Softness Discrimination With a Tool

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LaMotte, Robert H. Softness discrimination with a tool. J. Neurophysiol. 83: 1777–1786, 2000. The abilities of humans to discriminate the softness of rubber objects of differing compliance with a handheld tool (a stylus) was measured under experimental conditions that differed as to how the tool was used and the kind of sensory information available. When the subject actively tapped or pressed the compliant objects, they discriminated softness as well by means of a stylus as they did by contacting the objects directly with the fingerpad. Discrimination with the stylus was unaffected by whether the stylus was controlled by one or two fingers. While tapping or pressing a stylus held in a precision grip, the grip force increased before, reached a maximum at the same time as, and decreased in parallel with the compressional force. This relationship was suggestive of anticipatory motor control based on an internal model of the motor system and the physical properties of the object. Discrimination was significantly better when tapping as opposed to pressing the objects with the stylus. This was hypothesized as due to the presence of tactile cues generated by the rapid increase in force rate as the stylus struck and indented the object during tapping. During tapping, the magnitude and rate of compressional force produced by the stylus against the object were greater, the harder the object. An additional cue, possibly kinesthetic, during pressing and tapping was the magnitude of indentation of the specimen by the stylus that was greater, the softer the object. Subjects could discriminate differences on softness by tactile cues alone in the absence of kinesthetic when compliant objects were tapped at approximately the same velocity by the experimenter against a stylus in contact with the subject’s passive fingerpad. Discrimination deteriorated if the softer specimen of a pair was tapped with a slightly greater velocity than the harder and not possible if the specimens were pressed against the stylus without generating tactile cues of mechanical contact. In contrast, discrimination was possible during active pressing and unaffected by variations in velocity during active tapping. It is concluded that during active movements, kinesthetic information and knowledge of central efferent commands provide useful cues that are not present during passive touch. These cues allow the observer to discriminate differences in object compliance not confounded by differences in applied velocity.

INTRODUCTION

The softness of an object can be perceived through a tool by such means as tapping or pressing, as one can easily verify by means of a pencil or any other stiff object held in the hand. Perceived softness is the subjective assessment of an object’s compliance, the amount an object deforms in response to an applied force. The effective use of a tool usually requires sensing those physical properties of the target object that are transmitted through the tool. When the tool is held in the hand, forces are applied via the tool to the object. Simultaneously, forces are applied to an object and how does the force applied by the tool to the object? Tactual cues are clearly transmitted through the tool. When the tool is held in the hand, forces are applied by the hand to the tool itself to maintain a stability of grasp. As the tool contacts the object, tactual signals are generated that provide information about the object’s compliance and perhaps other physical properties such as its shape and texture. Sensing such properties, whether by tactual or other sensory cues, may be useful for optimal exploration or manipulation of the object with the tool. The forces applied to the tool must be coordinated with the forces applied to the object. If the grasping force is insufficient for the force of impact on an object, the tool may slip from the hand. If the force applied by the tool is too great, the object or the tool may be damaged.

Although sensory and motor processes in the dexterous manipulation of objects has received considerable attention (Johansson 1996), relatively little is known about the role of tactual signals in relation to the different ways in which a tool is used to sense the geometric and material properties of objects. To what extent is the force of grasping a tool coordinated with the force applied to an object and how does the generation and use of sensory cues change with differences in tool use, for example when pressing as opposed to tapping the tool against the compliant object? Tactual cues are clearly important when sensing the physical properties of objects by means of a tool (e.g., LaMotte et al. 1994; Wellman and Howe 1995). But information is lacking on the specific role of tactual and kinesthetic signals in the discrimination of softness with a tool.

In the present experiments, the ability of humans to discriminate softness, using a stylus as a generic tool, was measured under experimental conditions that differed in the motor performance required and the type of sensory information made available.

METHODS

Stimulus objects of differing compliance

Methods of construction and measurement were described in a previous study in which the same or similar objects were palpated with the fingerpad (Srinivasan and LaMotte 1995). The compliant specimens were made from transparent silicone rubber solution (RTV 615, General Electric) mixed with varying amounts of a diluent (RTV 910). As each specimen was indented with a flat-ended cylindrical probe (0.25 in. diam) at a constant indentation velocity of 0.5 mm/s, simultaneous measurements were made of force and displacement (Srinivasan and LaMotte 1995). Compliance was defined as the average slope of the approximately linear function relating displacement to force. The compliances of the specimens used in the present study were (in μm/N): 0.188, 0.278, 0.312, 0.407, 0.585, 0.692, 0.784, 0.946, 1.109, and 2.243.

