Individual Performance in Compliance Discrimination is Constrained by Skin Mechanics but Improved under Active Control

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Abstract— **Tactile acuity differs between individuals, likely a function of several interrelated factors. The extent of the impact of skin mechanics on individual differences is unclear. Herein, we investigate if differences in skin elasticity between individuals impact their ability to distinguish compliant spheres near limits of discriminability. After characterizing hyperelastic material properties of their skin in compression, the participants were asked to discriminate spheres varying in elasticity and curvature, which generate non-distinct cutaneous cues. Simultaneous biomechanical measurements were used to dissociate the relative contributions from skin mechanics and volitional movements in modulating individuals' tactile sensitivity. The results indicate that, in passive touch, individuals with softer skin exhibit larger gross contact areas and higher perceptual acuity. In contrast, in active touch, where exploratory movements are behaviorally controlled, individuals with harder skin evoke relatively larger gross contact areas, which improve and compensate for deficits in their acuity as observed in passive touch. Indeed, these participants exhibit active control of their fingertip movements that improves their acuity, amidst the inherent constraints of their less elastic finger pad skin.**

I. Introduction

We develop individual differences in touch acuity and exploratory procedures from daily interactions in our natural environment [1], [2]. For instance, individuals respond distinctly when discerning delicate textures using the fingertips [3], employ pressing, rubbing, or pinch grasp to judge the ripeness of soft fruits [4], [5], or encounter diverse levels of pleasantness under the same stroking over the arm [6]. In addition to these observed differences, individuals also inherently differ in their skin's mechanics, finger size and neural afferent density, and age-related factors tied to neural sensitivity; and thus, internal percepts of touch [2], [3].

Individuals interact in unique ways with new haptic displays [7], [8]. Likewise, the lack of tactile acuity for such haptic devices seems to arise primarily from the failure of designers to distinguish individualized characteristics [7]–[9]. Specifically, physical contact characteristics – e.g., contact regions, finger postures, surface pressure – vary widely across distinct users but are highly consistent within an individual [7]. Therefore, replicating a universal tactile paradigm alone does not afford perceptual acuity for distinct individual users, and may attenuate the fidelity and realism of tactile displays. The task of investigating the perceptual mechanism that underlies individual differences remains timely and relevant.

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As the primary interface in tactile exploration, the material properties of an individual's finger pad skin may directly affect their perceptual judgements [2], [10]. Indeed, naturalistic variance in skin mechanics – e.g., surface geometry, stiffness, elasticity – can directly impact mechanotransduction in cutaneous afferents, thus, forming individuals' tactile sensitivity [11]–[13]. In particular, skin sites with lower thickness exhibit a lower perceptual threshold to applied pressure [14]. Meanwhile, the increased skin elasticity, or "hardness", could render a lower perceptual sensitivity to surface pressure stimulus [14], [15]. Similar to elasticity, individuals with more compliant finger pad skin exhibit substantially lower perceptual thresholds in grating orientation discrimination, especially for younger individuals [2]. Furthermore, there is gathering evidence showing that individuals' tactile acuity differs between fingertip size and gender. Specifically, improved tactile spatial acuity is coupled with decreased fingertip size [3], [16], thus, superior perception performance is found in women who on average have relatively smaller fingers than men [3], [11]. Indeed, a higher density of tactile afferents in smaller fingers may result in a finer-grained neural encoding of tactile stimuli [3], [10]. By modulating the firing properties of tactile afferents, distinct skin material properties could impact sensitivity between individuals.

In summary, it remains unclear how and if distinct skin mechanics impact perceptual performance between individuals. As a step in this direction, this work studies individuals' tactile acuity in discriminating compliances amidst inherent constraints of skin elasticity. In particular, we focus on younger participants and stimuli near the limit of tactile discriminability. By employing compliant spheres that vary in elasticity and curvature to afford non-distinct cutaneous, contact area cues, we delineate the roles of inherent individual differences in skin mechanics and volitional exploratory movements in impacting an individual's acuity.

