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PERIPHERAL NEURAL REPRESENTATION OF THE SHAPE OF A STEP STROKED ACROSS THE MONKEY'S FINGERPAD.

R.H. LaMotte and M.A. Srinivasan*. Dept. of Anesthesiology, Yale Univ. Sch. Med., New Haven, CT 06510

In the present study, we investigated the peripheral neural representation of small shapes stroked across the finger. Each shape was a step change in height of a plate. The cross-sectional shape of the step from low to high approximated that of a half-cycle of a sinusoid. Step height was maintained at 0.5mm, while the half-cycle wavelength was varied from 0.45mm (steep) to 3.1mm (gradual). A servocontrolled mechanical stimulator stroked the step back and forth over the glabrous skin of the fingertip while maintaining contact force at 20g wt. Stroke distance along the mediolateral axis was 18mm and stroke velocity varied from 1 to 40mm/s. Each step was stroked first from the high to the low side of the step, i.e. step-stroking off the skin (SS-off) and then back again from low to high (step stroking onto the skin, SS-on).

Evoked action potentials in single primary mechanoreceptive afferent fibers innervating the fingerpad of the anesthetized monkey (M. fascicularis) were recorded by the methods of fiber dissection and single unit recording. Ten rapidly adapting fibers (RA) (Meissner type) and eight slowly adapting fibers (SA) (type I) were studied. Each fiber's responses to a step stroked in one direction provided a spatial response profile in which the occurrence of each action potential corresponded to a position of the step on the skin. The SAs, but not RAs, exhibited a base discharge that was interrupted by a sequence of "pause-burst-pause" for SS-on and "burst-pause" for SS-off. RAs exhibited a single burst to a step moved in either direction. Both SAs and RAs had a greater burst frequency for the SS-on than SS-off.

The spatial response profile of SAs and RAs were also altered by changes in step-shape and stroke velocity. For both SAs and RAs, discharge rate during the burst increased with increases in stroke velocity and with steepness of the step. The only response feature that remained more or less invariant over a range of stroke velocities was the spatial width of the burst in SAs which, for SS-on, decreased as step shape became steeper.

These results were interpreted as showing a close relationship between the spatial response profile and the profile of skin deformation expected to occur when a step was stroked across the skin. The base discharge of SAs and their greater sensitivity to changes in skin curvature distinguished the response profiles of SAs from those of RAs.

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RESPONSES OF CUTANEOUS RECEPTORS TO SMOOTH AND FINELY EMBOSSED SURFACES STROKED ACROSS THE PRIMATE FINGERPAD.

R.H. LaMotte, J.M. Whitehouse*, M.A. Srinivasan*. Dept. of Anesth., Yale Univ. Sch. of Med., New Haven, CT 06510

Three types of surfaces were stroked at a velocity of 10 mm/s under constant compressional force back and forth across the fingerpad of humans and anesthetized monkeys: 1) a smooth glass plate; 2) a smooth glass plate containing a single dot 550 um diameter, the height of which was varied from .75 to 80 um; 3) a glass plate textured with a distribution of uniformly spaced dots, each 50 um diameter and of the same height - varied from .01 to 5 um. Responses were recorded electrophysiologically from single, slowly adapting (SA), rapidly adapting Meissner corpuscle (RA), and Pacinian corpuscle (PC) mechanoreceptive fibers innervating the fingerpad of the anesthetized monkey. 1) Smooth plate. Human observers were able to identify differences in the direction of lateral stretch but had difficulty in detecting the presence or absence of steady movement. Monkey SAs, RAs, and PCs responded to initial skin stretch during onset of lateral movement, but only SAs continued to respond steadily. About half of the SAs exhibited directional sensitivity: their steady discharge rate was significantly greater for movements in one or the other direction even when the degree of lateral stretch was the same in both directions; 2) Plate with dot. The minimal height of a single dot detected by humans was between 1 and 3 um for a stroke velocity of 10 mm/s. Similar dot height thresholds were found for monkey RAs (2-4 um) but were higher for SAs (≥8 um) and PCs (≥21 um). The likely mechanical events activating RAs at threshold were local lateral deformations of the papillary ridges by the leading edge of the dot. 3) Textured plate. All PCs responded readily to laterally moving textures of 1 um height and 100 um spacing which did not activate the RAs - some PCs to textures with dot heights as low as 0.3 um. Variations in the density of dots produced different amounts of lateral skin stretch to which some of the SAs responded. Humans had no difficulty in perceiving the lateral movement of plates with detectable single dots or textures. Conclusion. The direction of movement of a smooth or finely textured plate stroked across the skin is encoded by activity in directionally sensitive SAs. The perception of the relative motion between the plate and the finger requires the existence of detectable surface features. If the feature is a single raised dot whose height is 4 um and diameter 550 um, its presence and its motion during lateral stroking are encoded only by the RAs. If the feature is a fine texture consisting of a pattern of dots, each of 1 um height, then only PCs can encode the presence and motion of the texture during lateral stroking.

