stimulators. Based on the early work of von Bekesy [9], who discovered that the human ear performs a frequency analysis of incoming sounds at frequency-selective regions in the cochlea, Saunders *et al.* [108] developed an auditory prosthesis which adjusts the perceived intensity of 16 electrodes, each corresponding to the sound intensity in a given passband in the audio spectrum. This commercially-available device, the Tacticon, provides enough "auditory" feedback to improve the speech clarity of deaf children. Blamey and Clark [14] and Boothroyd *et al.* [19] describe similar 8-channel electrotactile devices. Brooks and Frost [21], [22] describe a similar 16-channel vibrotactile device.

C. Two-Dimensional Display

Tactile Vision Substitution (TVS): A two-dimensional matrix of stimulators can display spatial information to the skin similarly to the way the eye presents spatial information to its retina. The television-type camera in a TVS system receives a "visual" image and presents it to the user's skin with vibrotactile or electrotactile stimulators. Each stimulator's intensity (pulse width or amplitude) is controlled by the light intensity at a single camera receptive pixel. Following the initial report of successful laboratory use of a vision substitution device [7], Bach-y-Rita [5], Collins [25], Collins and Bach-y-Rita [27], Collins and Madey [28], Craig [30], White [148], and others used TVS systems extensively in the early 1970's to study the skin's ability to interpret "visual" information. They found that subjects could immediately recognize vertical, horizontal, and diagonal lines. Experienced users could identify common objects and peoples' faces [5], and perform tasks such as electronic assembly under a microscope [6]. However, due partly to poor spatial resolution and dynamic range compared with the eye, TVS systems are not useful for acquiring information from "cluttered" visual environments such as hallways and are therefore not presently useful as navigation aids for the blind.

Similarly, Bliss *et al.* [17] developed the commercially-available Optacon (optical-to-tactile converter). It converts the outline of printed letters recorded by a small, hand-held camera to vibrotactile letter outlines on the user's fingertip. Exceptional blind users can read ordinary printed text at up to 90 words per minute with the Optacon [58].

Tactile Feedback: Performing detailed manual tasks is difficult for people with advanced cases of Hansen's disease (leprosy). They lack the sense of touch in the fingers and thus unknowingly injure their hands by grasping objects too tightly. Collins and Madey [28] developed a teletouch (tactile feedback) system in which strain gages mounted in a special glove measured the force (range 10 g to 5 kg) on each fingertip. Each of the five sensors controlled the electrotactile stimulation intensity of one forehead electrode. Subjects without sensation in the hands were able to distinguish smooth from rough surfaces, soft from hard objects, and by scanning were able to detect edges and corners, in spite of the low resolution of the display. It is likely that the large amount of perceived information from such a low-resolution display comes from 1) spatial information received by manually scanning complex objects (haptic exploration) with the few sensors (in effect, forming a "perceptual organ" [5]) and 2) receiving texture information from surfaces by the minute frictional vibrations recorded by the sensors [64].

Astronauts in space face a similar lack of sensation. The gloves of their pressurized suits reduce touch sensation because they are thick and pressurized. Their hands tire rapidly because they tend to overgrasp objects which could slip out of their grasp. One way to make space activity safer for astronauts is to use remotely-controlled robots to perform extravehicular activity (EVA). However, current remote manipulators lack teletouch, so it is difficult for the operator to perceive if an object has been properly grasped.

At the University of Wisconsin, we are developing teletouch systems for space gloves and space telerobots [8], and people with insensate feet and hands (common complications of diabetes) [78], [146]. Pressure sensors on the glove surface, end effector (gripper), shoe insole, and fingers, respectively, control the electrotactile stimulation perceived intensity.

Auditory Feedback: Sparks *et al.* [118], [119] use a two-dimensional display of 288 electrodes (36 columns of eight electrodes in a 1.3-cm-spacing square matrix on a belt [117]) to present auditory information to the abdomen. Each column corresponds to a certain band of frequencies, with the sound intensity in this passband controlling which electrodes in the column are active. Subjects could identify various segmental features of speech with 50–95% accuracy, depending on the particular set of sounds used. This performance is similar to that achieved with other auditory prostheses [93].

III. Mechanism of Stimulation

A. Sensory Physiology of the Skin for Normal Touch

Skin Anatomy: Human skin contains six types of tactile receptors that have been identified and characterized [37], [41], [110], [113]. Note that some receptors are found only in hairy or only in glabrous (hairless) skin. Table I lists several characteristics of these receptors, following the nomenclature of Schmidt [110] for hairy skin and Vallbo and Johansson [140] for glabrous skin. Some of the receptor characteristics in Table I are from primate studies [31], [132] where human data are not available.

Neural Response of Tactile Receptors to a Step Change in Skin Displacement: Phillips and Johnson [90] and Vallbo and

TABLE I
SKIN TACTILE RECEPTORS

PROBABLE RECEPTOR	CLASS (STEP INDENTATION RESPONSE)	RECEPTIVE FIELD (mm^2) (MEDIAN)	SKIN TYPE *	FREQUENCY RANGE (MOST SENSITIVE)	THRESHOLD SKIN DEFORM ON HAND (MEDIAN)	PROBABLE SENSORY CORRELATE	RECEPTORS/cm^2 FINGERTIP (PALM)
PACINIAN CORPUSCLE	**FA II** (RA II, QA II, PC)	10-1000 (101)	G,H	40-800 Hz (200-300 Hz)	3-20 μm (9.2 μm)	VIBRATION TICKLE	21 (9)
MEISSNER'S CORPUSCLE	**FA I** (RA I, QA I, RA)	1-100 (12.6)	G	10-200 Hz (20-40 Hz)	4-500 μm (13.8 μm)	TOUCH TICKLE MOTION VIBR FLUTTER TAP	140 (25)
HAIR FOLLICLE RECEPTOR	**FA** (RA, QA)	?	H	?	?	TOUCH VIBRATION	-
RUFFINI ENDING	**SA II**	10-500 (59)	G,H	7 Hz	40-1500 μm (331 μm)	STRETCH SHEAR TENSION (?)	9 (15)
MERKEL'S CELLS	**SA I**	2-100 (11.0)	G	0.4-100 Hz (7 Hz)	7-600 μm (56.5 μm)	EDGE (?) PRESSURE	70 (8)
TACTILE DISKS	**SA**	3-50	H	?	?	?	-

SA: SLOW ADAPTING FA: FAST ADAPTING
I: SMALL, DISTINCT FIELD II: LARGE, DIFFUSE FIELD
* G: GLABROUS SKIN H: HAIRY SKIN

SOURCES: [18], [30], [31], [61], [62], [63], [90], [109], [110], [113], [132], [135], [138], [147]

Johansson [140] provide excellent reviews of the responses of the known receptor types.

