Individual differences impacting skin deformation and tactile discrimination with compliant elastic surfaces

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Abstract— **Individual differences in tactile acuity are observed within and between age cohorts. Such differences in acuity may be attributed to various sources, including aspects of nervous system, skin mechanics, finger size, cognitive and behavioral factors, etc. This work considers individual differences, within a younger cohort of participants, in discriminating compliant surfaces. These participants exhibit a range of finger size and stiffness. Interestingly, both their finger size and stiffness well predict their discriminative performance, where softer/smaller fingers outperform stiffer/larger fingers. Stereo imaging captured biomechanical cues in the skin's deformation, including contact area and penetration depth, and their change rates. In those individuals with stiffer/larger fingers, who perceptually performed worse, we observed less distinguishable contact areas and eccentricities, compared to softer/smaller fingers. These particular cues well predicted individual differences observed in perceptual discrimination. In comparison, with two other cues, curvature and penetration depth, the imaging readily distinguished the compliant surfaces irrespective of finger stiffness/size, not aligned with discrimination. In conclusion, in passive touch, we find that individuals with softer/smaller fingers were better at discriminating compliances, and that certain skin deformation cues predict individual differences in perception.**

I. Introduction

As haptic displays become ubiquitous, designers are beginning to adapt them to individual end users. To effectively do so, we need to understand the extent and impact of individual differences, which can impact the efficacy of such displays [1]–[3]. Prior scientific investigations indicate that individual differences in tactile acuity may result from many factors, including skin stiffness, finger size, sex/gender, and age, as well as additional developmental, cognitive, and behavioral factors.

In particular, those with smaller finger size exhibit better tactile spatial acuity [4], [5]. In psychophysical experiments to investigate interactions of finger size and sex/gender on tactile acuity, women outperformed men. However, the effect of sex/gender vanished when finger size was taken into consideration. The rationale is that smaller fingers, with the same number of tactile afferents, afford a higher density to inform our perceptual judgments. Age and gender, in addition, may influence tactile performance. For instance, 2-point discrimination thresholds increase for elderly as compared to young cohorts [6]. Further, before about 40 years old, women exhibit better tactile acuity but both men and women share the same tactile acuity after this age [7]. As one contributing factor, decreased tactile acuity is expected as we age due to a loss of elastin fibers and with it increased wrinkling of the skin. Women experience a more dramatic reduction of sensing capacity because of the loss of skin thickness over time. With a constant size of bone, i.e., distal phalange, there is less tissue in the finger pad to drive the skin's mechanical response. Such effect is smaller in men due to relatively larger and thicker finger pads [8]. However, in considering the conformance of the skin to grating stimuli and their discrimination, Vega-Bermudez and Johnson showed that differences in skin stiffness are not the primary factor driving acuity between younger (19-36 years old) and older (61-69 years old) cohorts, but rather that losses in spatial acuity might be tied to neural mechanisms [9]. That said, their work did indicate that stiffness affects tactile acuity within a group, in particular for the younger cohort.

Finger pad skin stiffness – decoupled from aging – may impact tactile acuity, as the work of Vega-Bermudez and Johnson indicates, though there is not yet consensus on this topic. In particular, Woodward [10] and Peters et al. [4] found no relationship between skin compliance and tactile acuity. Francisco et al., however, argued that such results could be biased due to the compliance calculation, group division for the statistical tests, and the variance of acuity measurements [9]. This work also indicated that young people with softer fingers have lower tactile detection thresholds, which aligns with finite element analysis of the skin [11]. Furthermore within an age group, the stratum corneum is thicker in the fingers of males compared to females [12] and there is a positive correlation between finger size and stiffness [4]. Which factors tie to meaningful acuity in engineered systems and the cost to benefit ratios in addressing these remains an open question.

Herein, we consider the impact of individual differences on one's ability to discriminate surfaces that vary in compliance. We focus on differences in finger stiffness and size within a cohort of younger participants. Importantly, we image the deformation of the skin per person, where 3D stereo imaging through transparent substrates captures the skin's dynamics during passive indentation. Differences in skin deformation between stimulus compliance may give us a window into the origin of perceptual differences between individuals.

