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Surface Microgeometry: Tactile Perception and Neural Encoding

Robert H. LaMotte and Mandayam A. Srinivasan

When there is tangential relative motion between the fingerpad and the surface of an object, the presence of microscopic irregularities such as a scratch or fine texture can be readily perceived through the tactile sense. The following experiments were designed to determine the smallest surface features that humans can detect, and the peripheral neural events contributing to this detection. Another objective was to determine the importance of these events for the detection of the relative tangential motion (slip) of the object over the skin which could occur, for example, when an object such as a plate of glass is held between two fingers.

"Microgeometry" is defined here as the geometry of surface elevations with heights ranging from fractions of a micron to several microns. We determined first the smallest height of a single raised dot on a plane glass plate or an array of dots or bars comprising a texture on the plate, that humans could detect when there was slipping motion between the fingerpad and the plate. We next searched for candidate peripheral neural codes for the detection and recognition of surface microgeometry by applying these stimuli to the distal fingerpad of the anesthetized macaque monkey and recording evoked responses from single peripheral mechanoreceptive afferent nerve fibers.

The surface features were constructed using the techniques of photolithography whereby a computer generated pattern was etched into a small plate of glass. The height of the raised pattern on the plate was a function of the duration of etching and could be precisely controlled to less

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*We gratefully acknowledge the technical assistance of Karen Kramer, Lara Goldfedder and John Beggs. This research was funded by NIH grant NS15888 than a tenth of a micron (LaMotte et al., 1982). Single raised dots or patterns of raised dots or bars were constructed with heights that varied from less than a tenth to tens of microns.

TACTILE DETECTION OF A SINGLE RAISED DOT

Sensory Detection Thresholds

The capacities of humans to detect the presence of a single raised dot by actively stroking with the fingerpad was measured (Johansson and LaMotte, 1983). The minimal, i.e. threshold height of a dot that could be detected decreased with increasing dot diameter. The mean threshold was 6 μm for a dot diameter of 50 μm and about 1 μm for dots with diameters of 500 μm or greater.

Under conditions of passive stimulation, the capacities of humans to detect a single raised dot of 550 μm diameter was measured with dots of different heights stroked across the fingerpad (LaMotte and Whitehouse, 1986). The finger was restrained by means of a pedestal glued to the back of the fingernail and sunk into a plasticine hand holder. The sides of the fingerpad were not restrained so that the fingerpad could deform laterally as it might when it is actively stroked over a stationary surface. The plate was stroked across the volar distal pad by means of a servo-controlled electromechanical stimulator that maintained constant compressional force and horizontal stroke velocity (LaMotte et al, 1983). Each plate contained a raised dot or texture on transparent glass. Consequently, the contact between the skin and the surface of the plate could be viewed through a microscope and videorecorded.

On each trial, two plates were each stroked once across the fingerpad in succession at a velocity of 10 mm/s and a compressional force of 20 g wt. One plate was blank while the other contained the dot. The order among the pairwise presentations was randomized, and the subject was instructed to state whether the dot was present on the first or the second plate. For each subject the percentage of trials with correct responses increased monotonically with dot height. Detection thresholds for different subjects were all within the range of dot heights of about 1.5 to 2.5 μm. These thresholds, obtained under conditions of passive tactile stimulation, did not substantially differ from those measured during active touch in an earlier study (Johansson and LaMotte, 1983).

Peripheral Neural Events

In order to investigate which type of cutaneous mechanoreceptors contributed to these threshold sensory events, evoked responses to the same dot stimuli were recorded from 20 Meissner corpuscle rapidly adapting (RA), 21 slowly adapting type I (SA) and 9 Pacinian corpuscle (PC) mechanoreceptive peripheral nerve fibers innervating the monkey fingerpad (LaMotte and Whitehouse, 1986). For each fiber, the most sensitive spot in the receptive field was centrally located on the fingerpad. The response threshold of each fiber was defined as the minimal dot height evoking at least one impulse. These thresholds differed significantly for each type of fiber (Fig. 1). Only the RAs had dot height thresholds as low as 2 μm which was the mean detection threshold for humans. The dot height thresholds were 8 μm or greater for the SAs and 21 μm or greater for the PCs.

