Tactile Exploration Strategies with Natural Compliant Objects Elicit Virtual Stiffness Cues

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***Abstract*—When interacting with deformable objects, tactile cues at the finger pad help inform our perception of material compliance. Nearly all prior studies have relied on highly homogenous, engineered materials such as silicone-elastomers and foams. In contrast, we employ soft plum fruit varying in ripeness; ecological substances associated with tasks of everyday life. In this context, we investigate volitional exploratory strategies and contact interactions, for comparison to engineered materials. New measurement techniques are introduced, including an ink-based method to capture finger pad to fruit contact interactions, and instrumented force and optical sensors to capture imposed force and displacement. Human-subjects experiments are conducted for both single finger touch and two finger grasp. The results indicate that terminal contact areas between soft and hard plums are indistinguishable, but the newly defined metric of virtual stiffness can differentiate between the fruits' ripeness, amidst their local variations in geometry, stiffness, and viscoelasticity. Moreover, it affords discrimination independent of one's touch force. This metric illustrates the tie between the deployment of active, exploratory strategies and the elicitation of optimal cues for perceptual discrimination. Compared to single finger touch, perceptual discrimination improves further in pinch grasp, which is indeed a more natural gesture for judging ripeness.**

***Index Terms*—Human perception, haptic, tactile, ecological.**

I. Introduction

In our activities of daily living, we frequently interact with soft, compliant, and deformable objects. For example, we might judge the ripeness of a fruit or touch the arm of a friend to offer comfort [1], [2]. In more specialized environments, such as surgery, physicians may seek to distinguish tissue and ducts from fat and bone or palpate abnormalities. Such daily interactions require us to judge, recognize, and discriminate among individual objects and groups of objects. We do so by deploying active, exploratory procedures and relating the present context with our prior experiences and expectations.

Many on-going efforts are refining our understanding of the physical and perceptual cues that help encode our sense of compliance. Distinct efforts have focused upon cutaneous cues of contact area, skin deformation and spatial distribution of pressure [3]–[6]. However, recent studies have shown that the terminal contact area is not readily discriminable, and additional cues likely augment our judgments of compliance [7]–[10]. Among those, our proprioceptive system provides vital inputs through the kinesthetic sense of joint angles [10], spatiotemporal patterns in cutaneous contact [11], and visual-haptic integration [12]–[14]. These physical cues are recruited and integrated into multimodal signals, fine-tuned by optimal exploratory strategies, which modulate sensorimotor movements [15], and then transferred to perceptual space where compliances may be discriminated. It is highly likely that strategies vary between person, task, and compliance range. That said, certain exploratory movements are more optimal than others and can more efficiently link with and elicit certain perceptual cues, especially those mediated by interactions with naturalistic objects where our tactile sensory system has been finely tuned.

However, most current studies of compliance interactions use engineered materials, such as silicone-elastomers, foams, and robotic devices to stand-in for ecological materials. This is done because of the difficulty of acquiring, controlling, and quantifying the properties of naturally occurring soft objects such as animal or plant tissue, both from sample to sample and over time. To this point, in naturalistic settings, there have been very few studies of human interaction with ecological stimuli. For example, Katz (1938) studied bakers in their occupational interactions with dough and like substances, breaking down dimensions such as stickiness and elasticity [16]. Weber, et al. employed surface textures associated with fabrics, e.g., velvet, fleece, and drapery tape [17]. Another effort assessed the visual and tactile perception of the shape of bell peppers [18]. Recently, Cavdan, et al. considered perceptual dimensions of a very wide array of soft naturalistic objects and their associated exploratory procedures [19]. In a different field of study, robotics researchers have sought to sense differences in the properties of fruits and other naturalistic objects in order to sort, grasp, and manipulate them [20], [21].

In summary, we do not yet understand which exploratory strategies elicit which perceptual cues that most optimally encode the material compliance of ecologically relevant objects. As a step in this direction, this work uses a multi-measurement approach in studying the exploratory strategies and contact interactions with soft plum fruit in both single finger touch and two finger grasp.

