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Tactual Discrimination of Softness

M. A. SRINIVASAN AND R. H. LAMOTTE
Department of Mechanical Engineering and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139; and Department of Anesthesiology, Yale University School of Medicine, New Haven, Connecticut 06510

SUMMARY AND CONCLUSIONS

1. We investigated the ability of humans to tactually discriminate the softness of objects, using novel elastic objects with deformable and rigid surfaces. For objects with deformable surfaces, we cast transparent rubber specimens with variable compliances. For objects with rigid surfaces ("spring cells") we fabricated telescoping hollow cylinders with the inner cylinder supported by several springs. To measure the human discriminability and to isolate the associated information-processing mechanisms, we performed psychophysical experiments under three conditions: *1*) active touch with the normal finger, where both tactile and kinesthetic information was available to the subject; *2*) active touch with local cutaneous anesthesia, so that only kinesthetic information was available; and *3*) passive touch, where a computer-controlled mechanical stimulator brought down the compliant specimens onto the passive fingerpad of the subject, who therefore had only tactile information.

2. We first characterized the mechanical behavior of the human fingerpad and the test objects by determining the relationship between the depth and force of indentation during constant-velocity indentations by a rigid probe. The fingerpad exhibited a pronounced nonlinear behavior in the indentation depth versus force trace such that compliance, as indicated by the local slope of the trace, decreased with increases in indentation depth. The traces for all the rubber specimens were approximately linear, indicating a constant but distinct value of compliance for each specimen. The fingerpad was more compliant than each of the rubber specimens.

3. All the human subjects showed excellent softness discriminability in ranking the rubber specimens by active touch, and the subjective perception of softness correlated one-to-one with the objectively measured compliance. The ability of subjects to discriminate the compliance of spring cells was consistently poorer compared with that of the rubber specimens.

4. For pairwise discrimination of a selected set of rubber specimens, kinesthetic information alone was insufficient. However, tactile information alone was sufficient, even when the velocities and forces of specimen application were randomized. In contrast, for discriminating pairs of spring cells, tactile information alone was insufficient, and both tactile and kinesthetic information were found to be necessary.

5. The differences in the sufficiency of tactile information for the discrimination of the two types of objects can be explained by the mechanics of contact of the fingerpad and its effect on tactile information. For objects with deformable surfaces, the spatial pressure distribution within the contact region depends on both the force applied and the specimen compliance. Consequently, for a given net force, skin deformation is dependent on specimen compliance and tactile information is able to encode the compliance of objects with deformable surfaces. For compliant objects with rigid surfaces, the pressure distribution and skin deformation for a given net force are independent of object compliance and therefore tactile information alone is not sufficient to encode their compliance.

INTRODUCTION

All the objects in our environment are compliant: they deform under the application of forces. Perfect rigidity is an idealization that serves as a useful approximation when the resolution in the measurement of compliance is limited. Compliance of objects is a fundamental property that helps us discriminate, classify, and identify them. It plays an important role in the manipulation of objects as well, because the deformation of objects held in the hand depends directly on their compliance. Often, a high value of compliance is an indication of the fragility of an object. In exploring and manipulating such objects with the hand, the contact forces must be controlled so as to avoid crushing or damaging the object.

The degree of compliance of an object can be loosely defined as the amount of deformation caused by a unit measure of applied force. Thus, by definition, sensing of object compliance requires knowledge of both deformations and associated forces. When a compliant object comes in contact with an indentor such as our finger or another object, our vision can provide us some information concerning the deformation of the object surface around the contact region. But the high deformation within the contact region is obscured by occlusion between the object and the indentor. Furthermore, vision does not provide any information concerning the applied force. It is only by touching the compliant object and only through our tactual sensory apparatus that we can simultaneously get information about both the deformation of the object in the contact region and the force of contact. The associated perception of *softness* is a subjective measure of the *compliance* of the object.

A common mode of assessing the softness of an object with the hand is to squeeze or indent it with the fingerpads. The resulting predominantly normal forces applied on the object cause corresponding deformations of both the object and the fingerpad. The associated tactual information can be divided into two classes: *1*) tactile information, referring to the sense of the nature of contact with the object, mediated by the responses of low-threshold mechanoreceptors innervating the fingerpad skin within and in the neighborhood of the contact area; and *2*) kinesthetic information, referring to the sense of position and motion of limbs, along with the associated forces, conveyed by the sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, together with neural signals derived from motor commands. Our goals here are *1*) to investigate the ability of humans to tactually discriminate softness and *2*) to isolate the sources of tactual information that enables the discriminability.

Despite the behavioral importance of sensing compliance,

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surprisingly few studies have explored the ability of humans to discriminate softness. Beginning with the observation by Katz (1938) on the skills of test bakers, the investigations up to 1950 have been summarized by Harper (1952). Most of these were concerned with measuring the differential sensitivity of humans. The later work of Harper and Stevens (1964) concentrated on the form of the psychophysical law for scaling subjective judgments of hardness. However, in all these efforts the stimulus control was poor because diverse materials were used, ranging from sponge to clay, that differed in other physical properties such as surface texture and thermal conductivity. Also, the experiments were designed to measure human discriminability under active touch, without any investigation of the possible biomechanical or neural mechanisms that enable the discrimination. Recently, Tan et al. (1992, 1993) have measured the just noticeable differences (JND) in compliance between two rigid plates (driven by computer-controlled linear motors) grasped between the thumb and forefinger. The JNDs ranged from ~8% to 99%, depending on whether the subjects had cues stemming from terminal grasp force and/or total work done. In experiments by Jones and Hunter (1990), subjects were required to actively move the forearm about the elbow joint to sense the preprogrammed compliance of a linear motor attached to one of the wrists, and to match it by modifying the compliance of an identical linear motor attached to the other wrist. The estimated compliance JND under these conditions was ~23%.

From the point of view of tactual information processing, it is important to recognize that compliant objects can be classified into two major types: *1*) deformable objects whose surfaces are also deformable (such as rubber, fruits, etc.) and *2*) deformable objects whose surfaces are rigid (such as a key in a piano or a typewriter). In the present series of experiments, we constructed novel compliant objects of either type such that they exhibited elastic behavior, that is, the deformed objects under the applied load returned to their original unloaded state once the loads were removed. For objects with deformable surfaces, we cast transparent rubber specimens that varied only in compliance (controlled by varying the amount of a diluent). These specimens were visually identical and had no differences in extraneous features such as surface texture and thermal conductivity. For compliant objects with rigid surfaces, we constructed telescoping hollow cylinders with rigid end plates such that the inner cylinder was supported by several springs inside the outer cylinder. To measure human discriminability and to isolate the associated information processing mechanisms, we performed psychophysical experiments under three conditions: *1*) active touch with normal finger, where both tactile and kinesthetic information was available to the subject; *2*) active touch with local cutaneous anesthesia, so that only kinesthetic information was available; and *3*) passive touch, where a computer-controlled mechanical stimulator brought down the compliant specimen onto the passive fingerpad of the subject, who therefore had only tactile information.

METHODS

Specimen preparation

RUBBER SPECIMENS. The goal was to create transparent objects with planar deformable surfaces, whose compliance varied in a controlled fashion but which were otherwise indiscriminable. Twelve cylindrical rubber disks were cast in petri dishes in the following manner. A small horizontal slit was cut on the side wall near the bottom plate of each of the petri dishes (35 mm diam × 10 mm high) and a 75-mm-long, 25-mm-wide slide glass plate was inserted through the slit into each petri dish. The slit was then sealed with a quick-setting dental impression material (Permlastic). Transparent silicone rubber solution (RTV 615, General Electric) mixed with varying but measured amounts of a diluent (RTV 910) was then poured into the petri dishes to the brim, taking care to prevent formation of air pockets. This solution solidified after 24 h of curing at room temperature. The specimens that resulted were visually identical and had no discernable differences in extraneous features such as surface texture and thermal conductivity, but varied in their compliance. Their transparency allowed a clear view of the region of contact with the fingerpad. The slide glass plate projecting out of each petri dish allowed the specimens to be mounted on a computer-controlled tactile stimulator(Fig. 1).

SPRING CELLS. In contrast with the above, the goal here was to construct deformable objects with planar rigid surfaces. Each specimen consisted of two telescoping hollow cylinders with rigid end plates (Fig. 1) such that the inner cylinder made of Teflon could move freely inside the outer cylinder made of Delrin. The diameter and the range of motion of the inner cylinder were 33 and 2 mm, respectively. The gap between the two cylinders was controlled to a tolerance of 0.1 mm, so that neither scraping (which might have caused extraneous vibratory cues) nor wobbling occurred when the inner cylinder moved relative to the outer one. The inner cylinder was supported by four springs glued to the bottom plate of the outer cylinder. The compliance of these "spring cells" could be varied by changing the springs, and the cells could be mounted onto the tactile stimulator.