II. Methods

The work herein investigates how skin mechanics and exploration strategy might modulate individual differences in tactile acuity, particularly, in discriminating compliances. The methods include computational modeling of individuals' skin mechanics, as characterized by compression loading, whereas biomechanical measurements and psychophysical evaluations are conducted in differentiating small-compliant and large-stiff spheres in bare finger touch. Specifically, a finite element model of the distal finger pad was fitted for each individual to derive elastic moduli of one's skin under compression. Then, cutaneous cues evoked upon finger-to-stimulus contact – e.g., interior stress magnitude and gross contact area – were quantified in both passive and active touch interactions, via numerical simulations, customized setups, and biomechanical measurements. Finally, psycho-

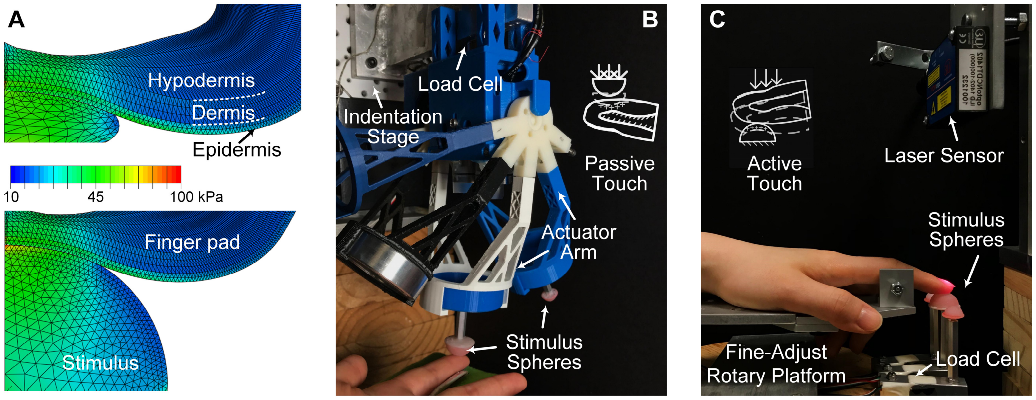

Figure 1. Computational modeling and experimental platforms for the finger pad-to-stimulus contact. (A) In finite element analysis, skin mechanics of the distal finger pad are modeled in simulated contact interactions with compliant stimuli. Hyperelastic material properties of three tissue layers are characterized and spatial distribution of stress is derived as the cutaneous response. (B) In passive touch, the spherical stimulus is indented into the stationary finger pad where the normal contact force is measured by a uniaxial load cell. (C) In active touch, the fixed stimulus is contacted by the index finger of the participant's own volition. Touch force and fingertip movement are measured by the load cell and laser sensor, respectively.

physical responses in discriminating compliances were evaluated using the psychophysical and signal detection methodologies. The derived tactile acuity for individuals was compared with corresponding skin elasticity and resultant tactile cues, thus revealing how individual differences in somatosensory perception could be attributed to distinct skin material properties and contact mechanics.

A. Geometry and Material Properties of the Model

The material elasticity of each participant's finger skin was characterized using two finite element models. Derived from the 3D geometry of the human distal phalanx bone [17], two simplified 2D models with plane-strain and axisymmetric elements were constructed [17]. Specifically, finger bones and nails were modeled as analytic rigid bodies and three layers of soft tissues were modeled as deformable bodies wrapped around the bone, namely epidermis, dermis, and hypodermis (Fig .1A). Triangular meshes were used throughout models with about 0.25 mm wide elements.

Hyperelastic material properties were used of the Neo-Hookean form of the strain energy function:

$$\Psi = C_{10}\left(\bar{I}_1 - 3\right) + \frac{1}{D_1}\left(J-1\right)^2, \tag{1}$$

where C_{10} and D_1 were material constants, $\bar{I}_1$ was the modified first strain invariant, and J was the volume ratio. Herein, the material elasticity was referred as its shear modulus G so that only one parameter is needed for material fitting, resulted in a more robust calibration. Instead of using a linear Young's modulus, a hyperelastic form was used to better simulate the deformation of soft objects in a finite-strain region.

