

Tactual Discrimination of Softness: Abilities and Mechanisms

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Summary. The ability of human subjects to discriminate softness was investigated. In addition, the associated mechanistic cues and the peripheral neural codes on which the discrimination may be based were investigated using monkeys. Two sets of compliant objects were constructed: (1) those with a deformable surface, composed of transparent silicone rubber of variable softness; (2) rigid plates supported by springs of variable compliance in cylindrical sleeves. To assess the relative contributions of tactile and kinesthetic information, psychophysical experiments were performed on human subjects under both active and passive touch, with or without local anesthesia that blocked the tactile information from the fingerpads. The results for *objects with deformable surfaces* show that whereas the subjects are quite good at discriminating subtle differences in softness under both active and passive touch without anesthesia, they are unable to discriminate even large differences under active touch with anesthesia. Therefore, we conclude that the discrimination is based entirely on tactile information. The mechanistic data for rubber specimens indicates that the basis for the perception of softness of rubber-like objects is likely to be the spatio-temporal variation of pressure on the skin (or, equivalently the skin displacement and its derivatives). Neurophysiological data shows that the resulting responses from slowly adapting type I afferent population within the skin might encode the compliance of the objects. For *compliant objects with rigid surfaces*, best discrimination was achieved only with active touch, due to the availability of both tactile and kinesthetic information; under passive conditions, the absence of kinesthetic information resulted in considerable deterioration of discriminability.

Introduction

Compliance, loosely defined as the amount of deformation of an object under a unit measure of applied force, is a fundamental physical property of objects that governs their mechanical behavior. To successfully perform any haptic task such as manual exploration or manipulation that involves physical contact with objects, it is necessary for us to know

how compliant they are, since the object motions and deformations caused by imposed forces are directly dependent on the object compliance. Compliant objects can be classified into two major types: (1) deformable objects whose surface is also deformable (such as rubber, fruits, etc.) and (2) deformable objects whose surfaces are rigid (such as a key in a piano or typewriter). Because the mechanical stimuli imposed on the skin depend on the type of object compliance, it is to be expected that the representation and processing of tactual information (which includes both tactile and kinesthetic sensory information) needed to discriminate object compliance depend on the type of object compliance.

Very little is known about the human ability to sense softness, a subjective measure of the compliance of an object. In particular, no literature exists on the biomechanical and neural mechanisms that enable the human discrimination of softness. Early work was focussed on the measurement of differential sensitivity of humans and the form of the psychophysical law (Katz, 1938; Harper, 1952; Harper and Stevens, 1964). Later work of Roland and Ladegaard-Pedersen (1977) examined the ability of subjects to discriminate the stiffness of springs held between the thumb and index finger. They showed that anesthetized skin and joints did not affect the discriminability. Based on a matching paradigm requiring the activation of the elbow joint, Jones and Hunter (1990) estimated the human compliance resolution to be about 23%. Recently, Tan, *et al.*, (1995) have measured the Just Noticeable Differences (JND) in compliance between two rigid plates (driven by computer controlled linear motors) grasped between the thumb and index finger. The JNDs ranged from about 8% to 99% depending on whether the subjects had cues stemming from terminal grasp force and/or total work done.

Our goals in this study are (1) to measure the ability of humans to tactually discriminate softness, (2) to clarify the roles played by tactile and kinesthetic information in the discrimination, and (3) to identify the nature of the peripheral neural codes, such as which fiber population enables the discrimination and whether the code is intensive, temporal, spatial or spatio-temporal. The psychophysical results on human discrimination of softness summarized here have been described in more detail in a recent paper (Srinivasan and LaMotte, 1995). In addition, we give here some of the results on the possible mechanistic cues and the associated peripheral neural codes from biomechanical and neurophysiological experiments performed on monkeys.