Tactile receptors can be roughly classified by the speed of their adaptation to a step change in applied pressure to the skin. A receptor's response is measured by its ability to produce a change in the firing rate of action potentials on its corresponding afferent nerve fiber; an action potential is always an all-or-none event. Table I describes the step displacement response of the four traditional divisions of receptors in glabrous skin: 1) fast adapting, broad-receptive-field FA II receptors, 2) fast adapting, small-receptive-field (FA I) receptors, 3) slowly adapting, large-field (SA II) receptors, and 4) slowly-adapting, small field (SA I) receptors. Note that in the literature, FA II is also called PC (Pacinian corpuscle), and FA is also called RA (rapidly adapting) or QA (quickly adapting). Finally, FA (without a I or II designation) sometimes refers specifically to FA I receptors, and sometimes it refers to both FA I and FA II receptors.

Sensory Psychophysics: The sensation produced by mechanical stimulation of the skin is determined by both mechanoreceptor properties and central neural mechanisms [140].

Weinstein [145] conducted an extensive study to determine the detectable static force applied by a fine wire to most body locations. For men, the lips were the most sensitive, needing 0.05 g for sensation, the fingertips and belly 0.63 g, and the sole of the foot 3.5 g. The thresholds for women were two–three times lower for the least sensitive locations. The fingertip threshold corresponds to a skin indentation of about 10 μm. Both peripheral (tactile receptors) and central mechanisms determine sensation thresholds [139].

Geldard [41] summarizes the sensation threshold for vibrotactile stimulation with a 1-cm^2 vibrator at most body locations. The fingertips are more sensitive than most body locations by at least one order of magnitude. The abdomen, in particular, is 60 times less sensitive than the fingertips to 200-Hz vibration.

In a comprehensive review paper, Verrillo [144] discusses the mechanisms influencing the sensation threshold of the (glabrous) palm to vibrating stimuli. The skin's sensation threshold is 5 μm peak amplitude from 25 to 650 Hz for stimulation areas less than 0.05 cm^2. For larger areas, the threshold is frequency dependent, achieving best sensitivity (0.16 μm) at 250 Hz with a stimulation area of 5 cm^2. He explains this characteristic with the "duplex model" which states that at least two functional types of receptors (Pacinian and nonPacinian) are present. The Pacinian (FA II) system integrates stimuli spatially and therefore is responsible for the threshold curve at stimulator areas larger than 0.05 cm^2, while the nonPacinian system does not, and accounts for the response to small-area stimulators. Further psychophysical studies by Gescheider *et al.* [44] and Bolanowski *et al.* [18] suggest that three and four, respectively, receptor populations may mediate touch in glabrous skin, likely corresponding to the four known glabrous receptors.

The threshold amplitude for vibrotactile stimulation increases after a strong conditioning stimulus. Gescheider and Verrillo [45] found that a 10-min stimulus 6 dB over threshold raises the sensation threshold amplitude by 2 dB, while a 40-dB stimulus raises the threshold by 20 dB. This adaptation occurs at least for frequencies from 10 to 250 Hz. Hahn [54], [55] reports that a 7–25-min conditioning vibrotactile stimulus results in full adaptation, i.e., the sensation threshold does not further increase at longer conditioning stimuli durations. Full recovery from adaptation occurs in approximately 2 min. Furthermore, a conditioning stimulus has more influence on the sensation threshold than on the suprathreshold perceived intensity.

Finally, the perception due to stimulation of only the FA II (PC) receptors summates over time. The vibrotactile threshold to a 250-Hz, 2.9-cm^2 stimulus falls by 12 dB as stimulus time increases from 10 ms to 1 s, whereas no threshold shift appears for a 0.02-cm^2 stimulator [143]. Because the FA II receptors themselves do not show temporal summation in electrophysiological recordings [132], higher neural mechanisms must be responsible for the perceived summation.

Spatial Resolution: Several experimental methods attempt to measure the spatial resolution of the tactile sense. Table II summarizes the simultaneous two-point-discrimination-threshold (TPDT) for static, vibratory, and electrotactile stimuli on sev-

TABLE II
STATIC SIMULTANEOUS TWO-POINT DISCRIMINATION THRESHOLDS (mm)

Body location	Static touch (a)	Vibro-tactile	Electro-tactile (d)
Fingertip	3	2 (b)	<7 (*)
Palm	10	?	8
Forehead	17	?	?
Abdomen	36	?	10
Forearm	38	?	9
Back	39	11-18(c)	5(e)-10
Thigh	43	?	10
Upper arm	44	?	9
Calf	46	?	9
Refs: a:[145], b:[16], c:[5], d:[115], e:[28]			
(*): 7mm was smallest distance which apparatus in [115] could measure.			

eral body locations. The TPDT (the oldest and simplest measure of tactile spatial acuity) is usually defined as the minimal distance at which two simultaneous stimuli are distinguishable from a single stimulus. The numbers in Table II should be used only as a guide to the TPDT; comparisons of absolute numbers between static, vibratory, and electrotactile stimuli may be inaccurate due to the differing methodologies of different investigators. Note that the TPDT is smaller if the stimuli are presented sequentially rather than simultaneously.

Other methods used to measure tactile spatial resolution include the determination of the minimum width of a deep groove which can just be detected on an otherwise smooth surface (0.87 mm on the fingertip) and the minimum width of parallel grooves in a square-wave grating that allows subjects to discriminate the orientation of the grating (0.84 mm on the fingertip) [65].

Furthermore, the skin can identify a frictionless position shift of a stimulus 10 times smaller than the TPDT [77], indicating that the skin's spatial resolution is much better for certain tasks than the TPDT suggests. Indeed, different grades of sandpaper (with very fine spatial features) are readily discriminated by touch. Clearly, ''spatial resolution'' is not a uniquely defined quantity, but depends on the particular type of stimulus and task to be performed [32]; temporal and intensive cues also provide spatial information at the perceptual level [66]. Gardner [35] discusses cortical mechanisms which may be responsible for resolving spatio-temporal information (such as from a moving stimulus).

A further illustration of the complexity of spatial processing is the phenomenon of ''funneling,'' which is the perception of several spatially-separated tactile stimuli as one stimulus in between the actual stimulation points [11], [12]. The neural mechanisms to account for funneling are higher than the peripheral afferent nerves [36].

B. Slowly-Varying Tactile Displays

Due to the rapid adaptation of the tactile sense to static stimuli and the high stimulus levels required, slowly-varying tactile displays are not generally used in sensory substitution systems, unless the user actively scans the display with the fingers (haptic exploration).

C. Vibrotactile Displays

It is tempting to tailor the frequency of a vibrotactile display to activate the low-temporal-frequency FA I receptors (most sensitive frequency 20–40 Hz) with their restricted receptor fields to achieve a display that responds to high spatial frequencies. However, Rogers [101] showed that the skin actually receives spatial information from an Optacon best at 250 Hz in spite of the spatially diffuse receptive fields of the FA II (PC). One explanation for this is that the spatial frequency of touch is not limited by the spacing of receptors or their receptive fields [77]. More likely is that even if the FA II are recruited, the fine spatial information is still provided by the smaller-field (FA I or more likely SA I) receptors [90]. The complex central mechanisms responsible for integrating information from all of these receptor types into useful percepts are only slowly being unraveled.