II. Methods

Within a younger cohort of ten participants, we investigate the relationships between an individual's finger size and stiffness, evoked patterns of skin deformation, and performance in discriminating compliant surfaces. First, we measure each participant's finger size and stiffness. Second, participants complete pairwise psychophysical discrimination of sets of compliant surfaces, which range from stiffer to softer than finger pad skin. Third, along with the psychophysical evaluation, a previously published 3-D stereo technique images the skin's surface deformation. To characterize and compare patterns in

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the skin deformation, upon contact with the compliant surfaces, five biomechanical cues including contact area, curvature, eccentricity, penetration depth and bulk force are used.

A. Participants

A total of ten subjects participated (mean = 23, SD = 1.2, 6 males, 4 females). None reported a history of injury and their fingers were free of calluses. Experiments were approved by the local institutional review board and were conducted under written, informed consent obtained from each participant. All devices and surfaces were sanitized following their use by a participant, and all participants wore facemasks during the experiments, following COVID-19 protocols.

B. Stimuli Fabrication

Seven silicone-elastomer substrates were fabricated with compliances ranging from 5 to 184 kPa. For reference, the reported mean modulus of human skin at the fingertip is about 42 kPa [13], [14]. Therefore, one substrate was poured near this modulus (45 kPa), with three substrates softer (5, 10, 33 kPa) and three harder (75, 121, 184 kPa). Each was poured into a custom-designed aluminum ring, fitted and sealed with a clean, dry glass disc (5.1 x 0.3 cm) into its collar (5.4 x 1.6 cm) using a syringe tip filled with diluted PDMS, and heated at 100 degrees Celsius until fully sealed. The three softer substrates were formed from a two-component PDMS (Solaris, Smooth-on Inc., Macungie, PA) diluted with silicone oil. The amount of silicone oil diluent was 400% for 5 kPa, 300% for 10 kPa and 200% for 33 kPa. The stimuli remained at room temperature until the air bubbles were removed at atmospheric pressure, and then were cured at 100 Celsius for 25 minutes before being cooled at room temperature. The harder substrates (75, 121,184 kPa) were made from a different two-component silicone rubber (Sylgard 184, Dow Corning, Midland, MI, USA) mixed with various ratios of silicone oil (ALPA-OIL-50, Silicone oil V50, Modulor, Berlin, Germany) to achieve differing compliances [15]. To eliminate stickiness caused by silicone oil, and maintain consistency in surface friction, a layer of silicone rubber (Sylgard 184) was applied to the surface of each substrate. The elastic moduli of all stimulus were obtained by following a standardized procedure [16].

C. Finger Size and Interaction Stiffness Measurements

The finger size was estimated by the area of an ellipse, where the major and minor axis were the length along the vertical and horizontal directions measured by a digital caliper.

Typically finger pad stiffness is measured by using compression with a rigid body, such as a plate or a cylinder, while simultaneously measuring force [17]. Though a much more accurate and preferred method, such a test was not conducted at the time of the experiments. Instead we derive “finger interaction stiffness” from the force-displacement of the finger pad with two elastic substrates. The stiff 184 kPa substrate was used, and for comparison the 33 kPa substrate, which was slightly less stiff than the skin. The “finger interaction stiffness” was measured as the slope of the linear regression of force-displacement at 2 mm displacement.

D. Experimental Procedures

Biomechanical experiments. A vertical indenter and 3-D imaging apparatus was used, as described in depth previously [15], [18]. Basically, an elastic substrate is vertically delivered to the participant’s index finger by a mechanical indenter, at a constant velocity of 1.75 mm/s to 2 mm displacement, in a displacement control mode. Control of displacement with elastic stimuli allows for their judgement via distinct force cues [19]. The finger was secured by a customized hand and finger cast at an angle of 30 degrees. The substrate was retracted at the