B. Fitting Elasticity Ratio of Skin Layers

The initial modulus of hypodermis was set as 1 kPa [18] and the ratio search ranges for dermis and epidermis were defined [17]. Surface deflection data from *in vivo* experiments were used in the plane-strain model to fit the elasticity ratio since deflection is only controlled by the layer ratio. Specifically, an exhaustive fitting was employed: with each candidate ratio, two rigid cylindrical stimuli (diameter of 3.17 and 9.52 mm) were used to simulate indentation into the finger pad at six displacements (0.5, 1.0, 1.6, 2.5, 3.0, and 3.5 mm). The skin surface deflection was then derived and compared with empirical results from [17]. The average of all ratios with $R^2 \geq 0.8$ were derived as the final elasticity ratio of epidermal, dermal, and hypodermal layers: 510.63: 21.37: 1.00.

C. Fitting Elastic Moduli of Skin Layers

After the ratios and surface deflection were fit, elastic moduli of materials were scaled to fit the force-displacement responses measured for each participant. Similar to [12], two rigid stimuli were passively indented into the index finger pad: a flat plate and a cylinder of 6 mm diameter with a maximum 2 mm and 3 mm indentation, respectively. For each participant, by optimizing the average R^2 of two stimuli using the L-BFGS-B algorithm, the optimal scaling coefficient k was determined. The final elastic modulus G of each skin layer was then derived based on the initial shear modulus, optimal ratio, and individual scale k. Therefore, the reciprocal of this elasticity scale k was used as a dimensionless quantity to depict the "softness" of each participant's finger pad.

D. Numerical Simulations

Two stimuli tips with covaried elasticity and curvature, 10 kPa-4 mm and 90 kPa-8 mm, were adopted and built [17]. Fingertip-to-stimulus contact mechanics were simulated to approximate these stimuli used in the passive touch interactions. Specifically, for each participant's fingertip model, compliant stimuli were indented into the finger pad at loads of 0.25, 0.5, 1, and 2 N. The response variable herein was derived as the cutaneous cue only, quantified as the spatial distribution of stress at the epidermal-dermal interface, where Merkel cell end-organs of slowly adapting type I afferents and Meissner corpuscles of rapidly adapting afferents reside [17].

E. Stimuli and Experimental Apparatus

Consistent with the finite element modeling, compliant spheres of 10 kPa-4 mm and 90 kPa-8 mm were adopted and used in empirical experiments [17]. For passive touch interactions, a customized motion stage was adopted to indent the stimulus into the stationary finger pad [17]. Customized circuitry and software were directly interfaced to control the indentation. As shown in Fig. 1B, stimuli were installed onto the interchangeable actuator arm and normal contact force was measured by an embedded load cell (22.2 N, 300 Hz, LCFD-5, Omega, OH). With physical constraint measures, the index finger was held at approximately 30˚ to the stimulus surface.

For active touch interactions, a setup based on a fine-adjust rotary platform was adopted from [4]. As shown in Fig. 1C, the contact force was measured by instrumented load cells (5 kg, 80Hz, TAL220B, HTC Sensor), and fingertip displacements were measured by a laser triangulation sensor (10 µm, 1.5kHz, optoNCDT 1402-100, Micro-Epsilon). The forearm and hand rested on a parallel beam with no constraints.

F. Measurements of Physical Contact Cues

For the fingertip displacement cue, recordings were first smoothed to remove any artifacts by a moving average filter [4]. Final displacement was derived as the absolute difference between the initiation and conclusion of the movement. Besides, to quantify contact area cues, the ink-based method was adopted to measure the gross contact area between the finger pad and stimulus for each indentation [4]. Specifically, washable ink was fully applied to the stimulus surface before each measurement. After contact, the stamped ink was transferred onto a sheet of white paper for scanning. Before each new trial, the remaining ink was removed from the finger pad. The gross contact area was derived by Gauss's formula based on the identified contact region and scaled pixels.