(Supported by NIH Grant 15888)

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TACTILE DISCRIMINATION OF SOFTNESS. M.A. Srinivasan*, J.M. Whitehouse*, and R.H. LaMotte (SPON:J.G. Collins) Dept. of Anesthesiology, Yale University Sch. of Med., New Haven, CT 06510.

A measure of the softness of an object is the ratio of the depth of indentation of the object to the force causing the indentation. During active touch, information about both the force and indentation depth of the object is available to the subject through sensory receptors in skin, joint and muscle. In contrast, when an object is applied to the passive skin surface, the subject can assess the force from the cutaneous receptor response, but the depth of indentation of the object is unknown. In order to determine the importance of non-cutaneous cues in judging softness, we investigated the capacity of humans to discriminate softness under both active and passive touch.

Twelve transparent cylindrical disks (35mm dia. x 10mm thick) made of silicone rubber of varying softness (controlled by varying the amount of a diluent) were cast. Objective measures of softness, or compliance, were determined by measuring the average slopes of force versus displacement traces obtained by constant velocity indentations with a rigid, flat probe (6mm diameter).

When human subjects actively indented each specimen with the fingerpad, their subjective ranking of softness was the same as the ordering based on the objective measure of compliance. Five specimens (2.8, 4.1, 5.7, 9.2, and 10.2 µm/gm), 100% discriminable with active touch, were chosen for passive touch discrimination. In pairwise discrimination tasks, each specimen of the pair was brought onto the subject's stationary fingerpad at a constant velocity, maintained steady for 1 s and then withdrawn. The subject stated which one of the pair was softer. Subjects could discriminate only the specimens 2.8 and 10.2 from the 5.7um/gm specimen at levels greater than 75% correct. In separate tests, when one member of each pair was applied at a slower or faster velocity than the other, threshold discriminations of softness were not possible even between specimens of 2.8 and 5.7 um/gm compliance. Thus human discrimination of softness was significantly better under active than passive conditions. Passive discrimination deteriorated when indentation velocity was varied.

In order to determine the relevant cutaneous cues for discrimination, contact areas between the passive fingerpad and the specimens were videotaped. Off-line analyses indicated that the variation in contact area versus time for the specimens was quite small, but the corresponding traces of total force (and thus pressure) versus time were distinct from each other. Thus active softness discrimination may be based on the combined responses of mechanoreceptors in skin (encoding the rate of change of pressure) and joint or muscle (providing the velocity of indentation of the object). The absence of the proprioceptive information leads to a considerable deterioration of discriminability.(PHS grant 15888).

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1. Psychophysics
2. Cutaneous
3. Mechanosensory
4. Softness

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Abstract submitted to the XXXI International Congress of Physiological Sciences, July 9 - 14, 1989, Helsinki, Finland.

DISCRIMINATION OF SOFTNESS BY ACTIVE AND PASSIVE TOUCH

M.A. Srinivasan, J.M. Whitehouse and R.H. LaMotte
Dept. of Anesthesiology, Yale University Sch. of Med., New Haven, Connecticut 06510, USA.

We investigated the relative importance of cutaneous and proprioceptive information in the discrimination of softness. The stimuli consisted of 12 visually identical, transparent cylindrical disks made of silicone rubber of varying softness. The compliance of each specimen was measured as the average slope of the displacement vs. force trace, obtained by constant velocity indentations with a rigid, flat probe.