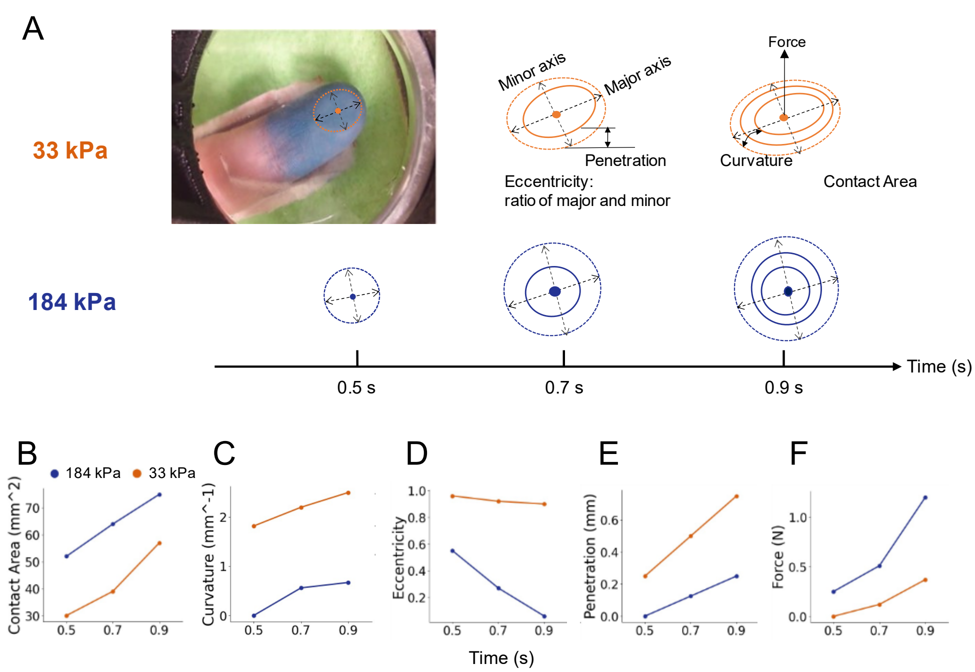

Figure 1. Illustrative example of five cues used to quantify skin deformation at 0.5, 0.7, and 0.9 second time points for 33 and 184 kPa stimuli. Experimental data from one participant are shown. The stiffer 184 kPa stimulus tends to generate higher contact area **B)** and force **F)** but lower skin surface curvature **C)**, eccentricity **D)**, and penetration depth **E)**. Also, eccentricity for the softer 33 kPa stimulus starts in the shape of an ellipse and remains as an ellipse, whereas the stiffer 184 kPa stimulus is circular, with greater growth along its minor axis.

same rate once it reached 2 mm displacement. A thin layer of blue ink is applied on the finger pad skin surface using a paint brush. Two stereo cameras capture images of the finger pad through the transparent substrates every 100 ms. The stimuli were delivered the finger pad individually, with 350 trials total (seven substrates, five repetitions, ten participants). The average time to complete this part of the experiment was about 30 minutes per participant, including a 5 minute break.

Psychophysical experiments. The perceptual study was conducted before the biomechanical study because it requires a higher amount of concentration from participants. Here, four sets of stimulus compliance were selected to cover a range harder and softer than the skin (184/121 and 33/5 kPa), and compliances nearer that of the skin (45/10 and 45/75 kPa). Participants were blindfolded to eliminate visual cues. Stimulus pairs were delivered to the index finger in a randomized order. Participants were asked to report which of the two stimuli was softer. There were 400 indentations (four pairs of stimuli, five repetitions, ten participants). The average time for this experiment was about 80 minutes including breaks.

E. Dependent Metrics

From the imaging point cloud data, which represent the 3-D surface of the finger pad every 100 ms, we fitted vertical-stacked ellipses, from first contact to greatest penetration [15]. Four cutaneous cue metrics were developed based on the ellipse methods. Contact area is defined as the ellipse formed at the contact surface. Penetration Depth represents the distance between the first and last formed ellipse, calculated as:

$$P = (N - 1) * 0.25$$

Curvature is the average slope between adjacent ellipses:

$$Slope_{ave} = \frac{\sum_{i=1}^{i=N} \frac{r(i+1) - r(i)}{r(i)}}{r(i)}$$

The eccentricity cue (e) is used to describe the shape of the contact surface, where a is the semi-major axis and b is the semi-minor axis. Eccentricity equals 0 for a perfect circle. Reaction force is also generated in the normal direction.

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

Figure 1 illustrates an example of progressive skin deformation quantified by the five cues for the 184 and 33 kPa substrates. The two surface-based metrics describe the area and shape of the contact surface, i.e., contact area and eccentricity. Within the 1 second duration, contact area is larger for the stiffer 184 kPa substrate, while eccentricity drops from 0.6 to 0 as the stimulus advances (Fig. 1B, D). Also, the 33 kPa stimulus generates greater curvature and penetration depth than the 184 kPa substrate (Fig. 1C, E). Force is greater and its rate increases for the stiffer 184 kPa substrate (Fig. 1F).