The above remarks only hold for very small stimulators; the optimal stimulation frequency may not be 250 Hz for stimulators over 0.05 cm^2 because the FA II will be increasingly recruited, possibly reducing the display's effective resolution.

Finally, the skin is particularly sensitive to make-and-break contact of a vibrotactor. For example, the vibrating pins in the Optacon's finger display contact the skin for only 20% of their vibrational period [17].

D. Electrotactile Stimulation

Stimulation Mechanism: Most investigators believe that an electric current passing through the skin directly stimulates afferent nerve fibers [23], [102], [129], although Pfeiffer [88] suggests that small electrodes (1 mm^2) stimulate receptors directly. Blamey and Clark [14], [15] intentionally chose electrode locations to stimulate entire nerve bundles in the finger for their auditory prosthesis. The sensation resulting from nerve bundle stimulation is not necessarily confined to a small skin region.

Subjects describe electrotactile sensations qualitatively as a tingle, itch, vibration, buzz, touch, pressure, pinch, and sharp and burning pain, depending on the stimulating voltage, current, and waveform, and the electrode size, material, and contact force, and the skin location, thickness, and hydration [29], [46], [80], [81], [88], [105], [129], [133]. The technique of single-afferent-fiber stimulation with microelectrodes is revealing the sensation qualities associated with activation of the different fiber types [135], [138].

Fine wire electrodes inserted in the skin also give rise to tactile sensation. Several investigators [3], [99], [97], [100] propose (invasive) subcutaneous stimulation as an alternative to surface electrodes. Among the advantages claimed are a reduction in the change in pulse repetition rate required for subject perception of the change (lower just-noticeable difference), high consistency over time of the sensations evoked, mechanical stability of the electrode interface, and elimination of the need to mount and remove skin electrodes.

Stimulation of a hair follicle with a needle electrode produces sensations of vibration or sharp pain depending on the insertion depth [109].

Finally, if a dry patch of skin moves over the electrode surface during 50-Hz stimulation, a weak vibrating sensation may be felt at currents as low as 2 μA. Grimnes [50] calls this sensation electrovibration and shows that it is probably due to electrostatically-generated mechanical deformation of the skin, not electrical stimulation of neurons. Strong and Troxel [121] describe a manually-scanned fingertip display based on this principle.

Electrochemistry of Electrode–Skin Interface: Because current flow through the skin is ionic, a transducer (electrode) is needed to convert electron flow in the lead wire to ionic flow (although it has been shown that a nerve may also be stimulated magnetically [95]). To reduce skin irritation and possible damage, the electrode should not introduce nonnative ions into the skin. The electrode must also not react chemically so as to produce an insulating layer between the electrode and the skin. Most sensory substitution systems use metal electrodes; the most common are gold, platinum, silver, and stainless steel. Greatbatch [49] and Mortimer [83] review the electrochemistry of implantable metal electrodes; the same general principles apply to skin electrodes.

Current Distribution Under Electrodes: Electrode–skin reactions under an electrode increase with the current density J, which should be kept as low and uniform as possible. Unfortunately, the distribution of J is not well-understood. Fig. 1 shows a cross section of the current density for a circular electrode contacting an "infinite" homogeneous volume conductor. Even in this homogeneous case, J is much higher at the edge of the electrode than at the center.

The conductive path through the skin, however, is not uniform at the microscopic level for any electrode type. Grimnes [52] and Saunders [104] show that current flows through small regions of low resistance (probably sweat ducts, sebaceous glands, and minute epithelial breaks, 1–6 per mm^2 skin area). Presently there is no adequate model of current distribution under a stimulation electrode which includes these nonuniformities.

Under large (> 100 mm^2) metal electrodes on dry skin, one of the skin's conductive paths will occasionally drop suddenly in resistance, shunting much of the electrode current through that pathway [46], [106]. The resulting high current density causes a sudden sharp sting and a red spot on the skin. The sting is most likely to occur with negatively-pulsed electrodes. Grimnes [51] proposes that a mechanism called electro-osmosis draws water through pores toward a negative electrode. Within about 1 s this considerably increases a pore's conductance and thereby might cause a positive feedback runaway condition in one pore as it rapidly becomes hydrated. Lin [74] found that coating 12-mm^2 metal electrodes with a conductive adhesive eliminates these sharp stings. The resistance of the adhesive may serve to equalize the current in several pathways, even if one has lower resistance than the others, or the adhesive may absorb excess water from the pore [53]. The exact mechanism is unclear.

Electrode Impedance: The resistive part of the impedance of the electrode–skin interface (R in Fig. 2) drops sharply with increased current [20], [46], [67]. The change in R is localized in the stratum corneum [20]. Because of this change, electrodes are usually stimulated with constant current rather than constant voltage. One disadvantage of constant current stimulation is that if an electrode makes poor skin contact, the reduced effective area results in a higher current density and a much stronger sensation. Saunders [104] suggests that a constant-power output circuit might be more suitable for electrodes prone to poor contact.

Fig. 3 shows the voltage of a 12-mm^2 active electrode on the forearm relative to a large indifferent electrode when stimulated with monophasic, 10-mA, 10-μs duration constant current pulses [105]. Fig. 2 shows the classical model of the electrode–skin interface which explains this waveform. The electrochemical half-cell potential and series resistive components are omitted because they are insignificant considering the high voltages

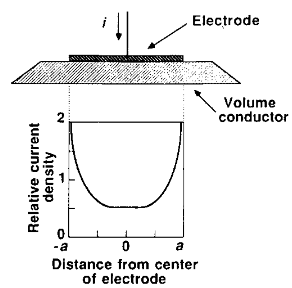

Fig. 1. Current density at the surface of a homogeneous volume conductor as a function of distance from the center of a circular stimulation electrode of radius a. Adapted from [150].

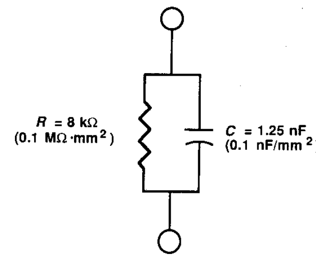

Fig. 2. Simplified electrical model of the electrode–skin interface. The resistance R and capacitance C shown are for a 12-mm^2 area metal electrode on the abdomen [105]. Values in parentheses are normalized to the electrode area. R and C vary with electrode type and skin condition.

