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Force-rate Cues Reduce Object Deformation Necessary to Discriminate Compliances Harder than the Skin

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Abstract

Grasping and manipulating an object requires us to perceive its material compliance. Compliance is thought to be encoded by relationships of force, displacement and contact area at the finger pad. Prior work suggests that objects must be sufficiently deformed to become discriminable, but the utility of time-dependent cues has not been fully explored. The studies herein find that the availability of force-rate cues improve compliance discriminability so as to require less deformation of stimulus and finger pad. In particular, we tested the impact of controlling force-rate and displacement-rate cues in passive touch psychophysical experiments. An ink-based method to mark the finger pad was used to measure contact area per stimulus, simultaneously with displacement and force. Compliances spanned a range harder and softer than the finger pad. The results indicated harder compliances were discriminable at lower peak forces when the stimulus control mode was displacement-rate (0.5 N) compared to force-rate (1.3 N). That is, when displacement-rate was controlled to be equal between the two compliances, the resultant force-rate psychophysical cues could be more readily discriminated. In extending prior studies, while some magnitude of finger pad deformation may be sufficient for discriminability, temporal cues tied to force afford more efficient judgments.

Index Terms

Human perception; haptic; tactile

1 Introduction

Our ability to differentiate compliance enables us to interact with and manipulate naturalistic objects. A precise understanding of the cues we rely upon to distinguish compliance is vital for the design of tactile displays to render virtual environments [1–5]. Psychophysical experiments with the bare finger—as opposed to probe or stick-based interactions—have investigated specific cues tied to the biomechanics of the finger [6–8]. While proprioceptive

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and cutaneous cues together convey compliance information, cutaneous cues related to the surface deformation of the finger pad appear to be relied upon more extensively [6, 9]. However, exactly which cutaneous cues are most essential remains unknown.

Relationships at the finger pad surface between force, indentation depth, and contact area are thought to be key to encoding compliance. The generally accepted paradigm is that we perceive compliance by contact area as a function of force; i.e., the same force applied to two different compliances will result in two contact areas, which can distinguish them [2, 3, 10]. However, work with tactile rendering displays suggests that replicating just these cues does not afford the same perceptual acuity as naturalistic stimuli [2, 3, 7, 9, 11]. Furthermore, we may rely on distinct sets of cues based on the relative compliance of the material [1, 8, 9, 12]. Although past efforts mostly considered compliances harder than the finger pad, there is evidence of a significant perceptual distinction between objects less compliant than the finger pad versus those more compliant—which are categorized by participants as “hard” and “soft,” respectively [8]. Besides characterizing an object by its force and contact area, cues of a time-dependent nature may underlie our perception of compliance.

Time-dependent cues, or information in the rate of change of skin deformation, may convey compliance in a manner more efficiently and rapidly. For these reasons, some of those building tactile displays have sought to control stimuli by force-rate, indentation-velocity and contact area-rate [2, 13]. Relatedly, probe-based efforts have suggested that judgments are based upon force-rate and velocity information, as opposed to steady-state relationships of force and displacement [13]. The psychophysical and neurophysiological basis for any particular time-dependent cue remains to be demonstrated. Only a couple of studies have considered force-rate cues in discrimination tasks with the bare finger [6, 8]. In one study, force-rates were randomized as an experimental control and in the other they were not found to effect estimates of compliance. That said, the movement of a stimulus by a small amount beneath one’s finger can alter estimates of compliance [14].

To understand the skin deformation cues available during interaction with compliant stimuli, we need to develop new techniques to both control and observe finger pad deformation over time. Observations along these lines have been performed involving grip and slip of the finger pad on transparent glass-plates, in which changing contact area is measured over the time course of slip [15, 16]. However, these recent studies focus upon interaction with a rigid plate. Likewise, work with compliant surfaces is needed both in terms of observation as well as the control of the deformation of the finger pad.

To investigate the utility of particular types of time-dependent cues on compliance perception, we conducted a series of biomechanical and psychophysical experiments. Building upon an initial effort [12], new methods were developed. In particular, stimuli were controlled either by force, indentation and/or their rates, a range of compliances both harder and softer than the finger pad were utilized, and biomechanical cues were measured between compliant stimuli and the finger pad.

2 Methods

Two new experimental paradigms were developed regarding control of the stimulus and measurement of finger pad deformation. First, to alter the availability of time-dependent cues, we ran passive touch, forced-choice experiments utilizing two control modes. In one control mode, stimuli were presented with identical 2-second triangle waves of force, leaving indentation velocity cues available to distinguish the objects. In a second control mode, stimuli were presented with identical 2-second triangle waves of displacement, leaving force-rate cues available. Additionally, biomechanical measurement of the deformation of the finger pad was done using an ink-based method to measure contact area between stimuli and the finger pad, given prescribed forces and displacements.

In all, four human-subjects experiments were conducted, two sets were biomechanical measurements, two sets were psychophysical experiments.

1. A biomechanical experiment generated a series of discrete relationships for a) force to contact area and b) displacement to contact area, between the stimulus and finger pad.
2. As the prior experiment could only take static measurements at peak displacements, a second biomechanical experiment was run with continuous displacement into the finger pad to examine force and displacement as they changed dynamically throughout indentation.
3. A forced-choice psychophysical experiment was run where either indentation velocity (displacement-rate) or force-rate were controlled between stimuli.
4. A second psychophysical experiment with only the harder set of compliances, where in each trial one stimulus was indented at twice the force-rate of the other to the same peak force, such that in half of the trials the more compliant object was indented at a higher force-rate than that less compliant.