Tactile stimulator

A servo-controlled mechanical stimulator driven by a hydraulic system (LaMotte et al. 1983) was used to determine the objective compliance of the specimens and the human discriminabilities of their softness. The stimulator was capable of moving an indenting probe or a specimen in the vertical or horizontal direction at preprogrammed velocities controlled by a computer. A resolution of ~2 μm in the vertical direction and ~6 μm in the horizontal direction was achieved by means of linear variable displacement transducers for position measurement along each axis of movement and analog feedback circuits for servo-control. The total compressive force exerted during an indentation could be measured with a force transducer (Sensotek) that had a resolution of ~1 gwt (weight of 1 gram mass = 9.81 mN). The force was transmitted to the transducer through contact with a spring-loaded lever, which was clamped to the glass plate projecting out of the specimen at one end and connected to the stimulator by means of a hinge at the other (Fig. 1). Local analog feedback circuits enabled an indentation to proceed at a preprogrammed velocity until a desired force was reached, followed by retraction at the same speed. The timing and the sequence of the stimuli were controlled by the computer. The motion of the probe, specimens, or subject's finger, and the contact region during indentation could be viewed and recorded from the top or from the side with a videomicroscopy system consisting of a videocamera mounted on a surgical microscope and connected to a monitor and video cassette recorder. In addition, a video mixing device superimposed the numerical values of force, elapsed time, and a video field count on the video signal.

Measurement of objective compliance

The compliance of each specimen was measured to obtain an objective scale against which the subjective psychophysical mea-

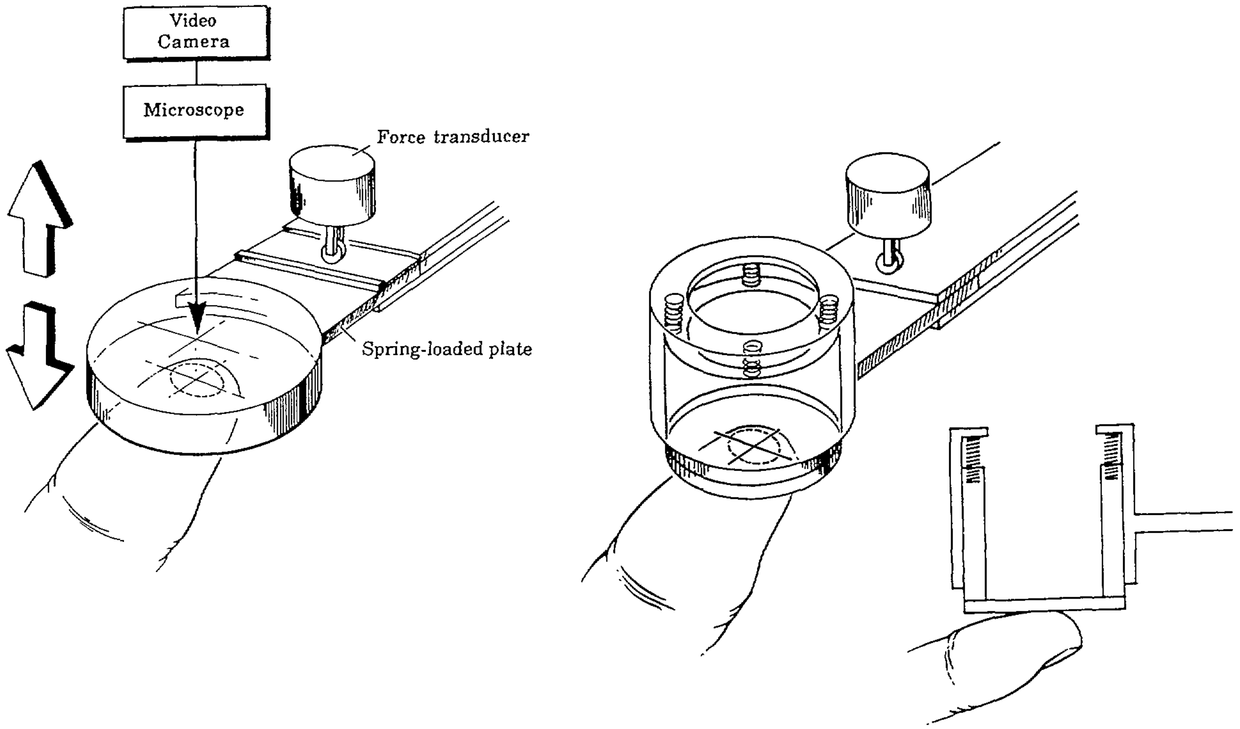

FIG. 1. *Left*: schematic of the apparatus for experiments with transparent rubber specimens of variable compliance. The specimen is mounted on the spring-loaded plate projecting out of a computer-controlled tactile stimulator. The plate is in contact with a force transducer that is able to measure forces of contact between the specimens and fingerpads under active or passive touch conditions. The contact regions are videotaped using a dissection microscope fitted with a video camera. *Right*: "spring cell" mounted on the same spring-loaded plate and in longitudinal section. These specimens were used in experiments on deformable objects with planar rigid surfaces. Each specimen consisted of 2 telescoping hollow cylinders such that the inner cylinder could move freely within the outer cylinder. Four springs glued to the bottom plate of the outer cylinder and connected to the inner cylinder determined the compliance of the specimen.

sures could be matched. Each specimen was placed on a rigid platform. A rigid, flat-ended cylindrical probe 6 mm diam bonded to a glass plate was attached to the tactile stimulator. The probe was brought down to indent the flat surface of the specimen centrally at a constant velocity of 0.5 mm/s until the force reached 100 gwt., followed by retraction. The displacement of the probe was displayed as a trace on a digital storage oscilloscope (Nicolet Instrument). The corresponding variation of the force of indentation was measured using the force transducer, whose output voltage was also displayed on the oscilloscope. To determine the depth of indentation by the probe at any instant of time during the ramp, the moment of contact had to be determined by detecting accurately the time at which contact force started increasing from 0. However, this task was complicated by the slow, nonlinear increase in force during the initial stages of indentation and the inevitable presence of noise in the force trace. Extreme care was therefore needed in conditioning and sampling of the signals to obtain consistent values during repeated trials. We found that when the force signals passed through a 10-Hz low-pass filter and were sampled at 2-ms time intervals, the moment of contact could be consistently determined to a high degree of precision. The depth of indentation of the probe, obtained from its displacement trace (or equivalently by multiplying the velocity of indentation by the time elapsed after contact), and the corresponding indentation force were measured for each of the specimens. The same experiment was also conducted on a human finger.

Experiments with rubber specimens

The basic approach we used was to compare the results of psychophysical results under active touch with normal finger, active touch with local cutaneous anesthesia, and passive touch (Table 1). To draw valid conclusions by comparing the performance of subjects under the three experimental conditions, we decided to keep the parameters of indentations the same for each of them. The major parameters are *1*) posture of the contacting finger and the joints activated, *2*) the relative velocity with which the fingerpad and the specimen approach each other, and *3*) the peak contact force. Even when only indentations normal to the specimen are allowed (as was done in all the experiments described here), it is likely that the finger posture and the joints activated affect both the kinesthetic information and the contact locus on the fingerpad. Control over the contact locus is important because the spatial density of receptors and compliance of the fingerpad are dependent on it. The receptor density affects spatial resolution of the perceived tactile information and fingerpad compliance affects the mechanistic aspects of contact such as the pressure distribution and contact area on the skin. Two other parameters, approach velocity and peak contact force, also affect directly the mechanics of contact and thus might influence the receptor population response and the performance of the subjects. In preliminary experiments, when the subjects were asked to rank or discriminate the specimens actively under almost natural conditions, we observed that all the three parameters listed above, namely, the posture, approach velocity, and peak contact force, varied across trials for the same subject as well as across subjects. Therefore our strategy was to maintain the same range of values of parameters under the three experimental conditions as much as possible. However, when modifications were necessary, such as in posture (see below), we performed the experiments under both natural and modified conditions. In all cases, care was taken to ensure that contact with edges of the specimens did not occur.

TABLE 1. *Experimental conditions and corresponding parameters*

Experiment	Active/Passive Touch	Normal/Anesthetized Finger	Experiment Type	Parameters
			A. Rubber specimens	
1	Active	Normal	Ranking	Unconstrained and constrained postures
2	Active	Anesthetized	Ranking	Unconstrained and constrained postures
3	Active	Normal	S3 vs. S1, S2, S4, S5	Unconstrained posture and force
4	Active	Normal and anesthetized	S3 vs. S5	Constrained posture, peak force = 75 ± 20 gwt.
5	Active	Normal	S3 vs. S1, S2, S4, S5	Constrained posture, peak forces = 25 ± 20, 50 ± 20, 75 ± 20, or 90 ± 20 gwt.
6	Passive	Normal	S3 vs. S1, S2, S4, S5	Indentation velocities randomized among 2.4, 3.0, and 3.6 mm/s, constant peak force = 25, 50, 75, or 90 gwt.
7	Passive	Normal	S3 vs. S1, S2, S4, S5	Indentation velocities randomized among 2.4, 3.0, and 3.6 mm/s, peak forces randomized among 60, 75, and 90 gwt.
			B. Spring cells	
8	Active	Normal	S1 vs. S5	Unconstrained posture and force
9	Active	Normal	S1 vs. S5	Unconstrained posture, peak forces = 50 ± 25, 75 ± 35, or 90 ± 45 gwt.
10	Passive	Normal	S1 vs. S5	Indentation velocities randomized among 2.4, 3.0, and 3.6 mm/s, constant peak force = 75 gwt
11	Passive	Normal	S1 vs. S5	S1 at 2.4 and 3.0 mm/s; S5 at 3.0 and 3.6 mm/s, constant peak force = 90 gwt.

