A. Specific aims

The aims of this project are to study the intensive and qualitative psychophysics of electrical stimulation of touch, and specifically to: (1) Characterize the dynamic range of electrotactile stimulation as functions of the physical stimulus parameters (waveform, electrode geometry and location, hydration), and (2) Characterize the qualitative or subjective nature of the electrotactile sensation as a function of stimulus waveform timing.

B. Studies and results

Instrumentation: We have completed development of the high-voltage bipolar voltage-to-current converter (HVB-VIC) described last year. We are now able to apply any arbitrary combination of pulse polarities and waveshapes to the skin, with excellent current control. A draft manuscript for journal submission is nearing completion.

We also developed a means to control the ambient humidity at the stimulation electrode, both inside and outside the electrode lumen (see Fig. 1 and discussion in following paragraphs).

Effect of skin hydration and stimulation polarity: We continued to investigate the effect of skin hydration on the electrical characteristics of the electrode–skin interface (i.e., resistance). Changes in skin hydration typically cause the majority of problems in controlling the electrotactile sensation, and this problem is exacerbated by using positive stimulation pulses, which we have used for many years because they have superior sensory properties compared to negative pulses.

Using the new HVB-VIC, we conducted a more detailed examination of skin hydration and stimulation polarity effects. We summarize the results as follows:

- With negative stimulation pulses, the electrode–skin resistance stabilizes within approximately 10 minutes after a change in humidity.
- Also with negative pulses, increased humidity inside the electrode lumen (“electrode airflow” in Fig. 1) reduces the electrode–skin resistance. The humidity outside the electrode (“controlled ambient air”) has minimal effect. This result, suggesting minimal diffusion of moisture parallel to the skin surface, will allow us to use simpler instrumentation that controls humidity only within the electrode, rather than in the larger ambient environment.
- With positive stimulation pulses, the electrode–skin resistance is relatively stable under high electrode lumen humidity conditions. With low humidity, however, the electrode–skin resistance increases rapidly (by several times) over the course of 15 min and is characterized by large fluctuations which we are continuing to investigate.

Dynamic range: We investigated the effect of both area (number of electrodes active on the fingertip) and waveform (number of pulses per burst, or NBP, when the stimulation pulse train is gated into bursts) on the magnitude-based dynamic range (MBDR) which, as described in the grant application, is an indication of how comfortable or acceptable the electrotactile sensation
feels at high intensities. A manuscript describing these results is in preparation. Our results may be summarized as follows (see Fig. 2):

- Increasing the area of stimulation increases the MBDR. This means that while maintaining an acceptable quality of stimulation (free from painful attributes), a larger number of electrodes in a given area results in a stronger, more vibratory sensation, presumably due to spatial summation in the mechanoreceptive afferent system.

- NPB did not significantly affect the MBDR. This was an unexpected and surprising result because previous studies on the abdomen and tongue showed large, statistically-significant increases in the MBDR with increasing NPB. This suggests that perceived strength of electrotactile sensations on the fingertip is temporally integrated differently on the fingertip than on the other loci studied. We are investigating this effect further.

_Tactile quality nomenclature:_ We developed a preliminary table of tactile sensation quality descriptors (i.e., tactile “colors”). This table, drawn from the collective experience of the project team, from human subject descriptions, as well as from the literature, presently contains 61 descriptors. Our long-term goal is to correlate each of these attributes to the physical stimulus variables (e.g., electrotactile waveform and geometry), and to reduce this list to a set of more fundamental tactile attributes.

_Number of qualitative dimensions:_ Using a paired-stimulus procedure and similarity ratings, we performed preliminary experiments to determine the number of dimensions of the electrotactile sensation by manipulating the stimulus waveform timing (Fig. 2, left). Multidimensional scaling (MDS) analysis revealed the following:

- Manipulating a single waveform variable (in this case, frequency F, with NBP=1) over a wide range (10–200 pulses/s) resulted in up to three perceived dimensions of tactile sensation; these cannot yet be clearly defined. Anecdotal reports suggest that different regions of this frequency range affect the sensation in different ways.

- Manipulating frequency and current (factorially, 4 levels each) over a narrower frequency range (10–80 pulses/s) resulted in two tactile dimensions roughly correlated with the two stimulation variables.

_C. Significance_

There is apparently a compromise in choice of stimulation polarity: While positive pulses result in better sensation quality (from previous work), negative pulses result in a more stable electrode–skin interface.

The electrotactile stimulus–response space may be more complex than it is for other sensory modalities, where for example perceived visual color is affected primarily by wavelength. This may be because electrotactile stimulation bypasses the normal tactile mechanoreceptors and their specific stimulus transduction mechanisms. Or it may be because we do not yet have adequate descriptors for tactile sensations.

_D. Plans_

_Skin resistance and waveform control:_ We will continue to investigate the interaction between stimulus waveform and humidity on electrode–skin resistance and electrotactile sensation. We will explore the possibility that a more complex waveform incorporating both positive and
negative pulses will yield a stable electrical interface while maintaining adequate perceptual properties.

*Sensation quality and perceptual dimensions*: We will expand our inquiry of tactile dimensions using MDS, manipulating a greater variety of waveform variables known a priori to influence the electrotactile sensation quality and MBDR.

In parallel, we will conduct rating-scale measurement of tactile quality and correlate these results with the waveform manipulations, as proposed.
E. Publications:


Summary figures for progress report

**Figure 1.** Skin resistance during negative electrotactile pulses is affected by the humidity near the skin along the path of current flow, inside the lumen of the coaxial electrode (electrode airflow). Ambient humidity, outside the electrode lumen, does not affect the skin resistance. “High” humidity is 80–85% RH; “low” humidity is 5–10%. All measurements are taken at room temperature.

**Figure 2.** Electrotactile pulses of current I, width W, and rate PRR (pulse repetition rate) are grouped into bursts with NBP (number of pulses per burst). The base frequency of the waveform F is the rate of burst repetition. The fingertip magnitude-based dynamic range (maximal comfortable intensity) is affected only slightly by NPB, unlike previously-reported results for abdomen and tongue. However, increasing the number of electrodes from 1 (small dots) to between 4 and 9 (large dots) does increase the maximal comfortable intensity on the fingertip.
Because of methodological differences, the maximal magnitudes may not be directly compared across skin locus.