As a raised dot slides across the fingerpad, what is the mechanical event that triggers the threshold responses of the RAs? Our observations supported the idea that it was a lateral deformation of the papillary ridges

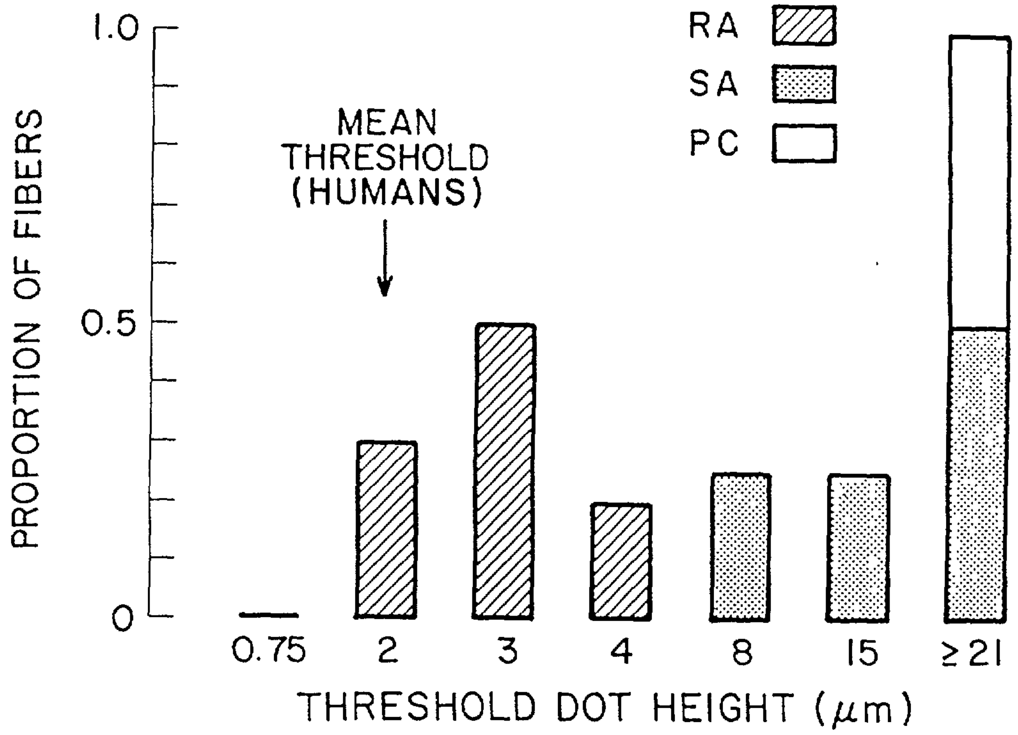

Figure 1. The proportion of RAs, SAs and PCs with response thresholds of the indicated dot height. The arrow points to the mean detection threshold obtained from human subjects. (from LaMotte and Whitehouse, 1986).

by the leading edge of the dot. Thus, when stroking a dot plate across the most sensitive spot in the receptive field in different directions with respect to the orientation of the papillary ridges on the monkey fingerpad, the number of impulses evoked in the RAs (and also the SAs) was greater for strokes across as opposed to along the ridges. Further, analyses of the temporal relation between the position of the dot on the skin, as recorded on videotape, and impulse activity in RA fibers, demonstrated a frequent correspondence between the occurrence of an action potential and the passage of the leading edge of the dot across a papillary ridge. We therefore concluded that the trigger for the response of the RA (that presumably terminates in Meissner corpuscles in the dermal papillae) is most likely a tweaking of the papillary ridge above the receptor by the edge of the dot.

