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In the Tactile Discrimination of Compliance, Perceptual Cues in Addition to Contact Area Are Required

Chang Xu, Yuxiang Wang, Steven C. Hauser, Gregory J. Gerling

University of Virginia, VA, USA

Abstract

In our ability to discriminate compliant, or ‘soft,’ objects, we rely upon information acquired from interactions at the finger pad. We have yet to resolve the most pertinent perceptual cues. However, doing so is vital for building effective, dynamic displays. By introducing psychophysical illusions through spheres of various size and elasticity, we investigate the utility of contact area cues, thought to be key in encoding compliance. For both active and passive touch, we determine finger pad-to-stimulus contact areas, using an ink-based procedure, as well as discrimination thresholds. The findings indicate that in passive touch, participants cannot discriminate certain small compliant versus large stiff spheres, which generate similar contact areas. In active touch, however, participants easily discriminate these spheres, though contact areas remain similar. Supplementary cues based on stimulus rate and/or proprioception seem vital. One cue that does differ for illusion cases is finger displacement given a volitionally applied force.

INTRODUCTION

In a seamless manner, when we volitionally control our hand and finger exploration in active touch, we are able to integrate cues from our tactile and proprioceptive systems, as well as from visual identification of objects and past recollections of similar interactions. In contrast, in passive touch, when objects are indented into a stationary finger, we rely almost exclusively upon tactile, or cutaneous, cues (Kaim & Drewing, 2011; Srinivasan & LaMotte, 1995; Tiest & Kappers, 2009). Such cues are derived from mechanosensitive afferents in the skin as well as muscle. Indeed, distinct physiological elements come together to afford our abilities in the various dimensions of touch. These dimensions include pressure, temperature, vibration, surface roughness, texture, slipperiness, stickiness, and geometry, amongst others including compliance (Jones & Lederman, 2006).

Our ability to differentiate compliant, or ‘soft,’ objects is key to interacting in our everyday world, for example in grasping the hand of another or in palpating internal organ tissues and irregularities in surgery. Multiple groups have built tactile displays to render the sense of compliance (Bianchi, Battaglia, Poggiani, Ciotti, & Bicchi, 2016; Bicchi, Scilingo, & De Rossi, 2000; Nakamura & Yamamoto, 2016; Stanley & Okamura, 2015; Yazdian, Doxon, Johnson, Tan, & Provancher, 2014). They have used mechanisms of fabric stretch, concentric rings, electrostatic force, particle jamming, and tilting plates. The task of aligning actuation mechanisms with the most efficient, salient, and naturalistic perceptual cues remains relevant and timely.

The precise sets of tactile cues that drive our percept of compliance have yet to be resolved. The generally accepted paradigm is that rendering devices should focus upon the cue of contact area, typically as a function of force or displacement (Bianchi et al., 2016; Bicchi et al., 2000). Other recent studies have considered time-dependent cues, such as force-rate, which may more efficiently convey information (Hauser & Gerling, 2016, 2017). Additional efforts are employing imaging techniques to observe the contact interactions between the skin and compliant surfaces (Hauser & Gerling, 2018).

Herein, we investigate the utility of contact area cues, by introducing a tactile illusion. The hypothesis is that for certain combinations of stimulus spheres, if one decouples its elasticity from its radius of curvature, one might expect similar contact area interactions for spheres that differ in compliance. This hypothesis follows from prior computational work involving finite element analysis of the human fingertip (Wang & Gerling, 2014). In simulating spherical indenters of radii (4, 6 and 8 mm) and elasticity (10, 50 and 90 kPa), that modeling effort predicted that distributions of stresses in the skin would be nearly identical for certain combinations of spheres – in particular those are small and compliant versus large and stiff. Furthermore, while illusions under circumstances of passive touch, these same cases were speculated to be discriminable under active touch, when finger movement is allowed.

The work herein seeks to behaviorally evaluate this hypothesis and therein determine the utility of the perceptual cue of contact area through this purported illusion case. To do so, we conduct human-subjects experiments that combine biomechanical measurement of contact at the skin surface with psychophysical experiments in both passive and active touch.