S1–S5, signify varying degrees of specimen softness. 1 gwt. = weight of 1 gram mass = 9.81 mN.

All the active touch experiments were done under both unconstrained and constrained postures. The latter was necessary because of considerations concerning the blocking of only cutaneous information using local anesthesia, whereas the kinesthetic information was to be left intact. When we tried to inject the anesthetic into the distal phalanx, a low dosage of the anesthetic failed to anesthetize the entire skin (including the region surrounding the fingernail), whereas a high dosage caused the fingerpad to swell, an undesirable effect because it affected the mechanics of contact. Injections into the middle phalanx solved this problem, but anesthetized the skin around the distal joint and thus affected the kinesthetic information. Although the information from the proximal joint and the skin around it appeared unaffected, to be sure that the subjects had full kinesthetic information under constrained posture, we instructed the subjects to use only the metacarpophalangeal (MP) joint.

RANKING. In this set of experiments, subjects were presented with 12 randomly ordered rubber specimens on a table and were asked to rearrange them in the order of increasing softness. A translucent plastic mask covered the visual field of the subjects, so that they could locate the specimens but could not base their discrimination on visual cues of the deformation of the specimens. The subjects were asked to press the central flat surface of each specimen with the fingerpad of the middle finger of the dominant hand while taking care not to apply any lateral forces. They were allowed to indent each specimen as many times as they wished, to lift and move the specimens with the other hand by grasping the rigid sides of the petri dishes, and to go back to a specimen they had pressed before. Sometimes the subjects poked a specimen briefly and lifted their fingers from its surface, or at other times repeatedly indented it while resting the finger continuously on the surface. As described in RESULTS, in one set of experiments the fingerpad was anesthetized, whereas in another set the sensation was normal.

PAIRWISE DISCRIMINATIONS—ACTIVE TOUCH. To obtain quantitative measures of the ability of subjects to discriminate softness under various conditions of active touch, we conducted pairwise discrimination experiments. We employed a two-interval, two-alternative forced-choice paradigm. In the case of rubber specimens, the pairwise comparisons were among the five specimens that had the traces marked S1–S5 in Fig. 2: specimen S3 was chosen as *standard* in all the four pairwise discriminations, with any one of the harder (S1,S2) or softer (S4,S5) specimens serving as *comparison.* An opaque cloth screen prevented the subject from viewing the hand, thus eliminating any visual cues.

The discriminability of a pair by a subject was based on the subject's performance over a number of trials (28–56, depending on the conditions of the experiment). Each trial consisted of one active indentation of each specimen of the pair, with the first specimen chosen pseudorandomly as the standard or comparison with equal probability. The subjects were allowed to press a specimen briefly with a fingerpad and lift the finger from the specimen surface, all the while taking care not to apply lateral forces. At the end of each trial, the subject was asked to judge which one of the two specimens presented was softer. The percentage of trials for which the subject responded correctly was taken to be a measure of the subject's performance. The subject was said to have discriminated between the standard and the comparison if the subject responded correctly to ≥75% of the trials, the midvalue between chance and perfect discrimination. As described in more detail in RESULTS, three experiments conducted were the following: *1*) unconstrained active indentation with normal finger; *2*) active indentation with normal and anesthetized finger in a constrained posture; and *3*) active indentation with normal finger in a constrained posture at various force levels. Six subjects performed unconstrained active indentation, whereas three subjects performed in the remaining two experiments.

PAIRWISE DISCRIMINATIONS—PASSIVE TOUCH. In these experiments, the subject's hand was stationary and passive while the tactile stimulator applied the specimen to the fingerpad with controlled velocity and force. The same four specimen pairs as well as the paradigm employed in pairwise active touch experiments

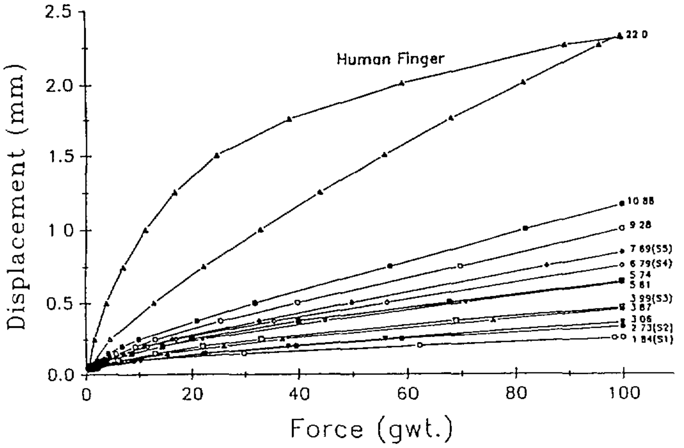

FIG. 2. Traces of displacement vs. force for each of the rubber specimens and a human fingerpad indented by a flat-ended cylindrical probe (0.25 in. diam). The velocity of indentation was maintained constant at 0.5 mm/s. Numbers at the *right end* of each trace: average slope, which represents an objective measure of the compliance (in microns/gwt) of the corresponding specimen. S1–S5: 5 specimens used for the pairwise discrimination experiments. Note that the fingerpad has a pronounced nonlinear force-displacement relationship and is more compliant than all the rubber specimens.

were used. The subject's hand was placed on a rigid platform with the palm facing upward. The middle finger was elevated by rotation around the MP joint so that the angle of the finger with respect to the horizontal was 20–30°, and the region of skin contacting the specimen was about the same as in the active touch case. A post was glued to the fingernail. The post and the backside of the finger were pressed against plasticine to prevent any lateral movement of the finger. Also, the plasticine was so stiff that it acted as an almost-rigid base, and any vertical motion due to its compression during application of the specimen to the fingerpad was negligible. The sides of the fingerpad were not restrained, thereby allowing the fingerpad to deform as it might when actively indenting the specimens.

For each indentation, the tactile stimulator brought down a specimen at a constant vertical velocity in air as well as after contact with fingerpad until a desired force was reached, after which the specimen was withdrawn at the same speed. The velocities of the two indentations in a trial were chosen in random order from one of seven pairs, consisting of six pairs of unequal velocities chosen from 2.4, 3.0, and 3.6 mm/s and one pair of equal velocity of 3 mm/s. These magnitudes were about the same as those used naturally by the subjects in unconstrained active indentation experiments. Each pair of velocities was repeated in 8 trials, bringing the total number of trials for discriminating one pair of specimens by a subject to 56, which was doubled for some of the discriminations to ensure reliability of the results. The pairwise discriminations under passive touch with randomized velocities of indentation were performed under two conditions: the maximum force was either constant or allowed to vary from trial to trial, as described in RESULTS.

Experiments with spring cells

Psychophysical experiments were conducted with spring cells using approximately the same procedure as with rubber specimens (Table 1). Discrimination experiments were conducted using a pair of spring cells whose objective compliances matched those of rubber specimens S1 and S5. In all the experiments, we ensured that the fingerpad was in contact with the central flat region of the end plate, and no contact with the edges of the plate was permitted. As with the rubber specimens, the experiments involved both active and passive touch with normal finger, and the same two-interval, two-alternative forced-choice paradigm was employed. Also, the same three subjects were used, and as before, an opaque cloth screen eliminated any visual cues to the subjects. Two experiments were conducted under active touch: *1*) unconstrained active indentation with normal finger and *2*) active indentation at various force levels with constrained posture. Under passive touch, two experiments were performed with randomized velocities of indentation while the peak force was kept constant. In one of these experiments the stimulus sequence was designed on the basis of the ramp times determined for each subject from the force versus time characteristic curves obtained for each spring cell indenting that subject's fingerpad. More details of these experiments are given in RESULTS.

RESULTS

Experiments with rubber specimens

OBJECTIVE COMPLIANCE The first set of experiments was designed to determine objectively the compliances of the 12 rubber specimens, against which the ability of the subjects to sense the softness of the specimens could be compared. The depth of indentation of the probe versus the corresponding force was plotted for each specimen and a human finger (Fig. 2). A quantitative objective measure of compliance of a specimen was defined as the slope of the straight line that best fit (in the least-square error sense) the data points for that specimen. The compliance of each specimen was $\geq$12% different from its neighbors, except for two pairs: specimens with compliances of 3.87 and 3.99 μm/gm differed by 3%, and those with compliances of 5.61 and 5.74 μm/gm differed by 2.4%. Although extreme care was taken in measuring the objective compliances, owing to the presence of noise and the consequent uncertainty in determining the time of contact (see METHODS), such differences of <5% were not considered reliable. Thus, among the 12 rubber specimens used in ranking experiments, only 10 had distinctly different compliance values.