Softness discrimination was measured under two testing procedures. Under the first, subjects were allowed to rank the softness of all 10 specimens, under a variety of experimental conditions, by actively palpating each specimen, in a natural way, either directly with one
finger or indirectly by means of a stylus. The goal was to provide as little constraint as possible on the number of times and the order in which each specimen was examined. Stimuli and responses were more constrained under the second testing procedure. With this procedure, pair-wise discriminations of the softness of a subset of five specimens were made under conditions that differed as to the kind of sensory information made available to the subject. The experimenter determined the number of times and order in which the specimens were delivered and whether the discriminations were based on tactile information alone or were made in the presence of kinesthetic as well as tactile cues. Aside from a single experiment that investigated the role of auditory signals in discriminations between hard objects, all discriminations occurred in the absence of auditory and visual cues.

**Ranking softness**

Ten objects of differing compliance were laid out on a table, and the subject was instructed to feel each one, in a specifically described manner, and rank them in a row from the hardest to the softest. The specimens were of identical appearance, and the lighting was sufficiently dim to prevent the use of any visual cues. Auditory cues were eliminated by masking noise delivered through earphones. Each specimen could be felt as many times as desired but always indented in a vertical direction (perpendicular to the table) and without lateral movement. Each misjudged specimen in a given task was counted as a single error. Nearly all errors were between adjacent specimens in the physical ordering. The number of incorrectly ordered specimens was divided by the number of specimens judged (i.e., 10) and expressed as a percentage.

Eight subjects were given a series of tasks that differed as to how each specimen was to be felt. The first three tasks required only the use of the distal pad of a single finger, the middle finger of the dominant hand. **Task 1**: the center of the specimen was briskly tapped with the fingerpad (Fig. 1A). **Task 2**: the specimen was slowly pressed and indented with the fingerpad, thereby greatly reducing or eliminating tactile cues generated by rapid impact. **Task 3**: the specimen was briskly tapped with a stylus that was pushed by the fingerpad of the middle finger (Fig. 1B). For this task, the lower end of the stylus, the stylus tip, was made of hard plastic, hemispherically shaped with a diameter of 3 mm. The upper end of the stylus, in contact with the skin, was shaped as a hemisphere, 10 mm diam. The stylus was mounted perpendicular to an arm that pivoted at the opposite end as shown in Fig. 2.

**Softness discrimination based solely on tactile cues, nontactile cues, or both**

Subjects made pair-wise discriminations between objects of different compliance under a two-interval, two-alternative forced-choice procedure. Two objects, one of which was softer than the other, was presented for 60 trials. The order of presentation on each trial was randomized, and the subject was required to state whether the second object was softer or harder than the first. Threshold discrimination for a given pair was defined as 75% correct. In each experiment, the stylus (with tip diameter of 3 mm) was mounted perpendicular to an arm that pivoted at the opposite end as shown in Fig. 2.

**PAIR-WISE SOFTNESS DISCRIMINATIONS BETWEEN OBJECTS THAT Emitted AN AUDIBLE SOUND WHEN STRUCK WITH THE STYLIUS.** The effect of auditory cues was determined on discriminations between solid disks made of metal (aluminum) and plywood or between metal and the hardest rubber specimen (“S1,” 0.188 m/m/mN). There were no visual cues. Six subjects were each tested under three experimental conditions. Under the first condition, tactile, kinesthetic, and auditory cues were permitted. Subjects were instructed to make relatively brisk taps, normal to the surface of the specimen. Under the second condition, the experimenter tapped the two specimens on each trial, and the subject discriminated using only auditory cues. The latter condition was repeated while subjects wore headsets that delivered white noise that was adjusted in volume until performance fell to 50 ± 10% (mean ± SE). The subjects again actively tapped the specimens.