II. Methods

The work herein studies human perception alongside physical contact interaction cues in the discrimination of a naturally-occurring compliant object, the plum. The plum was chosen because it is commonplace, can be grasped in one hand, and represents a naturalistic task in which compliance discrimination might determine relative ripeness. Methods were developed and adapted for use with this natural object. In particular, an ink-based method was used to capture the finger pad to stimulus contact area, and force sensors and a non-contact laser captured imposed force and fingertip displacement. Setups were built such that plum interactions could be measured for single finger touch and thumb-index pinch grasp. In a human-subjects study with thirteen participants, five pairs of plums were used, each with one riper than the other. Psychophysical experiments were performed alongside biomechanical measurements, where participants operated under their own active, volitional control of their finger movements. The resultant physical contact and interaction cues were analyzed. Several considerations in the experiment's design were made to accommodate the readily perishable and easily damaged fruit specimens.

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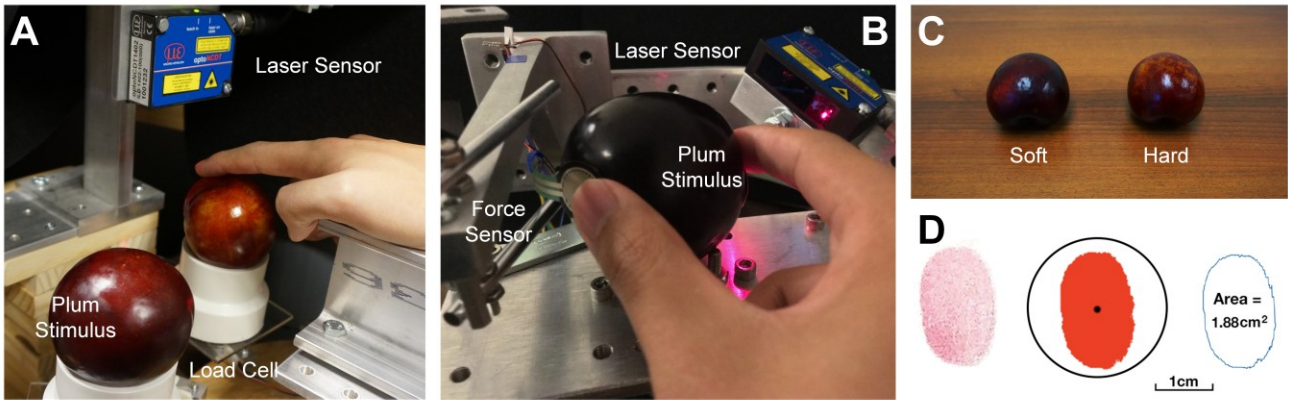

Figure 1. Experimental setup of test rigs and ink-based contact area analysis. A) In the setup for single finger touch, a set of two platforms is installed on a rotary table to present the designated plum. Imposed force is measured by a load cell underneath each platform. The position of the fingertip is monitored by a laser displacement sensor. B) The setup for thumb-index pinch where the plum is grasped and held in a horizontal orientation. Grasp force is the average reading of two force sensitive resistors which are firmly attached to the plum's surface and are contacted by the finger pad(s). The position of the index fingertip is tracked by the laser sensor. C) One pair of soft and hard plums. D) Plum contacted fingerprints are stamped onto a sheet of white paper and then digitized. The contact region is identified and color-enhanced. Contact area is calculated using Gauss's formula based on the exterior outline and scaled pixels.

A. *Experimental Apparatus*

For the grounding condition of single finger touch, an experimental test rig was built as shown in Fig. 1A. Specifically, two platforms were installed on a fine-adjust rotary table that can be rapidly rotated into position to present the designated stimuli. Each of the platforms was fitted with a circular pipe upon which the spherical object was set and could be rotated. An instrument load cell (5 kg, HTC Sensor TAL220B, China) was mounted beneath each platform to measure the imposed force at 80 Hz. A non-contact laser displacement sensor (optoNCDT ILD 1402-100, Micro-Epsilon, Raleigh, NC) was mounted above to measure the position of the participant's fingertip nail at 1.5 kHz. The participant's forearm and wrist rest on a beam parallel to the table surface without constraints.

For the condition of thumb-index pinch grasp, a test rig was built as shown in Fig. 1B. The plum was held by four carriage bolts which fixed on the platform so that participants could grasp the plum on the bolts. Force sensitive resistors (0.1-10 kg, Interlink Electronics 400/402, Camarillo, CA) were firmly attached on symmetrical sides of the plum and contacted by the thumb and index finger pads in measuring touch force. The position of the index finger was measured by the aforementioned laser sensor, mounted horizontally.