The same experiment, when performed by substituting the rubber specimens with a human fingerpad, showed that the fingerpad had a pronounced nonlinear behavior. The gradual decrease in the local slope of the displacement-force trace with increase in displacement or force indicates that the fingerpad is initially significantly more compliant than all the specimens, but becomes stiffer as indentation proceeds. This local slope at any point on the trace is greater than that for almost all the rubber specimens (except for the softest one at higher forces). Therefore all 12 rubber specimens were generally less compliant than the human fingerpad.

RANKING. The purpose of these experiments was to investigate the relationship between the objective compliance and subjective sensation of softness of the rubber specimens. The subjects were asked to rearrange 12 randomly ordered specimens in the order of increasing sensation of softness.

Experiment 1: ranking with normal finger. The experiment was conducted under two conditions: unconstrained and constrained posture. Unconstrained posture denotes the condition where the subjects could use any posture of the arm and choose to make any of the joints mobile. In the constrained posture case, the subjects had to rest the palm on a 1-in.-high wooden block placed on the table, and had to

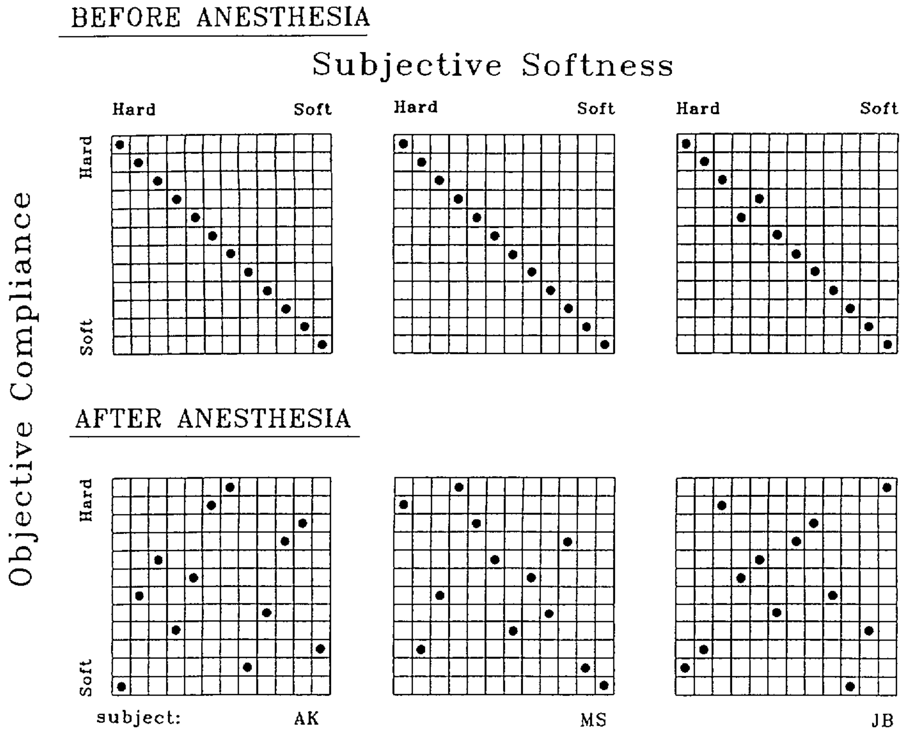

FIG. 3. Results of ranking experiments before and after the administration of local anesthesia to the fingertips of 3 subjects. The confusion matrices plotted here show that the subjective judgment of the relative softness of the specimens coincided with objective compliance when tactile information was available to the subject. Under anesthetized conditions, when tactile information was absent, subjects could not even distinguish between the hardest and the softest specimens.

indent the specimens by using only the MP joint. This forced the subjects to achieve 20–30° angle at the MP joint during maximum indentation, which was verified by using the videomicroscopy system. The subjects reported that these constrained indentations felt quite natural. Fourteen subjects were tested in the unconstrained condition, and 3 of these subjects were tested under the constrained condition.

Under normal finger conditions (both unconstrained and constrained postures), the ranking of the specimens by every one of the subjects coincided exactly with the ranking based on objective compliance. The subjects differed in ordering only one pair of specimens, which were determined to have had identical compliances (Fig. 3). Thus, under these almost natural conditions where the subjects had both tactile and kinesthetic sensory information, there was a one-to-one correspondence between the objective compliances and the subjective judgment of softness, demonstrating that the subjects could distinguish compliances that differed by $\geq 12\%$.

To determine whether the velocity with which the subjects' fingerpads approached the specimens had a major effect on the ranking, we conducted another set of experiments. Two of the subjects were trained to employ approach velocities of ~1, 3, and 6 mm/s in ranking the specimens. The results were identical to the above for each subject at each velocity, showing that these approach velocities did not affect the ranking.

Experiment 2: ranking with anesthetized finger. A local anesthetic, Bupivocaine, was injected into the skin at multiple sites within a narrow strip of skin circumscribing the middle phalanx of the middle finger. This caused the skin regions distal to the injection site to be completely anesthetized for several hours. But in the proximal regions, such as around the MP joint, there was no discernable deterioration in cutaneous or kinesthetic sensation. The subjects rank ordered the specimens with their anesthetized fingers under both unconstrained and constrained postures as in Experiment 1. Three of the same subjects tested under both conditions of Experiment 1 were employed in these experiments.

The difference in the ordering by each one of the subjects as compared with their corresponding performance with normal finger was dramatic: As demonstrated by the confusion matrices in Fig. 3, none of the subjects had any information on the compliances of the specimens, but because they were forced to rank order to the best of their ability, merely arranged the specimens in random order. This observation was corroborated by the introspective remarks made by the subjects that they had no sensation of softness at all with any of the specimens. These experimental results demonstrate that when tactile information is absent and only kinesthetic information is available, the subjects were unable to discriminate even large differences in compliance.

PAIRWISE DISCRIMINATIONS—ACTIVE TOUCH. To obtain quantitative measures of the ability of the subjects to discriminate softness, we employed a two-interval, two-alternative forced choice paradigm. The specimen marked S3 (Fig. 2) was chosen as the standard for four pairwise discrimination, with any one of the harder (S1.S2) or softer (S4,S5) specimens serving as comparisons. Experiment 3 was conducted on six subjects, three of whom participated in the rest of the experiments.

Experiment 3: unconstrained active indentations with normal finger. The specimens were mounted rigidly on to the spring-loaded plate of the tactile stimulator, which was in contact with the force transducer. Each subject's hand was placed on a platform in a comfortable position. Except for

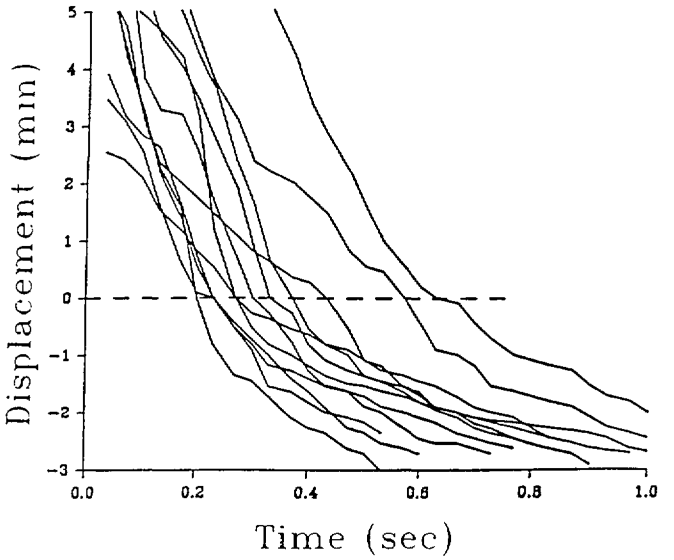

FIG 4. Trajectories of the fingernail of 1 subject during unconstrained active indentation of a rubber specimen. Each trace represents 1 indentation, with arbitrary starting time. Dashed line at 0 displacement: contact with the specimen, with traces above representing motion of the finger in air, and the traces below indentation of the specimen. The mean velocity of application of the fingertip during indentations of the specimen was 3.35 ± 0.85 (SD) mm/s.

allowing only one indentation per specimen, no other constraints were imposed on the six subjects who participated in this experiment. The motion of the indenting fingertip (in particular, a dot painted on the side of the fingernail) of some of the subjects was recorded using the videomicroscopy system. The corresponding force of indentation was measured with the force transducer.