G. Data Analysis

To analyze fingertip displacements across all participants, a normalization procedure was applied since individuals had distinct ranges of finger movements. Individual displacements were normalized to the range of (0, 1) by a sigmoid membership function. The center of the transition area was the average of the data normalized and the growth rate was 1 [4].

H. Participants

The human-subjects experiments were approved by the Institutional Review Board at the University of Virginia. Eight naïve participants (4 females, 4 males, 28.8 ± 2.6 years of age) were recruited with written informed consent. No evidence of upper extremity pathology was reported. All participants showed right-hand dominance and completed all experimental tasks with no data was discarded.

I. Experimental Procedures

Task 1 – Biomechanical measurement in passive touch: To measure the biomechanical relationship between touch force and gross contact area in passive touch, both stimuli (10 kPa-4 mm and 90 kPa-8 mm) were indented into each participant's finger pad at 2 N load for three times. Each stimulus was ramped into the finger pad for one second and retracted for one second. The ink-based procedure was applied after each indentation for gross contact area measurements.

Task 2 – Biomechanical measurement in active touch: To measure the gross contact area in active touch, both stimuli (10 kPa-4 mm and 90 kPa-8 mm) were contacted three times by each participant's index finger at 2 N load. Specifically, participants were instructed to actively press into the stimulus and a sound alarm was triggered to end the current exploration when the imposed force reached 2 N. The ink-based procedure was then applied to measure the gross contact area.

Task 3 – Psychophysical experiments in passive touch: Psychophysical discrimination of compliances was conducted to evaluate individual perceptual sensitivity. Following the rule of ordered sampling with replacement, four stimulus pairs were prepared: (10,4) & (10,4), (10,4) & (90,8), (90,8) & (10,4), and (90,8) & (90,8). The test order within each pair was determined as (first) & (second). Participants were blindfolded to eliminate visual cue and no feedback was given. Using the same-different procedure, after exploring one stimulus pair (one touch per stimulus), participants reported whether the compliances of the two stimuli were the same or different. This procedure fits well with the task scope since participants can utilize any cues that are available and applicable. In passive touch, within each trial, stimuli from one pair were ramped into the finger pad successively, with an interval of 2 seconds. The indentation rate was 1 N/s and the terminal load was 2 N, as consistent with *Task 1*. For each participant, there were two trials for each stimulus pair. All trials were separated by a 15-second break and the test order was randomized to balance the response bias.

Task 4 – Psychophysical experiments in active touch: Discrimination tasks were conducted under participants' fully active, behavioral control. The same psychophysical procedure and stimulus pairs were employed as in *Task 3*. Within each trial, participants actively explored the compliances by contacting each stimulus (from one pair) successively, with an interval of 2 seconds. A sound alarm was triggered to end current exploration when imposed force reached 2 N load. Fingertip displacements were measured simultaneously. For each participant, there were three trials for each stimulus pair. Time break between trials was consistent with *Task 3* and test orders were also randomized to balance carry-over effects.

III. Results

A. Skin Elasticity Differs Between Individuals

To collect force-displacement at the finger pad, uniaxial compression tests were performed (Fig. 2A). The elasticity of individual's skin layers was computationally characterized by curving fitting. As noted in *Methods*, by optimizing the scaling coefficient *k*, responses from each individual's model well matched their experimental measurements, with an average R^2 of 0.968 (Fig. 2A). Final elastic moduli per participant were derived by the initial modulus of hypodermis (1 kPa), final elasticity ratio (510.63: 21.37: 1.00), and individual's scale *k*. Since the other two parameters are fixed, individual's skin elasticity is solely proportional to the individual's scale *k*. Thus, the coefficient k^{-1} was used to quantify the "softness" of finger pad skin, i.e., the higher k^{-1} value related to the softer skin. For instance, with the optimal *k* of 3.52 for Subject 2, the elastic moduli for epidermis, dermis, and hypodermis were derived as 1.80 MPa, 75.30 kPa, and 3.52 kPa, respectively. Each individual's skin material properties are detailed in Table I and are comparable to results by Wu et al. [18].