2.1 Experimental Apparatus: Stimuli and Indenter

We constructed two sets of stimuli, one less compliant or the “hard” set (153 and 163 kPa), and one more compliant or the “soft” set (15 and 38 kPa). We refer throughout to the 153 and 163 kPa stimuli as “Hard 1” and “Hard 2,” respectively, and 15 and 38 kPa stimuli as “Soft 1” and “Soft 2.” Each stimulus was cylindrical with a diameter of 38 mm and height of 10 mm, so that its diameter was larger than the area of finger pad contact. Stimuli were constructed with a silicone elastomer (BJB Enterprises, Tustin, CA, USA; TC-5005), the compliance of which was controlled through a ratio of crosslinker [17–19]. These compliance estimates were generated using the unconstrained, uniaxial compression of a plate into cylindrical punches 10 mm tall by 10 mm diameter of identical batches of silicone elastomer. The compliance values were chosen to be approximately greater or lesser than that of finger pad skin, which has been measured in the range of 42 to 130 kPa at forces <4 N [20, 21]. In addition to modulus, the stiffness of each stimulus was subsequently determined using a 6 mm flat-plate indenter, indenting at 0.5 mm/s, to a force of 1 N. This procedure was identical to the material characterization done in [6], and showed that our hard stimuli compared favorably to their stimuli, while our soft stimuli were much more compliant (comparison shown in [12]). A small indentation at the center of the surface of each stimulus, approximately 1.0 mm in diameter with a depth of 0.3 mm and not readily noticeable to participants, was introduced in the casting process. It was used later as a consistent point of comparison between stimulus indentation levels as a means to decipher the directional spread in contact area (i.e., proximal-distal versus lateral-medial).

To indent the stimuli into the finger pad, we controlled a Newport ILS-100 MVTP Linear Motion Stage with a Newport XPS Motion Controller (Fig. 1). A Windows 7 PC running software written in Python 2.7 commanded indentations through an Ethernet connection with the motion controller, which directly interfaced with the motion stage. Force was measured by a load cell (0 – 22.4 N range; Omegadyne LCFD-5, Stamford, CO, USA) mounted to a cantilever attached to the motion stage. Force was sampled through an analog-to-digital converter built into the motion controller. Custom circuitry was built to allow the indenter to profile force in time, which was utilized to control stimulus force-rates in some experiments [22] _A 3D-printed housing for stimuli was constructed with an embedded servo motor (pictured in Fig. 1). This device allowed stimuli to quickly be switched during the forced-choice experiments. A padded armrest was bolted onto the base of the motion stage to secure the forearm with Velcro straps. The index finger was likewise held in place. The angle of the finger was held at approximately 30 degrees relative to the surface of the stimuli.

2.2 Participants

The human–subject experiments were approved by the Institutional Review Board at the University of Virginia. There were fifteen participants in total (mean age = 23.5, SD = 2.7, 9 male, 6 female). All enrollees granted their consent to participate. All participants continued to completion and no data were disregarded. The dimensions of each participant's distal phalange were measured via caliper (Table 1).

2.3 Measurement of Contact Area

We developed a method to measure the area of finger pad-stimulus contact upon indentation by compliant stimuli. Specifically the method measures "gross contact area" between stimulus and finger pad, as the measurement did not take into account the grooves on the finger pad. The method takes single measurements at the peaks of discrete magnitudes of indentation. An example overview of the process is given in Fig. 2 and below.

In specific, washable ink (Studio G Red, Hampton Art, Washington, NC, USA) was applied to the stimulus before each indent with a stamp pad. After each indent, a sheet of plain white paper was carefully rolled onto the finger pad in order to transfer the ink to the paper. Between indents, the finger was gently wiped with a moist paper towel to remove ink. This process was repeated several times at various levels of indentation, each time stamping the ink onto a section of paper not previously used. Afterwards, the sheets of paper were marked with a 5.0 cm line to scale the data, scanned and digitized into image files, and processed by custom software (written in Python 2.7). Within the software were identified the points in each fingerprint created by the small indentation on the bottom of each stimulus. The color threshold was adjusted to distinguish the area of the red ink from the background.

We used blank sheets of paper with a drawn-on 5.0 cm reference line to record fingerprints. Additionally, we constructed stimuli with small indentations in their surface, so that a marker would be left on each fingerprint at a consistent reference point. After a series of indentations, the sheet of paper was scanned into an image format (.jpg) and loaded into software. The software displayed the image and requested that the user identify the marker within each fingerprint. After clicking on each marker, the analyst designated a radius from the marker in which to search for each fingerprint. Fingerprints were stored as a marker location, radius pair.

After selecting each fingerprint on the page, the analyst used a slider to select a threshold value for the fingerprint ink color. This updated the on-screen image with bright red indicating thresholded pixels. The threshold value was modified until the edges of all fingerprints were thresholded. Next the analyst used another tool in the software to identify the 5.0 cm line in the image. Each end of the line was selected and the software calculated the length of each pixel in centimeters, which was later used to calculate the area of each fingerprint.

For each marker location and radius identified per fingerprint, from earlier, a serial search was conducted to determine the bounds of the fingerprint. Edges of the fingerprint were determined by searching from the top-to-bottom of each circle for transition to thresholded color, then bottom-to-top. This resulted in a series of points, which outlined the fingerprint. This set of points was subtracted from the marker point such that coordinates were consistent between fingerprints from the same stimuli. The final set of points was used to determine an area in pixels using Gauss's area formula, which was scaled to a physical area in squared centimeters through calculations from the reference line. The final output consisted of a set of coordinates and an area per fingerprint

2.4 Experimental Procedures

2.4.1 Establishing basic psychophysical discriminability of stimuli—Basic discriminability of stimuli within each set was determined through a brief psychophysical experiment with three participants. The experiment utilized forced-choice discrimination to evaluate the pairs of less and more compliant stimuli. Using the setup described in the next paragraph, we were able to quickly alternate the sets of stimuli (8 sec between successive stimulus presentations). A total of 40 trials were run per participant, 20 trials between the two hard stimuli and 20 trials between the two soft stimuli. Within the hard or soft set, each stimulus was presented first and second in the trial the same number of times. In each trial, the first stimulus was indented into the finger pad at 2 mm/s and force was measured on the load cell. The indentation speed of 2 mm/s was similar to the range of velocities used in [6], which ranged from 2.4 mm/s to 3.6 mm/s. A limitation of a constant indentation velocity was that the participants could possibly distinguish the objects based on the total time of indentation; however, informally participants made no mention of indentation time as a factor in their estimates. The indenter stopped moving when the force reached 3 N and remained still for 1 second. Then the indenter retracted and the next stimulus was presented in the same manner approximately 8 seconds later. After each trial participants were asked to choose which of the two stimuli was harder. Participants were able to discriminate each set of objects with a mean correct response rate of 78% (± 2.9%).