METHODS

To evaluate the aforementioned hypothesis, we conducted human-subjects experiments by employing nine compliant, spherical stimuli, which differed in their combinations of radii and elasticity. In separate sets of experiments, we first used an ink-based procedure to indent stimuli into the constrained fingers of human participants to various levels of force, from which we extracted contact area. A similar experiment was done in active touch where participants employ particular levels of force. From these data, we determined three stimulus combinations which led to similar contact areas, across cases of both passive and active touch. These were deemed possible illusion cases. Next, we conducted psychophysical experiments using the method of constant stimuli to determine if participants indeed faced difficulty discriminating the stimuli.

Experimental Apparatus: Stimuli and Indenter

As illustrated in Figure 1, a vertically-moving indenter (ILS-100 MVTP, Newport, Irvine, CA, USA) was controlled via a Newport XPS Motion Controller. A load cell (0 – 22.4 N, LCFD-5, Omegadyne, Sunbury, OH, USA) was mounted onto the cantilever to record contact force (Hauser & Gerling, 2017). A 3-D printed fixture was firmly attached to the cantilever. With an embedded servo motor, different sets of stimuli are quickly interchanged. The subject's forearm was constrained on a fixed padded armrest with Velcro straps. In the active touch setup, each stimulus was mounted onto a parallel beam load cell (0 – 98 N, HTC Sensor TAL220, Colorado USA).

The compliant stimuli were made of a room temperature curing silicone elastomer (BJB Enterprises, Tustin, CA; TC-5005 A/B/C). Based on the desired modulus, we added corresponding percentages of cross-linker based on past data (Carson et al., 2011; Gerling et al., 2018). These formulations were cast into nine 3-D printed molds of three radii (3, 4, 6 mm) and three moduli (10, 50, 90 kPa) to become stimulus tips, which were identical to prior computational modeling work (Wang & Gerling, 2014).

Participants

The biomechanical and psychophysical experiments were approved by the Institutional Review Board at the University of Virginia. Four subjects in total consented to participate (2 female, 2 male, mean age = 25.3, SD = 0.96). No radiographic or history evidence of upper extremity pathology or chronic disease was reported among the subjects. All subjects exhibited right hand dominance following the Edinburgh-handedness inventory (Oldfield, 1971). All subjects continued to completion and no data were discarded.

Measurement of Finger Pad to Stimulus Contact Area

An ink-based method was adopted to directly measure the contact area at various levels of force (Hauser & Gerling, 2016). This process is illustrated in Figure 1 and is briefly summarized as follows. Before each trial, washable ink (Studio G, Hampton Art Inc., Washington, NC, USA) was fully applied to a stimulus. After each indentation, the participants were instructed to carefully roll their finger pads onto a sheet of plain white paper, in order to completely transfer the stamped ink onto the paper. The stamped ink was then completely removed and the finger pad was cleaned.

A 5.0 cm scale line was drawn onto each data sheet before it was digitized and processed. The analyst identified a central mark for each fingerprint which was a non-perceptible indent in each stimulus, as well as the circumferential extent. After all the fingerprints from all the trials were identified, a desirable color threshold was selected and all fingerprints were color-enhanced. All edges of the fingerprint polygon were also clearly thresholded. Within the circle area, the boundary pixels of the fingerprint were identified and one array of exterior outline points was returned. Using the 5.0 cm scale line, the final results were calculated in pixels using Gauss's method, and then scaled to a physical area in squared centimeters.

Measurement of Fingertip Displacement

A 3-D electromagnetic tracking device (trakSTAR, Ascension Technology Corp., Shelburne, VT, USA) was used to monitor the movement of the fingertip. As illustrated in Figure 1, a Model 800 Sensor was firmly attached onto the position of distal phalange of the index finger and the positive z-axis of the sensor was initially pointed downward.

A segmentation procedure was applied to the resultant data stream based on tangential velocity. Movement onset was defined when velocity crossed 3% of peak velocity for the first time. Movement conclusion was defined as the first time tangential velocity dropped below 3% of peak velocity, after passing 50% of peak velocity (Zollo, Gallotta, Guglielmelli, & Sterzi, 2011). A moving average filter smoothed the segmented data to

remove electrical artifacts and tracking discrepancy. A transformation matrix was then applied to give finger displacement.