Off-line video analysis showed that for each subject the velocity of application of the fingertip as measured by tracing the fingernail trajectory (Fig. 4) and the maximum force varied significantly from one indentation to the next. The mean velocity of application of the fingertip during indentations of the specimens was 3.35 ± 0.85 (SD) mm/s, and the mean maximum force was 98.71 ± 26.17 (SD) gwt. Despite such significant variations in indentation parameters, the subjects discriminated each of the specimen pairs at levels >90% correct (Fig. 5), thus corroborating the results of the ranking experiments. Specimen S2 was discriminated from S3 with an average score of 91% correct, whereas all the other pairs were discriminated at levels >96% correct.

Experiment 4: constrained active indentations with normal and anesthetized finger. To observe the effect of presence or absence of tactile information on the human discriminability of softness, pairwise discriminations between specimens S3 and S5 were conducted under active touch before and after local anesthesia of the indenting finger, as in Experiment 2. The subject's hand position was the same as in ranking experiments with constrained posture: the palm rested on a wooden block whose surface was ~1 in. higher than that of the specimen, and the indentation of the specimen was accomplished by 20–30° rotations of only the MP joint. The discrimination procedure was identical to that in Experiment 3, except that the subjects were instructed to apply indentation forces within the interval of 75 ± 20 gwt. Whenever the applied force was outside this window, an alarm sounded and the trial was rejected. The window interval of ±20 gwt. was based on preliminary experiments on the ability of the subjects to indent the specimens to a desired peak force. It represents the best choice for having as low a variability as possible in peak forces while keeping the number of rejected trials to ~20% or less. It also matched with the SD of the forces the subjects used naturally in Experiment 3.

Interestingly, the number of rejected trials due to the violation of constraints on force magnitude were about the same whether the finger was normal or anesthetized. However, the difference in the discriminability of the compliances was striking: when the finger was normal, each of the subjects made ≥93% correct judgments, as would be expected for the easiest pair of the four used in Experiment 3; under anesthesia, which blocked the tactile information, each of the subjects were ≤55% correct, indicating that they were making random calls (Fig. 6). The introspective observation of the subjects confirmed that they had no information on the compliance of the specimens when tactile information was absent.

Experiment 5: constrained active indentations with normal finger at various force levels. Because force is an important parameter that could affect the neural code and discrimination performance, the effect of the peak force of indentation on the discriminability under active touch was investigated in this set of experiments. The same four pairs of specimens used in Experiment 3 were employed. As in Experiment 4, the subjects' hand posture was constrained so that only 20° to 30° rotations of the MP joint were utilized during the indentations. Separate sets of trials were administered where the subjects performed pairwise discriminations

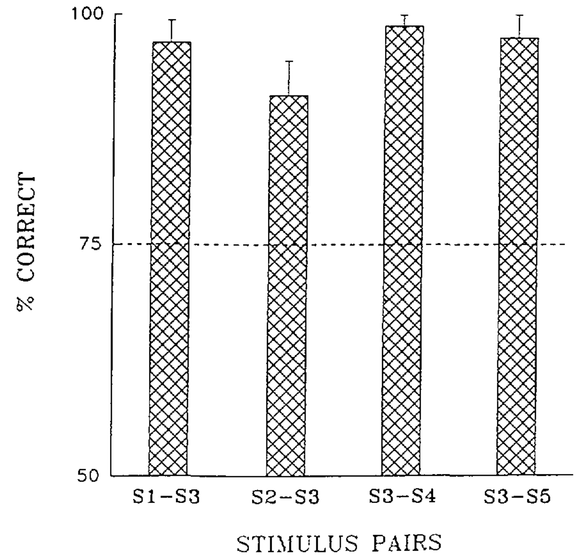

FIG. 5. Results of pairwise discrimination experiments under unconstrained active touch conditions with rubber specimen S3 as the standard and each of S1, S2, S4, and S5 as comparisons. The mean percent of correct calls for each of the four specimen pairs is shown; error bar indicates mean ± SE. Under these conditions, both tactile and kinesthetic information was available to the subjects, and they discriminated each of the specimen pairs at levels >90% correct.

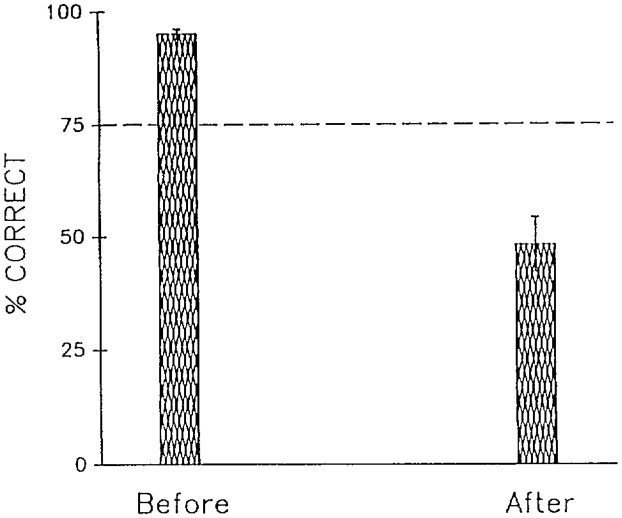

FIG. 6. Discriminability of the softness of rubber specimens S3 and S5 under constrainted active indentation before and after the administration of local anesthesia to the fingertips of subjects. The subjects were allowed to use peak forces of 75 ± 20 gwt. The results show that in addition to kinesthetic information, when tactile information was also available, the subjects made ≥93% correct judgments, whereas in its absence, they were making random calls (≤55% correct).

by applying peak forces of 25 ± 20, 50 ± 20, 75 ± 20, or 90 ± 20 gwt. In each set, whenever the peak force exceeded the limits, an alarm sounded and the trial was rejected.

From Fig. 7*A*, it is clear that the subjects could discriminate all the four pairs at the two higher force ranges. At the lower force ranges, only the specimens S2 and S3 could not be discriminated, and even for the other pairs, lower forces resulted in only a slight deterioration in performance. Thus, when both tactile and kinesthetic information was available, even with strong constraints on the magnitudes of indentation forces, the discriminability of the subjects remained almost as good as in Experiment 3, where no constraints were imposed.

PAIRWISE DISCRIMINATIONS—PASSIVE TOUCH. In these experiments, the subjects' hand was stationary and passive, while the tactile stimulator (see METHODS) applied each specimen to the fingerpad with controlled velocity and force. Therefore the subjects had only tactile information concerning the compliance of the specimens, whereas the kinesthetic information was absent. The same four specimen pairs as well as the paradigm employed in active touch Experiments 3 and 5 were used. The same three subjects who participated in the active touch experiments were tested under passive touch conditions. Unlike the active touch experiments, where significant variations of indentation velocity and peak force occurred naturally, here the stimulator was precisely computer controlled and was capable of delivering the stimuli with negligible variance from one indentation to the next. Systematic cues that were related to the compliance of the specimens but not to the sensation of softness had to be eliminated by carefully choosing the indentation parameters. To eliminate the ramp time or force rate as consistent cues for softness discrimination, we randomized the indentation velocities while taking care that the active and passive indentation parameters were matched.