Materials and Methods

Compliant objects with deformable and rigid surfaces were fabricated so that they exhibited elastic behavior, that is, the deformed objects under the applied loads returned to

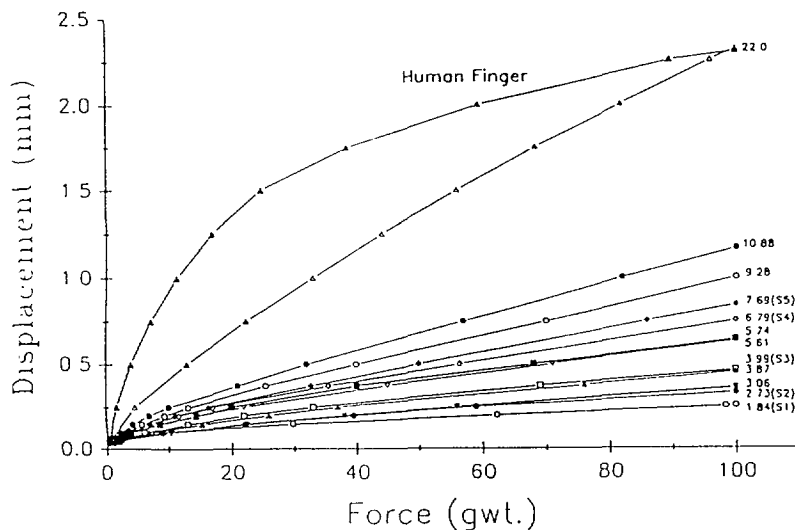


Figure 1: Traces of displacement vs. force for each of the rubber specimens and a human fingerpad indented by a flat-ended cylindrical probe (0.25 in diameter). The velocity of indentation was maintained constant at 0.5 mm/s. Numbers at the *right end* of each trace: average slope, which represents an 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 (from Srinivasan and LaMotte, 1995).

their original unloaded state once the loads were removed. For objects with deformable surfaces, transparent rubber specimens that varied only in compliance (controlled by varying the amount of a diluent) were cast. For compliant objects with rigid surfaces, telescoping hollow cylinders with rigid end plates were constructed such that the inner cylinder was supported by several springs inside the outer cylinder. Objective compliance, defined as the average slope of the displacement-force trace for a 0.25 inch diameter rigid probe indenting the rubber specimen at constant velocity of 0.5 mm/s, was determined for each of the specimens using a computer controlled tactile stimulator. The traces for the rubber specimens are shown in Fig. 1.

To measure the human discriminability of softness and to isolate the associated information processing mechanisms, psychophysical experiments were performed 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; (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. The experiments consisted of ranking, where the subjects had to rearrange a set of 12 specimens in the order

of increasing softness, and pairwise discriminations using a 2-interval, 2-alternative forced choice paradigm. These series of experiments are described in more detail in Srinivasan and LaMotte (1995).

To determine the possible mechanistic cues on which the softness discriminations and the associated neural codes could be based, biomechanical and neurophysiological data were simultaneously gathered for each of the specimens indenting the fingerpads of *Mecacca Fascicularis* monkeys under the same passive touch conditions as in the psychophysical experiments. The biomechanical data consisted of the variations over time of the net contact force (measured by using a load cell) and overall contact area (recorded with a videomicroscopy system), both of which enabled the calculation of the average pressure on the skin as a function of time. To infer the peripheral neural codes for softness, the responses of slowly adapting type I (SAI) and rapidly adapting type I (RAI) single afferent fibers in monkeys to the same stimulations used in psychophysical and biomechanical experiments were recorded electrophysiologically.

Results

1. Compliant objects with deformable surfaces

For rubber specimens, the ranking experiments with normal finger showed that the subjective sensation of softness correlates one-to-one with the objective determination of compliance – specimens with distinct compliances were discriminated, whereas those without, caused some confusion (Fig. 2). Compliance, as defined above, is therefore an appropriate objective measure relative to which the ability of the subjects can be judged. To distinguish the objective compliances of the specimens, high precision instruments needed to be operated under carefully controlled conditions. However, human subjects rank-ordered these specimens rather easily, and hence we conclude that humans have excellent softness discriminability. This ability was invariant across all subjects (14 in number) who used a variety of velocities and forces of indentation. Although our goal was not to measure the human JND (Just Noticeable Difference) for softness, based on the ranking experiments, we can estimate it to be about 12% or better.