B. *Naturalistic Stimuli*

Ten plums were employed in the experiments. Of several varieties available, the pluot (Honey Punch Pluot) was selected, which is a hybrid fruit developed in the late 1980s that is 75% plum and 25% apricot. They resemble plums with smooth skin and similar shape and originate from California, USA. The perceptual effects brought by surface roughness and texture can be eliminated due to the smooth surface of the plum. The plums were about 6.3 ± 0.2 cm in diameter. A brief psychophysical experiment was conducted to establish basic discriminability of the plums. This experiment used an insertion sort procedure to evaluate the compliances, resulting in a sorted plum array from the hardest P_1 to the softest P_{10}. The first five were denoted as the "hard" plums, with the last five as the "soft" plums. Finally, five pairs consisting of one hard and one soft plum were assigned accordingly as: (P_1, P_6), (P_2, P_7), (P_3, P_8), (P_4, P_9), and (P_5, P_{10}). In the subsequent experiments, each pair was used by one of the five participant groups respectively, and those experiments were completed within 24 hours of purchase. The number of times a location on the plum successively touched was controlled to avoid irrevocable damage to the plums.

C. *Measurement of Displacement and Force-rate*

As illustrated in Fig. 1A, the emitted laser was aimed at the surface of the participant's fingernail to monitor its position. Readings from the laser sensor were smoothed to remove any electrical artifacts by a moving average filter with a window of 100 neighbor values. Fingertip displacement was derived by the absolute difference between initiation and conclusion of the finger movement. On the other hand, to calculate force and force-rate, readings from the force sensor were first filtered by the aforementioned filter. The ramp segments were then extracted according to the first-order derivatives. As reported previously, the ramp onset and ending were defined based on the peak derivatives [10]. Finally, a linear regression was applied to the ramp and the slope was noted as the force-rate.

D. *Measurement of Virtual Stiffness*

Stiffness describes the resistance of an elastic object to deformation or deflection by an applied force. In active exploration of compliant objects, physically perceived stiffness – i.e., the relation between force and displacement – could be utilized to encode the perception of compliance [22]. The overall estimate of virtual stiffness K was derived by a data fusion procedure where two individual observations of the perceived stiffness were combined through the Kalman filter: $K = x_1 + \sqrt{\sigma_1^2 / (\sigma_1^2 + \sigma_2^2)}(x_2 - x_1)$ where $x_{1,2}$ and $\sigma_{1,2}$ denoted the mean

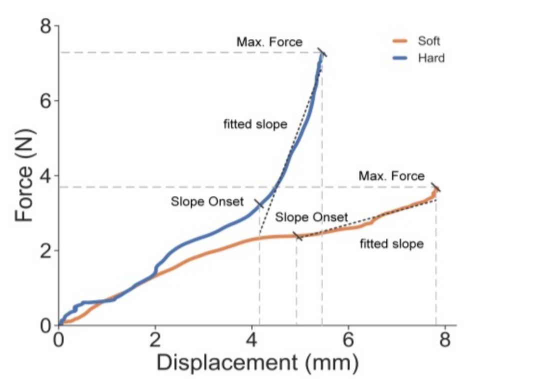

Figure 2. Relationships of touch force and fingertip displacement for exemplar soft and hard plums for one trial. A linear regression is applied to the segments from slope onset to the peak to obtain the rate of change of the curve, defined as the observation of fitted virtual stiffness.

and standard deviation of aggregated experimental results of these two observations respectively. The first observation from the peak point was derived as the maximum applied force divided by the corresponding fingertip displacement, as done with a simple physical model in tapping. The second observation was derived from the fitted slope. As shown in Fig. 2, the ramp of the force-displacement curve was extracted by the same procedure as aforementioned. Linear regression was applied to obtain the rate of change of the ramp, defined as another observation of virtual stiffness.