When human observers actively indented each of the 12 specimens with the fingerpad, their subjective rankings of softness were the same as the ordering based on the objective measures of compliance. In pairwise discriminations among 5 specimens using active touch, subjects discriminated nearly perfectly between a standard compliance of 5.7 um/g wt and comparisons of 2.8, 4.1, 9.2, and 10.2 um/g wt. In passive discrimination tests, the same stimulus pairs were indented into the stationary fingerpad by a servo-controlled tactile stimulator, to a peak force of 100g wt. When each specimen of a pair was brought down at the same velocity of 3 mm/s (the average velocity used by the subjects in active touch), the subjects discriminated only the compliances of 2.8 and 10.2 from the standard. Discriminability deteriorated further when one specimen was applied at a higher or lower velocity than the other (3 mm/s $\pm$ 20%). Under these conditions, none of the compliance pairs was discriminated. Thus, human discrimination of softness was significantly better under active than passive conditions.

The same 5 stimuli were presented to the stationary fingerpad of the anesthetized monkey, while recording evoked responses in single slowly adapting mechanoreceptive peripheral nerve fibers. During each indentation, the force and contact area were measured as functions of time. Traces of average pressure vs. time and discharge rate vs time depended on both the compliance and the velocity of indentation in a manner consistent with the psychophysical results.

A theory of softness discrimination was developed. It indicated that active discrimination of softness is based on the combined responses of mechanoreceptors in the skin (encoding the rate of change of pressure) and joint, muscle or `efferent copy' (providing the velocity of indentation of the object). During passive discrimination, the absence of proprioceptive information leads to a considerable deterioration of discriminability, since the subject cannot separate the effects of the compliance and the indentation velocity of the object on the rate of change of surface pressures, and consequently on the responses of cutaneous receptors.

(PHS grant 15888 and ONR contract N0014-88-K-0604)

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REPRESENTATION OF SHAPE IN THE RESPONSES OF CUTANEOUS MECHANORECEPTIVE AFFERENT FIBERS. M.A. Srinivasan* and R.H. LaMotte (SPON: S. E. Kapadia). Research Lab. of Electronics, MIT, Cambridge, MA 02139 and Dept. Anesthesiology, Yale Univ. Sch. Med., New Haven, CT 06510.

The distribution of surface curvature of an object defines its shape. In order to investigate the peripheral neural representation of shape, we recorded responses of slowly and rapidly adapting mechanoreceptive afferent fibers (SAs and RAs) to cylinders differing in curvature, and to a pattern of curvatures forming a smooth wavy surface applied to the monkey fingerpad. The discharge rates of both SAs and RAs to indentations by the cylinders increased with curvature. SA responses discriminated the curvatures very well both during the ramp and steady phases, in comparison to the ramp responses of RAs. RA responses were well modulated by the curvatures when the cylinders were sinusoidally vibrated: Their response thresholds decreased with increases in curvature. When the wavy surface was stroked at constant force over the fingerpad, both SAs and RAs responded with bursts to the convex portions and pauses to the concave. The width and frequency of SA responses were correlated with the wavelength and radius of the skin curvature, respectively. The RAs responded only to the leading half of the convex portions with poorer modulation. These findings are consistent with our earlier hypotheses [J. Neurosci. 7(6) 1655-1695]: SA discharge rates increase with increases in the depth of indentation and curvature change at the receptive field, and SAs do not respond to the unloading of curvature; RA discharge rates increase with increases in the velocity of indentation and rate of curvature change at the receptive field.

(PHS grant NS 15888 and ONR contract N00014-88-K-0604)

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3. Mechanosensory
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CUTANEOUS AND PROPRIOCEPTIVE CONTRIBUTIONS TO TACTUAL DISCRIMINATION OF SOFTNESS. R.H. LaMotte and M. A. Srinivasan* Dept. of Anesthesiology, Yale Univ. Sch. of Med., New Haven, CT. 06510 and Research Lab. of Electronics, MIT, Cambridge, Ma 02139.