In both ranking and pairwise discrimination experiments, the difference in the performance of the subjects before and after the administration of local anesthesia to the fingertips was dramatic (Fig. 2). In contrast to the ranking results described above for active indentations with normal finger, under anesthetized conditions, the subjects could not even distinguish between the hardest and the softest specimens. In pairwise discrimina-

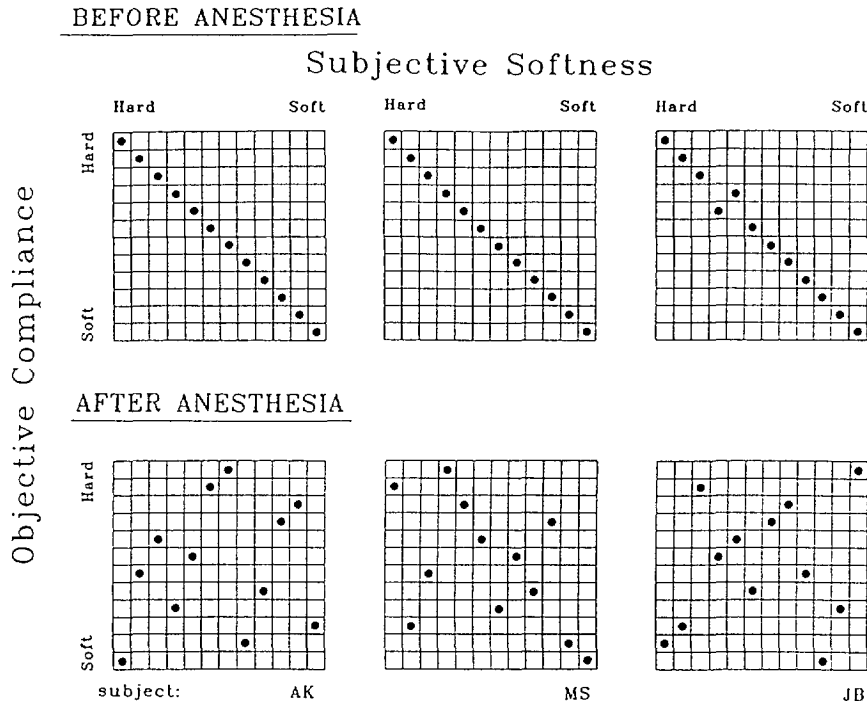


Figure 2: Results of ranking experiments before and after the administration of local anesthesia to the fingertips of 3 subjects. The confusion matrices plotted here show that the subjective judgment of the relative softness of the specimens coincided with objective compliance when tactile information 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 (from Srinivasan and LaMotte, 1995).

tions of the softness of rubber specimens S3 and S5 under active indentations, the subjects made 93% or greater correct judgments with normal finger. But after the administration of local anesthesia to the fingertips, the subjects could only achieve 55% correct or less, indicating that they were making random calls. Based on the results of both ranking and pairwise discrimination experiments with anesthetized fingerpads, we conclude that kinesthetic information alone is insufficient to discriminate the softness of rubber specimens and that tactile information is absolutely necessary.

Next, pairwise discrimination experiments were conducted under active and passive touch without anesthesia, with rubber specimen S3 as the standard and each of S1, S2, S4 and S5 as comparisons. Active touch experiments without any constraints on how the subjects indented the specimens enabled us to measure the velocities and forces used by subjects under almost normal conditions and to determine quantitatively their best performance among a variety of conditions. The standard deviations for both velocities (3.35 ± 0.85 mm/sec SD) and forces (98.71 ± 26.17 gwt SD) were approximately 25% of the mean values. In spite of such significant variations in indentation parameters, the subjects could discriminate each of the four specimen pairs at levels greater than 90%

correct. Even under constrained conditions where the subjects were asked to employ only the metacarpophalangeal joint and to limit peak forces to pre-defined values, the performance of the subjects under active touch deteriorated only slightly (Fig. 3A).