E. Measurement of Contact Area

An ink-based method developed in prior work was applied to measure the gross contact area between the plum surface and finger pad at various levels of imposed force [5], [23]. An overview of the basic steps is shown in Fig. 1D, and detailed as follows. Washable ink (Craft Smart, Michaels Stores, Inc., Irving, TX) was fully applied onto the plum surface at the beginning of each trial to ensure there is always a sufficient amount left on the surface. After contact with the plum, the participant was instructed to gently indent the finger pad onto a sheet of plain white paper, fully transfer the stamped ink. Before each new trial, remaining ink was completely removed from the finger pad. After all trials were completed, each individual's sheet of fingerprints was digitized and processed with a 5.0 cm scale line. Custom-software was used for analysis. In particular, the analyst identifies a center point within each fingerprint, as well as the region enclosing the fingerprint. The desired color threshold is selected to enhance the image. Next, a serial search is conducted within the identified region of interest to outline the area with boundary pixel points. After determining the length of each pixel in centimeters via the scale line, the final area is calculated using Gauss's formula and scaled in squared centimeters.

F. Data Normalization

To aggregate experimental results across all participants, a data normalization procedure is required because of distinct perceptual capabilities among participants. For each task, all recordings of a measured tactile cue from each participant were first normalized to the range of (0,1) by the sigmoidal membership function [10] and then aggregated across all participants. The value of the sigmoid midpoint was set as the average of the data normalized, and the sigmoid function's slope was set to 1.

G. Participants

The study was approved by the Institutional Review Board at the University of Virginia. In total, 13 healthy subjects were recruited to participate in this study (8 females, 5 males, mean age = 24.8, SD = 2.0). According to Edinburgh-handedness inventory, all participants were right-handed [24]. All participants provided informed consent and were assigned to five plum pairings consisting of 3, 2, 2, 2, and 4 members, respectively. The first four groups completed Task 1-4 and the last group completed the second part of Task 4 only. The third participant in group 1 completed only Task 1-3 because the experimenters were concerned that the plum had been irrevocably damaged and would not yield reliable results. Additionally, note that the data on fingertip displacement and virtual stiffness from group 1 are not shown because the finger (due to its small size) moved out of the range of the laser on some trials. This went unnoticed until after all tasks were completed and 4.9% trials were discarded in total.

H. Experiment Procedures

1) Task 1: Biomechanical Measurement with Behaviorally Controlled Force in Single Finger Touch

To measure the biomechanical relationship between imposed force and contact area in single finger touch, this task was designed where force levels (2, 4, and 6 N) were behaviorally controlled and presented during three sessions respectively. The test order of the sessions was randomized to balance the effects of fatigue or inattention. Participants were instructed to press the index finger downward into the stimulus and a sound alarm was triggered to end the trial when the force reached a predefined constraint. The contact area was then measured by the ink-based method. For each participant in group 1, there were two trials for each plum at each force level, for a total of 36 trials. For the other groups, there were three trials for each plum at each force level, for a total of 108 trials. All trials were separated by a 20-second break.

2) Task 2: Psychophysical Discrimination with Fully Active Touch in Single Finger Condition

Psychophysical discrimination of three combinations of the two plums in one pair (soft-hard, soft-soft, and hard-hard) was conducted under the participants' fully active, volitional control. Combinations were presented in a randomized order. Participants were blindfolded to remove visual information about the plum ripeness and their finger movements. Using the same-different procedure, after exploring both stimuli from one combination, participants were instructed to report whether the compliances of the two were the same or different. Force and displacement were recorded simultaneously. Each participant completed three trials for each combination, for a total of 81 trials. All trials were separated by a 30-second break.

3) Task 3: Psychophysical Discrimination with Fully Active Touch in Pinch Grasp

The same three combinations for each plum pair were randomly presented in this task. Participants were instructed to use the thumb and the index finger to pinch the plum on the fixed bolts horizontally, as illustrated in Fig. 1B. After exploring both plums, participants reported whether the compliances of the two plums were the same or different. Each participant completed three trials for each combination, for a total of 81 trials. All trials were separated by a 30-second break.

4) Task 4: Biomechanical Measurement with Behaviorally Controlled Force in Pinch Grasp

In the first part, the biomechanical relationships between force and contact area were measured at three behaviorally controlled force levels (low, medium, and high) which were presented during three randomly ordered sessions. Participants pinched the presented plum at their own volitional control and notified the experimenter to end the current trial when the grasp force reached the desired level. The contact area was then measured by the ink-based method. For group 1, there were two trials for each plum at each force level, for a total of 24 trials with two participants. For the other groups, there were three trials for each plum at each force level per each participant, for a total of 108 trials. All trials were separated by a 20-second break.