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**FIG. 1.** Different modes of contact used when ranking the softness of rubber objects of differing compliance. A: subjects ranked softness by actively tapping (task 1) or pressing (task 2) each specimen with the distal pad of the middle finger. B: a stylus with a tip diameter of 3 mm was mounted to a torque motor. A sphere, 10 mm diam, was mounted to the upper end of the stylus. During task 3, the stylus exerted an upward force of 15 g (147.2 mN) against the fingerpad and the subject tapped the stylus against the specimen. During task 4, the stylus exerted a downward force of 1 g (9.8 mN) after being placed by the experimenter on the specimen chosen by the subject. C: the unconstrained stylus was held in a precision grip and was either tapped or pressed against the specimen (tasks 5 and 6, respectively). Task 7 was identical to 5 except that the stylus diameter was 9 mm.
Comparison that was either harder (S1 or S2, 0.188 and 0.278 m/mN) or softer (S4 or S5, 0.692 and 0.784, respectively). Six subjects were tested under conditions in which they either actively manipulated the specimen and the displacement of the stylus during active pair-wise softness discrimination. The stylus (a) was attached to an arm that pivoted on a shaft whose angular displacement was measured by a transducer attached to the shaft of a torque motor (b). When the stylus was gripped by the thumb and index finger, the thumb pressed against a moveable plate (c) in contact with a pancake load cell (d) used to measure grip force, as shown in the inset by a 90° rotated, expanded view. The specimen (e) was mounted to a load cell (f), used to measure compressional force. B: apparatus used to deliver tactile information to the passive fingertip during pair-wise softness discriminations. A torque motor (a) was used to maintain a base force of 15 g (147.2 mN) by pressing a hemispherically shaped head of the stylus (b) against the subject’s fingertip via a lever attached to the shaft of the motor. The finger rested against a holder (c) and was restrained by a post glued to the fingernail. The upper end of the stylus (e) was contacted by the specimen. The specimen was mounted to an arm whose angular displacement was measured by a potentiometer (d). The experimenter gripped a post mounted to the back of the specimen holder and either tapped or pressed the specimen against the stylus.

While auditory cues were masked with the white noise so that only kinesthetic and tactile cues were available.

**PAIR-WISE SOFTNESS DISCRIMINATIONS BETWEEN RUBBER SPECIMENS.** Most of these objects emitted only faint or inaudible sounds when struck with the stylus. In any case, auditory cues were eliminated by masking noise delivered through headphones. Visual cues were prevented as well by means of a blindfold. On each trial, the subject was presented with a pair of specimens, one of which was the standard, 0.407 m/mN (which was termed “S3”), and the other, a comparison that was either harder (S1 or S2, 0.188 and 0.278 m/mN, respectively) or softer (S4 or S5, 0.692 and 0.784, respectively). Six subjects were tested under conditions in which they either actively tapped or pressed each specimen with a stylus held in a precision grip (Fig. 2A) or were passively stimulated on a single, restrained fingertip by a stylus that was tapped or pressed by specimens applied by the experimenter (Fig. 2B). An additional five subjects were tested under conditions in which they used a single finger to actively tap or press the stylus against each specimen. In this way, it could be determined whether two fingers (used in the precision grip) afforded any advantages over one finger during active discrimination and whether any differences between active (2-finger) and passive (1-finger) discriminations were due to the number of fingers stimulated.

During *active* tapping and pressing of rubber specimens, when kinesthetic cues were available, the stylus was mounted as described to a pivoting arm and was either pushed by a single finger or grasped in a precision grip with the thumb and forefinger. At the onset of a tapping motion, the stylus tip was located in the air above the specimen. At the onset of a pressing motion, the stylus tip was already in contact with the specimen, having been placed there by the experimenter before the stylus was contacted by the subject. During active discriminations with one finger, the upper end of the stylus was pushed by the distal pad of the middle finger, as described for the ranking of *task 3* (Fig. 1B). That is, the stylus, attached to a torque motor via a lever arm, maintained an upward force of 15 g (147.2 mN) against the fingerpad during tapping and a downward force of 1 g (9.81 mN) against the specimen when pressing was required.