In passive touch experiments, to mimic the velocity variations observed in active touch experiments and to eliminate any cues arising out of slower ramp times for softer specimens to attain the desired force, the velocities with which the specimens were applied to the passive finger were randomized among 2.4, 3, and 3.6 mm/s. Separate sets of experiments performed at peak force values of 25, 50, 75, and 90 gwt. show that the discriminability of the subjects under passive touch conditions, especially at higher forces, is about the same as that under active touch conditions (Fig. 3B). To further eliminate any possible temporal and intensive cues, the peak forces were also randomized among 60, 75, and 90 gwt., in addition to the 3 indentation velocities (Fig. 3C). The resulting subject performance was still almost the same as that under active touch at 50 or 75 gwt. peak force. Because almost no difference was observed in the discriminability of the subjects under active and passive touch, we conclude that tactile information alone is sufficient to discriminate the softness of the rubber specimens.

To investigate the biomechanical and peripheral neural basis for softness discrimination, each of the five rubber specimens S1 to S5 were applied to the passive monkey fingerpad by the tactile stimulator. For each indentation, the stimulator brought down a specimen at a constant vertical velocity until a desired force was reached, after which the specimen was withdrawn at the same speed. The same velocities (2.4, 3.0 and 3.6 mm/s) and forces (60 to 90 gwt) used in the psychophysical experiments were employed. Each stimulus was repeated twelve times to ensure the consistency of the fiber responses. Typical force vs. time traces and the associated responses of an SAI and an RAI to the application of specimen S1 (harder) and S3 (softer) are shown in Fig. 4. The rate of change of force is lower for the softer specimen. Correspondingly, the rate of change of the neural impulse frequency (impulse/sec) is lower in the SAI response. The RAI response, however, is about the same for both the specimens, which are quite easily discriminated by human subjects. Thus tactile discrimination of softness is likely to be based on SAI responses, and in particular, their discharge rates.

The plots in Fig. 5 show that when the specimens are applied to the fingerpad at the same velocity, the softer the specimen, the lower is the rate of change of net force and higher is the rate of change of overall contact area. Therefore, at a given instant of time during the indentation, the difference in the average pressures between two specimens is

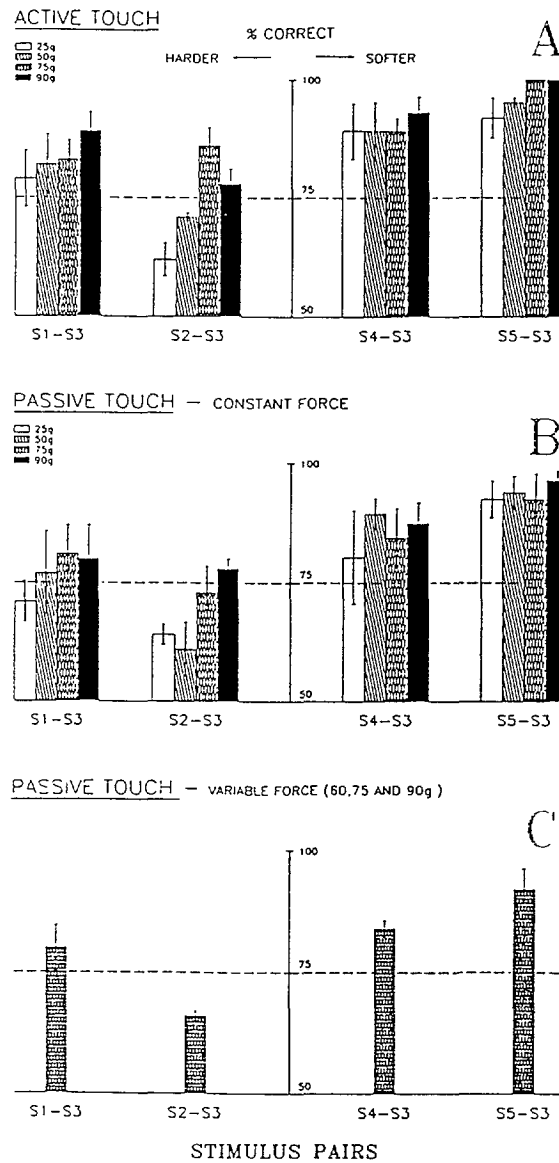


Figure 3: Results of pairwise discrimination experiments with rubber specimens under active and passive touch at various contact force values. In each experiment, specimen S3 was the standard and each of S1, S2, S4, and S5 were comparisons. Each bar represents the mean percent of correct calls for the corresponding specimen pair and force value, with the error bar indicating the SE. The labels 'HARDER' and 'SOFTER' indicate the relationship of the comparisons to the standard. (A) constrained active touch: The subjects were constrained to utilize 20° to 30° rotations of only the metacarpophalangeal joint, and peak forces within ± 20 gwt deviation from the mean values shown. Except for the 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 (from Srinivasan and LaMotte, 1995).