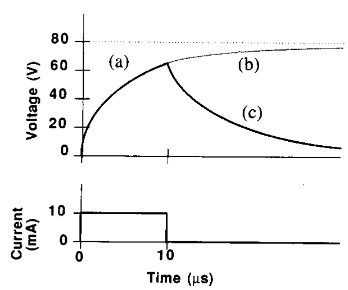

Fig. 3. Voltage on the 12-mm^2 area active center with respect to the outer ring of a coaxial electrode stimulated with 10-μs constant current pulses. (a) Charging region; (b) resistive heating region; (c) discharge region. Adapted from [105].

used for stimulation. Note that the first part of the voltage curve (a) rises exponentially with a time constant of approximately 10 μs, as the capacitor charges. An extrapolation of this curve for long pulse durations (b) shows a constant voltage. We can calculate $R = 8$ kΩ and $C = 1.25$ nF. Normalized to the 12-mm^2 area electrode, these values can be expressed as approximately 0.1 M$\Omega \cdot mm^2$ and 0.1 nF/mm^2. Pfeiffer [88] summarizes the findings of several investigators, who found that R varies from 0.25 to 40 M$\Omega \cdot mm^2$ and C from 0.031 to 0.4 nF/mm^2 for sinusoidal excitation at various frequencies and electrode sizes. R varies widely with skin condition and it decreases markedly at high stimulation currents. Indeed, Gibson [46] found that for a 330-mm^2 electrode R drops from 32 to 3 M$\Omega \cdot mm^2$ as the stimulation current increases from 0.1 to 5 mA. The related time constant RC drops from 1.2 to 0.13 ms over this current range, showing that $C = 40$ pF/mm^2 varies little over this cur-

TABLE III
ELECTROTACTILE SENSATION THRESHOLDS AND PAIN/SENSATION CURRENT RATIOS

Ref. []	Electrode type/matl skin prep. (e)	Body location	Electr. area (mm^2)	Wave-form	Freq. (Hz)	Pulse width limits (ms)	Sen-sation Current (mA)	Sen-sation Charge (nC)	P/S
102	?	?	?	M	Single pulse	0.02	6.2	150	?
						100	0.2	2000	
88	?	?	1	Sine	60	N/A	0.1	N/A	?
			10	Sine	60	N/A	0.2		
104	Silver coaxial	?	0.78	M-	40	0.005	6.0	30	1.2
			3.14	M-	40	0.005	5.5	28	1.8
			7.06	M-	40	0.005	10	50	3.0
74	3M/Littman	Abdomen	12.6	M-	?	0.01	5.0	50	5.5
						1	0.3	300	10
107 105	Silver coaxial	Abdomen	15.9	M-	60/200	0.002	20	40	8
						0.7	0.1	70	
47	Gold, silver coaxial gelled	Abdomen	11	M-/B	Single pulse	0.062	5.0	312	?
						1	1.5	1500	
				M+	Single pulse	0.062	6.1	381	
						1	2.5	2500	
57	Silver square	Wrist	49	M	Single pulse	0.1	2.7	270	?
						1	1	1000	
116	SS coaxial gelled	Trunk	8.42	M	(a)	0.1	1.5	150	1.6
		Fingertip	8.42	M	(a)	0.1	6	600	
1	SS/ aluminum coaxial	Abdomen	0.785	M	50	0.25	0.4	100	6.25
81	Steel electrode pair	Fingertip	0.0078	M	(b)	0.5	(c) 0.2	100	1.5
							(d) 1.0	500	
29	Coaxial	Forearm back abdomen	7.07	PT	25	1	17	17	8.4
						100	2.5	250	

Waveforms: M is monophasic, + or - indicated if known; B is biphasic; PT is the pulse train similar to Fig. 11(c).
Comments: (a) Best frequency 1-100 Hz; (b) Best frequency 1-200 Hz; (c), (d) 0.79 and 6.35 mm electrode spacing. (e) SS is stainless steel; P/S is pain/sensation current ratio.

rent range. Boxtel [20] discusses in some detail the change in R with current.

Thresholds of Sensation and Pain: The useful intensity dynamic range of an electrotactile stimulator is the ratio (threshold of pain): (threshold of sensation) or P/S. Table III shows that the P/S ratio varies from under 2 (6 dB) to about 10 (20 dB) at best. This range is limited compared to other senses; the ear has a dynamic range of 120 dB and the eye 70 dB. If we assume a maximal comfortable vibratory stimulus amplitude of 0.5 mm for a 0.78-mm^2 stimulator [25], the vibrotactile range of the skin is about 40 dB.

Table III summarizes the results of several investigators who determined the current required to elicit electrotactile sensation and pain. A model predicting the thresholds as functions of electrode size, material, waveform, etc. is difficult to formulate owing to the great variations in methodology between investigators.

At least four factors account for the disparities in results among investigators in determining P/S. 1) There is no uniform definition of "pain"; it could be defined as mild discomfort to intolerable. 2) The psychological condition and training modify the threshold of pain; experienced subjects tolerate at least twice the stimulation levels of naive subjects [104]. 3) At least for thermally-induced pain, noxious stimuli may raise or lower the pain threshold [134]. 4) The P/S ratio is a function of electrode size, material, and placement as well as by the parameters of the stimulation waveform; all of the relevant factors are rarely reported.

Furthermore, skin condition has a profound influence on the dynamic range and comfort of stimulation; dry skin has a high impedance and a prickly sensation (likely due to nonuniform current distribution). Effective skin preparation ranges from applying electrodes 20 min prior to stimulation to allow sweat to build up [80], to premoistening the skin with water [129] or saline [104] before applying the electrodes. Once stimulation starts, sweat production increases and provides sufficient moisture. While commercial conductive electrode gels provide a low skin resistance, they can short-circuit adjacent electrodes in a closely-spaced array and increase the required current levels. Furthermore, the gel can dry out and require reapplication after several hours of operation.

Finally, the sensation and pain thresholds can change significantly with small (1 mm) changes in electrode position.

Mechanism of Sensation and Pain Thresholds: Fig. 4 shows that the required sensation threshold current increases with decreasing pulse width, suggesting that the threshold of sensation

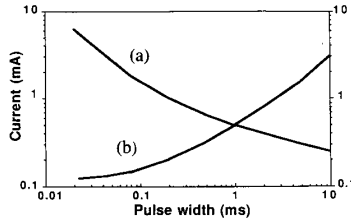

Fig. 4. Electrotactile sensation threshold (a) current and (b) charge as a function of monophasic pulse duration. Data from [102].

is determined by the pulse charge (current × duration). Fig. 4 also shows that for pulse durations longer than 100 μs, the threshold charge increases, leading Rollman [102] and Girvin *et al.* [47] to conclude that temporal integration of electric charge leading to electrotactile sensation occurs only partially above 100 μs and not at all above 5 ms. At least two mechanisms may be responsible for this temporal integration. 1) The electrode–skin interface temporally summates charge. The electrode–skin model in Fig. 2 has a time constant that varies approximately from 10 μs to 1 ms depending on skin condition and stimulus current [46]. 2) The afferent nerve fiber membrane temporally summates charge. Butikofer and Lawrence [23] used the Frankenhauser-Huxley model [34] to predict the threshold charge across the membrane of a peripheral afferent myelinated nerve necessary to produce an action potential. Their model showed temporal integration up to only 50 μs.

Geddes and Baker [38] and Mouchawar *et al.* [84] review several competing mathematical descriptions of this strength-duration relationship.

Because of the limited electrotactile temporal integration of the skin and the reduction of dynamic range with longer durations, current pulses with duration less than 0.5 ms are the most appropriate. In fact, Saunders and Collins [107] use very short pulses (5–20 μs).

Finally, for pulse durations longer than 500 μs, the pain threshold drops more quickly than the sensation threshold [46], indicating that different integration mechanisms may determine the sensation and pain thresholds.