Experimental Procedures

Biomechanical experiment to determine contact area—To determine the relationship between force and contact area, in passive touch, the nine stimuli were each indented into participants' finger pads at four levels of force (1, 2, 3 and 4 N). The stimuli were ramped into the finger pad for one second and then retracted away for one second. In order to achieve a consistent indentation duration of 2 seconds, force-rate was controlled at 1 N/s to 4 N/s. There were three trials for each stimulus at each force level per each of three participants, for a total of 324 trials.

In the active touch experiment, participants were instructed to press the designated stimulus, as illustrated in Figure 1. The load cell recorded the imposed force. A sound alarm was triggered when peak force reached the desired level. The participants were instructed to retract and remove their finger upon hearing the alarm, and then complete the ink-based procedure for contact area measurement. Displacement of the finger was recorded simultaneously. The same number of force levels and trials were used as in the passive touch experiment.

Psychophysical discrimination experiment with controlled force.—Two alternative, forced-choice discrimination was utilized in both the passive and active psychophysical experiments to evaluate pairs of stimuli. Participants were asked to choose which of the two stimuli was less compliant. In the passive touch scenario, stimuli were temporally interchanged between successive indentations. In each force-rate controlled trial, each stimulus was indented onto the finger pad with a triangle force ramp, peaking at the 2 N level at $t = 1$ second. Only 2 N was used as this aligned with prior work (Hauser & Gerling, 2017). A total duration of 2 seconds was maintained between indents to remove the temporal influence on subjects' discrimination.

Six stimuli were prepared in passive touch discrimination. These were chosen based off of findings in the biomechanical experiments. In the 'Passive Illusion' cases, radius-elasticity parameters of the three stimuli were 10 kPa – 3 mm, 90 kPa – 4 mm, and 90 kPa – 6 mm. In contrast, the 'Passive Distinct' set consists of the three most distinct stimuli with parameters of 90 kPa – 3 mm, 10 kPa – 4 mm, and 10 kPa – 6 mm. Each participant performed a total of 45 trials, which included one randomized set of 15 trials where the same stimulus was indented twice, and another randomized set of 30 trials where different stimulus combinations were indented.

The same set of illusion stimuli were prepared for the active touch discrimination experiments. Each participant was instructed to touch the designated pair of stimuli one after the other to a peak force of 2 N.

RESULTS

Biomechanical Experiment in Passive Touch

As illustrated in Figure 2, the biomechanical relationship of force and contact area, in passive touch, was measured at four force levels. Between individuals, the force-contact area relationship appeared to be consistent. Traces for the three ‘Passive Illusion’ stimuli well overlapped across subjects, especially at the 2 N force level, which is explicitly presented in the left column in Figure 4. For the other six stimuli, traces were well separated and distinct from illusion case stimuli, especially for the three distinct stimuli used in the ‘Passive Distinct’ experiment.

Biomechanical Experiment in Active Touch

As illustrated in Figure 3, the relationship of force and contact area, in active touch, was measured at four force levels. Traces for the three illusion case stimuli well overlapped across subjects. At the force level of 2 N, the contact area results clustered around 1.0 cm², which is also explicitly presented in the right column in Figure 4. For the other stimuli, traces were well separated and quite distinct from the illusion case stimuli.

Psychophysical Experiment with Controlled Touch Force

The psychophysical discrimination experiments were performed under both passive and active touch. As illustrated in Figure 5, participants were able to discriminate the illusion case stimuli by active touch with a detection rate of 88%. In the distinct stimuli passive touch scenario, the detection rate was 78%. However, participants could not accurately discriminate stimuli of the ‘Passive Illusion’ scenarios.

Fingertip Displacement in Active Discrimination

In the active touch psychophysical experiments, fingertip displacement was monitored as participants imposed 2 N of force on the stimuli. As illustrated in Figure 6, an increase in either indenter radius or elasticity will lead to a decrease in the displacement of the fingertip. The displacement of the stimulus with the smallest radius and most compliant was clearly distinct from the other two. The difference among these three illusion cases were statistically significant by the Mann-Whitney U Test.