During discriminations in which two fingers were used to grip the stylus, measurements were obtained of the stylus trajectory, the grip force, and the compressional force of the stylus against the specimen (Fig. 2A). Compressional force was measured using a load cell beneath the specimen. The stylus contained a pancake load cell (Sensotek) on which rested a small plate that was free to move when pressed (*inset*, Fig. 2A). The pancake load cell allowed measurement of the grip force with an accuracy of ±3 mN. The stylus was mounted, as described, to the lever of the torque motor. The motor, turned off to avoid exertion of torque, contained a transducer that sensed the angular displacement of the stylus with an accuracy of ±1 μm. The subject’s thumb and index finger, when not grasping the stylus, were positioned on opposite sides of the pancake load cell in a resting position. A 1-mm sized nob on one side of the stylus could be felt by the fingerpad of the index finger so that any necessary minor adjustments in finger position could occur before grasping began. Before each tap, the experimenter placed the specimen on the load-cell platform, rested the stylus against the specimen, and signaled the subject to begin. The subject then grasped the stylus and raised it to a fixed height indicated tactually by a protruding marker. The tap was then delivered and the stylus returned to a resting position on the specimen. When actively pressing, the subject grasped the stylus and pressed it against the specimen without breaking contact between the specimen and the stylus tip.

During *passive* tapping and pressing of rubber specimens, the torque motor was used to press a stylus with a hemispherically shaped head, 10 mm diam, against the subject’s fingertip at a base force of 15 g (147.2 mN). The back of the subject’s middle finger was attached to a restraining device and prevented from moving by a post glued to the fingernail (Fig. 2B). The stylus tip (3 mm diam) was mounted to the upper end of the stylus. The specimen was mounted to an arm whose angular displacement was measured by a potentiometer. The experimenter gripped a post mounted to the back of the specimen holder and either tapped or pressed the specimen against the stylus.

**FIG. 2.** Schematics of the apparatus used to measure force and displacement during active and passive tapping and pressing. A: apparatus used to measure the grip force on the stylus, the force exerted by the stylus on the specimen and the displacement of the stylus during active pair-wise softness discrimination. The stylus (a) was attached to an arm that pivoted on a shaft whose angular displacement was measured by a transducer attached to the shaft of a torque motor (b). When the stylus was gripped by the thumb and index finger, the thumb pressed against a moveable plate (c) in contact with a pancake load cell (d) used to measure grip force, as shown in the inset by a 90° rotated, expanded view. The specimen (e) was mounted to a load cell (f), used to measure compressional force. B: apparatus used to deliver tactile information to the passive fingertip during pair-wise softness discriminations. A torque motor (a) was used to maintain a base force of 15 g (147.2 mN) by pressing a hemispherically shaped head of the stylus (b) against the subject’s fingertip via a lever attached to the shaft of the motor. The finger rested against a holder (c) and was restrained by a post glued to the fingernail. The upper end of the stylus (e) was contacted by the specimen. The specimen was mounted to an arm whose angular displacement was measured by a potentiometer (d). The experimenter gripped a post mounted to the back of the specimen holder and either tapped or pressed the specimen against the stylus.
as the maximal compressional force divided by the elapsed time from the beginning of the increase in compressional force to the peak; 3) the duration of the force ramp, defined as the time from the beginning of the increase in force to the maximal compressional force; 4) the duration of compressional force, designated as the time from the beginning of the increasing force to the return to base force; 5) the maximal grip force; 6) the difference in time to reach the grip and compressional maximal forces; 7) for tapping, the stylus velocity, defined as the last 2 mm of stylus travel before impact divided by the travel time; and 8) the maximal indentation of the specimen by the stylus.

The measurements of these parameters were obtained during the first three presentations of each specimen to five of the six subjects tested in the pair-wise softness discrimination of the rubber objects. Supplementary data were obtained from additional presentations of each specimen for compressional and grip maximal forces to measure more accurately the correlation between these variables.

STATISTICAL ANALYSES. These are described where appropriate in RESULTS. All statements referring to statistical significance were based on the criterion of a probability level of <0.01.