TACTILE DETECTION OF A FINE TEXTURE

Sensory Detection Thresholds

The capacities of humans to detect the presence of a fine texture, that is, to discriminate it from a featureless, blank surface, was measured as a function of the height of the elements that make up the texture. One series of textures consisted of parallel bars each about 45 μm wide and spaced about 105 μm center to center. Another texture series was a matrix of dots with alternatingly staggered rows within which dots were spaced 100 μm

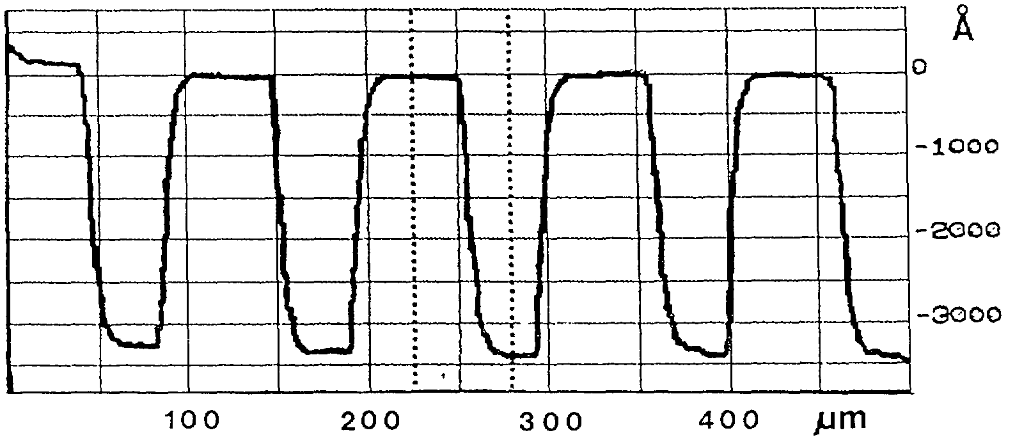

Figure 2. Tracing of a bar texture made by a profilometer. The average height of each bar was 0.33 μm and the average width, 44 μm.

center to center. The dimensions of each texture were then measured with a profilometer. A profilometry tracing in Fig. 2 of a bar texture with a bar height of only 0.33 μm demonstrates the precision of the photoetching process. When a texture with bars or dots of sufficient height was stroked at 10 mm/s across the human fingerpad (the bars oriented perpendicular to the direction of stroking), a local, high frequency vibration was felt. In order to measure detection threshold, the two-interval, two-alternative forced choice task described earlier was used. Subjects were instructed to discriminate between a blank plate and a textured plate by stating after each pair of presentations whether the texture was on the first or the second of two plates presented in succession. Each plate was stroked once in a medial to lateral direction at 10 mm/s over the fingerpad of the middle finger of the right hand.

The percentage of trials on which the bar texture was correctly detected was averaged for 5 subjects and plotted in Fig. 3 as a function of bar height. The mean detection threshold at 75% correct was a height of 0.06 μm. Higher dots were required before the dot textures could be