DISCUSSION

A better understanding of the perceptual cues that drive our judgment of object compliance is vital for building the next generation of tactile rendering displays. Here, we investigated the utility of contact area cues, by introducing a tactile illusion, whereby for spherical stimuli we varied both radius of curvature and elasticity. The hypothesis was that certain combinations would produce similar contact area interactions, which might render these stimuli perceptually indistinguishable.

Based on measurements of contact area at the finger pad surface, we indeed found that certain stimulus combinations (i.e., small compliant versus large stiff spheres, as noted in Figure 4) generate similar contact areas. Psychophysical evaluation further indicated that

these stimuli were not discriminable in passive touch yet were readily discriminable in active touch, Figure 5. This finding indicates that contact area cues alone are not vital to discrimination, though often speculated to be a main driver of compliance judgments.

Indeed, the experiments indicate that another perceptual cue likely augments contact area. In cases where contact area cues are non-differentiable, supplementary cues based on stimulus rate and/or proprioception may prove vital. For instance, subjects may rely on proprioceptive cues, such as finger displacement given a volitionally applied force, as illustrated in the ‘Active Illusion’ case, Figure 6. A proprioceptive cue of this nature also tends to align with conclusions generated from computational modeling (Wang & Gerling, 2014). That said, our results on this particular, singular metric are certainly not definitive, but serve as one possible starting point.

Furthermore, the findings herein only considered contact area at steady state, where maximum force was applied. The rate of change of contact area was not considered. Prior work by our group has indicated that contact area is highly correlated with the displacement of a stimulus into the skin (Hauser & Gerling, 2017). A next step might consider at the change of stimulus rate over the time course of both passive and active stimuli, for example, the change in contact area rate, or change in force rate or displacement rate.

Finally, contact area only informs us of a contiguous area on the skin with a super-threshold contact pressure. It does not contain full information on how such pressure is spatially distributed in skin layers that house the end organs of mechanosensitive afferents. For this reason, for example, one is able to distinguish a cylindrical object (peak pressure at edge) from a spherical object (peak pressure at center) even though they may present similar contact areas. With the help of computational modeling of the skin, one might analyze the impact of such pressure distributions, and perhaps tie these to the recruitment of populations of mechanosensitive afferents.

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Figure 1.

Experimental setups and contact area analysis of fingerprints. A) In the passive touch case, the finger pad rests under the fixture where the designated stimulus is mounted. The indenter units are firmly attached to a cantilever which indents vertically into the finger pad. Vertical contact force is recorded by the load cell. B) In the active touch case, a participant is instructed to touch the designated stimulus mounted on the load cell. The motion sensor tracks the position of the finger in real time. C) Fingerprints are stamped onto a sheet of white paper, and then digitized for analysis. D) Target fingerprints are identified and color-enhanced. The exterior outlines of the fingerprints were digitized into polygon shapes. E) Contact area is calculated using Gauss's formula based on the exterior outline.

Figure 2.

In passive touch, biomechanical relationships of force and contact area for all nine stimuli. Left: Force-contact area relationship for one example subject. Right: Force and contact area relationships for all three subjects aggregated. Error bars denote 90% confidence intervals.

Figure 3. In active touch, biomechanical relationships of force and contact area for all nine stimuli. Left: Force-contact area relationship for one example subject. Right: Force and contact area relationships for all three subjects aggregated. Error bars denote 90% confidence intervals.

Figure 4. Contact area measured at 2 N for the three tactile illusion case stimuli. Left: Passive touch data retrieved from the right column in Figure 2. Right: Active touch data retrieved from the right column in Figure 3. Error bars denote standard deviation.

Figure 5.

Psychophysical experiment results in which three tactile illusion stimuli were used in both active and passive experiments, denoted as 'Active Illusion' and 'Passive Illusion'. In contrast, three most distinct stimuli were used in passive experiment with one subject, denoted as 'Passive Distinct.' Error bars denote standard deviation.

Figure 6. Displacement measurements with all three subjects aggregated in which three tactile illusion stimuli were presented in active psychophysical experiments. **Significance and ****significance are denoted at $p < .01$ and $p < .0001$ by the Mann-Whitney U Test, respectively. Outlier observations are indicated. Error bars denote standard deviation.