RESULTS

Effects of differences in tool use on sensory-motor performance while discriminating softness

CAPACITIES OF SUBJECTS TO RANK THE SOFTNESS OF OBJECTS ACTIVELY TAPPED OR PRESSED WITH A STYLUS. Regardless of the method of contacting the specimen, for example, by direct touch with the skin or indirectly through the stylus, the ranking of subjective softness by a typical subject was very similar to the ranking of objective compliance (Fig. 3A). Nearly every error of each subject was made between specimens with adjacent rankings in objectively measured compliance. The significance of differences in the mean percentage correct obtained from the eight subjects tested under tasks 1–6 (Fig. 3B) was determined using logistic regression analyses. The first analysis, based only on data obtained with one finger, found no significant differences for a given testing condition (tapping or pressing) between percentage scores obtained by direct contact between finger and specimen and those obtained using the stylus. However, the percentage correct was significantly higher when tapping than when pressing regardless of whether the finger or the stylus contacted the specimen and whether one or two fingers were in contact with the stylus. The second analysis was based solely on the data obtained with the stylus. It was found that for either tapping or pressing, the results obtained with one finger were not significantly different from those for two fingers nor was there any significant interaction. That is, the available factual information was sufficient to allow optimal discrimination of softness regardless of whether the movements of the stylus were constrained by its attachment to the torque motor or the tactile signals were restricted to one as opposed to two fingerpads. As for task 7, subjects performed equally well when actively tapping with a stylus tip of 9 mm diam (mean of 95% correct) as opposed to 3 mm (90%). That is, a three-fold difference in diameter of the stylus had no effect on the ability to judge softness by stylus tapping. In summary, the ranking of softness was better when tapping as opposed to pressing the specimen regardless of whether the skin contacted the specimen directly or indirectly through a stylus and whether the stylus was in contact with one or two fingers.

MEASUREMENTS OF STYLUS-APPLIED FORCES AND DISPLACEMENTS DURING PAIR-WISE SOFTNESS DISCRIMINATIONS. A subset of five rubber specimens (ranked from hardest, “S1” to softest, “S5”) was used in pair-wise discriminations between a standard compliance (S3) and two harder (S1, S2) and softer (S4, S5) specimens. The characteristics of motor performance are described first. Sensory discriminations are described in Contribution of nontactile cues to softness discrimination.

With the stylus held in a precision grip during active tapping, measurements were made of the position of the stylus and the forces applied to the stylus and specimen. There was a slight increase in grip force as the stylus was raised to the designated position before the onset of tapping (Fig. 4). The grip force increased monotonically as the stylus was brought toward the specimen and reached a maximum simultaneously with the peak compressional force delivered to the specimen after which both forces decreased together.

The mean velocities of the stylus, measured for the 2 mm of travel before impact with the specimen, varied from 210 to 444 mm/s for the five subjects. There was no consistent relationship among subjects between stylus velocity and the other seven parameters with the exception of the compressional force rate, which increased as a function of increasing velocity.

During active pressing, the grip and compressional forces increased together to maximal values and then decreased together (Fig. 5). The grip force typically began to increase earlier than the compressional force but the grip and compressional maximal forces were reached at approximately the same time. The increase in grip force began significantly earlier by a mean of 176 ms (paired t-test).

For both tapping and pressing, there were relationships between the compressional and grip forces in time and magnitude. Both reached maximal values at the same time. The mean differences in time for the maximal grip and compressional force, averaged for each specimen and subject, were not significantly different from zero (paired t-tests on differences, obtained for each subject, for all presentations of each specimen both for tapping and for pressing). There was a significant positive correlation between the maximal compressional and maximal grip forces for each subject both during active tapping and active pressing (Fig. 6). The significance of differences in forces applied under each condition (tapping vs. pressing) for the different subjects was determined using two-way analyses of variance (ANOVA; condition × subject) with repeated measures on both variables. Subjects differed significantly in the mean maximal grip and compressional forces they applied both during tapping and pressing. However, the overall differences between subjects were less for pressing than for tapping owing primarily to subjects B and D, whose forces were consistently higher for pressing than for tapping.

There were significant differences between subjects for both tapping and pressing tasks in the mean values for the duration, rate, and the maximal magnitude of compressional force as well as the maximal grip force applied (2-way ANOVAs with repeated measures on task and subject). Although the maximal grip force was always greater than the maximal compressional force during each tap or press, subjects differed significantly in
the magnitude of the difference. Whether the reasons for this are more related to cognitive variables or to stimulus parameters such as differences in friction between stylus and skin cannot be accurately determined without measurements of tangential forces applied to the stylus. Despite the considerable differences in duration, rate, and magnitude of applied forces exhibited by different subjects, there were no appreciable differences in sensory performance. For both tapping and press-

![Graph showing accuracy of ranking softness under different methods of contact. A: data from one subject indicate the correspondence (●) between the subjective and objective ordering of compliance. A perfect correspondence follows the diagonal from top left to bottom right. Methods of contacting the specimens were tapping or pressing the specimen either with a single finger (directly or via a stylus) or with 2 fingers holding a stylus in a precision grip. B: mean percentage correct for all subjects in the ranking task under each contact condition.](image-url)
ing, there was only an 8% difference in the overall mean percentage correct.