2.4.2 Experiment 1: Biomechanical, Ink-based Experiment with Discrete Displacements—The first biomechanical experiment utilized our method of measuring the contact area between the stimulus and finger pad. The four stimuli were indented into the finger pads of the participants, to different levels of displacement. Contact area and force were measured at each displacement level. Velocity was controlled at 2 mm/s. A point of contact for each stimulus was determined where the stimulus first made visible contact with the index finger and the participant detected contact. Then, a subsequent set of 15 indentations (5 sets of 3 replications) up to 5 mm was made for each stimulus.

2.4.3 Experiment 2: Biomechanical, Force-Displacement Experiment with Continuous Displacement—As the first experiment could only take static measurements at peak displacements, a second biomechanical experiment was run with continuous displacement into the finger pad to examine force and displacement as they changed dynamically throughout indentation. Only force was recorded, as the contact area measurement method could not be applied to a continuous indent. Force was sampled at approximately 50 Hz as each stimulus was indented from contact to 4 mm at 1 mm/s. Measurements were taken with all 4 stimuli.

2.4.4 Experiment 3: Psychophysical Experiment with Controlled Indentation Velocity or Force-rate—In a forced-choice psychophysical experiment, either indentation velocity (displacement-rate) or force-rate were controlled between stimuli. Using a 3D-printed device with servo-motor, stimuli could be switched out very quickly between indents with approximately 3 seconds between. For 8 participants, 80 trials in total were performed: 40 with the hard set of stimuli and 40 with the soft set. Two additional participants were run with just the hard set of stimuli. Within each set, 20 trials controlled force-rate between stimuli and 20 controlled indentation velocity. Each stimulus within a set was presented first and second in the trial an equal number of times. In every trial, the total duration in which the finger pad and stimulus maintained contact was kept constant at 2 seconds per indent such that it could not be used in participants' judgments. In a forcerate controlled trial, each stimulus was indented into the finger pad with a triangle-wave of force peaking at a desired force level at t=1 second. In an indentation velocity controlled trial, each stimulus was presented with a triangle-wave of displacement peaking at a desired displacement at t=1 second. After each trial participants were asked to choose which of the two stimuli was harder. Force and displacement were sampled during each trial at approximately 300 Hz for further analysis.

For the hard set of objects, brief experiments were run to the presented trials to determine a force-controlled condition in which participants could not distinguish the objects. The first trials began with 5–6 trials of 4 N/s to 4 N, and discriminability was estimated from these few responses. Every participant could discriminate at this force level, so next the force-rate was lowered to 2 N/s to 2 N and another brief set of trials was run. Force level was systematically lowered in this manner in the set [4, 2, 1, 0.8, 0.5] N until the participants could not discriminate based on the small number of trials (<75%). After a force level was found at which participants could not tell the objects apart, a full set of 20 trials was run at that level. Afterwards displacements were selected to produce lower forces to test in displacement-controlled experiments (typically 1 mm/s to 1 mm). For the soft set of objects, a similar procedure was employed. However, every participant could discriminate at 0.5 N/s to 0.5 N, which was the smallest force condition we could reliably deliver with our setup.

2.4.5 Experiment 4: Psychophysical Experiment with Varied Force-rates—A final forced-choice psychophysical experiment varied force-rates between the hard set of stimuli. The experiment was performed on eight participants with 40 trials each. Within each trial, one stimulus was indented with a triangle wave of force at 0.5 N/s to 0.5 N and the other with a triangle wave of force at 1 N/s to 0.5 N. Time was not controlled within trials, such that the object with the higher force rate was presented for half as long as the other. Both objects in the set were presented an equal number of times with the higher or lower force rate, and also as first or second in the trials. Participants were asked to choose which stimulus was harder after each trial. Two participants could not discriminate the stimuli in either case: for them, a second set of trials were run with one stimulus indented with a triangle wave of force at 1 N/s to 1 N and the other with a triangle wave of force at 2 N/s to 2 N.

2.5 Data Analysis and Statistics

Data analysis was performed using goodness-of-fit models for normality testing, F-tests for evaluating the equal variance assumption, and t-tests for comparing the sample means. Normality of all data distributions was confirmed by single-sample Kolmogorov-Smirnov tests (α=.05) using transformed data ($\mu = 0$, $\alpha = 1$). After normality was confirmed, the assumption of equal variances was tested between comparison samples via 2-sample F test (α =.05). In each experiment it was determined that the comparison samples had unequal variances, so 2-sample t-tests were performed on all comparison data under an unequal variance assumption (Behrens-Fisher problem, Satterthwaite's approximation for effective degrees of freedom). This process was used to compare peak forces per control mode in Experiment 3 for both hard and soft sets of stimuli, and additionally to compare mean psychophysical response rates in Experiment 4. The Statistics and Machine Learning Package of MATLAB version 2016b (Mathworks, Natick, MA) was the analysis software used.