The P/S ratio increases with electrode size as long as sudden stings do not occur. Saunders [104], [106] found that 10–15 mm^2 is the optimal area of metal electrodes on the (hairy) abdomen; this is a compromise between larger electrodes (higher P/S) and smaller electrodes (less possibility of sudden stings). Gibson [46] specified 175 to 700-mm^2 area for hairy skin and 50 mm^2 for glabrous skin. However, Gibson used longer pulses (500 versus 10 μs) and may have used conductive gel (possibly equalizing current flow in the current pathways) under electrodes while Saunders did not.

Solomonow and Preziosi [116] determined sensation and pain thresholds for a gelled 8.4-mm^2 coaxial stainless steel electrode pulsed for 100 μs on several body locations. They found that the sensation threshold was about 2 mA on most trunk sites and about 7 mA on the palmar and plantar surfaces.

Several mathematical models have recently appeared which predict the stimulation of afferent nerve fibers in response to an external electric field such as that produced by an electrode [72], [91], [92], [94], [95], [141], [142]. Of these models, only Larkin and Reilly [72] and Rattay [91] deal with surface stimulation (the others deal with invasive electrodes). Rattay [91] does not consider capacitance; his model is a static model. Larkin and Reilly [72] use an arc discharge (point) stimulation. We are not yet aware of any unified dynamic model which adequately explains the sensation and pain thresholds of electrotactile stimulation using surface electrodes, although great strides have been made in this area.

Subjective Magnitude of Electrotactile Stimulation: The subjective intensity of a train of pulses is increased by raising the pulse current, width, or, to a lesser extent, pulse rate (frequency). Rollman [102] summarizes the results of several investigators who fit electrotactile data to Stevens' power law [120]

$$\Psi = (\phi - \phi_0)^n$$

where Ψ is the subjective magnitude, ϕ_0 is the sensation threshold (which is sometimes set arbitrarily to zero), and ϕ is the stimulus level (in this case, current). Only Rollman's data were taken from a localized cutaneous sensation (electrode away from nerve bundles); his value for n increased from 2.3 to 3.0 (with ϕ_0 set to 0) as the number of pulses in a burst increased from 1 to 30. The value n (rate of subjective magnitude growth) is high compared to other sensory modalities such as pressure on the palm of the hand ($n = 1.5$) and loudness of a 1-kHz tone ($n = 0.3$) [120]. This result indicates that the stimulation current must be carefully controlled to avoid unpleasantly strong sensations. Furthermore, if current is to be modulated to convey information, a careful mapping must be made from the sensed variable (e.g., pressure) to the stimulation current.

Because electrode impedance decreases with increasing current but is not affected by pulse duration, Saunders [104] does not recommend current modulation. Both pulse duration [29] and frequency [14] modulation have been used for sensory substitution. Szeto [122] found that subjects perceive a constant stimulation level (but varying "quality") if pulse duration and rate are varied according to the relationship

$$\log PW = 2.82 - 0.412^* (\log PR)$$

where PW is the pulse width in microseconds and PR is the pulse rate in hertz. Finally, Saunders [104] describes a technique using the 10-kHz pulse bursts in Fig. 5(c) in which the number of pulses in each burst varies from 0 to 40. For clarity, Fig. 5(c) only shows monophasic pulses; Saunders actually used biphasic pulse pairs.

The subjective intensity of a continuous train of pulses [Fig. 5(a)] decreases with time due to adaptation. The adaptation rate varies with frequency; while little adaptation occurs at 10 Hz, the sensation produced by a 1000-Hz pulse train decreases within seconds [129]. As with vibrotactile stimulation, electrotactile adaptation has more effect at the sensation threshold than at suprathreshold levels. A modulated pulse train [Fig. 5(b)] reduces the adaptation [29]. With bursts of 500-Hz pulses gated at a 25-Hz rate, this waveform elicits a "buzz" sensation.

Subjective Description of Sensation: In 1943 Bishop [13] found that electrically stimulating the skin in very small areas with spark discharges caused two distinct sensations depending on the location; prick and touch, with the prick locations being more numerous. Moving the stimulus location by as little as 0.1 mm changed the sensation. Therefore, on most skin loci, electrodes of about 1-mm^2 area give a prickly, uncomfortable sensation which becomes painful at levels just above threshold [106]. Larger electrodes result in a more comfortable stimulation described as touch or vibration, probably because 1) both touch and pain (prick) fibers are stimulated, and the touch sensation can partially mask the pain [23], and/or 2) the large-diameter touch fibers are stimulated at lower current densities

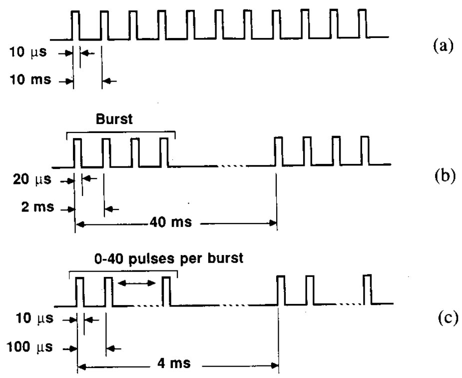

Fig. 5. Electrotactile stimulation waveforms. (a) Continuous 100-Hz pulse train, subject to adaptation; (b) 500-Hz bursts of pulses at a 25-Hz rate, less subject to adaptation; (c) 10-kHz bursts of pulses, the subjective intensity increases with the number of pulses per burst.

than the pain fibers [141]. However, even 1-mm position shifts of larger electrodes can change the subjective sensation as well as the sensation and pain thresholds. Because of the great variations in experimental methods and the vagueness of sensation descriptions, it is difficult to predict which stimulation waveforms, body locations, etc. give rise to which types of sensations, much less determine the underlying neural mechanisms. Nevertheless, some investigators have proposed mechanisms [23], [24], [56], [80], [102], [121].

Pain: Pain sensations are the major disadvantage of electrotactile stimulation, although comfortable stimulation is normally assured if several design recommendations are adhered to. The three most common types of pain or discomfort are 1) prickly sensations at all stimulation levels, 2) sudden stings at low-to-moderate stimulation levels, and 3) burning sensations at high stimulation levels [80]. Prickly sensations are best avoided by using electrodes of 10-mm^2 area and allowing sweat to build up [106]. Partial loss of electrode contact reduces the effective electrode area and must therefore be prevented to avoid prickly, painful sensations. Mason and Mackay [80] propose that the sudden sting phenomenon is due to pinpoints of corneal burning due to high current density. The stings are largely avoided by using electrodes smaller than 100 mm^2 [106] or by using conductive polymer coatings on the electrodes [74]. Burning sensations represent the upper limit of electrotactile stimulation intensity. Note that we distinguish a burning sensation from true thermal damage to the skin.

IV. Human Tactile Information Processing

Sherrick [111] lamented that as a communication channel, the tactile sense is often considered inferior to sight and hearing. However, the tactile system possesses some of the same attributes as both of the "primary" senses [5]. With over 10 000 parallel channels (receptors) [29] capable of responding to stimulus interruptions as short as 10 ms [5], the tactile system may be capable of processing a great deal of information if it is properly presented.