In the second part, the biomechanical measurement on grasp force and index finger displacement were conducted at two force levels (low

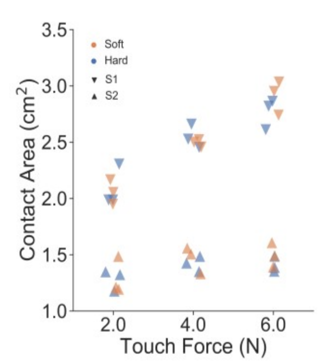

Figure 3. For the index finger touch, biomechanical relationships of force and gross contact area for the soft-hard plum from two participants.

and high). Force sensors were contacted and covered by the finger pads over the course of one trial. Participants notified the experimenter to end the current trial when they perceived the applied grasp force has reached the desired levels. There were 10 trials for each plum at each force level, for a total of 80 trials with two participants. For the other two participants, there were 9 trials for each plum at each force level, for a total of 72 trials. All trials were separated by a 20-second break.

III. Results

A. Biomechanical Cues in Single Finger Touch

Biomechanical relationship of touch force, contact area, and fingertip displacement in single finger touch was measured at three force levels. As shown in Fig. 3, within each participant, gross contact areas for the soft and hard plums were overlapped to be non-distinct across all force levels. Differences between the two participants were mostly due to the individual dimensions of their finger pads. With all participants aggregated, gross contact areas were overlapped to be non-differentiable, as shown in Fig. 4. This indicated that participants could not rely only upon gross contact area cues in differentiating the compliances of the soft and hard plums.

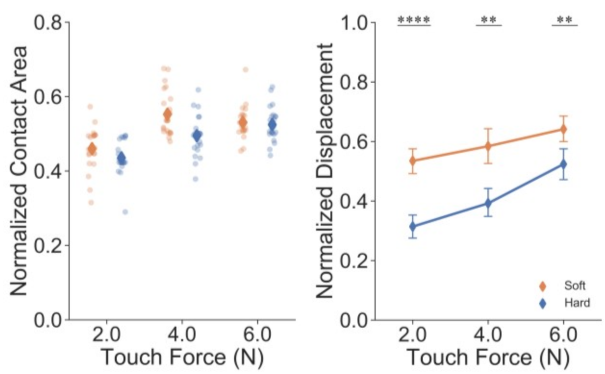

Figure 4. For the single finger touch, biomechanical relationships of force, contact area, and displacement for the soft and hard plums. Left: Normalized contact area and force with all trials aggregated. Points denote the trial data and diamonds denote the means. Right: Normalized displacement and force with all trials aggregated except for the first group. The **significance and ****significance are denoted at p < 0.01 and p < 0.0001 by a paired-sample t-test. The Cohen's *d* values of the significant results are -1.79, -1.18, and -0.81 respectively. Error bars denote 95% confidence intervals.

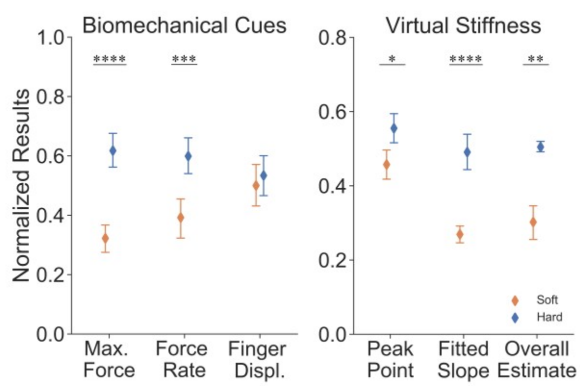

Figure 5. For the single finger touch, perceptual cues in discriminating the soft-hard plums with all participants except for group 1. Left: Normalized peak force, force-rate, and displacement. Right: Normalized observations of peak point, fitted slope, and overall estimate of the virtual stiffness. The *significance, **significance, ***significance, and ****significance are denoted at p < 0.05, p < 0.01, p < 0.001, and p < 0.0001 by a paired-sample t-test. The Cohen's *d* values of the significant results are 1.15, 0.67, 0.45, 1.04, and 2.94 respectively. Error bars denote 95% confidence intervals.