3 Results

3.1 Experiment 1: Ink-based Experiment with Discrete Displacements

Contact area, force, and displacement relationships were measured for 5 participants at several discrete displacement levels (Fig. 3). Between individuals, force-contact area relationships appeared to be well separated for the two soft stimuli, but less so for the two hard stimuli (Fig. 3D). There was a consistent relationship between displacement and contact area across all individuals and stimulus compliances (Fig. 3C). A linear relationship fit contact area to displacement up to 2.5 mm with an R2 value of 0.92.

3.2 Experiment 2: Force-displacement Experiment with Continuous Displacement

We performed a separate biomechanics experiment with a single participant to examine the force-displacement relationships between finger pad and stimuli at greater resolution (Fig. 4). Force was sampled at a high rate as each stimulus was pressed into the finger pad at a constant velocity. We found that inter-set differences in these relationships were not consistent between the hard and soft sets (Fig. 4C, D). An equal force applied to both soft stimuli resulted in large displacement differences between them; however, an equal force applied to both hard stimuli resulted in much smaller displacement differences (Fig. 4C). With an equal displacement applied to both stimuli, force differences were very similar within both the hard and soft sets (Fig. 4D). The results suggest that the soft stimuli may be more differentiable by indentation depth, when force is controlled, than hard stimuli.

3.3 Experiment 3: Psychophysical Experiment with Controlled Indentation Velocity or Force-rate

Next we performed a psychophysical experiment with the hard set of stimuli in which either force-rate or indentation velocity (displacement-rate) was controlled between stimuli (Fig. 5). These control modes attempted to replicate conditions along the independent axes of Figure 4C and D, in which force or contact area was controlled between stimuli through time. The total time of each indent was held constant within trials to exclude it from judgments. The mean time-course of all trials for an example participant is plotted in Figure 5A and D. The participant could only discriminate the objects in displacement-controlled mode, even though peak mean forces and displacements were much greater in the force-controlled mode (Fig. 5A, D). With 9 additional participants, we consistently found that stimuli were discriminable in velocity-controlled trials at much lower forces and displacements than force-rate controlled trails, despite some individual variability in discrimination ability (Fig. 5B, E). On average, participants could discriminate the hard objects in displacement-controlled experiments at ~0.5 N, but not in force-controlled experiments at ~1.3 N (Fig. 5C, F). These forces were significantly different by 2-sample t-test ($p<.01$). Force-rate cues may therefore better discriminate hard objects than displacement-rate cues.

A similar psychophysical experiment was run with the soft stimuli (Fig. 6). Trials employing both velocity and force-rate control modes were run at low forces with the soft stimuli and the 8 of the same 10 participants. In contrast to trials with the hard stimuli, the soft stimuli were consistently discriminable in both control modes at the smallest forces we could reliably deliver (no significant difference between force or displacement, $\alpha = .05$). These data suggest that the soft set may be equally discriminable by force-rate or displacement-rate.

3.4 Experiment 4: Psychophysical Experiment with Varied Force-rates

We ran a final experiment with 8 participants in which we indented the hard stimuli at different force-rates within a trial (Fig. 7). In half of the trials, the softer stimulus was presented “correctly” at a lower force rate than the harder stimulus; in the other half, the softer stimulus was presented “incorrectly” at a higher force rate. Unlike in previous experiments, time was varied such that peak force was consistent within trials. Participants were able to easily discriminate the objects (81% correct) when force-rate was lesser for the soft object. However, the participants could no longer discriminate the objects (46% correct) when force-rate was greater. The difference in correct responses were statistically significant ($p<.01$) by 2-sample t-test with unequal variance assumption.

4. Discussion

In extending prior studies which indicate that we perceive compliance by contact area as a function of force, we suggest that the availability of temporal cues makes us more efficient in discriminating compliances, by reducing the amount that the finger pad or stimulus must be deformed. In particular, the results suggest that force-rate cues are critically important in discriminating objects harder than the finger pad. This assessment is based upon three findings. First, compliances harder than the finger pad were more readily discriminable when force cues were available – i.e., when displacement was controlled between stimuli. Second, stimuli were discriminable at lower deformation when force-rate cues were available – i.e., when displacement-velocity was controlled between stimuli – than vice versa. In contrast, compliances softer than the finger pad were equally discriminable at low deformation, regardless of control mode. Third, when changing the paradigm to direct control of force-rates between objects, incorrect forcerate information confused the participants. In particular, two compliances were less discriminable if that which was more compliant was indented at a greater force-rate than if that which was more compliant was indented at a lesser force-rate.

4.1 Temporal cues are efficient

The results suggest that the participants could use temporal cues to discriminate compliances more efficiently, by reducing the required deformation of the finger pad or stimulus. Many prior studies have focused on the static force-displacement and force-contact area relationships between the stimulus and finger pad as cues for compliance, which for the most part are not affected by the rate at which a stimulus is presented [3, 6, 8, 23]. These static relationships may indeed be sufficient for discrimination, and we informally note that all stimuli seemed discriminable at some deformation level regardless of the indentation strategy used. However, it seems that participants use temporal cues to make judgments more efficiently. In particular, of the temporal cues examined, force-rate cues were more useful than displacement-rate or contact area-rate. [Note in this study, our paradigm was to vary force-rate *cues* by controlling *stimulus* displacement-rates, or velocities. Likewise, we varied displacement-rate *cues* by varying *stimulus* force-rates.] The stimuli presented at a controlled displacement-rate (i.e., where force-rate cues were available) required less deformation than those presented at a controlled force-rate. We did not see this same pattern with the soft set of stimuli, which were discriminable in either control mode—this difference might be explained by the much larger differences in displacement and contact area at a given force as compared to the hard objects, denoted in Figure 4C. In prior studies it was noted that participants used a steeper finger angle when interacting with harder compliances [23], which might be an attempt to increase the efficiency of contact area-rate information. Auxiliary to our findings of the importance of temporal cues, one's judgments may as well be impacted by small differences in peak force between two stimuli, as compared to displacement, observable in Figures 5A and 5D.