B. Cutaneous Contact Simulated for Individuals

To help evaluate the relationship between skin mechanics and tactile discriminability of compliance, we used the model to simulate spatial distributions of compressive stress interior to skin layers. Within each participant, stress distributions at the contact locations were nearly identical between the small-compliant and large-stiff stimuli across the four load conditions (Fig. 2B). This aligns with prior work and indicated that only non-distinct cutaneous cues are perceptible [17].

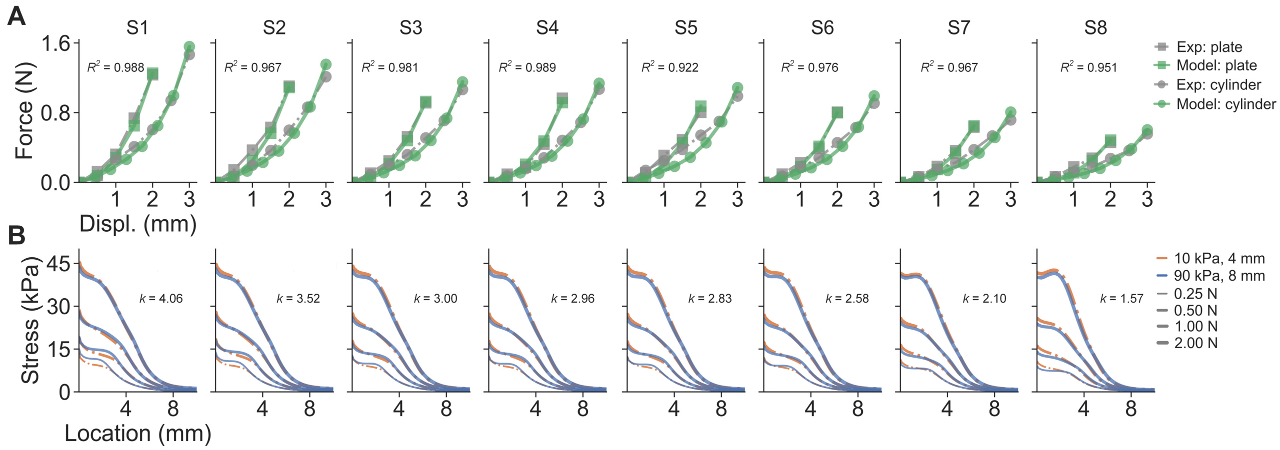

Figure 2. Individual differences in skin hyperelastic material properties and stress distributions interior to the skin's layers upon passive contact. (A) Uniaxial compression tests are performed on individual's finger pad to derive force-displacement curves. Model generated elastic moduli are found by optimizing individual's finger model to match experimental measurements. (B) For small-compliant (10 kPa-4 mm) and large-stiff (90 kPa-8 mm) spheres, stress distributions at the epidermal-dermal interface are nearly identical within each participant, across the four force loads. Individual differences in cutaneous responses may be attributed to skin softness, where a higher elasticity (i.e., higher scale k) may lead to higher interior stress.

To further investigate individual differences in cutaneous contact, average interior stress (within lateral contact locations from 0 to 10 mm, at 2 N load) was calculated per stimulus and participant. As shown in Fig. 3A, for the same indentation magnitude and rate, greater interior stress is observed for those individuals with stiffer skin. The linear regression yielded a strong negative correlation between skin softness and average stress of two stimuli, with a Spearman's coefficient of -0.99. This model result illustrates that differences in individual skin mechanics may indeed evoke variance in interior stress magnitude, which thus, could potentially lead to individual differences in perceptual acuity.