**Contribution of nontactile cues to softness discrimination**

**NEED FOR AUDITORY CUES FOR OPTIMAL DISCRIMINATIONS BETWEEN THE HARDEST OBJECTS.** As shown in Fig. 7, discrimination between metal and plywood was perfect during active tapping as long as auditory cues were present. When auditory cues were masked, subjects were unable to discriminate at levels better than chance. The results of these experiments indicate the importance of sound for the discrimination of differences in the compliance of hard objects. In contrast, active tactual discrimination between metal and the hardest rubber specimen, S1, was well above threshold in the absence of auditory cues.

**TACTILE DISCRIMINATIONS OF SOFTNESS WITH AND WITHOUT KINESTHETIC CUES.** Pair-wise discriminations of the softness of rubber specimens were made between a standard (S3) and a comparison that was either harder (S1 and S2) or softer (S4 or S5). Auditory and visual cues were not available. As described in METHODS, six subjects were tested under the experimental conditions in which specimens were either actively tapped versus pressed by a stylus held with two fingers (precision grip) or passively tapped or pressed by the experimenter via a stylus in contact with the subject’s restrained fingerpad. However, because active discriminations were obtained using two fingers and passive discriminations with only one, an additional group of five subjects was tested under the condition where only one finger was used to actively tap or press the stylus against each specimen.

During active tapping and pressing, all specimen pairs were discriminated well above threshold regardless of whether one or two fingers were used (Fig. 8). Similarly, all specimen pairs were discriminated above threshold during passive tapping with the exception of S2-S3 for one subject and S4-S3 for another. In contrast, discrimination was typically well below threshold for all specimen pairs during passive pressing.

A logistic procedure was used to determine the statistical significance of differences in percentages obtained from subjects tested under both active tapping and active pressing; one group using two fingers (precision grip) and the other using only one finger. No significant difference was found between percentages obtained between these two groups. The rest of the
statistical analyses were performed on data obtained from using one finger. Performance was significantly better under active than passive conditions (both active vs. passive tapping and active vs. passive pressing) and the difference was significantly greater for pressing than for tapping. Performance was significantly better for tapping than pressing (for both active tapping vs. active pressing and for passive tapping vs. passive pressing). In summary, during active touching, and in agreement with results obtained when specimens were ranked, softness discrimination with a stylus was better for tapping than pressing regardless of whether one or two fingers were in contact with the stylus. Discrimination was poorer under passive touching and possible only when the specimens were tapped rather than pressed against the stylus. The absence of discrimination under passive pressing demonstrates the importance of tactile cues generated by the impact of the specimen against the stylus.

When questioned, each subject stated that the tactile sensations and the tactile cues used in pair-wise softness discriminations were qualitatively the same whether actively or passively delivered to the skin. To determine the nature of the tactile signals that might be needed for the discrimination of softness during active tapping or pressing, measurements were obtained of the compressional forces applied to the specimen and the indentation of the specimen by the stylus. The mean maximal compressional force, mean compressional force rate, and the mean maximal indentation of the specimen by the stylus was obtained from the first three presentations of each specimen to each of five subjects. The grand means for all subjects for each specimen are in Table 1. For tapping, there were significant differences, due to compliance, in the maximal compressional force, compressional force rate, and maximal indentation (1-way repeated measures ANOVAs). In general, the compressional force reached a higher maximum at a faster rate for the hardest than for the softest specimen and was associated with a lesser maximal indentation.

Another force rate parameter that correlated with specimen compliance during active tapping, but which was not quantitatively analyzed in the present experiments, was the rate at which the compressional force increased at the moment of impact between the stylus and specimen. As shown in the insets in Fig. 4, the temporal profiles of the transition from baseline to an approximately linear phase of the rising compressional force traces were gradual for the softest specimen and abrupt for the hardest. Taps delivered to specimens with compliances graded between the extremes of hardest and softest evoked transition profiles that were graded in shape from abrupt to more gradual.