4.2 Tactile rendering displays

Significant work is presently underway to develop the next generation of tactile rendering displays and the work herein seeks to inform those efforts. In wearable and other passive touch displays, certain presentation strategies may more efficiently convey compliance. For example, presenting virtual objects at constant velocity (where force rate cues will vary) is likely to be more efficient than presenting it at constant force-rates (where displacement-rate cues will vary). Across tactile displays, utilizing temporal cues to increase discrimination efficiency may help reduce actuation requirements. Less actuation may allow for the use of novel materials, such as electroactive polymers[24, 25], which are currently only able to render small forces.

4.3 Ties from passive to active touch

Prior research has indicated that compliance discrimination in passive touch is nearly as effective as in active touch [6, 8, 11, 26]. While this may or may not be correct, work remains to determine if temporal cues have the same impact in active touch [14]. It is plausible that the addition of proprioceptive information would make displacement-rate a more meaningful cue, thereby increasing the efficiency of exploring objects at a controlled force-rate. That said, the cues conveying displacement and displacement-rate in passive touch are not fully understood. For example, contact area may be utilized as an analogue for displacement—we found contact area and displacement to be highly correlated across individuals — and recent work has suggested that contact area spread-rate may act as a proprioceptive cue for finger motion [27]. Further study is required to apply our results to active touch.

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Biographies

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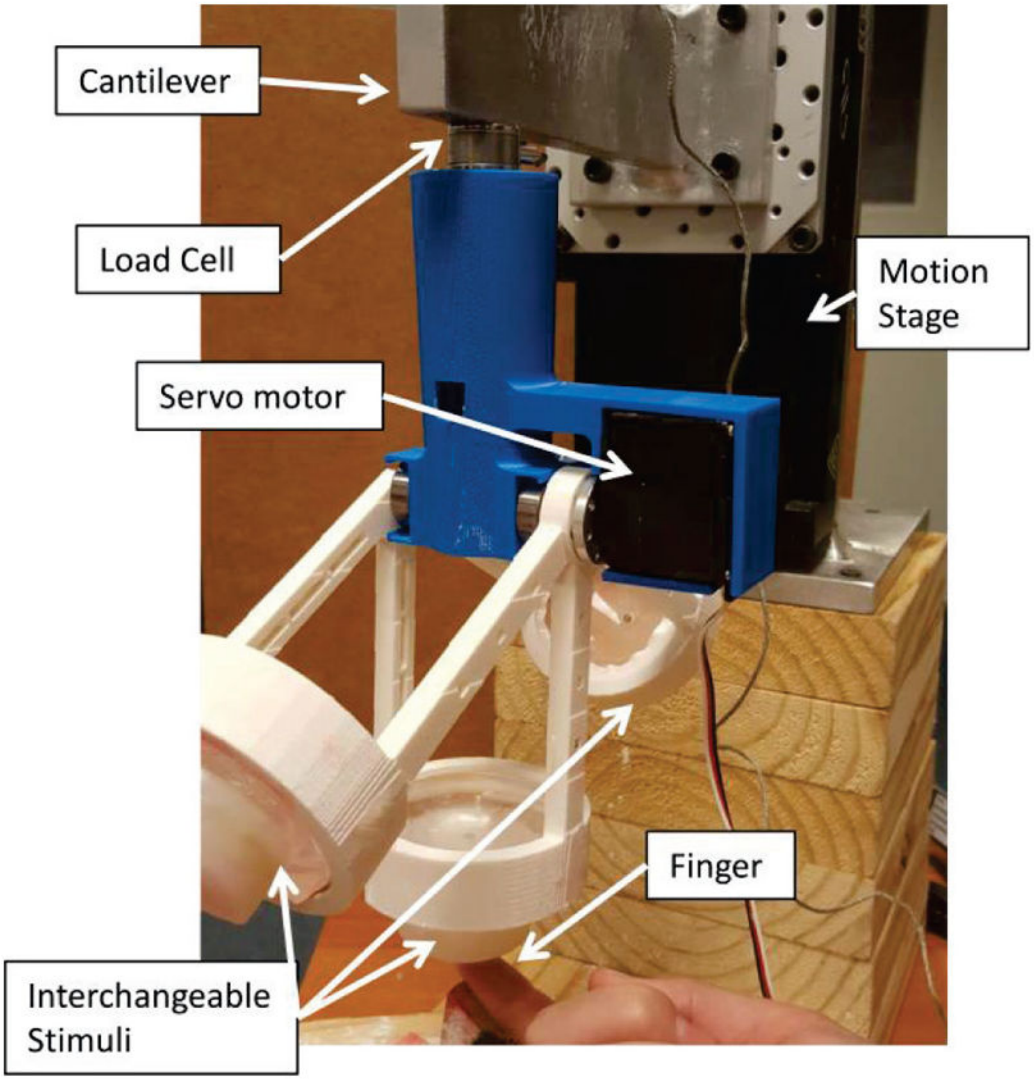

Fig. 1.

Indenter setup where the servo motor is used to quickly interchange stimuli between the forced-choice discrimination psychophysical experiments.