C. *Individual Differences in Contact Biomechanics*

Derived from the finite element simulation, we computationally showed that skin mechanics may evoke individual differences in contact responses. To further validate this observation, gross contact area was measured in passive and active touch interactions. In passive touch within individual, gross contact areas for these two stimuli indeed overlapped (Fig. 3B). Moreover, the linear regression yielded a strong positive correlation between individuals' skin softness (k^{-1}) and average gross contact area with the Spearman's coefficient of 0.87 (p = 2.01e-15). This illustrates that larger gross contact area is evoked by individuals with softer skin.

In active touch within individual, gross contact areas of two stimuli remained overlapped (Fig. 3C), as consistent with the passive touch (Fig. 3B) and computational modeling (Fig. 2B) results. Furthermore, the linear regression yielded a negative correlation between individuals' skin softness and average gross contact area with the Spearman's coefficient of -0.58 (p = 1.38e-5). However, opposite to the results in passive touch, larger gross contact areas were evoked by individuals with harder skin. This indicates that, in active touch, individuals could move their fingers differently to evoke additional cutaneous cues as opposed to passive touch.

TABLE I. SKIN MATERIAL PROPERITIES PER INDIVIDUAL SUBJECT.

Sub.	k^{-1} *	Epidermis (MPa)	Dermis (kPa)	Hypodermis (kPa)
S1	0.25	2.07	86.66	4.06
S2	0.28	1.80	75.30	3.52
S3	0.33	1.53	64.14	3.00
S4	0.34	1.51	63.28	2.96
S5	0.35	1.44	60.45	2.83
S6	0.39	1.32	55.22	2.58
S7	0.48	1.07	44.84	2.10
S8	0.64	0.80	33.52	1.57

*. Higher k^{-1} value related to the softer skin.

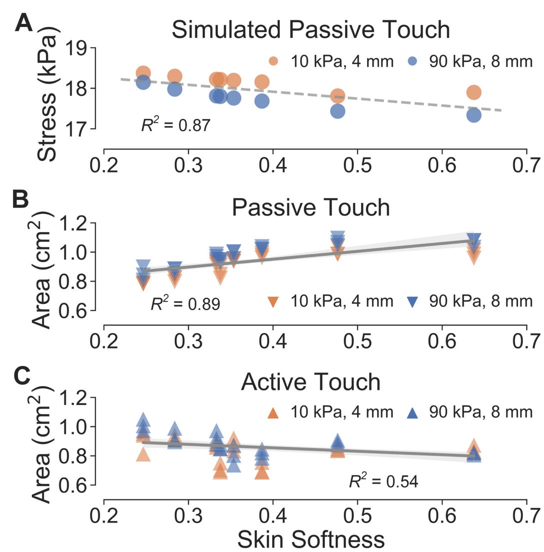

Figure 3. Biomechanical relationships between individuals' skin softness (k^{-1}) and their cutaneous contact cues represented by (A) simulated average interior stress in passive touch, and gross contact areas measured at 2N in (B) passive and (C) active touch. Each data point denotes one measurement. Linear regression is applied for each cutaneous cue and the goodness of fit is indicated by R^2. In passive touch under the same contact load, individuals with softer skin proportionally exhibited lower (A) interior stress and larger (B) gross contact areas. Overall, within individual, non-distinct cutaneous cues are consistently elicited by the two spherical stimuli used. Therefore, in differentiating the compliances, individual differences in discrimination performance might be impacted by the magnitude of tactile afferents recruitment, thus, originally derived from the skin softness.

D. Individual Differences in Perceptual Sensitivity

To further investigates whether individuals' skin mechanics could impact perceptual performance, relationships between individuals' skin softness and psychophysical responses were analyzed. Specifically, for each participant, the aggregated percentage of correct discriminations for all stimulus pairs was calculated and compared with individual's skin softness. The correlation was quantified with the psychometric function, which was fitted by the beta-binomial model and the goodness of fit was indicated by the deviance [19]. In passive touch (Fig. 4A), discrimination correctness was positively correlated with the skin softness, where individuals with softer fingers indeed achieved better performance. For all participants aggregated, the average percentage of correctness was 51.6% ± 18.2, which is indeed at the limit of discriminability.