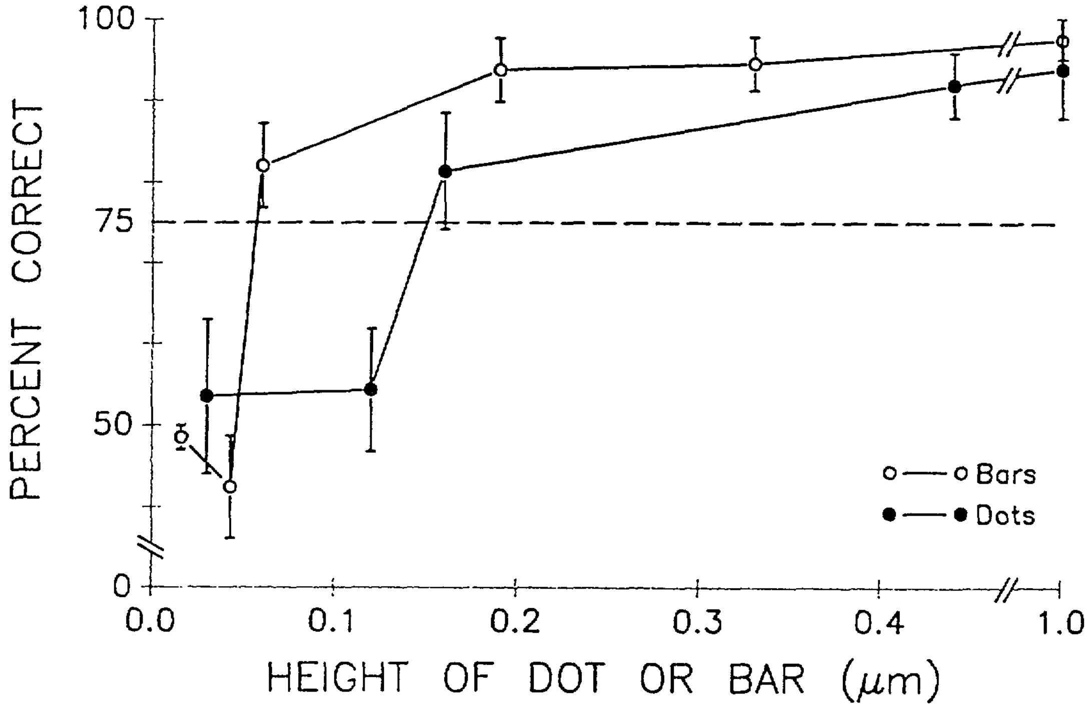

Figure 3. The capacity of humans to detect the presence of a texture consisting of raised elements the heights of which were varied. The elements were either parallel raised bars (five subjects tested) or an array of raised dots (three subjects tested). The mean number of trials on which the texture was correctly detected (± SEM.) is plotted for each height tested. The dashed horizontal line is the detection threshold.

detected. The mean detection threshold was a dot height of 0.16 μm.

Informal observations made when actively stroking these textures with the fingerpad demonstrated that detection thresholds would not differ substantially depending on whether the stroking was active or passive. Further, the introspective reports made by each subject indicated that the subject was attending to the vibratory signal set up by the texture on the fingerpad during stroking and not to any spurious cues such as a difference in lateral tension, minute differences in the way the plates were passively applied to the skin and so forth. Thus, it is clear that humans with presumably normal sensory capacities are able to detect the presence of surface textures made up of elements of extremely small heights.

Peripheral Neural Events

In two neurophysiological experiments with anesthetized monkeys we searched for the class of primary mechanoreceptive afferent fiber that contributed to the sensory detection of these finely textured surfaces.
In the first experiment, the responses of 33 SAs, 20 RAs and 15 PC afferent fibers were recorded to a plate half of which was blank and the other half contained a dot texture with a dot height of 1 μm. The SAs responded tonically to the steady pressure of the plate and, for about two-thirds of the fibers studied, this response was directionally selective. The difference in discharge rates for the two directions was a mean factor of two. Some of the directionally sensitive SAs responded differentially to the higher lateral tension or skin stretch exerted by the blank as opposed to the textured half of the plate. However, none of the SAs responded to the pattern of the texture per se. RAs also failed to respond to this texture and gave only 1 or 2 impulses to the initial skin stretch in either direction. In contrast, the majority of PCs with receptive fields on the fingerpad responded vigorously to the textured side of the plate but not to the blank side.

In a second experiment we recorded from 11 PC afferents, each of which had the most sensitive region of the receptive field on the fingerpad. The threshold height for the dot texture for each fiber was within the range of 0.05-0.4 μm in close agreement with the detection thresholds of human observers.