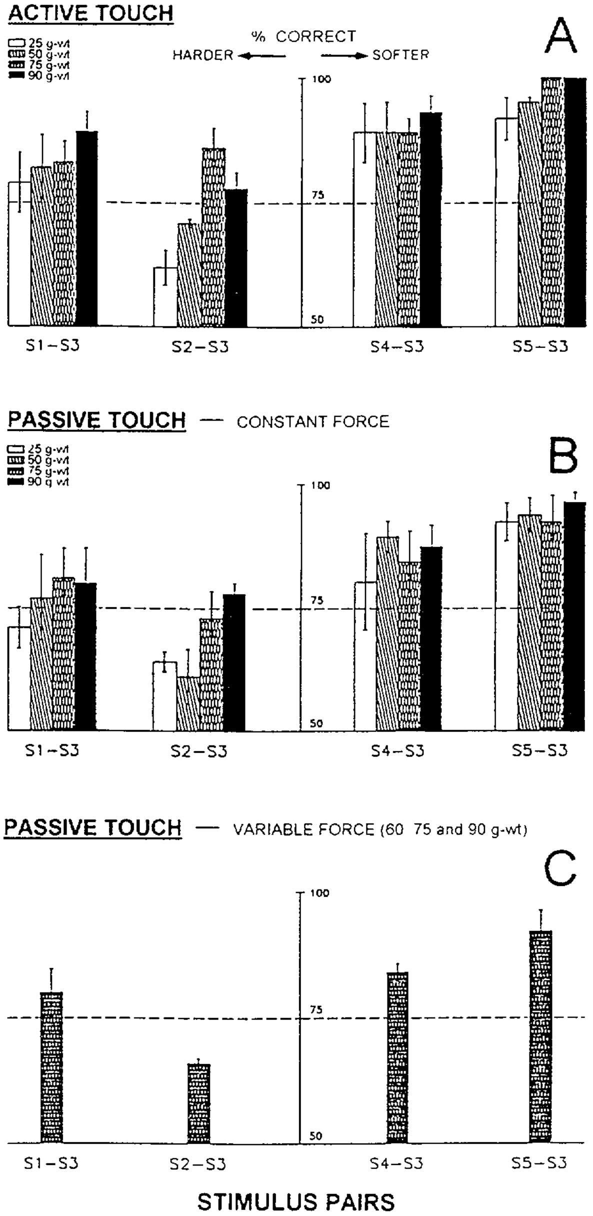

FIG. 7. Results of pairwise discrimination experiments with rubber specimens at various contact force values. In each experiment, specimen S3 was the standard and each of S1, S2, S4, and S5 were comparisons. Each bar represents the mean percent of correct calls for the corresponding specimen pair and force value, with the error bar indicating the mean ± SE. The labels "HARDER" and "SOFTER" indicate the relationship of the comparisons to the standard. *A*: constrainted active touch: the subjects were constrained to utilize 20° to 30° rotations of only the metacarpophalangeal (MP) joint, and peak forces within ±20 gwt deviation from the mean values shown. Except for the pair S2–S3 at low forces, all the other pairs were discriminated by the subjects, with lower forces resulting in a slight deterioration in performance. *B*: passive touch under constant force: separate sets of experiments were performed at each of the forces shown. For each set, the velocity of indentation was randomized among 2.4, 3, and 3.6 mm/s. The discriminability of the subjects in the absence of kinesthetic information deteriorated only slightly compared with active touch performance shown in *A*, where both tactile and kinesthetic information were available to the subjects. *C*: passive touch under randomized forces: both the forces (60, 75, and 90 gwt) as well as the velocities (2.4, 3, and 3.6 mm/s) were randomized. Despite the elimination of both temporal and intensive cues, together with the lack of kinesthetic information, the subjects performed almost as well as they did under active touch at 50 or 75 gwt.

Experiment 6: passive touch with constant force, but randomized velocities. In this set of experiments the peak force of indentation was kept constant for each set of trials, with its value being the same as the mean values used in active touch Experiment 5–25, 50, 75, or 90 gwt. The velocities of indentation were randomized among 2.4, 3, and 3.6 mm/s, which were about the same as those used by the subjects naturally in Experiment 3. The trials consisted of all pairwise combinations of the three velocities, in addition to both the specimens applied at 3 mm/s. The experimental protocol was carefully chosen to avoid stimulus bias: the softer specimen was presented equal number of times at a higher or lower velocity than the other, and as the first or second stimulus.

As shown in Fig. 7*B*, the discriminability of the subjects deteriorated only slightly compared with that under active touch for each of the four forces and specimen pairs. Therefore elimination of kinesthetic information, as well as consistent cues arising from ramp time or force rate, did not prevent the subjects from discriminating the compliance of the specimens. Also, as would be expected from active touch results (Experiments 3 and 5), S3 versus S2 was the most difficult, and S3 versus S5 the easiest.

Experiment 7: passive touch with randomized forces and velocities. To eliminate further any other cues based on temporal and intensive information, even the peak force value was randomized between 60, 75, and 90 gwt, in addition to randomizing the indentation velocities as in Experiment 6. Maximum force for the two indentations in each trial for each velocity combination were chosen in random order from one of seven pairs, consisting of six pairs of unequal forces chosen from 60, 75, and 90 gwt and one pair of equal force of 75 gwt. The stimulus pairs were chosen so that the softer specimen could be indented to a higher, equal, or lower force, and the higher force was attained either during the first or the second indentation.

Despite further elimination of the temporal and intensive cues, the subjects performed (Fig. 7*C*) at about the same level as for 50 or 75 gwt in Experiment 6 (Fig. 7*B*). Thus there was no significant deterioration in discriminability as compared with active touch (Experiment 5, Fig. 7*A*) or passive touch with constant maximum force (Experiment 6, Fig. 7*B*).

Experiments with spring cells

The primary purposes of these experiments were to determine *1*) whether the human discrimination of compliant specimens with rigid surfaces was better or worse relative to the discriminability of rubber specimens, and *2*) what associated peripheral source of information accounted for the discrimination. At first springs were chosen for two specimens such that their objective compliances matched those of rubber specimens denoted as S3 and S5 in Fig. 2. Preliminary results indicated that subjects could not discriminate these two spring cells well. In the final set of experiments, the discrimination experiments were performed between spring cells having the same compliances (measured as described in METHODS) as the rubber specimens S1 and S5, either of which could be thought of as the *standard,* while the other was the *comparison.*

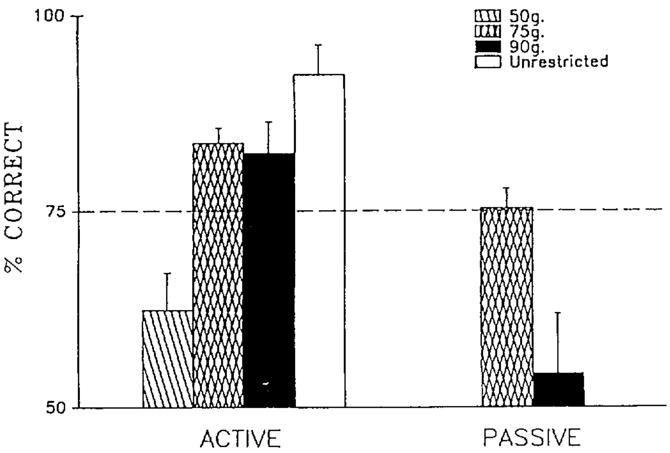

FIG. 8. Results of pairwise discrimination experiments with spring cells S1 and S5 at various force values under active or passive touch. Under active touch, unrestricted condition was the same as the unconstrained case for the rubber specimens (Experiment 3), and the force ranges for the other three cases were 50 ± 25, 75 ± 35, and 90 ± 45 gwt. The subjects could discriminate the specimens when the mean peak force exceeded 75 gwt., but the discriminability was poorer compared to that for rubber specimens with even lesser difference in compliance (e.g., S3 and S5). Under passive touch, the hatched bar refers to the case of constant peak force of 75 gwt, with randomized velocities (2.4, 3, and 3.6 mm/s). The subjects barely discriminated the two specimens, and their performance correlated with the hypothesis that it was based on ramp time. The filled bar refers to the case of constant peak force of 90 gwt, with velocities randomized among 2.4, 3.0, 3.6 mm/s such that ramptime cues were eliminated. In this case, the RESULTS show that the subjects were making random calls in the absence of kinesthetic information.

PAIRWISE DISCRIMINATIONS—ACTIVE TOUCH. *Experiment 8: unconstrained active indentations.* The procedure was identical to Experiment 3, including the video recording of the motion of the fingertip. The magnitudes and variability in indentation velocities and maximum forces were approximately the same as with indentations of the rubber specimens. As shown in Fig. 8, the subjects discriminated the compliances of the specimens at levels >90% correct.

Experiment 9: active indentations at various force levels. The same general procedure as in Experiments 3 and 5 was used. In preliminary experiments, we found that the ability of the subjects to consistently apply forces such that the maximum force was within a prescribed range was poorer with spring cells. Therefore the range of forces allowed around the desired mean value was higher than with rubber specimens. Pairwise discrimination experiments were conducted with peak force ranges of 50 ± 25, 75 ± 35, and 90 ± 45 gwt. As before, whenever the peak force exceeded the limits, an alarm sounded and the trial was rejected.

None of the subjects discriminated the spring cell compliances at 50 gwt, but all the subjects could discriminate at both 75 and 90 gwt (Fig. 8) at ~83% correct. It should be recalled that the spring cell compliances corresponded to the rubber specimens S1 and S5, whereas even with the rubber specimens S3 and S5 for which the difference in compliances was smaller, the same three subjects had 93%–96% correct at 50 gwt, and 100% correct at 75 and 90 gwt. Thus the discriminability of the subjects was poorer with spring cells relative to that with rubber specimens. Nevertheless, under active touch when both tactile and kinesthetic information was available, the subjects were able to discriminate the spring cells when the mean peak force of indentation exceeded 75 gwt.

PAIRWISE DISCRIMINATIONS—PASSIVE TOUCH. To study the discriminability of the subjects when kinesthetic information was absent, we performed discrimination experiments with spring cells under passive touch conditions. As with rubber specimens, some of the systematic timing cues were eliminated by randomizing the indentation velocities. The peak forces were kept constant in each of the following two experiments.

Experiment 10: passive touch with constant force, but randomized velocities. The experimental protocol was identical to that of Experiment 6, except that only the peak force of 75 gwt was used. As before, all pairwise velocity combinations of 2.4, 3.0, and 3.6 mm/s were used in addition to both spring cells applied at 3.0 mm/s; there was no stimulus bias with respect to higher or lower velocity and which of the specimens were presented first. The subjects barely discriminated the two specimens. In fact, at the end of the experiment, their introspective observation was that they had done poorly and that they were surprised to see that they had ~75% correct.