A. What Information is Important?

We introduce this section with simple yet representative human information-processing task. Suppose a person is shown ten pictures of people and is asked to simply identify whether each picture is of a man or a woman. Unless considerable effort is expended to choose ambiguous pictures, this task could probably be accomplished in about 10 s. According to the classical definition of information rate

$$\text{rate (bits/s)} = \text{(decisions/s)} \times \log_2 \text{(number of choices in decision)}$$

the information rate of the subject's response is (1 decision/s) $\times \log_2$ (2 choices) = 1 bit/s. Yet the pictures contain far more information than 1 bit each. Indeed, such a pattern recognition task would be formidable for a personal computer (which can perform approximately 10^6 operations/s).

This admittedly trivial example illustrates the difficulty of defining a useful information-transfer rate for any of the human senses, including the tactile sense. The key issue is deciding what information is important. Then, formal information theory can be applied meaningfully to predict the usefulness of specific sensory feedback codes.

Clearly, "information" is not a uniquely-defined quantity in a system. Biological systems, in particular, exhibit a great deal of divergence (one stimulus may activate hundreds of sensors) and convergence (a single CNS decision may be made on the basis of thousands of neural inputs). As a further illustration, Lindblom [76] notes that a vibratory stimulus of up to 200 Hz results in synchronized firing of afferent nerve fibers, showing that the tactile sensing units are capable of great physiological information flow. However, we perceive only a smooth vibration. A loose description would be that the higher neural centers treat this data stream as highly redundant or trivial. Indeed, Gibson's definition of information (reviewed in Epstein [33]) implies some behavioral significance to the information carried in a stimulus. An alternative interpretation is that the volume of neural information from the simple vibrating stimulus is placed into one "chunk" with the redundant, useless information being discarded [82]. Information theory would state that the information in the afferent fibers has a low variance; it is somewhat predictable with a simple vibratory stimulus.

B. Estimates of Tactile Information Flow

Table IV shows the results of several investigators who calculated the rate at which humans process vibrotactile and electrotactile information at the perceptual level (2–56 bits/s). Although there are large differences in methodology, we may loosely compare these rates with those quoted by Schmidt [110] for understanding spoken speech (40 bits/s) and reading (30 bits/s). The approximate maximal rates of information flow at the receptor level (based on the number of receptors and their afferent nerve fibers) for the eye, skin, and ear are 10^7, 10^6, and 10^5 bits/s, respectively [110].

Not included in Table IV are the numerous studies which determined not the information rate, but only the number of discernible levels of stimulation (just-noticeable differences or JND's). Table V summarizes these studies; the number of JND's has been estimated at from 6 to 59 levels for electrotactile stimulation and 15 levels for vibrotactile stimulation [39], [40]. The wide electrotactile variations are due in part to the different waveform quantity being manipulated to change the "level." In particular, it is possible that increasing the current by small steps at a slow rate will yield a large number of steps because at each step, some of the perceptual level increase will be lost due to adaptation. Table V reflects this effect with the

TABLE IV
ESTIMATES OF PERCEPTUAL INFORMATION FLOW FROM TACTILE STIMULI

Ref. []	Method	Number of channels	Information rate (bits/s)
110	?	?	5
102	Reaction time	1	5
69	Fusion freq. of vibratory bursts	1	2-56
69	Optacon reading	144	5-10
149	Counting stimuli	1	12

TABLE V
DISCERNIBLE LEVELS OF SUBJECTIVE INTENSITY OF ELECTROTACTILE AND VIBROTACTILE (*) STIMULATION (NUMBER OF JND'S)

Ref. []	Location	Variable	Number of levels
107	Abdomen	Current	59
1	Abdomen	Current	32
114	Palm	Frequency	13
130	Arm	Energy	8-16
130	Arm	Frequency	6-8
39	? (*)	Amplitude	15

TABLE VI
JUST-NOTICEABLE DIFFERENCES OF ELECTROTACTILE AND VIBROTACTILE (*) STIMULATION

Ref. []	Location	Variable	JND %
28	Abdomen	Width	> 6
85	Arm	Current	9-29
	Arm (Sub)	Current	8-42
88	?	Current	2-6
	?	Frequency	> 2
100	Arm	Frequency	15-30
	Arm (Sub)	Frequency	10-25
104	Abdomen	Current	3.5
	Abdomen	# Pulses	10
114	Palm	Frequency	19-24
126	Arm	Frequency	16-38
	Arm	Width	37-46
129	Several	Width	8-10
	Several	Current	8-10
68	? (*)	Frequency	5-10

number of JND's for current being higher than the number of JND's for frequency.

The JND itself is a measure of channel sensitivity. Table VI summarizes the results of investigators who reported the JND for electrotactile and vibrotactile stimulation. The JND is expressed as a percentage because it is roughly proportional to stimulus level or frequency.

Note that the number of JND's is not the same as the number of absolute levels which can be reliably classified. For example, only four or five levels of vibrotactile stimulation duration [39], [40] and six levels of electrotactile stimulation frequency [97] can be reliably classified. This is not likely a limitation of the tactile sense, however. Miller [82] found that subjects classifying pitch and loudness of tones, counting dots presented on a screen, identifying locations of tactile stimuli, recall of spoken words and numbers, and similar tasks could typically "process" from five to nine discrete pieces of information. . .which averages to his magical number seven.

C. Spatial Information Processing

The skin appears to thrive on a flood of information for "visual" pattern recognition tasks, suggesting that system spatial processing should not reduce the amount of information delivered to the skin [148]. However, edge-enhancement of TVS images often improves subject performance, as edges appear to carry the most important information for pattern recognition [5]. Curiously, scrambling the columns in a TVS system does not significantly impair the performance of subjects identifying letters by touch, although training time is longer than with a spatially-corresponding TVS system, i.e., one with object shapes preserved [30]. This finding illustrates the remarkable adaptability of the human sensory system.

D. Temporal Information Processing

In spite of the slowness of the CNS to react to tactile input (200 ms) [102], the perceived stimulation can vary significantly with small (<1 ms) variations in the timing of successive stimulations. For example, von Bekesy [10] and Gescheider [43] note that if two square-wave mechanical tactile stimulators spaced about 5 cm apart or even on different fingertips are simultaneously pulsed for 1 ms, a single sensation will be felt midway between the stimulators. However, if the pulses are staggered by as little as 0.2 ms, the perceived position of this "phantom" stimulus moves toward the earlier stimulus. An even larger shift in apparent position occurs when the amplitudes of the two stimuli are unequal, with the sensation appearing closer to the stronger stimulus [2], [43], [46], [79]. Mann and Reimers [79] use the position of a phantom sensation to display the angle of a prosthetic arm. Furthermore, Verrillo [143] showed that the threshold for vibrotactile stimulation drops as the stimulus time increases to one second, i.e., the skin exhibits temporal summation over one second.

Finally, while we have presented spatial and temporal information separately, they do in fact strongly interact [42].