The capacities of humans to discriminate between objects that varied in softness were measured under conditions that differed as to the relative contributions of cutaneous and proprioceptive cues available to the subject. A series of disks that differed in compliance (slope of displacement vs. force trace obtained by vertical indentations of each disk with a rigid probe) were cast using silicone rubber. Subjects made two-interval forced-choice discriminations using the distal pad of the middle finger. When the maximal force of indentation allowed was low (80g), optimal discrimination was achieved under active touch, wherein both proprioceptive and cutaneous information was available. Under passive touch, when only cutaneous cues were present, discrimination was much poorer and was confounded by alterations in indentation velocity. When the maximal force of indentation was higher (160g) under active touch, and cutaneous cues were eliminated by a local anesthetic, discrimination based on proprioceptive signals alone was not possible. However, without the anesthetic, optimal dicriminination was possible under passive conditions based on cutaneous information alone, in spite of variations in indentation velocity. Reponses of slowly adapting mechanoreceptive afferent fibers innervating the monkey fingerpad discriminated better the differences in the compliance of the rubber disks at higher forces of indentation. At lower forces, differences in responses to compliances were confounded by variations in the velocity of indentation in accordance with the corresponding psychophysical results.
(PHS grant NS15888 and ONR contract N00014-88-K-0604).

KEY WORDS: (see instructions pg. 4)

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Departments of Neurology and Nephrology, University of Basel, CH
Common carotid volume flow was measured by means of a novel cw Doppler flowmeter (1) in 38 patients having a unilateral and 4 patients having a bilateral EC/IC bypass.

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SOFTNESS DISCRIMINATION

R. H. LaMotte and M. A. Srinivasan
Department of Anesthesiology, Yale University School of Medicine, New Haven, CT and Research Lab. of Electronics, M.I.T., Cambridge, MA.

Human subjects could easily discriminate, with pairwise comparisons, the softness of rubber disks that differed in compliance by actively pressing each disk with the fingerpad. Discrimination was poorer when disks were passively indented into the restrained fingerpad at a constant velocity and peak force equal to mean values observed during active touch. Discrimination was even poorer when the velocities were different for the two indentations of a pair of compliances. Discrimination improved under both active and passive conditions as the peak force of indentation was increased. When the peak force was maximal at 160g, under active touch, and cutaneous cues were eliminated by a local anesthetic, discrimination based on proprioceptive information alone was not possible. Responses of slowly adapting mechanoreceptive afferent fibers innervating the monkey fingerpad discriminated better the differences in compliance at higher forces of indentation. Differences in responses to compliance were confounded by variations in indentation velocity as observed in the psychophysical studies. We conclude that both proprioceptive and cutaneous cues contribute to softness discrimination.

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Human-Machine Interfaces for Teleoperators and Virtual Environments, Eds. Durlach NI, Sheridan TB and Ellis SR, NASA Conference Publication 10071,199

TACTILE DISCRIMINATION AND REPRESENTATIONS OF TEXTURE, SHAPE, AND SOFTNESS

M. A. Srinivasan
Research Lab of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

and

R. H. LaMotte
Department of Anesthesiology
Yale University School of Medicine
New Haven, Connecticut

We present here some of the salient results on the tactual discriminabilities of human subjects obtained through psychophysical experiments, and the associated peripheral neural codes obtained through electrophysiological recordings from monkey single nerve fibers. Humans can detect the presence of a 2 microns high single dot on a smooth glass plate stroked on the skin, based on the responses of Meissner type rapidly adapting fibers (RAs). They can also detect a 0.06 microns high grating on the plate, owing to the response of Pacinian corpuscle fibers. Among all the possible representations of the shapes of objects, the surface curvature distribution seems to be the most relevant for tactile sensing. Slowly adapting fibers respond to both the change and rate of change of curvature of the skin surface at the most sensitive spot in their receptive fields, whereas RAs respond only to the rate of change of curvature. Human discriminability of compliance of objects depends on whether the object has a deformable or rigid surface. When the surface is deformable, the spatial pressure distribution within the contact region is dependent on object compliance, and hence information from cutaneous mechanoreceptors is sufficient for discrimination of subtle differences in compliance. When the surface is rigid, kinesthetic information is necessary for discrimination, and the discriminability is much poorer than that for objects with deformable surfaces.

COMPUTATIONS IN TACTILE SENSING

M.A. Srinivasan
Research Lab of Electronics, MIT
Cambridge, MA 02139

Abstract

Our tactile sensation is the culmination of a series of events: Physical contact with an object causes mechanical loading on the skin surface and results in distortions of mechanoreceptors; the receptors, in turn, respond with electrical impulse trains that are subsequently processed by the nervous system. In this paper, we present detection of slip, microtexture, shape, and compliance as examples of computations in tactile sensing. We draw upon results from our experiments on the biomechanics, neurophysiology, and psychophysics of tactile sense, as well as theoretical analyses employing the mechanics of deformable media.