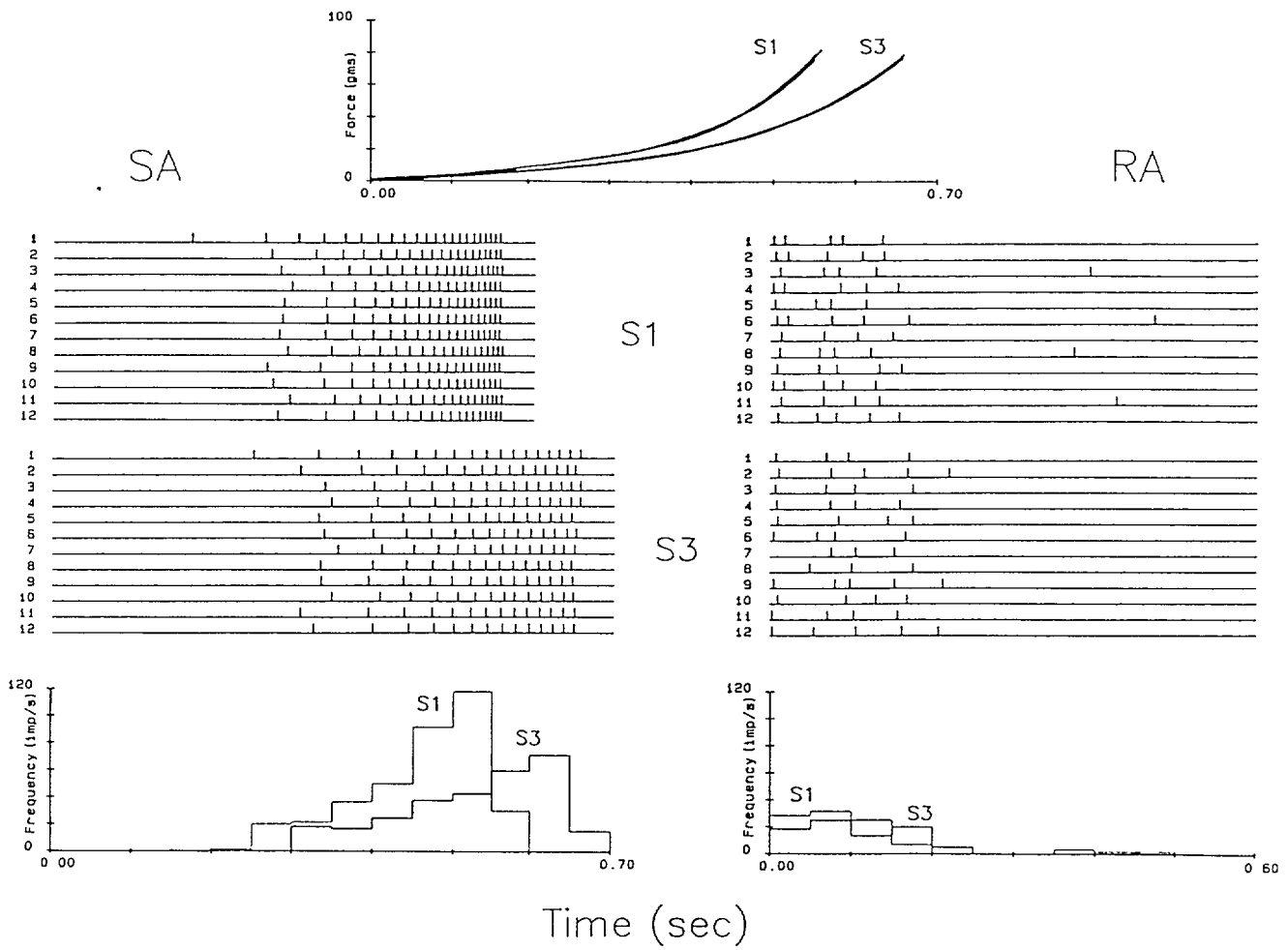


Figure 4: Responses of an SAI and an RAI to rubber specimens S1 and S3 indenting the monkey fingerpad at 3.0 mm/s. The top panel shows the corresponding force traces over time. Each horizontal line in the middle two panels represents one indentation, and each vertical tick represents the occurrence of an action potential at that time. The bottom panels show the corresponding discharge frequency histograms.

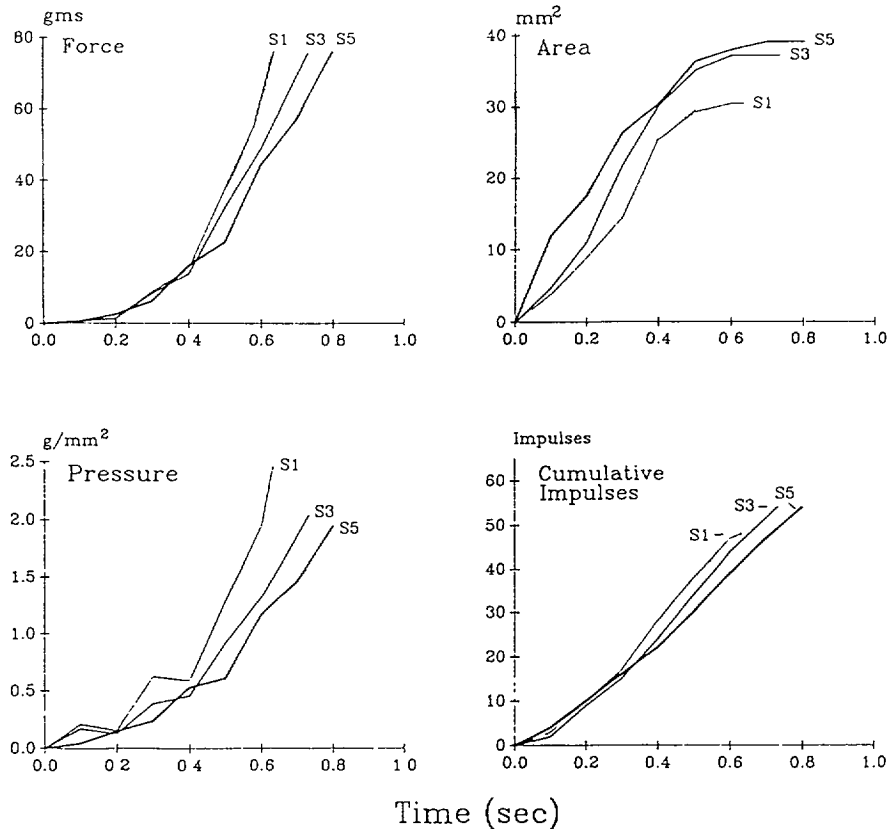


Figure 5: The variations over time of net force and overall contact area, together with the associated average pressure (net force/overall contact area) are shown for the standard specimen S3 and the two comparisons S1 and S5, all applied to the fingerpad at 3 mm/s. To illustrate the differences in the discharge rates of an SAI to the three specimens, its responses are plotted as cumulative impulses over time.

higher than the corresponding differences in either the forces or the contact areas. Just as the pressure increases more slowly for the softer specimen, the SAI discharge rate also increases more slowly (as shown in Fig. 4), resulting in a slower increase in cumulative impulses (Fig. 5).