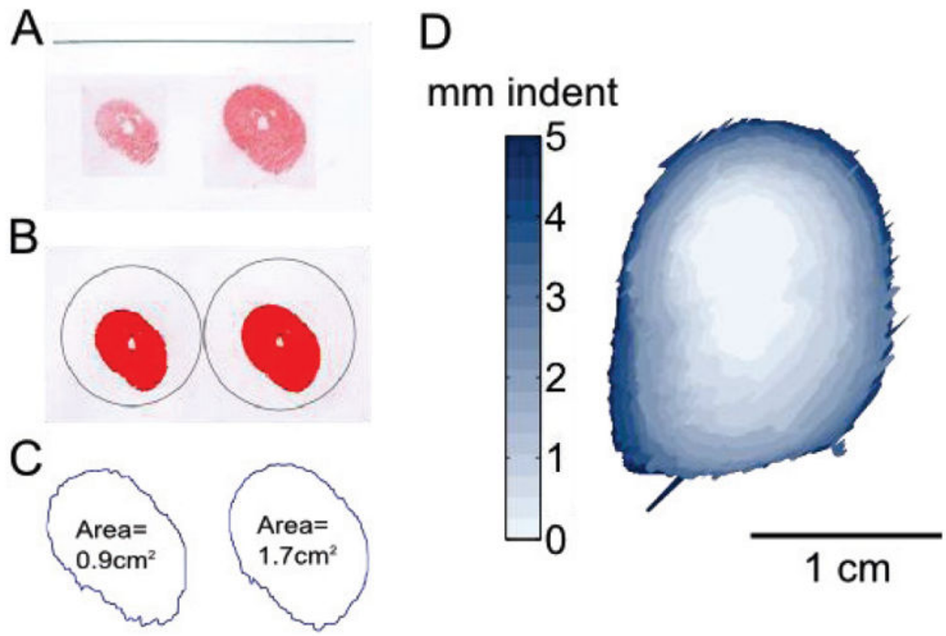

Fig. 2.

Fingerprints and shape/area analysis. A) Fingerprints are stamped onto a sheet of paper after successive indents with the Soft 2 stimulus, and digitized. The uncolored area in the middle of the print represents the marker in the stimulus to identify a consistent reference point for the same stimulus between successive indents of different depth. B) The fingerprint is identified, color thresholded, and an exterior outline is determined. C) A set of vertices are found, representing the shape of the fingerprint's exterior outline and an area determined by Gauss's formula. D) The contact areas for a series of 20 displacements are overlaid in sequence from 0 mm to 5 mm depth of indentation.

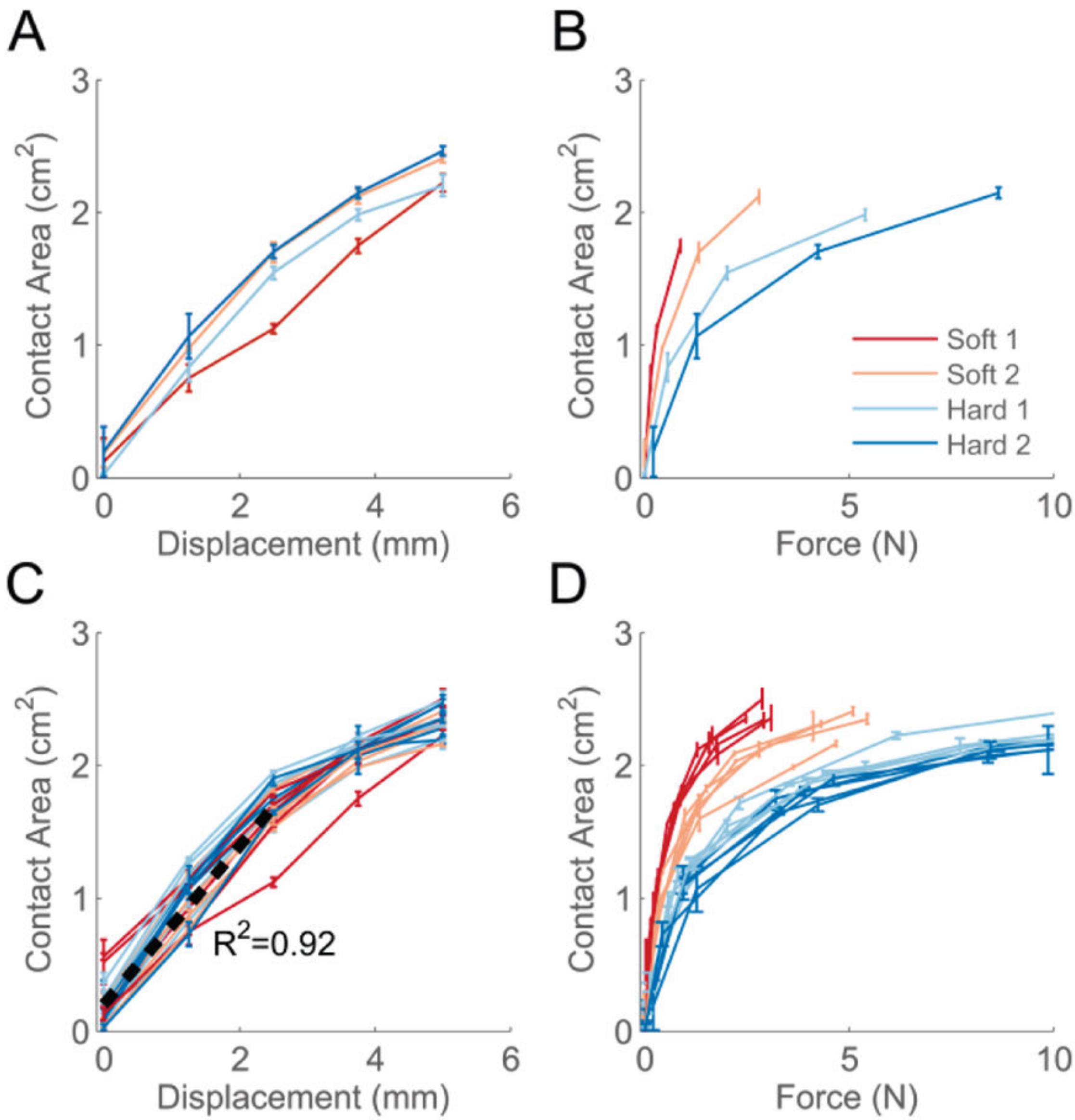

Fig. 3.