Oral presentation
Category: C. Experimental
Theme: E. Sensory Systems (1) Somatosensory

Presented at the Computation and Neural Systems (CNS*92) meeting, San Francisco, July, 1992.

Computations in tactile sensing *

M.A. Srinivasan
Research Lab of Electronics, MIT
Cambridge, MA 02139

Summary

We constantly grasp, press, squeeze, or stroke objects with our fingerpads. We use physical contact with objects to explore their geometrical properties such as surface texture and shape, as well as material properties such as compliance. While manipulating the objects, say, moving them from one location to another using a pinch grasp, contact conditions give us information about the weight of the object, whether the object is slipping, and if so, whether the control action of increased grasp force has terminated the slip. Yet, we know very little about the nature of the contact between the fingerpad and various objects that differ in their physical properties, the kind of spatio-temporal contact information gathered by our tactile sensors, or as to how it is processed by the central nervous system and is used in controlling the contact conditions with the help of the motor system. Although psychologists have measured human tactual discriminabilities under various conditions, and neurophysiologists have characterized mechanoreceptor responses, very little attention has been paid to the computational aspects of the sense of touch. We present here some of the results of our investigations on computations in tactile sensing supported by psychophysical, neurophysiological, and biomechanical experiments on primates, together with theoretical analyses based on the mechanics of deformable media. It should be noted that the computational aspects of these results are relevant to robot tactile sensing as well because of the similarities between human and robotic tactual sensory systems.

Tactual information consists of two components: (1) contact information which specifies the nature of direct contact with the object; (2) kinesthetic information which refers to the position and motion of the limbs. In this paper, we shall mostly be concerned with contact information, which in primates is mediated by four types of peripheral afferent fibers. Two of these are slowly adapting fibers (SA I and II) that are associated with Merkel cells and Ruffini endings, and are responsive both when an object in contact is moving against the skin as well as steadily indenting it. The other two types are rapidly adapting fibers which respond only when the skin is moving, one type (RAs) terminating in Meissner corpuscles, and the other (PCs) in Pacinian corpuscles. When a probe indenting the skin is vibrated, lowest response threshold amplitudes for SAs are at frequencies of 0-10 Hz, for RAs at 20-50 Hz, and for PCs at 100-300 Hz. We summarize below our viewpoint, our approach, as well as some of the results we have obtained on the neural computations involved in the detection of slip, microtexture, shape, and compliance.

From an information processing point of view, tactile sensing of objects can be seen as the flow of information from the object surface to the brain. The path of this flow consists of several stages,

*Oral presentation. Category: C. Experimental. Theme: E. Sensory Systems (1) Somatosensory with a different representation of the information at each stage. Some of the stages relevant to our purpose here are the geometry and material properties of the object itself, the mode of contact and mechanical loading on the skin surface, stress and strain fields within the skin (especially at the receptor locations), spatio-temporal patterns of action potentials in afferent fibers, and further transformations within the nervous system. At each of these stages, the representation of object properties can be achieved by several candidates. The problem of understanding how these properties are detected through touch requires an investigation of what representations are actually used by the somatosensory system at each stage of the information flow.

Although humans use a large set of descriptive terms to distinguish a variety of tactual perceptions, they are really combinations of a few 'building blocks' or 'primitives'. For simplicity, normal indentation, lateral skin stretch, relative tangential motion, and vibration are the primitives for the *conditions of contact* with the object; surface micro-texture, shape (mm-size), and compliance could be thought of as the primitives for the majority of *object properties* perceived by touch[1]. It is plausible that by understanding the peripheral and central processing involved in each pair-wise combination of the primitives for object properties and contact conditions, we will be able to understand the processing of stimuli which are more general combinations.