As shown in Fig. 4, fingertip displacements were well separated for the soft and hard plums. Participants applied significantly higher fingertip displacements for the soft plums as opposed to the hard ones (2 N: $t_{(17)} = -6.929$, $p < 0.0001$; 4 N: $t_{(17)} = -3.210$, $p < 0.01$; 6 N: $t_{(17)} = -2.244$, $p < 0.01$). This indicated that, in the behaviorally-controlled condition, when touch force is volitionally controlled to be the same, participants could still control their finger movements to elicit significantly different displacement cues between soft and hard plum pairs. These results are in line with prior work done with engineered stimuli [7], [9], [10].

B. Perceptual Cues in Psychophysical Discrimination with Single Finger Touch

Perceptual cues of force and displacement were measured for single finger touch. As shown in Fig. 5, participants applied significantly higher peak force ($t_{(80)} = 5.725$, $p < 0.0001$) and force-rate ($t_{(80)} = 2.871$, $p < 0.001$) for the hard plums. Note that the aggregated R^2 value for the force-rate fit was 0.98 ± 0.01 (mean ± SD). In contrast, similar fingertip displacements were applied in discrimination. This indicated that in fully active exploration, participants tended to volitionally control their movements to obtain similar displacement and applied discriminable force-related cues between the soft and hard plums. This finding aligns with prior work showing the same strategy in discriminating the compliances of man-made stimuli [10], [15].

As shown in Fig. 5, virtual stiffness was calculated for the soft and hard plums. For the observations of the peak point ($t_{(80)} = 2.289$, $p < 0.05$) and fitted slope ($t_{(80)} = 4.695$, $p < 0.0001$), significantly higher stiffness values were obtained for the hard plums. Note that the aggregated R^2 value for the fitted slope was 0.89 ± 0.09. The overall estimate yielded the same result by the data fusion procedure ($t_{(5)} = 5.628$, $p < 0.01$). These results indicated that the human perceived stiffness, as quantified in our measurement setup via virtual stiffness, indeed aligns with the actual compliance of the stimuli. Furthermore,

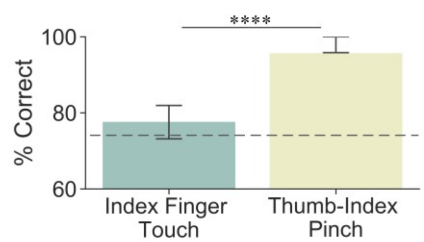

Figure 6. Psychophysical discrimination in the soft-hard plums with all participants aggregated. The discrimination threshold is set as 75 %. The ****significance is denoted at p < 0.0001 by a paired-sample t-test. The Cohen's *d* value is -1.11. Error bars denote 95% confidence intervals.

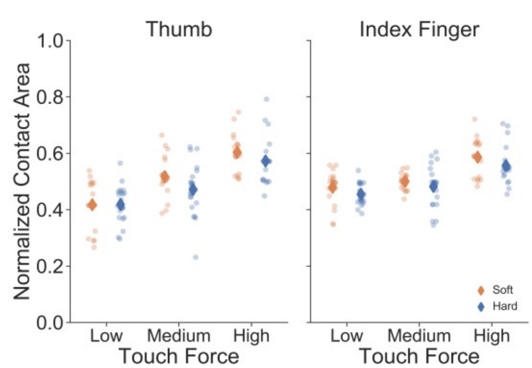

Figure 7. For the thumb-index pinch grasp, biomechanical relationships of touch force and contact area in the thumb (left) and index finger (right) for the soft and hard plum with all trials aggregated. Points denote the data from each trial and thin diamonds denote the mean values.