Aside from signalling the presence of a microtexture, the responses of Pacinian afferent fibers also conveyed temporal information related to the spatial pattern of the texture by the intervals between successive nerve impulses. The interspike interval histogram in Fig. 4 was obtained from the

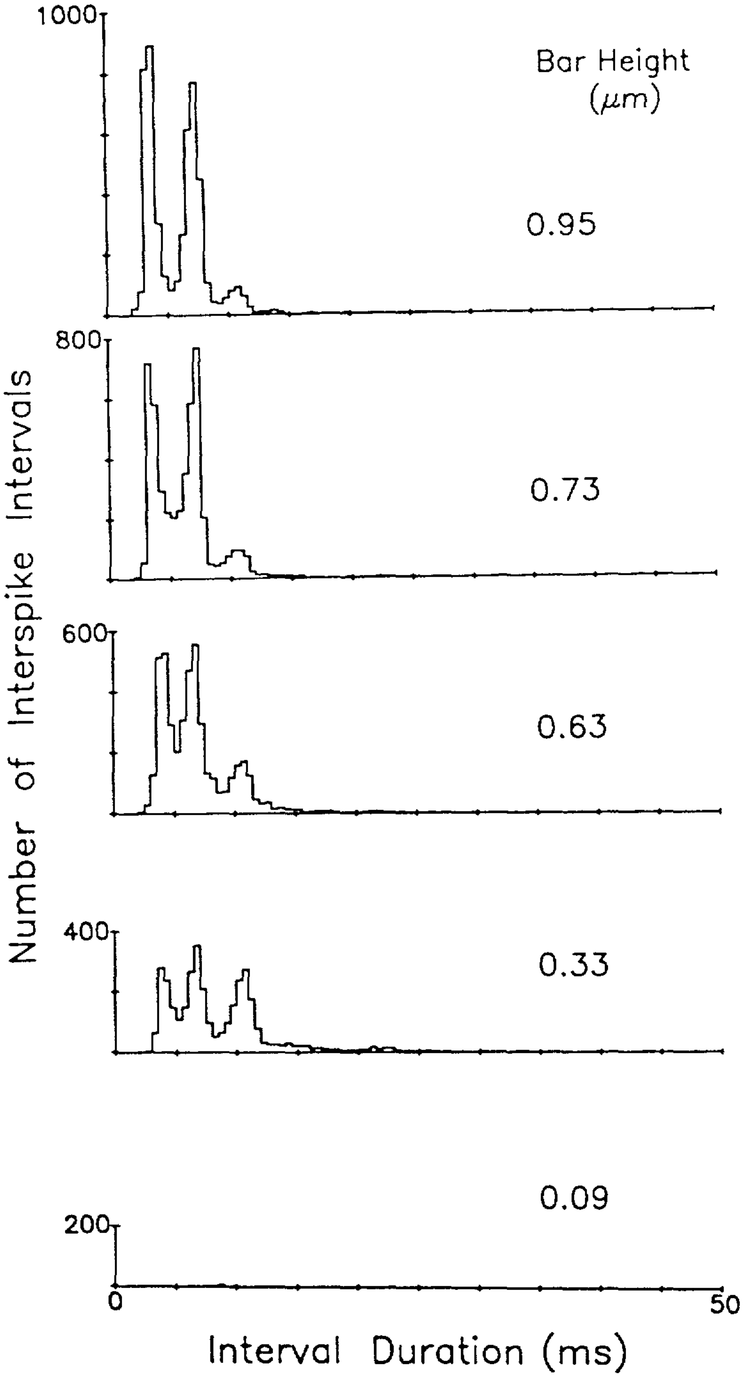

Figure 4. Interspike interval histograms for the responses of a PC fiber to bar textures each with bars of different height. The most sensitive region in the fiber's receptive field was centrally located on the fingerpad of the monkey's middle finger. Each histogram is labelled with the height of the bars in the texture. The bar width was 45 μm and the spacing, 105 μm. Each texture was stroked 10 times in the medial to lateral direction at 10 mm/s.