To analyze the basis of the result above, the data for force versus time curves for each of the spring cells indenting each of the subjects' fingerpads at various velocities was obtained. The procedure was similar to that described for measuring objective compliance of the human finger (see METHODS), except that the probe was replaced by each of the spring cells, and the velocity of indentation was 2.4, 3.0, or 3.6 mm/s. The force increased nonlinearly with time, with its rate being higher for either higher velocity or lower compliance. On the basis of this data, the ramp times for each of the stimulus combination delivered in Experiment 10 were measured. It was found that the subject's discrimination performance correlated well with the hypothesis that the specimen with the longer ramp time was the softer one. To eliminate this systematic ramp time cue so that the subjects were forced to discriminate on the basis of perceived softness, the following experiment was conducted.

Experiment 11: to check whether ramp time was the basis of discrimination. To ensure that any reduction of discriminability was not due to lack of sufficient force, the peak force of indentation was increased to 90 gwt. However, among the velocities 2.4, 3.0, and 3.6 mm/s, the spring cell S1 was presented at either 2.4 or 3.0 mm/s, whereas the spring cell S5 was presented at either 3.0 or 3.6 mm/s. This ensured that if the subjects used the hypothesis of equating longer ramp time with the softer specimen, they could only be correct in 50% of the trials.

None of the subjects could discriminate the spring cell compliances under these conditions (Fig. 8). In fact the mean of 54% correct was (with 67% correct being the highest score) quite close to the *a priori* prediction of 50% on the basis of either ramp time judgments or purely random calls. We conclude that the subjects could not discriminate the compliance of spring cells when only tactile information was available and irrelevant cues based on ramp time were eliminated.

DISCUSSION

Compliance is an important physical property that helps us in the discrimination, identification and manipulation of objects. Because it is a ratio of the amount of deformation of the object to the applied force, we can sense softness—a subjective measure of compliance—only through touch. Physical contact with a compliant object, such as when pressing it with a fingerpad introduces complex dynamics at the skin-object interface that depends on the mechanical properties of both the fingerpad and the object. The peripheral neural response is directly dependent on the forces and displacements (and their temporal and spatial variations) at the contact interface. The primary issue addressed here is the clarification of the relative roles played by tactile and kinesthetic information in the peripheral neural coding of the compliance of objects with deformable or rigid surfaces.

We now summarize the results from experiments with rubber specimens. *1*) Each of the experiments (1, 3, 4, and 5) involving active touch with normal fingers show that when both tactile and kinesthetic information was available, the subjects discriminated all the specimens presented to them under both unconstrained and constrained (Figs. 3, 5, 6, and 7*A*) conditions. *2*) In contrast, in each of the experiments (2 and 4) involving active touch with anesthetized fingers, when only kinesthetic information was available, the subjects could not even distinguish between the hardest and the softest specimens presented to them (Figs. 3 and 6). Thus kinesthetic information alone is insufficient to judge the relative softness of objects with deformable surfaces. *3*) In each of the experiments (6 and 7) involving passive touch, when only tactile information was available, the subjects performed at approximately the same level as under active touch (Fig. 7, *B* and *C*). This result was achieved in spite of the randomizing of velocities and forces of specimen application. Thus tactile information alone is sufficient to discriminate the softness of objects with deformable surfaces.

In the case of spring cells, in experiments (8 and 9) involving active touch with normal fingers, the discrimination performance of the subjects was poorer compared with that for rubber specimen pairs. The discriminability of spring cells with a wide difference between their compliances (S1 and S5) was worse than that for rubber specimens with much lesser differences in compliance, such as S3 and S5 (Fig. 8). Thus, even when both tactile and kinesthetic information was available, the subjects have less information with compliant objects with rigid surfaces as compared with those with deformable surfaces. In addition, in the passive touch experiments (10 and 11) with spring cells, the subjects could not discriminate the specimens at all when irrelevant cues based on ramp times were eliminated by suitably randomizing the velocity of indentation (Experiment 11). Therefore, unlike the case of objects with deformable surfaces, tactile information alone is insufficient to discriminate the compliance of objects with rigid surfaces, and both tactile and kinesthetic information are necessary.

Having delineated the sources of tactual information that enables the discrimination of compliances of objects with both deformable and rigid surfaces, the next step is to isolate the mechanistic variables that provide the critical cues for discrimination and to identify the associated peripheral neural codes. When a compliant object and a fingerpad come in contact, the mechanistic variables of the contact interface at any instant of time are the net contact force, area of contact, pressure distribution within the contact region, and the displacement distributions within both the fingerpad and the object. During the indentation phase, all these variables change with time. In general, they are functions of the compliance of the fingerpad as well as that of the object, and the relative velocity with which the fingerpad and object approach each other. Thus an analysis of the contact interactions is not simple, and the presence of any nonlinear mechanistic behavior among the contacting entities further exacerbates the complexity.

Compliant objects with deformable surfaces

The displacement versus force plotted in Fig. 2 demonstrates that the traces for the rubber specimens are approximately linear, whereas the human fingerpad exhibits a pronounced nonlinear behavior. Although for small indentations the fingerpad is significantly more compliant than all the rubber specimens, it becomes stiffer as indentation proceeds. However, even at the higher indentations, its compliance, as measured by the local slope of its trace, was less than that of only the softest specimen. It should be noted that these force-displacement traces are dependent on the area of contact between the probe and the fingerpad or a rubber specimen. A larger-diameter probe would cause the forces to be higher for the same displacement, resulting in lower slopes and thus lower values for the compliances. Preliminary data that we have obtained on compliances (defined as the average slope of net force vs. displacement traces) measured under larger-diameter probes indicate, however, that the percentage change in the compliance of each specimen due to a difference in the diameter of the probe remains about the same for all the specimens and the fingerpad.

When the fingerpad and a rubber specimen contact each other either under active or passive touch conditions, complex mechanistic interactions occur at the interface. Increases in the net contact force cause increases in the area of contact and the displacements within both the fingerpad and the specimen. Initially, because the fingerpad is much more compliant than the specimen, the displacements in the fingerpad exceed those in the specimen. As indentation proceeds, the area of contact increases and both the fingerpad and the specimen become less compliant. A question then is whether the earlier statement that the rubber specimens are stiffer than the fingerpad is still true. Note from the discussion above that the percentage change in the compliance due to a change in contact area of the probe is likely to remain the same for each specimen and the fingerpad. Therefore the percentage difference between the compliance of the fingerpad and any of the rubber specimens is likely to remain the same as in Fig. 2, even when the contact area changes. Thus each of the rubber specimens S1 through S5 will still remain stiffer than the fingerpad and suffer less deformation than the fingerpad. In other words, as indentation proceeds, the ratio of the compliance of the fingerpad and that of each of the specimens is likely to remain the same, despite increases in the contact area.

Let us now try to isolate the mechanistic variables that might provide cues for the discrimination of two rubber specimens, say, S3 and S5. For the sake of simplicity, consider first the case of equal-velocity indentations (i.e., the relative velocity with which the fingerpad and the specimen approach each other), under either active or passive touch conditions. Because S3 is less compliant than S5 and fingerpad compliance is common for both, the rate with which the net contact force increases is expected to be greater for S3 than for S5. This expectation is supported by the preliminary data we have obtained. A consequence of the higher force rate for S3 is that a given peak force is reached earlier, resulting in lower ramp time. Another expectation that is supported by preliminary data is that the overall area of contact increases at a slower rate for S3. Thus, net force rate, ramp time, or overall area rate could be candidate cues for discrimination. But they are all strongly dependent on indentation velocity. When indentation velocities are unequal, such as when S3 indents a passive finger at 2.4 mm/s followed by S5 at 3.6 mm/s, the net force rate for S3 can become less, and ramp time higher, but the overall area rate can remain to be less than those for S5. The opposite would be true when the velocities are interchanged. Therefore net force rate, ramp time, or overall area rate are unlikely to provide unequivocal cues for discrimination when indentation velocities are randomized. Because subjects discriminated S3 from S5 when indentation velocities were randomized (Fig. 7*B*), these three variables are unlikely to be the bases for discrimination. In addition, because the subjects also discriminated S3 from S5 when the peak forces were randomized along with indentation velocities (Fig. 7*C*), large variations in ramp time or net force and overall area of contact at the end of the ramp did not seem to adversely affect discrimination.

A variable that may be invariant with respect to the randomization of indentation velocity and peak force is the rate of change of average pressure. Here average pressure is defined as net force divided by overall area of contact at any instant of time. For a given specimen indenting the fingerpad, the higher the indentation velocity, the higher are the rates of change of both the net force and overall area of contact. However, depending on how much the contact area changes for an increment in force and how this relationship is affected by indentation velocity, the average pressure rate could be invariant with respect to velocity. If so, because under *equal velocity indentations* the average pressure for S3 would be higher than that for S5 at any time during the ramp (because the net force is higher *and* the overall area is lower), it implies that at *all combinations of velocities* the average pressure as well as its rate is higher for S3, thus providing an unequivocal cue for discrimination even when indentation velocities and peak forces are randomized. This hypothesis needs to be verified with experimental data. A more general version of this hypothesis would be that the spatial pressure distribution within the contact region and its temporal variations would be distinct for S3 and S5, despite changes in indentation velocity. It should be noted that the spatial distribution of pressure within the contact region directly affects the spatial distribution of skin displacement. Therefore statements about average pressure, its rate, or spatiotemporal pressure distribution being the cues for softness discrimination, are equivalent to average skin displacement, skin velocity, or spatiotemporal skin displacement distribution (e.g., the curvature of the skin and its change during the ramp) being the cues, respectively.