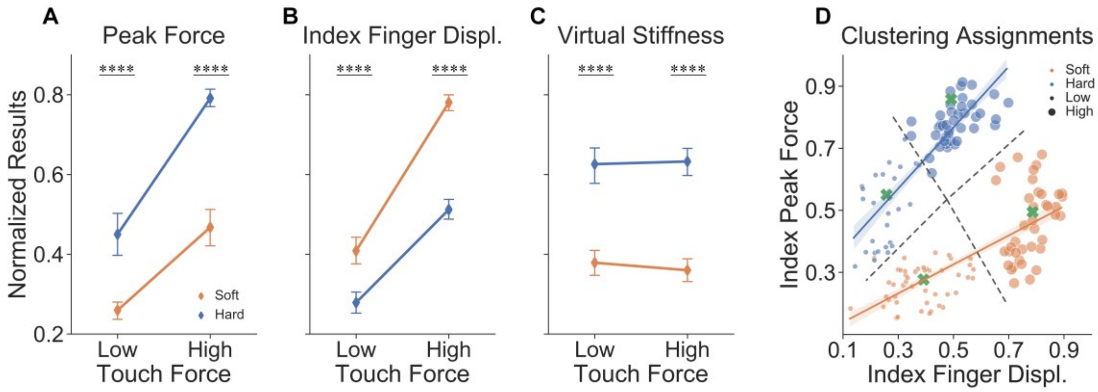

Figure 8. For the thumb-index pinch, biomechanical measurements of physical cues and multidimensional clustering analysis. Normalized results of peak grasp force (A), fingertip displacement (B), and overall estimate on virtual stiffness (C) for the soft and hard plums with all trials aggregated. The ****significance is denoted at $p < 0.0001$ by a paired-sample t-test. Error bars denote 95% confidence intervals. The Cohen's *d* values of the significant results are 1.67, 3.52, -1.33, -3.84, 2.01, and 2.69 respectively. D) All trial data are partitioned into four exclusive clusters based on peak grasp force and displacement. Centroids and dashed line indicate the cluster regions. Linear regression procedures are applied to visualize the correlation on clustered data. Translucent bands denote 95% confidence intervals for regression estimations.

the metric of virtual stiffness gives insight into the exploratory strategies, in particular, the relationship between applied force and fingertip displacement in discriminating compliances. Participants indeed volitionally control their fingertip displacement to obtain differentiable quantities of force.

C. *Psychophysical Discrimination in Two Conditions*

As shown in Fig. 6, when discriminating with index finger touch, participants were able to differentiate the soft and hard plum with a threshold detection rate of 77.8%. Under the index-thumb pinch grasp condition, participants were able to improve their discrimination performances significantly with a correct response rate of 95.8% ($t_{(8)}$ = -3.290, $p < 0.0001$). This indicated that compared to the single finger touch, with additional perceptual cues evoked by the pinch grasp, participants could achieve better discrimination performance in a more natural manner.

D. *Biomechanical Cues in Thumb-Index Pinch*

As shown in Fig. 7, biomechanical relationships of force and contact area were measured at three force levels. Compared to the single finger touch, with the stabilization support from the thumb, greater terminal contact area was obtained. However, for both fingers, the contact areas for soft and hard plums were still overlapped to be non-distinct. This indicated that the terminal contact area is not vital to discrimination, independent of force. The improved performance in pinch grasp may likely result from other perceptual inputs.

As shown in Fig. 8A, a significantly higher peak force was applied to the hard stimuli across all force levels (Low: $t_{(37)}$ = 6.751, $p <$ 0.0001; High: $t_{(37)}$ = 17.554, $p < 0.0001$). For the low force level, peak force was significantly lower compared to the high level (Soft: $t_{(37)}$ = 11.096, p < 0.0001, Hard: $t_{(37)}$ = 13.062, p < 0.0001). This indicated that participants could indeed behaviorally control their movements to accurately impose touch forces according to the instructions. This result in part aligns with prior work demonstrating that the indentation force is related to the experimenter's instructions during active haptic exploration [25]. As shown in Fig. 8B, significantly higher displacement was applied for the soft plum (Low: $t_{(37)}$ = -5.375, $p <$ 0.0001; High: $t_{(37)}$ = -14.575, $p < 0.0001$). As shown in Fig. 8C, significantly higher virtual stiffness was obtained for the hard plums (Low: $t_{(37)}$ = 6.850, $p < 0.0001$; High: $t_{(37)}$ = 8.524, $p < 0.0001$). Note that the aggregated R^2 value for the virtual stiffness fit was 0.94 ± 0.12. However, there is no significant difference for virtual stiffness across different force levels (Soft: $t_{(37)}$ = -3.790, p = 0.395, Hard: $t_{(37)}$ = 0.285, p = 0.820). This indicated that virtual stiffness is a reliable measure to quantify the compliance of the plums, independent of touch force. Indeed we observe, in the psychophysical discrimination with single finger, that participants volitionally control fingertip displacement to perceptually differentiate force.