(A) Detection of Slip

Slip, or tangential relative motion between skin surface and the object surface is essential to detect microtextures on surfaces, and generally improves tactile perception even for mm size features. In order for the central nervous system to extract the object features from the spatially and temporally varying tactile 'image', the existence and direction of relative motion must first be detected. We have shown that humans cannot detect the slip of a smooth glass plate on the skin, and that existence of detectable features on the surface is necessary for slip detection. However, surprisingly small features (for example, 4μm high dot causes RAs to respond and 1μm high dot texture causes PCs to respond) on smooth surfaces are detected by humans and lead to the detection of slip of these surfaces, with the geometry of the microfeatures governing the associated neural codes. The division of labor among the different types of fiber populations in signalling the different events on the skin is clear-cut: SAs signal the direction of skin stretch and hence the direction of impending slip; RAs and PCs signal the occurrence of slip with spatiotemporal or intensive codes depending on whether the microfeature is a local one on a smooth background, or is distributed on the surface, respectively. When the surface features are of sizes greater than the response thresholds of all the receptors, redundant spatiotemporal and intensive information from all three afferent fiber types is available for the detection of slip. The peripheral neural codes under these various conditions govern the computational algorithms needed to infer contact conditions and object features.

(B) Microgeometry

Microgeometry is defined here as the geometry of surface features with heights ranging from fractions of a micron to tens of microns. Surface microgeometries consisting of single raised dots or patterns of raised dots or bars were etched precisely on glass using photolithography. Human detection thresholds and the associated peripheral neural codes were determined for each of these microgeometries. We have demonstrated that humans can perceive extremely fine gratings composed of bars that are 0.06 micron high, 50 microns wide, and 100 microns apart. We show that these textures are coded by Pacinian corpuscles whose temporal responses are precisely related to the spatial period of the gratings and the velocity of stroking.

[1]Here, we will not consider temperature or pain sense, since these are mediated by a different set of afferent fibers.

(C) Shape

Among the different possible geometric representations of the shape of objects, the intrinsic description, i.e., the surface curvature as a function of the distance along the surface, seems to be relevant for tactile sensing. By using cylindrical specimens of varying curvature and corrugated surfaces consisting of alternating convex and concave curvatures, we demonstrate the direct relationship between SA and RA discharge rates, and the curvature change at the most sensitive spot on the receptive fields. By applying the results from contact mechanics, we show that the receptors are responding to the low-pass filtered versions of surface pressures. Thus curvature, which we know from differential geometry is approximated by the second spatial derivative of surface deflection, is coded without differentiating (which is a noise enhancing process), but by exploiting its relation to surface pressure. Use of a linear elastic material model enables us to build an idealized computational theory for neural coding and decoding of arbitrary object shapes indenting the skin.

(D) Compliance

Compliant objects can be of two types: (1) Those with a rigid surface (such as a piano key); (2) Those with a deformable surface (such as cheese). For the former, we used glass plates supported by springs in a cylindrical sleeve. For the latter, by drastically altering the relative proportion of constituents used in casting silicone rubber, we were able to design transparent specimens that varied in softness, but were identical otherwise. In order to assess the relative contributions of contact and kinesthetic information in softness discrimination, we conducted psychophysical experiments under both active and passive touch, with or without local anesthesia that blocked the contact information. We show that humans are very good at discriminating subtle differences in the softness of objects with deformable surfaces, and the discrimination is based entirely on contact information. For compliant objects with rigid surfaces, we show that with active touch, discrimination of differences in softness is possible, due to the availability of both contact and kinesthetic information. In discriminations under passive conditions, the absence of kinesthetic information results in considerable deterioration of discriminability. Using a simplified theory of softness discrimination that is based on mechanics of contact, we infer the neural computations that are consistant with the human performances.

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TACTILE DISCRIMINATION AND IDENTIFICATION OF THE SHAPES AND ORIENTATIONS OF ELLIPSOIDAL OBJECTS

R.H. LaMotte, M.A. Srinivasan* and A. Klusch-Petersen, Dept. of Anesthesiology, Yale University School of Medicine, New Haven, CT 06510 and Research Laboratory of Electronics, MIT, Cambridge, MA 02139.