Because the discrimination of the softness of rubber specimens is based on purely tactile information, the possible peripheral neural codes are based on information from slowly adapting type I (SAI; Merkel cells) and type II (SAII; Ruffini endings) as well as rapidly adapting type I (RAI; Meissner corpuscles) and type II (RA II; Pacinian corpuscles) afferents. It is unlikely that SAIIs play a role in softness discrimination under the experimental conditions described here, because skin stretch is very small under indentations by the specimens. Net force rate or ramp time could be coded by any of the remaining three afferent populations. The rate of change of overall area of contact may be signalled by the rate at which SAI and/or RAI populations are recruited at the contact boundary. The RAIIs are probably too large, sparse, and located too deeply within the fingerpad, resulting in a lack of sufficient spatial resolution to signal small differences in contact area, especially for the low velocities employed here. However, as was discussed before, net force rate, ramp time, and overall area rate do not provide unequivocal information for softness discrimination when indentation velocity is randomized. The average pressure, its rate, or spatiotemporal pressure distribution are likely to be coded by both SAI and RAI populations (and not RAII, for the same reasons mentioned above). Again, these expectations, as well as whether the peripheral neural codes are purely temporal (e.g., average pressure rate) or spatiotemporal (e.g., temporal variations of spatial pressure distribution), need to be verified by suitable neurophysiological experiments. An intriguing connection with our previous work on peripheral neural coding of object shapes is whether the exquisite sensitivity of SAIs to the curvature of the skin during indentations (LaMotte and Srinivasan 1993; Srinivasan and LaMotte 1987, 1991) also plays a major role in softness discrimination by coding the skin curvature as a function of time during indentations by each rubber specimen.

Compliant objects with rigid surfaces

The major difference between a rubber specimen and a spring cell is that the surface of the latter does not deform at any of the force values used here. A consequence is that the compliance (defined as before as the slope of displacement vs. net force trace) of the spring cell is independent of probe diameter, or, in general, of contact area. As the fingerpad indents or is indented by the spring cell, the compliance of the fingerpad continues to decrease (due to both increases in contact area and the nonlinear force-displacement relationship) while the compliance of the spring cell remains the same. Therefore the ratio of the fingerpad compliance and specimen compliance do not remain even approximately constant, unlike the expectation for experiments with rubber specimens. This might contribute to some of the deterioration in the discriminability of spring cells as compared with that of rubber specimens, even under active touch conditions.

As in the case of rubber specimens, when two spring cells of different compliances are indented by the fingerpad at the same velocity, for the stiffer cell the net force rate is higher and consequently the ramp time to reach a given force is lower (supported by preliminary data). However, it is well known from basic mechanics that unlike the case with rubber specimens, because the spring cell surface is not deformable, the area of contact and the spatial distribution of pressure as well as skin displacements during the ramp are completely governed by the variations of net force of contact during the ramp and are independent of the compliance of the object. Therefore the rate of change of contact area, average pressure and its rate, or even the spatiotemporal distribution of pressure and skin displacements do not contain any more information for discrimination than the rate of change of net force (or equivalently, the ramp time).

Because the net force rate is dependent on the velocity of indentation, information on both of these variables is necessary to discriminate the compliance of spring cells when velocities are randomized. When subjects actively indented the spring cells (Experiments 8 and 9), although their velocity of indentation was variable from trial to trial, because they had information on both force rate (from tactile as well as kinesthetic sources) and overall indentation velocity (from kinesthetic sources only), discrimination of compliance was possible. For Experiment 10 under passive touch conditions, despite the lack of information about the randomized velocities, subjects could barely discriminate the specimens, because the ramp time information available from tactile sources alone was sufficient to achieve 75% correct calls. However, for Experiment 11 (also under passive touch conditions), where the velocities were randomized such that ramp time information was insufficient, the subjects were incapable of discriminating the specimens. All the discrimination results for the spring cells can thus be explained as consequences of information available to the subjects, which is governed by the mechanics of contact interactions. The tactile sources of information on the rate of change of net force could be SAI, RAI, and/or RAII; the kinesthetic sources of force rate and indentation velocity under active touch conditions are uncertain, given that we do not yet fully know the kinesthetic mechanism of encoding limb posture and movement information (Clark and Horch 1986; Matthews 1988).

Differences in haptic interactions with deformable and rigid surfaces

The discussion above indicates that the differences in the discriminability of compliant objects with deformable and rigid surfaces can be explained by the differences in the mechanics of contact between the fingerpad and the objects. For the sake of simplicity, consider planar compliant objects of either type being pressed with a fingerpad. During indentation, as the object is pressed more over time, the compressive force of contact between the object and fingerpad increases, whereas during retraction it decreases. For an object with a deformable surface, the spatial distribution of a given net force and the corresponding deformation of the fingerpad depend on the object compliance. To clarify this fact, consider the indentation of such deformable objects with a rigid probe having the same shape as that of a fingerpad. Then, for a given net force at an instant of time, the spatial variation of pressure distribution within the contact region and the extent of the contact region depend on the object compliance. The same is true when the compliant fingerpad indents the object. The fingerpad deforms such that in addition to the pressure distribution within the contact region and the contact area, the shape of the contact interface also depends on the object compliance. Consequently, purely tactile information from cutaneous mechanoreceptors (mainly SAI and RAI) within and in the neighborhood of the contact region is sufficient for the discrimination of object compliance even when indentation velocities and peak values of forces are randomized, and is likely to be based on spatiotemporal information. In contrast, for compliant objects with rigid surfaces, the spatial distribution of a given contact force within the contact region, and thus the deformation of the fingerpad under that force are independent of object compliance. Therefore tactile information alone is insufficient to determine object compliance; both tactile and kinesthetic information are necessary to discriminate the compliance of objects with rigid surfaces, which is likely to be based on purely temporal information.

Under active touch conditions, one could possibly discriminate the rubber specimens in the same manner as the spring cells. In such a case, because indentation velocity is variable (Fig. 4), information on force rate from tactile and/or kinesthetic sources needs to be combined with information on overall indentation velocity from kinesthetic sources for reliable discriminability. This requires integration of tactile and kinesthetic sensory information, and perhaps knowledge of intended movements from the motor system. A consequence is that multiple means of computing and discriminating the compliance of objects exist, but the resolution in the discriminability may be different for each. For example, discriminability of softness of the rubber specimens S3 and S5 based on spatiotemporal tactile information (Fig. 7, *B* and *C*) is far superior compared with that based on purely temporal information from the kinesthetic system (after anesthesia in Fig. 6), because of the lower resolution of the kinesthetic system. The reasons for the discriminability of spring cells being much poorer than that for rubber specimens might be the lower resolution of the kinesthetic system as well as any loss of information in integrating several sources of information.

The behavioral importance of sensing of object compliance with the hand during haptic exploration of objects as well as their manipulation cannot be overemphasized. Compliance governs the deformation and motion of objects due to applied forces, and often is an indicator of their fragility. To successfully discriminate or identify compliant objects, or to manipulate them without damaging them, the contact forces during pressing or grasping the objects must be adjusted on the basis of object compliance. In experiments with rubber specimens, the discrimination performance was better under unconstrained conditions (Fig. 5) than under constrained conditions (Fig. 7*A*), and indicates the possibility that optimality in perceived information is best achieved when motor effort can be adjusted in relation to the received sensory information without artificial restrictions. Under constrained active touch conditions (Experiments 4 and 5) the peak forces exerted on the rubber specimens could be controlled to within ±20 gwt. of the desired values under both normal and anesthetized conditions with equal ease. This implies that the absence of tactile information in the latter case did not significantly affect the desired resolution in force control. In contrast, larger force deviations (±25–45 gwt) needed to be accepted for constrained active indentations of spring cells (so that the force exceeded the limits in <20% of the trials), indicating that the performance of the motor system in controlling contact forces was affected by whether the surface of the compliant object was rigid or deformable. Also, the discriminability was better at higher forces (Fig. 8). In experiments on the ability of subjects to control forces applied by the fingerpad on a glass plate during force tracking with visual feedback (Srinivasan and Chen 1993), the mean error with locally anesthetized fingerpads was ≥50% more than that with a normal fingerpad. Thus the presence or absence of tactile information significantly affected active force control. In general, the consequences of the two modes of compliance sensing, one based on purely tactile information and the other on kinesthetic information, to sensorimotor integration in the exploration and the manipulation of objects with deformable or rigid surfaces is not known and warrants further investigation.

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Address for reprint requests: M. A. Srinivasan, 36-796, Research Laboratory of Electronics, MIT, Cambridge, MA 02139.

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