Multidimensional clustering analysis was conducted to verify which perceptual cue could optimally discriminate the compliances. As shown in Fig. 8D, plum compliances could not be differentiated solely by peak grasp force or fingertip displacement. In contrast, the combination of these two cues could partition all trial data into four exclusive groups by the *k*-Means algorithm. The match rate between original and clustered data was 92.1%. Each group represented a combination of plum compliance (soft or hard) and peak force (low or high), which was partitioned into the four cluster regions. Linear regression procedures were applied to the clustered data. The Spearman's rank coefficient yields correlations of 0.86 (p = 1.01e-20) and 0.77 (p = 6.24e-18) for the hard and soft plums respectively. These statistics quantify particular correlations between peak force and fingertip displacement cues by which different compliances may be encoded. Together, they reinforce that the virtual stiffness cue could afford discrimination by solely correlating force and displacement.

IV. Discussion

The work herein – to the authors' knowledge – is the first of its kind to quantify touch interaction cues and exploratory strategies that drive our perception of naturalistic and ecological interactions, in particular, the palpation of soft plum fruit. Nearly all prior work to study human perception of compliance, upon direct bare finger contact, has been performed with silicone-elastomers and foams. To enable such study, sophisticated measurement techniques and experimental designs were developed and adapted for work with these natural objects. Overall, we find that gross contact area cues were non-differentiable for the soft-hard plums. In contrast, touch force and fingertip displacement differed significantly. These two variables were coupled into the virtual stiffness cue, which quantified the perceived compliances and differed significantly in discrimination (Fig. 5). The newly defined metric of virtual stiffness illustrates how volitional strategies of exploratory movement may be tuned to generate discriminable perceptual cues. In fully active exploration, participants tended to move their fingers to particular displacements so as to elicit differences in reaction force, driving the discrimination of naturalistic compliances (Fig. 5). We also noted that discrimination improved significantly for the more natural interaction of pinch grasp, despite non-differentiable gross contact areas (Fig. 6). Indeed, for judging the differences in ripeness between the fruit stimuli, in addition to the gross contact area, virtual stiffness cues likely augment discrimination.

Noteworthy, there is no prior studies that evaluate the equivalence of perceptual strategies with silicone-elastomers, foams and other engineered stimuli to ecologically naturalistic materials. Interestingly enough, however, we do find that engineered stimuli are, in general, reasonable approximations to these ecologically compliant objects. In particular, there was a consensus on the role of peak force as a reliable perceptual cue [5], [10], [15], [25]. Moreover, exploratory strategies described in prior studies aligned with the exploration of the soft fruit. Specially, when discriminating soft-hard plums, participants tended to volitionally match their displacement cues so to elicit discriminable force-related cues (Fig. 5), although displacement cues could also be utilized when force cues are behaviorally controlled to be non-distinct (Fig. 4). Similar findings were reported when terminal contact area cues are non-differentiable [10]. Such exploratory strategies can be quantified by the virtual stiffness which maps the estimate of perceived stiffness from physical relation between touch force and fingertip displacement. As shown in Fig. 8C, virtual stiffness can accurately quantify the perceived stiffness and map it to the actual compliance of the plums. Further clustering analysis reinforced that the integration of force and displacement – quantified by the virtual stiffness cue – could optimally afford discrimination between plum fruit, independent of the touch force one imposes.

Furthermore, the findings herein consider tactile cues only at terminal indentation. Cues of a time-dependent nature, e.g., the rate of change of contact area, 3D deformation of the skin, and force/displacement rate may afford optimal efficiency and fidelity. Specially, the spatiotemporal change of contact surface can induce proprioceptive cues [8], [11]. Moreover, temporal cues of force and displacement, quantified by information within the ramp onset in Fig. 2, may further aid in encoding the percept of compliance [5], [26].

Several aspects regarding the experimental design could be taken into account for future work due to inherent difficulties in working with delicate objects that change over time, such as ripe fruit. Finally, the plum represents one instantiation of a natural object of our daily interactions. Others as well are of interest, including tissues of the body, amongst others. More effort is needed to consider these and associated cues and ties back to the perception of compliance, and how to represent such natural objects with robust representations akin to silicone-elastomers and foams.

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