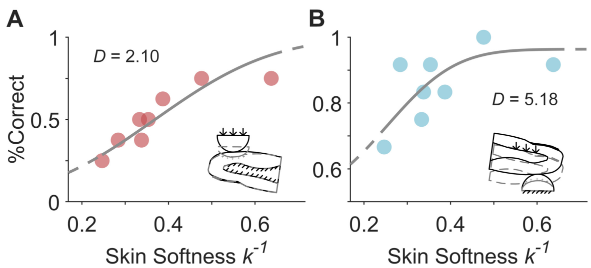

Figure 4. Relationships between skin softness and discrimination performance is characterized by the psychometric curve. The goodness of fit is indicated by deviance. (A) In passive touch, with only cutaneous cues available, individual correctness is proportional to skin softness. (B) In active touch, with additional perceptual cues, individual performance is improved but with a weaker correlation between skin softness.

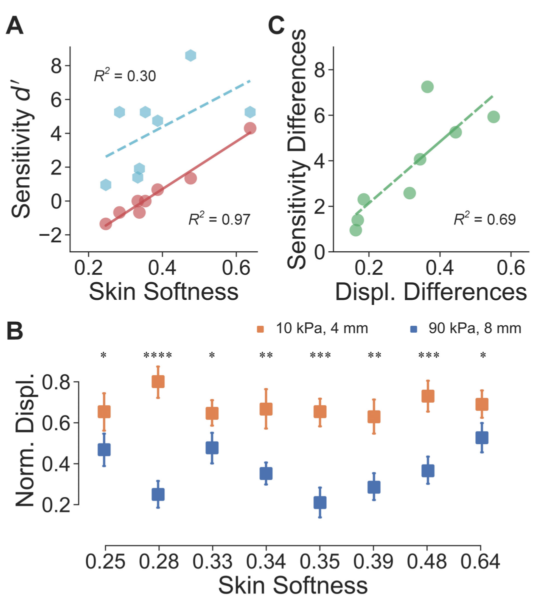

Figure 5. Relationships between individual skin softness, perceptual sensitivity, and exploratory strategies in active touch. (A) In passive touch (red) where cutaneous cues are non-distinct, individual perceptual sensitivity could be derived by skin softness. In active touch (blue) where supplementary cues are available, individual sensitivity is improved. (B) In active touch, participants move their fingers to evoke significant differences in displacements for discrimination. (C) The improvement in individual sensitivity is positively correlated with the displacement differences one evokes to help discrimination. The goodness of fit is indicated by R^2. Error bars denote 90% confidence intervals and *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and ****$p < 0.0001$, by the Mann-Whitney U test.

In active touch (Fig. 4B), individual's performance was all improved but the correlation was weaker than passive touch (D = 5.18). For all participants aggregated, the average correctness was indeed improved to 85.4% ± 10.7.

Furthermore, for each participant, the sensitivity index d' was computed to provide a bias-free measure of individual discriminability of compliance [20]. As shown in Fig. 5A for passive touch, the linear regression yielded a strong positive correlation between skin softness and individual sensitivity index with the Spearman's coefficient of 0.96 (p = 1.78e-4). This indicates that, in passively discriminating compliances with non-distinct cutaneous cues, individual perceptual sensitivity could be attributed to individual skin mechanics, where participants with softer finger pad could proportionally afford higher sensitivity. Note that negative d' values were derived as the hit rate was lower than the false alarm rate in the passive discrimination task. This also aligns with the chance performance shown in Fig. 4A.