Biomechanical relationships of force, displacement, and contact area for 5 participants. The ink-based method was used to measure the contact area along with force and displacement in biomechanics experiments with 5 participants. A) Displacement-contact area relationships for all four stimuli per one example participant. B) Force-contact area relationships for the same participant, for displacements up to 3.75 mm. C) and D) plot the same as above but for all 5 participants. In C) a line fits displacement to contact area from 0 to 2.5 mm.

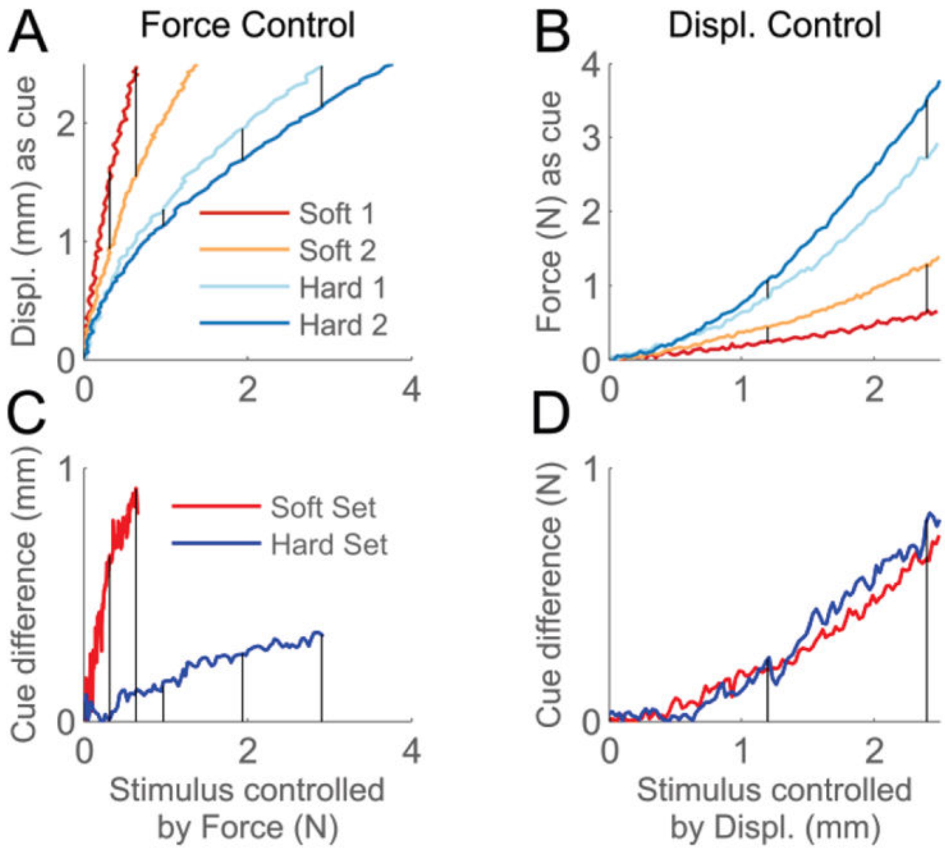

Fig. 4.

Force-displacement relationships and cue differences between stimuli. Each stimulus was indented into the finger pad of one participant at a rate of 1 mm/s from contact to 2.5 mm and force was measured at approx. 50Hz. A) Force-displacement relationships for each stimulus with force on the x-axis. Vertical lines between stimuli represent differences in displacement at a given force. B) The same force-displacement relationships in A., but plotted with displacement on the x-axis. Vertical lines represent differences in force at a given displacement. C) Differences in displacement at the same applied force between the objects in each set. Vertical lines match those in A. D) Force differences within each set at a given displacement.

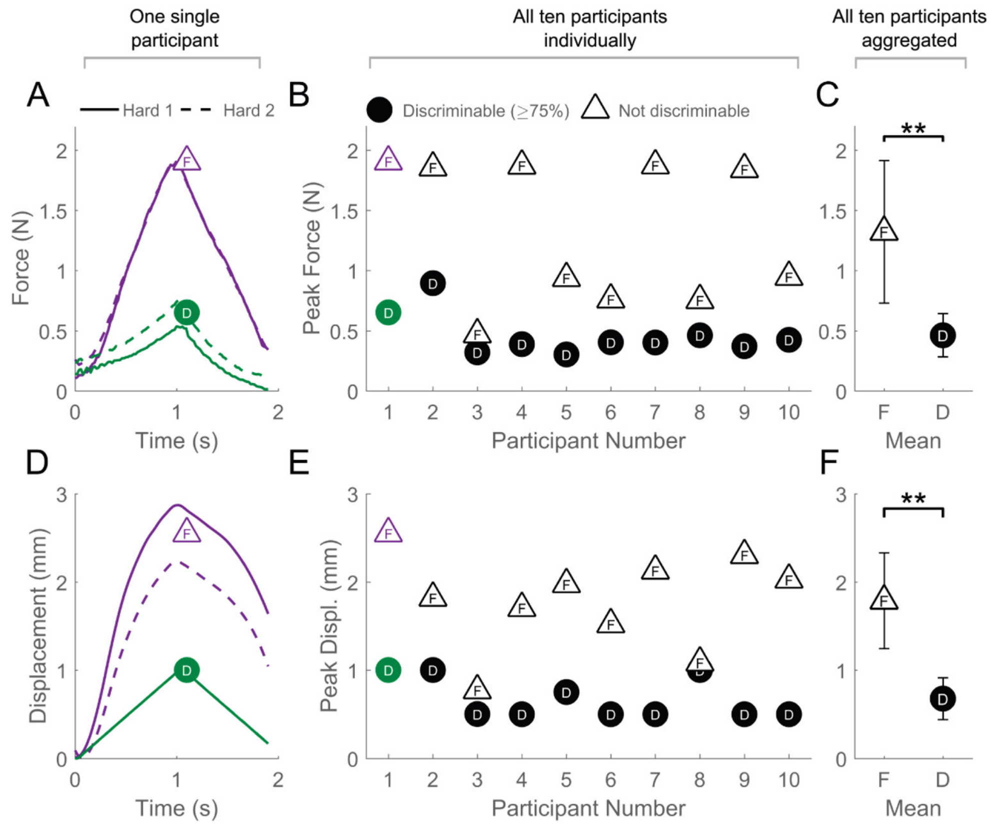

Fig. 5.