For active pressing, neither the maximal compressional force nor the compressional force rate changed significantly with compliance. The only variable that was significantly related to differences in specimen compliance, during active pressing, was the maximal indentation of the specimen (Table 1 and Fig. 5). The mean maximal indentation was 5.7 times greater for the softest specimen, S1, than the hardest, S5, during active pressing as opposed to 4.7 times greater for active tapping. The maximal indentation was significantly greater for pressing than for tapping by a mean factor of 1.6. Different subjects exerted more comparable maximal compressional forces during pressing than tapping (Fig. 6) perhaps to achieve a consistently higher indentation. If softness
discrimination during pressing is based on the kinesthetically perceived ratio of the magnitude of indentation to the magnitude of force applied, larger indentations may lead to better discrimination.

COMPARISON OF ACTIVE AND PASSIVE TAPPING UNDER VARIABLE VELOCITIES OF TAPPING. A method was devised that ensured that both active and passive subjects received their respective tactile stimuli from the same taps. Softness discriminations between specimens S3 and S1 or S5 were made simultaneously by pairs of subjects: one who actively tapped the specimen against the stylus and another who passively received the taps. Three subjects doubled on different occasions as tapper and receiver. During each test, the tapper was given additional instructions without the passive receiver’s knowledge: the tapper was told either to keep the velocity of tapping approximately constant (Control in Fig. 9) or, in other tests, on designated trials (indicated to the tapper but not to the passive subject) to make the first or second of a pair greater or lesser in velocity. Each subject wrote down which specimen of the pair felt softer on each trial.

The results indicated that the active tapper performed well despite variations in the velocity of tapping (Fig. 9). The passive receiver performed well only when velocity was held approximately the same on each trial (control) or when the harder of the two specimens was tapped at a higher velocity than the softer. When the softer specimen was tapped at a faster velocity than the harder, discrimination deteriorated. The im-
location and general physical properties, in relation to the forces that must be exerted by the motor apparatus against the stylus and the object. These forces must be sufficiently great to generate the desired sensory information about the compliance of the object on impact without dislodging the stylus from the grasp. At the same time they should not be excessive to the point of damaging the object. Similarly, anticipatory motor behavior in relation to expected and perceived sensory events is exhibited in the pattern of muscle responses occurring before catching an object (Johansson and Westling 1998; Lacquaniti and Maioli 1989). In the case of tapping, because the goal was to achieve a sufficient force of impact followed by a rapid withdrawal of the tool, the position of the object in relation to the position of the tool had to be known before the initiation of movement. For example, if the position of the object was unexpectedly raised or lowered, the tap often caused the stylus to slip or a premature retraction to occur without impact (unpublished observations). It seems likely that the choice of grip force while tapping must also take into account the properties of the tool, such as its surface texture or weight, just as it does during the precision lifting of a passive object (Johansson and Westling 1984).

Sensory information obtained through the tool

There were three findings from the study of tool use. The first was that, for a given type of active palpation (tapping or pressing), differences in softness were as discernable by the use of a stylus as they were by direct contact with the fingerpad. The second was that, for a given type of palpation with a stylus, softness discrimination was better for active touch than for passive. The third finding was that better discrimination of softness was obtained by tapping as opposed to pressing the object with a stylus.

The results of the present study indicate that the rate of change in the force applied to the skin by a tool that was tapped against an object was a major tactile signal related to the object’s compliance. There were two components to the rising phase of the force signal. The first occurred within several milliseconds after impact and had a temporal profile that was sharpest for the hardest object and more rounded or gradual for softer objects. The second component was a more linear phase whose slope was inversely related to compliance. Objects of different compliance, when tapped against a stylus held in contact with a passive fingerpad, produced correspondingly different force rates on the fingerpad and different sensations of softness each of which felt natural despite the absence of kinesthetic cues. Further research is needed to analyze the physical parameters contributing to the development of each of these components on the skin during tapping and pressing and to determine the effects of manipulating each component on perceived softness.

When a tool is already in contact with an object, the softness of the object can still be discerned by actively pressing the tool into the object. It is hypothesized that the discrimination is based on the perceived magnitude ratio of the distance traveled by the stylus into the object to the force exerted against the skin at each moment in time during pressing.