However, in active touch, the correlation between skin softness and individual sensitivity became weaker (Spearman's coefficient of 0.66, p = 0.08). This indicates that distinct from passive touch, the improved individual sensitivity cannot be solely attributed to the skin softness. Indeed, participants actively evoke significant differences in fingertip displacements to help discriminate these two stimuli (Fig. 5B). Moreover, there is a positive correlation between differences in individual's displacement and individual's improvement in sensitivity from passive to active touch (Spearman's coefficient of 0.93, p = 8.63e-4, Fig. 5C). This indicates that, in active touch, individuals employ distinct strategies to evoke supplementary cues, thus, optimally improve sensitivity.

IV. Discussion

This work considers how individual differences in the skin's mechanics might impact perceptual acuity with compliant materials, near the limit of discriminability. By employing elastic spheres that vary in curvature and elasticity to afford non-distinct cutaneous cues, we find that individuals tend to actively control their exploratory movements in order to optimally improve their acuity, which is inherently, in at least this younger cohort of participants, derived by elastic material properties of their skin. That is, while those with harder skin appear to inherently perform worse in passive touch, participants can and do improve by actively changing their exploration strategies. In so doing, they move distinctly to generate cues of contact area (Fig. 3C) and fingertip displacement (Fig. 5B), which are independent of skin mechanics, and in line with our prior work [17].

Therefore, there are several implications in the design of engineered haptic systems to afford individual differences. For touch-enabled displays grounded to user's finger, we find individuals exhibit distinct contact profiles in affording surface pressure and retaining gross contact regions (Fig. 3). These align with observations in interacting with touch devices where diverse pressure inputs [9] and contact locations [8], [21] are behaviorally applied by users. These together argue that individualized design and actuation mechanisms may render a better tactile acuity to individual users [21].

As noted, in passive touch where cutaneous cues only are perceptible, individual differences in perceptual acuity could be attributed to differences in skin elasticity. As in line with discriminating surface pressure [14], [15] and grating orientation [2], individuals with softer fingertips proportionally exhibit higher perceptual sensitivity (Fig. 4A and 5A). Indeed, when stimuli are passively indented into softer finger pad, larger gross contact areas and slightly more differences between two stimuli are retained from larger surface deformations (Fig. 3B), thus, it may well be the case that more populations of mechanoreceptors are solicited and recruited to augment individuals' tactile perception [11]. Noteworthy, as we only consider a younger cohort herein, the relation between skin mechanics and tactile acuity might be distinct for older individuals, where the general decline in acuity could be attributed to the lower mechanoreceptive sensibility [2], [10].

Furthermore, in active touch, individuals could improve their performance by individualizing their exploration strategies. In particular, to compensate for poor perceptual acuity constrained by skin elasticity, individuals with harder skin behaviorally move their fingertips to create larger gross contact areas (Fig. 3C), which may recruit a larger number of tactile afferents. Indeed, improved tactile acuity is positively correlated with differences in proprioceptive cues employed for discrimination (Fig. 5C). Such exploration strategy of behavioral control aligns with how we explore naturalistic soft objects [4], [22]: individuals utilize distinct fingertip displacements to readily differentiate compliances. Overall, in the context of natural exploration, individuals could actively control their movements to achieve optimal perceptual performance, even amidst inherent constraints of skin mechanics.

Moreover, the study herein only considers elastic moduli of finger pad layers to characterize skin mechanics. Prior studies suggest that variance in skin thickness and stiffness may also affect perceptual sensitivity [11], [14]. For instance, higher skin thickness can increase distances between mechanoreceptors and surface pressure, thus, may attenuate afferent firing for perceptual threshold [14]. Ultimately, the ability to transform a surface stimulus into an afferent population response is vital to creating a percepts [3], [14]. Thus, changes in skin mechanics cannot fully account for variance in individuals' tactile acuity. Factors including sex differences in density of mechanoreceptors [3], the loss of mechanoreceptive sensitivity and changes in skin's mechanical properties with aging [2], or more behaviorally, individual exploratory movements (Fig. 5C) may together play a role in processing stages that underlie tactile perception.

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