responses of a sensitive PC afferent to the bar textures stroked at 10 mm/s in a medial to lateral direction 12 times over a monkey's fingerpad. Three peaks are evident even at a height of 0.33 μm -two larger ones at 4 and 7 ms and a smaller one at 11 ms. The mechanical events responsible can be explained in terms of the leading and trailing edges of several bars simultaneously passing over the peaks of several papillary ridges. The shortest interspike interval (first peak) in the histogram is due to the occurrence of one impulse each to the leading and trailing edges of individual bars. The next peak corresponds to single impulses evoked by the trailing edge of one bar and the leading edge of the next bar. The third and minor peak may occur when there are missing responses to the weaker mechanical stimulus produced by the trailing edges. This analysis was made in part by means of a videoanalysis of the contact area which took into account the spacing between papillary ridges and the slight angle between the orientation of these ridges and the bars of the textures.

A periodic but slightly more complex temporal pattern of impulses was also evident in the responses of the same PC afferent to the dot textures of different heights stroked in the same medial to lateral direction across the fingerpad. The interspike intervals could be related to the geometry of the dot pattern as in the case of bar textures.

THE ROLE OF SURFACE MICROGEOMETRY IN THE DETECTION OF SLIP

The tactile detection of surface microgeometry can obviously be important for the process of object identification. But it may also be required for successful manipulation of the object by signalling any tangential relative motion or slip between the surface and the fingerpad which, if detected, might result in preventing the object from being dropped (Johansson and Westling, 1984). We therefore investigated the role of surface microgeometry in the detection of slip (Srinivasan, et al., 1990). Three types of plates were stroked at 10 mm/s and 20 g wt. of force across the passive fingerpads of human subjects: (1) A perfectly smooth (blank) plate, (2) A plate textured with the 1 μm high dot array and (3) a plate containing a single raised dot 550 μm wide and 4 μm high -a height just above detection threshold. In one experiment, subjects were asked to discriminate between two directions of skin stretch produced by a plate stroked across the fingerpad. In another experiment, they were instructed to distinguish between the presence and absence of relative motion by discriminating between a short stroke, which produced skin stretch but not slip, and a long stroke which caused stretch followed by relative motion.

In response to long and short strokes with the featureless blank plate, the subjects were able to discriminate the direction of skin stretch with or without the presence of slip. Presumably the peripheral neural encoding mechanism for this is contained in the responses of the SAs. Further, introspective reports of human observers indicated that the direction of stretch was quite apparent for the duration of lateral deformation of the skin when the RAs and PCs were not responding and only SAs were active. However, when asked to discriminate the presence of the relative motion of a plate, that is, discriminate between skin stretch alone and stretch plus relative motion, they could not do so when the plate was blank, but could readily do so when the plate contained a detectable microgeometry. Subjects reported detecting the successive positions of the single dot to which RAs alone respond as the dot moved across the skin, and they reported detecting the high frequency vibrations produced by the dot texture on the skin, to which the PCs alone respond. Thus, while SAs alone can encode the direction of skin stretch produced by an object's surface, only RAs or PCs are capable of signalling the presence of slip. Naturally, for surface features of sufficiently greater dimensions, all three classes of mechanoreceptive afferents may contribute to the detection of slip.

CONCLUSIONS

(1) Humans possess a remarkable capacity to feel microfeatures on a smooth surface of an object when there is tangential relative motion between the object and the fingerpad skin. A single raised element, in our experiments a dot as small as 2 μm high, can be felt due to local lateral deformations of papillary ridges by the edge of the dot which activates the RA afferent fibers. A texture consisting of periodically arranged elements with heights as low as 0.06 μm, can be detected when stroked across the fingerpad and this accounted for by activity evoked in the most sensitive PC fibers.

(2) While one can sense the direction of movement of a blank, featureless plate over the fingerpad, the detection of slip requires the presence of detectable surface features. The minimally detectable geometric features used in the present study resulted in the detection of the slip of these surfaces due to the selective activation of the RA and PC afferents.

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