When actively tapping specimens with a stylus held in a precision grip between two fingers, small differences in compliance were easily discriminated despite moderate differences in the velocity of the stylus. During active touch, kinesthetic information about the position and movement of joints, mus-

DISCUSSION

Tool manipulations when sensing softness

When sensing softness with a stylus, the goal of the manipulative behavior is to maintain grasp stability while achieving a desired contact with the object. To accomplish stability without fatigue, the grip force must be coordinated with the compressional force produced when the tool contacts the object. That is, the grip force must be sufficient to prevent the stylus from slipping from the grasp yet not excessive so as to produce fatigue. This is a requirement for most manipulative tasks where a passive object is stabilized within the grasp as it is moved or used as a tool (Johansson 1996). Grasp stability was achieved in the stylus task, and in many others, for example during the precision lifting of passive objects (Johansson and Westling 1984), by a parallel change in forces normal and tangential to the grip. While contacting an object during a tap or a press, the grip force began to increase in anticipation of a reactive force generated by contact with the specimen. The grip and compressional forces increased to maximal values, reached at the same time, followed by a parallel decrease. This synchrony suggests that target forces were selected in advance of the movement and based on memory representations of object properties (Johansson and Westling 1988).

The preparatory increase in grip force that occurs during an active tap just before impact indicates the presence of an internal model (Flanagan and Wing 1997) of the object, such as its
icles, and skin, in addition to knowledge of central efferent commands, provides useful cues that are not present during passive touch. These cues may allow the observer to discriminate differences in object compliance unconfounded by differences in applied force and velocity.

When it is the skin and not a tool that touches the compliant object, the sensory requirements for optimal softness discrimination depend on whether the surface of the object remains rigid or changes its shape as the skin is indented. Srinivasan and LaMotte (1995, 1996) found that softness discrimination of deformable (rubber) objects can optimally occur based solely on passive tactile cues in the absence of kinesthetic information. Discriminations of the softness of compliant objects with rigid surfaces (on springs) require kinesthetic information in addition to tactile cues. When such objects were pressed against the stationary fingerpad with a constant indentation velocity to reach a given maximal force, softness discriminations were based on differences in force rate and ramp duration. That is, higher rates and shorter durations signaled harder objects. These temporal tactile cues could be confounded during passive presentations by changes in the velocity of indentation, as shown in the present study, when the more compliant object was applied at a greater velocity than the less compliant one.

The present study describes many but certainly not all the ways in which a tool can be used to obtain information about object compliance. For example, one common method is to maintain a sufficiently light grip on a tool as it is allowed to drop onto and bounce against the object. It is obvious from common knowledge of the physical properties of objects that the amplitude, frequency, and duration of bouncing of the tool will provide information about object compliance. As shown in Fig. 4, the amplitude of bouncing is initially higher, the frequency lower, and the total duration of bouncing longer for the softer specimen than for the harder.

Mechanoreceptors contributing to softness discrimination with a tool

In preliminary studies using the apparatus described in Fig. 2B, evoked responses to tapping the stylus with hardest and softest object used in the present study (S1 and S5) were obtained from six slowly adapting and seven rapidly adapting (type I) fibers innervating the monkey fingerpad (unpublished observations). The greater rate of change in the rising phase of the force applied to the skin when tapping the harder object was generally reflected by a significantly higher peak discharge rate and a shorter duration of response. However, the differences in responses of these two classes of mechanoreceptive afferents to objects so different in compliance were surprisingly small.

Rapidly adapting type II (Pacinian) afferent may play a predominant role in coding tactile sensations evoked by touching objects with hand held tools (Johnson and Hsiao 1992). Although these afferents are known to signal the occurrence of transient contacts between hand-held objects and the environment (Westling and Johansson 1987), little is known of their capacities to encode the physical properties of objects such as compliance. Another possible contribution, available in humans but not in monkeys, may come from the activation of SAI afferent fibers. Because they are sensitive to the direction and/or magnitude of changes in lateral stretching of the skin (Johansson 1978), they would be expected to respond to changes in the lateral tension of the skin when a tool, held in a precision grip, was tapped or pressed against a compliant object. Further research is needed to determine the respective roles of different mechanoreceptor populations in coding tool-generated tactile signals required for sensory discriminations of softness and other object properties such as texture and shape.

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