These results suggest that different types of temporal processing with "time constants" ranging over at least 0.2 ms to greater than 1 min occur in the human somatosensory system. Therefore, the precise effects of such real system characteristics as time delay, time skew between elements, and phase shift are difficult to predict and might need to be determined empirically for a specific system.

E. Integration of Information from Tactile Receptors

Although some correlation between tactile receptor activity and the quality of the perceived sensation is known, for complex (and even many simple) stimuli the percept depends on input from several receptors types [18].

F. Ramifications for Sensory Substitution Systems

Clearly, a sensory substitution system must accommodate the unique sensory characteristics of the skin, particularly if cross-modality (visual-to-tactile or auditory-to-tactile) substitution is attempted. For example, an auditory prosthesis cannot simply use the microphone signal to directly control electrode current because the skin has insufficient high-frequency response. The auditory information must be processed to match the properties of the tactile sense.

The dynamic range (ratio of maximal to minimal signal level) of a given sensor usually does not match the dynamic range of a given tactile display. For example, in a TVS system the range of light input to a camera is much higher than the typically 6–20 dB range of electrotactile stimulation. Some form of amplitude compression or scaling may be desired. For a teletouch system, one approach might be to implement a transfer function from the pressure sensor to the tactile display so that the perceived stimulation magnitude closely matches the perceived magnitude of the same pressure stimulus on normal skin.

Based on Miller's [82] absolute-level identification conclusion (above), it is useful to optimize tactile display parameters to maximize the number of absolute-level identifications? Perhaps the parameter choice need only guarantee some (as yet unspecified) minimum number of levels n. Furthermore, whether the information channel to the tactile display may be quantized to n levels without loss of end-application system performance remains an open question. Another open question is the relationship between the JND of a display stimulus and the end-application system performance.

Finally, an electrotactile display undoubtedly stimulates afferent fiber types in different proportions than normal touch, and not much control is presently available over which fiber types are stimulated. Such differential excitation may be necessary to produce more effective sensory substitution displays [18], [138]. A similar situation exists with a vibrotactile display where a constant (dc) level is presented as a sinusoidal stimulus.

V. Practical Considerations

A. Safety

Burns: Electrodes and vibrators can both generate sufficient heat to cause painful sensation of heat as well as burns. LaMotte [71], in a review of thermally-induced pain, reports that for a 3-s application of radiant heat to a 7.5-mm diameter patch of glabrous skin on the hand the average threshold temperatures for perception of warmth and pain without tissue damage are 40 and 47°C, respectively. Three minutes of exposure at 49°C are required to cause a minor burn. In terms of radiant energy, the pain and burn thresholds are 0.92 W/cm^2 and 2.0 W/cm^2, respectively, for 3-s exposures [41]. However, Taige [131] found that 12-mm-diameter vibrotactile transducers are uncomfortably warm at continuous average power levels above only 62 mW (55 mW/cm^2). This lower power is likely due to the fact that the transducers (and mounting hardware) are in physical contact with the skin, trapping heat, in contrast with the radiant heat studies.

Burns under electrodes are of at least three types. 1) Electrochemical burns and irritation due to a net flow of ions are largely prevented by ensuring that the net dc current flow at an electrode is zero. However, Szeto and Saunders [129] recommend biphasic pulse pairs to prevent the net electrochemical reactions that occur even with capacitively-coupled (no net dc flow) monophasic pulses. 2) Large thermal burns are not likely to occur at the frequencies of interest in sensory substitution system (< 1 kHz) unless the stimulation level is driven well into the pain region. For example, from the data in Table III, a 15.9-mm^2 electrode requires 20 mA $\times$ 8 = 160 mA for 2-μs pulses at a 200-Hz rate to cause pain [107]. If we assume the maximal voltage to be 100 V, the average power density at the electrode is 40 mW/cm^2, well below the burn level. 3) Tiny black marks (0.25 mm diameter) are visible on the skin under magnification after sudden stings from an electrode. Mason and Mackay [80] propose that the marks are burns caused by high power density in a single conductive pathway. However, their calculations assume that the dynamics of the electrode voltage and current are measurable during a sting with a stripchart recorder and that most of the current flows through one pathway.

Electric Shock: To prevent the possibility of cardiac fibrillation, the stimulator output circuit should be designed so that the maximal current flow across the user's torso is under 0.1 mA at any time [87], even if there is a circuit fault or if a body part contacts another metal object, grounded or otherwise.

B. Comfort

Electrotactile: The maximal level of comfortable electrotactile stimulation varies between individuals and even varies with one individual. The user must have a simple means of adjusting the stimulation level and quickly turning it off completely if necessary.

Vibrotactile stimulation is comfortable with amplitudes up to 0.5 mm for a 1-mm diameter stimulator [25] unless the heat generated at the stimulator is greater than 62 mW/cm^2 [131].

General: The mechanical comfort of any tactile display is heavily influenced by the method used to hold the display to the skin. A compromise must often be made between performance and comfort. For example, the sensation produced by electrotactile stimulation is most comfortable when the electrode–skin interface is wet with perspiration and the electrodes are held firmly against the skin.

C. Repeatability and Spatial Uniformity

Because of the high variations in thresholds of electrotactile sensation and pain between subjects, a fixed relationship between the desired information (e.g., force) and the stimulation parameter (e.g., current) is not practical or desirable. The system user must be free to adjust the stimulation intensity and dynamic range as desired. Tursky and O'Connell [137] showed that for a single subject, suprathreshold levels are more repeatable than the sensation threshold.

We are not aware of any studies for electrotactile or vibrotactile stimulation which report the amount of variation of sensation or pain thresholds over an array of stimulators on one body surface.

D. Power Consumption

Low system power consumption is desirable in portable sensory substitution systems. This section comments on the power consumed by example tactile displays.

Electrotactile: A 3-mm diameter electrode consumes 1.2 mW/pixel at a comfortable continuous stimulation level of 6 mA, based on the waveform in Fig. 5(b) used by Collins [25]. However, in a practical system, only a fraction of the stimulators are active at a given time, leading to an average power dissipation as low as 1 μW/pixel [29].

Vibrotactile: Kovach [70] used the mechanical properties of the skin to estimate the mechanical power dissipated in abdominal skin for a 250-Hz, 4-mm-diameter vibrotactile stimulator. The threshold power is 0.4 mW, with an "adequate" continuous stimulation level 8 dB higher requiring 2.5 mW, close to Collins' [25] estimate of 10 mW for a 1-mm-diameter stimulator. The electrical power consumption of the actual 4-mm vibrator (Star Micronics QMB-105 audio transducer) is considerably higher (138 mW for sine waves at threshold) due to conversion inefficiency and coupling losses. The resulting energy-conversion efficiency of 0.29% is too low for practical use of this transducer. To work around this problem, Nunziata *et al.* [86] and Taige [131] developed a special driving waveform for this transducer so that it dissipates only 0.05 mW average power. However, this power was attained by using 40-ms bursts of 250-Hz stimulation and 2-s rest periods between bursts, creating a very small duty cycle. The 2-s time between bursts would make the system slow to respond to changes in the desired stimulus level.