However, the force, contact area, and discharge rate are affected by the velocity of indentation. For the same specimen, lower indentation velocity results in lower force and area rates, giving rise to a lower discharge rate (Fig. 6, top panel) at a given instant of time during the ramp. Since the discharge rate of a single fiber is affected by both the compliance of the specimen and the velocity of indentation, two specimens of differing compliances can be made to give rise to the same single fiber response by appropriately adjusting their velocities of indentation. The bottom panels of Fig. 6 show that the variation of cumulative impulses as a function of time is about the same for S3 applied at

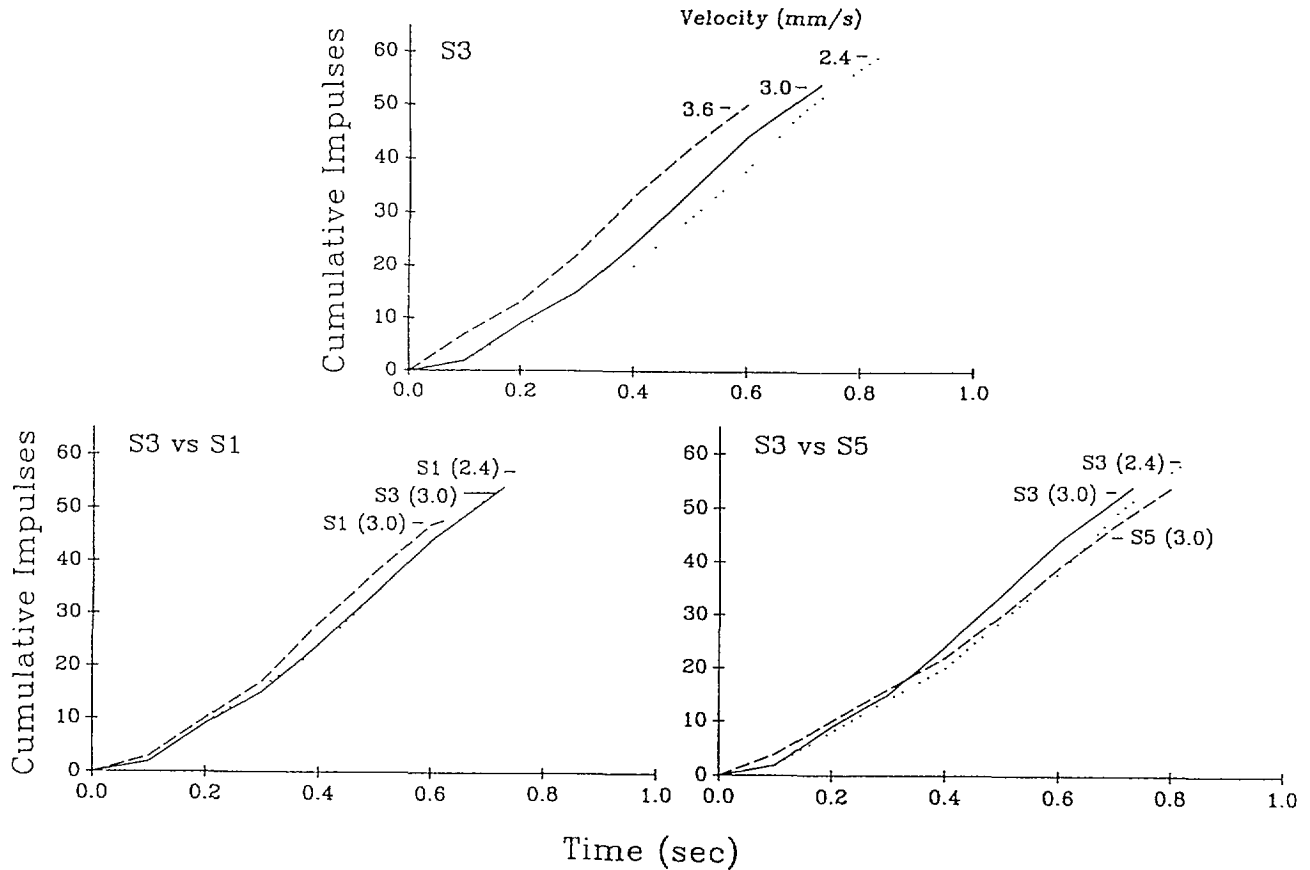


Figure 6: Cumulative impulses discharged by an SAI during the indentation ramp are shown as functions of time. Top panel shows the traces for the standard specimen S3 applied at indentation velocities of 2.4, 3.0, and 3.6 mm/s. Bottom left panel shows the traces for specimen S1 applied at 2.4 and 3.0 mm/s and S3 at 3 mm/s. Bottom right panel shows the traces for specimen S3 at 2.4 and 3 mm/s and S5 at 3 mm/s.