The shape of an object is physically defined by the principal curvatures and their orientations at each point on its surface. The magnitude and/or rate of change in the curvature of the skin brought in contact with the object is then represented in the discharge rates of certain cutaneous mechanoreceptors (Srinivasan and LaMotte, Wenner-Gren Intl. Symp. Series, Vol.57, Ch.5, 1991). As part of ongoing studies of the neural coding of tactually perceived shape, we measured the capacities of humans (1) to detect deviations from sphericity of ellipsoidal objects applied to the fingerpad and (2) to discriminate or identify differences in the orientation of the major axes of ellipsoids or a cylindrical bar, relative to the axis of the finger and/or the direction of stroking the object over the skin. Each object had a radius of 5 mm along one axis, and for the ellipsoids, radius along the orthogonal axis ranged from 4.75 to 1 mm. A servo-controlled stimulator with 4 degrees of freedom rotated the object to a desired orientation in the horizontal plane and then vertically indented the stationary fingerpad to a maintained force of 40 gwt. Either the contact center was fixed, or the object was stroked along a linear or circular trajectory over the skin.

The subjects detected deviations in sphericity on the order of 1mm in radius and, for the cylinder, discriminated differences in orientation of 5-10° and identified about 6 categories of orientation in 30° steps. Discrimination and identification of orientations deteriorated as the deviations from sphericity reduced. Results were interpreted in relation to the known sensitivities of rapidly and slowly adapting mechanoreceptive nerve fibers to changes in curvature of the skin brought about by contact with objects of different shapes.

Supported by ONR Contract N00014-91-J-1566 and PHS grant NS 15888.

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RESPONSES OF CUTANEOUS MECHANORECEPTORS TO TWO- AND THREE- DIMENSIONAL SHAPES STROKED ACROSS THE MONKEY FINGERPAD R.H. LaMotte, M.A. Srinivasan*, C. Lu and A.-K. Petersen, Dept. of Anesthesiology, Yale University School of Medicine, New Haven, CT 06510 and Research Laboratory of Electronics, MIT, Cambridge, MA 02139.

We investigated the peripheral neural representation of two- and three-dimensional objects (2DOs and 3DOs). The 2DOs were corrugated surfaces consisting of alternating convex and concave cylindrical bars of differing radii of curvature. The 3DOs were ellipsoidally shaped with a radius of 5 mm along one axis, and differing radii of 1, 3 or 5 mm along the orthogonal axis. A servocontrolled translation device brought each object down onto the stationary fingerpad to achieve a desired force that was maintained as the object was stroked back and forth across the skin along a single linear trajectory with 2DOs, or a series of laterally shifted parallel linear trajectories oriented 0, 30, 60, 90, 120 or 150 degrees with respect to the long axis of the finger with 3DOs. Spatial Event Plots (SEPs showing relative location of the receptive field on the object whenever an impulse occurred) were obtained from electrophysiologically recorded responses of slowly adapting type I and rapidly adapting (Meissner Corpuscle) mechanoreceptive afferents innervating the monkey fingerpad.

Interpretation of the discharge rate profiles derived from SEPs as instantaneous responses of a spatially distributed population of fibers led to the following conclusions. Discharge rate, an intensive measure of neural response, encodes the magnitude and rate of change in curvature of the skin produced by the object. The widths of bursts of impulses evoked by the object and the pauses between bursts, which are spatial measures, encode the sizes of the convex and concave regions of the object in contact with the skin. The overall shape as a distribution of curvatures is represented by the spatially distributed pattern of peripheral neural discharge rates. The spatial aspects of neural responses were generally invariant with respect to moderate variations in force, velocity and trajectory orientation.

Supported by NIH grant NS15888 and ONR contract N00014-91-J-1566.

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TACTILE SENSE: MECHANICS AND MECHANISMS

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[16b]

The mechanics of contact between the skin and an object determines the information about the object that the neural mechanisms of tactile sense can extract. In order to understand the peripheral neural coding and central decoding of tactile information concerning the physical properties of objects and their mode of contact with the skin, we have conducted experimental and theoretical studies involving biomechanics, neurophysiology and computational models. We have performed biomechanical experiments to measure the geometric and material properties of human and monkey fingerpads. We have obtained electrophysiological recordings of the responses of single cutaneous mechanoreceptive afferent fibers innervating monkey fingerpads to controlled contact with objects of various physical properties. We have constructed two- and three-dimensional finite element models to infer or predict the mechanics of contact, transmission of mechanical signals through the skin, and their transduction into spatio-temporal trains of neural impulses by the receptors. We have also investigated possible information processing algorithms for decoding the peripheral information by the central nervous system. We will present an overview of the results with examples, and their implications to further research. (Supported by grants from NIDCD and ONR).

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