Finally, as with electrotactile stimulation, only a small percentage of the stimulators will be active at any given time, reducing considerably the average power consumption.

Static tactile arrays using electromechanical solenoids require at least 1 W/pixel to produce forces well above threshold, making them impractical for limited-power applications. They also suffer from severe adaptation to constant stimuli lasting longer than 1 s.

E. Electrotactile Skin Irritation

Szeto and Saunders [129] present informal comments on skin irritation as well as report on a 10 h/day, two-week trial in which five subjects wore stimulators driving silver coaxial electrodes on the upper arm. They found that while a biphasic waveform caused the least long-term skin irritation a monophasic waveform caused less transient skin reddening. They concluded that either waveform is suitable.

Riso *et al.* [97] report that long-term use of subcutaneous electrodes does not cause skin infection if the electrode site is cleaned daily with alcohol.

More research is necessary to determine the long-term effects of electrotactile stimulation as functions of electrode types and waveforms.

VI. Performance Evaluation

Developing an optimal display for sensory substitution requires some objective method to evaluate the performance of the display. Preferably numerical performance criteria should be established regarding issues such as information transfer and practicality. Each of the performance criteria can then be optimized by varying the parameters of the display (waveforms, signal processing, etc.). A possible list of performance criteria is

1) minimal power consumption
2) maximal stimulation comfort
3) minimal poststimulation skin irritation
4) minimal sensory adaptation
5) maximal information transfer measured by
   a) minimal just-noticeable difference (JND) of the modulation parameters current, width, frequency, and number of pulses per burst
   b) minimal error in identifying the absolute stimulation level of a randomly stimulated electrode
   c) minimal error in manually tracking a randomly varying target stimulus [60], [98], [124], [125], [127], [136]
6) maximal dynamic range: max. comfort level/sensory threshold
7) minimal variation of sensory threshold and max. comfort level with the precise electrode location on a given skin region.

Performance criteria should be chosen carefully with the final system application in mind. Does the chosen evaluation method criteria mimic (at least in theory) the final task? For example, if the final application is a sensory prosthesis for the insensate hand, are small changes in the JND (system gain) really meaningful? In light of Miller's [82] conclusion that the absolute identification of stimuli levels is a high-level process largely independent of the sensory modality, it may be meaningful to optimize a cutaneous display for the greatest number of discriminable levels only if the end task requires absolute judgements. Furthermore, such absolute judgements might be better provided by a warning-signal approach where some appropriate circuit or microprocessor algorithm makes the judgements. We do not believe that traditional psychophysical measures should be applied simply because they are available. Where practical, final task measures (such as word discrimination with an auditory prosthesis) are preferable to more abstract criteria.

Finally, with multiple performance measures for a system there may be no unique set of optimal parameters; engineering judgment will determine which performance measures are most important.

VII. Training

In order to effectively use information from a sensory substitution system, the brain must form new functional neural pathways by means of "unmasking" of previously underused pathways [5]. Our normal senses were developed over a period of years; the ability to use sensory substitution information will also take time.

For example, users of tactile vision substitution systems such as the Optacon can immediately recognize vertical, horizontal, and diagonal lines presented to the display. Forty hours of training enable tactile reading rates of 10 words/min [17]; further training typically raises the rate to about 28 wpm [59]. For the exceptional reading rate of 90 wpm, over 100 h of experience are required. Some users of TVS systems can recognize familiar objects after 20 h of training [4].

VIII. Future Research

Sensory substitution systems currently enjoy little use partly because of 1) uncomfortable or impractical displays and 2) a lack of understanding of how displays can efficiently transfer useful information to the tactile sense. Further research is therefore needed in the following areas.

A. Electrodes and Stimulation Waveforms

The waveform and electrode parameters determine the mode of information transfer to the user, the qualitative sensation, and the level of skin irritation.

The current distribution under stimulation electrodes of various sizes and geometries must be accurately modeled. Investigation needs to continue into the coupling of skin-electrode-induced cutaneous electric fields with afferent nerve fibers in the time domain to supplement existing models. Because it may be necessary to differentially excite different afferent fiber types to achieve the desired information transfer [18], a model is needed to predict which fibers are preferentially excited by different waveform and electrode parameters.

The subjective level of stimulation (including the definitions of thresholds of sensation and pain) is not sufficiently characterized, although it has been extensively studied. The varying methodologies of different investigators make it impossible to write down a single magnitude-estimation function of all the relevant variables:

Subjective intensity = f(electrode and waveform variables)

or even

Threshold of sensation = f(electrode and waveform variables).

The qualitative sensation (vibration, tingle, sting, etc.) is clearly a function of the electrode material, size, geometry, skin preparation, and stimulus waveform, but the relationships are reported largely anecdotally in the literature. Systematic study of this area is necessary because uncomfortable sensations are the primary disadvantage of electrotactile stimulation. This area will also benefit from knowledge of differential excitation of afferent fiber types.

Present electrodes and waveforms may cause skin irritation after several hours of stimulation. Electrode and waveform parameters need to be optimized to minimize the irritation level.

Finally, uniform skin contact of each electrode in an array is difficult to achieve. Improved electrodes and mounting methods are needed.

B. Vibrators and Diving Waveforms

Although the mechanical properties of the skin and the psychophysical response to vibrating stimuli are largely understood, few practical vibrator arrays have been developed. Off-the-shelf transducers will likely never prove practical due to low energy-conversion efficiency. An optimal vibrator will likely need to be a custom design (such as that in the Optacon) to meet the simultaneous practical constraints of small size, low noise, low power consumption, and an adequately large dynamic range. Only a careful electromechanical design will achieve the efficient coupling of stimulation energy to the skin necessary to meet the above constraints.

C. Tactile Information Processing

Much effort has been expended characterizing tactile display technologies with specific psychophysical performance measures such as JND, number of discernible levels, absolute level identification, two-point discrimination thresholds, and tracking of varying stimuli. What is needed to complement this extensive body of knowledge is some correlation between these standardized measures and the performance of complete sensory substitution systems in their end applications.

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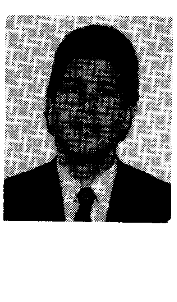

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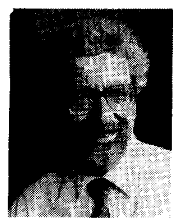
Dr. Webster has been a member of the IEEE-EMBS Administrative Committee and the NIH Surgery and Bioengineering Study Section. He has been Associate Editor, Medical Instrumentation, of the IEEE Transactions on Biomedical Engineering, and Chairman of the IEEE-EMBS Fellow Committee.



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habilitation (Baltimore, MD: University Park, 1980) and *Traumatic Brain Injury* (New York: Demos 1989); coeditor (with C. C. Collins) of *The Control of Eye Movements* (New York: Academic, 1971) and (with G. Lennerstrand) of *Basic Mechanisms of Ocular Motility and Their Clinical Implications* (Oxford, England: Pergamon, 1975), as well as numerous journal articles and book chapters.

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