Psychophysical results in which force-rate or indentation velocities were controlled between stimuli. We systematically controlled forcerate and indentation velocity to determine their importance to compliance discrimination. An example participant was run in 2 control modes: 1) force-rate controlled per stimulus to 2 N, and 2) displacement-rate (indentation velocity) controlled per stimulus to 1 mm. In all figures, a filled-in marker indicates that the set of trials was discriminable (participant answered 75% correct). A) Mean force values throughout the time-course of all trials for the one single participant. The mean peak values for each control mode (averaged between stimuli) are marked with an "F" for force-controlled modes or a "D" for displacement-controlled modes. B) Data in the force domain for each of ten participants individually. Each symbol marks the mean peak force from control modes as in A). C) Data from B) of all ten participants aggregated for both force-control and displacement-control modes. Peak forces were significantly higher ($p<.01$) for experiments in which stimuli were controlled by force, as determined by 2-sample t-test with unequal variance assumption. Error bars denote standard deviation. D) Mean displacement values throughout the time-course of all trials for one single participant. E) Data in the displacement domain for each of ten participants individually. F) Data from E) of all ten participants aggregated. Mean peak displacements were significantly higher in the force-control experiments ($p<.01$), determined by 2-sample t-test as in C). Percent correct responses for each participant in force control mode (in order of participant number): 40%, 45%, 45%, 50%, 70%, 60%, 65%, 50%, 30%, 45%. Percent correct responses for each participant in displacement control mode: 100%, 85%, 80%, 80%, 95%, 80%, 80%, 90%, 90%, 75%.

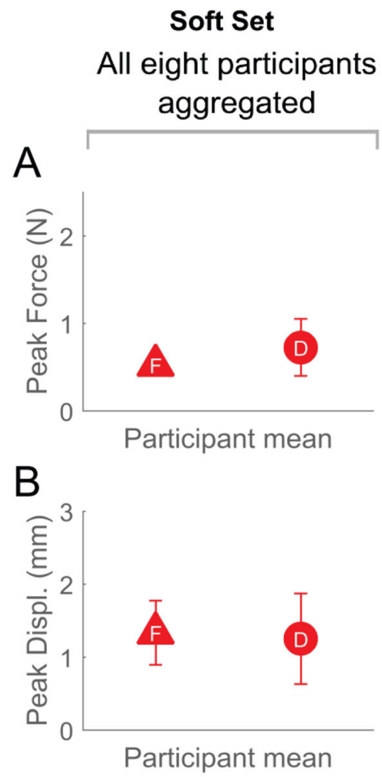

Fig. 6.

Effect of control mode on discriminability with soft compliances. Aggregate results from all participants are plotted. A) Mean peak force used in force-controlled and displacement-controlled control modes for all participants with the soft set of objects. B) plots data from A with mean peak displacement instead of force. Participants were able to discriminate the objects regardless of control mode. Error bars denote standard deviation.

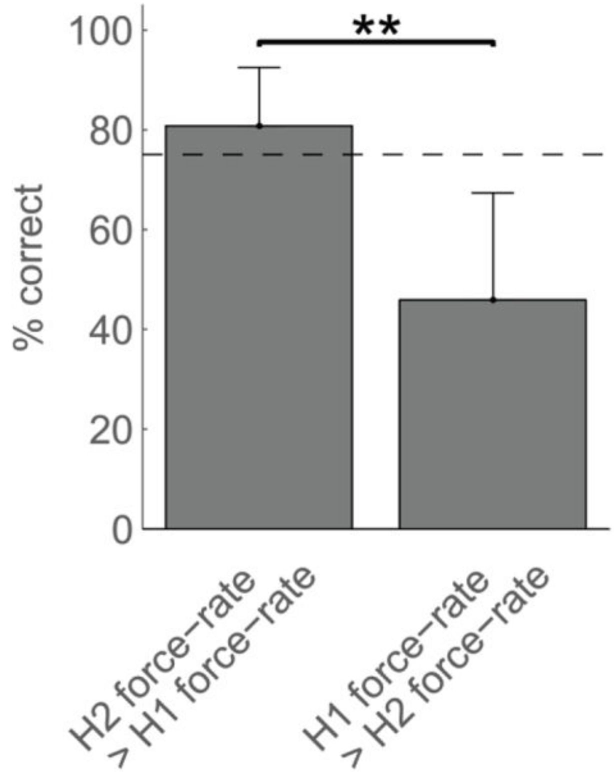

Fig. 7.

Psychophysical results in which force-rates were varied between stimuli. A comparison of correct responses when the Hard 2 stimulus was indented at a greater force rate than Hard 1 (H2 force-rate > H1 force-rate), and vice-versa (H1 force-rate > H2 force-rate), Each stimulus was indented with triangle waves at either 1 N/s to 0.5 N (greater force rate) or 0.5 N/s to 0.5 N (lower force rate) within each trial. Two participants could not discriminate in either case and were instead run with stimuli indented at either 2 N/s to 1 N or 1 N/s to 1 N. **Significance is denoted at $p < .01$ by 2-sample t-test with unequal variances. Error bars denote standard deviation.

TABLE 1

Summary of The Dimensions of Each Participant's Distal Phalange (Units of Millimeters)

	Lateral-medial	Thickness	Distal-Proximal
Max	19.0	15.0	29.9
Min	14.0	9.1	22.3
Mean (± SD)	15.7 ± 1.6	11.3 ± 1.5	25.9 ± 2.2

Tabulated are summary finger pad measurements for the 15 participants. All units in millimeters.