3.0mm/s and S1 applied at 2.4 mm/sec or for S3 applied at 2.4 mm/s and S5 applied at 3.0 mm/s. Thus the discharge rate in a single SAI fiber does not unequivocally encode the compliance of the object.

2. Compliant objects with rigid surfaces

The ability of subjects to discriminate the compliance of the ‘spring cells’ was consistently poorer compared to that of the rubber specimens. In active touch experiments, the force control of the subjects was also poorer for spring cells. These results are to be attributed to the non-deformability of the surfaces of spring cells, which result in decreased tactile information regarding the compliance of the object: the contact area depends solely on the force applied and not the compliance of the spring cell, whereas it depends on both for the rubber specimens.

In the case of spring cells, in pairwise discrimination experiments involving active touch

with normal fingers, the performance of the subjects was poorer compared to that for rubber specimen pairs with even closer compliances. 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 with spring cells, the subjects could not discriminate the specimens at all when irrelevant cues based on ramp times were eliminated. Therefore, unlike the case of objects with deformable surfaces, tactile information alone is insufficient and kinesthetic information is necessary to discriminate the compliance of objects with rigid surfaces.

4. Discussion

For rubber specimens, the one-to-one correlation between the subjective sensation of softness and the objective compliance indicates that the latter is a good standard relative to which the former can be judged. Both ranking and pairwise discrimination experiments with and without local anesthesia showed the insufficiency of the kinesthetic information and the necessity of tactile information. The active and passive pairwise discrimination experiments showed the sufficiency of tactile information for softness discrimination. Therefore, in identifying the mechanistic basis for the discriminability, we only need to examine the possible cues on the skin surface within the contact region.

It has been shown that subjects can discriminate softness based on the temporal signals resulting from tapping a specimen with a rigid probe (LaMotte et al. 1994). In the experiments described above, however, the ramp velocities are much lower and the specimens come into contact gradually with the soft fingerpad. Therefore the transient mechanical signals immediately after contact are not as significant to discrimination as the more gradual variation of net force and contact area over the indentation ramp. It should be noted that the contact area can be measured in two ways: (1) The overall or nominal contact area, which is the entire area within the boundaries of contact; (2) the actual contact area, which is the sum of the areas of all the islands of contact formed with the ridges on the fingerpad skin. The net force and overall area are dependent on indentation velocity whereas the subjects could discriminate the specimen presented even when the velocities were randomized. Therefore, the net force and overall area are not the relevant cues, but their ratio, the average pressure could be invariant with respect to indentation velocity (Srinivasan and LaMotte, 1995). Thus the temporal variations of average pressure, or the spatio-temporal variations of pressure distribution over the nominal or actual contact region might be the relevant mechanical signals for the discrimination of softness of rubber

specimens.

It should be noted that the temporal variation of average displacement of the skin, or the spatiotemporal variation of skin displacement distribution are equivalent to the descriptions above in terms of pressure distributions. This raises the possibility that the sensitivity of SAIs to skin surface curvature changes (LaMotte and Srinivasan, 1993; Srinivasan and LaMotte, 1987, 1991) might play a major role in softness discrimination as well. Since single fiber response depends on indentation velocity in addition to the specimen compliance, the tactile neural code for softness must be based on population response, particularly in SAIs. Whether this response depends only on the temporal variation of average skin curvature or the spatio-temporal variation of skin curvature over either the nominal contact area or the actual contact region at the fine level of fingerprint ridges remains to be investigated.

In the case of spring cells, because their surface is not deformable, the area of contact and the spatial distribution of pressure as well as skin displacements at any instant of time during the ramp are completely governed by the net contact force, and are independent of the compliance of the cell. A consequence is that tactile information can only encode variation of net force over time, which is directly affected by indentation velocity. Therefore, to unequivocally determine the compliance, subjects need kinesthetic information to know the overall indentation velocity, in addition to the force rate information which may be obtained from either tactile or kinesthetic sources.

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