F. Data Analysis

Pearson's correlation coefficient (r) was used to test the linear dependency between two variables and ANOVA was used to test the significant differences among groups.

III. Results

A. Measurement of Finger Size and Stiffness

The relationship between finger size and interaction stiffness across ten participants indicates the two variables are highly correlated (Fig. 2). Furthermore, the relative order of the individual participants remains consistent across the 184 kPa and 33 kPa stimuli. Within the ten participants, the four male participants (7-10) exhibited greater finger size and stiffness compared to the six female participants (1-6).

Our measurements of finger interaction stiffness are slightly lower than previous reports ~ 0.4 compared to ~ 0.16 N/mm [17]. This is due, in part, to our use of a 184 kPa stimulus instead of a rigid body, which generates lower contact force. Also, stiffness in Han et al. was calculated as the ratio of force and displacement instead of fitting just the linear region, which may lead to higher stiffness [17]. Miguel et al. [13] indented a glass plate into the finger at a contact angle of zero degrees, compared to 30 here, reporting 1.03 N, lower than 1.75 N here, due in part to the contact geometry. Oprişan et al. [14] estimated finger stiffness by indenting a cylinder into the finger pad, reporting 0.07 MPa at the displacement of 2 mm. There is a consistency in each individual's finger interaction stiffness relative to the other individuals between the 184 and 33 kPa stimuli. The Pearson correlation coefficient (r) was used to determine the linear dependency between the finger size and interaction stiffness. The correlation is significant ($r > 0.8$) for both 184 and 33 kPa stimuli across ten participants, where participant 1 has the lowest finger stiffness and participant 10 has the highest finger stiffness.

B. Psychophysical Experiments

As Fig. 3 indicates, the psychophysical evaluations closely follow both the finger size and finger stiffness of the participants. For example, for 184/121 kPa stimulus pair, participant 10 has the largest finger size but the lowest detection rate.

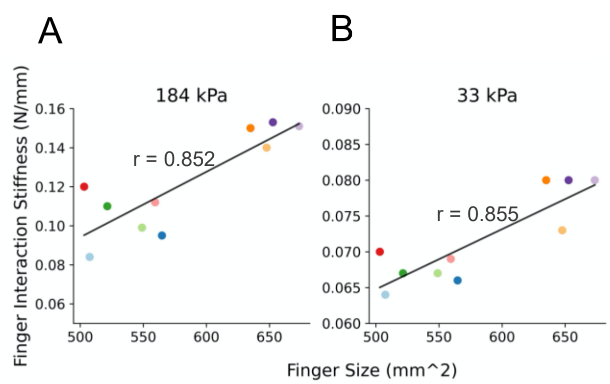

Figure 2. Relationship between the finger size and interaction stiffness for 184 and 33 kPa stimuli across ten participants. Each color represents corresponds to a different participant. Finger interaction stiffness approximates an individual's finger stiffness calculated from the linear region of the force-displacement curve when indented by a 184 kPa stimulus. Note that we refer to this approximation as "finger interaction stiffness" because it is not "stiffness" as would normally be reported using a flat plate test using a rigid body. Such a test was not conducted at the time the experiments. A second such plot is generated using the 33 kPa substrate (slightly softer than the skin) as another point of reference. Note the consistency in each individual's finger interaction stiffness relative to the other individuals between the plots.

C. Aggregated Biomechanical Experiments

To characterize the skin deformation over time, the five metrics quantified skin surface deformation every 100 ms. Figure 4 shows aggregated biomechanical data from the ten participants across the seven compliant surfaces. The stiffer stimuli generated larger terminal contact areas, but softer stimuli exhibit a more rapid change rate (Fig. 4A). The 45 and 10 kPa stimulus pair are the most distinguishable across the five cues, aligning with their psychophysical discriminability (Fig. 3E). In contrast, the 45 and 75 kPa show fewer statistical difference, which aligns with their lack of discriminability (Fig. 3H).

D. Individual Differences Biomechanical Experiments

Within individual participants, we compared the differences in biomechanical cues between stimulus pairs, using the

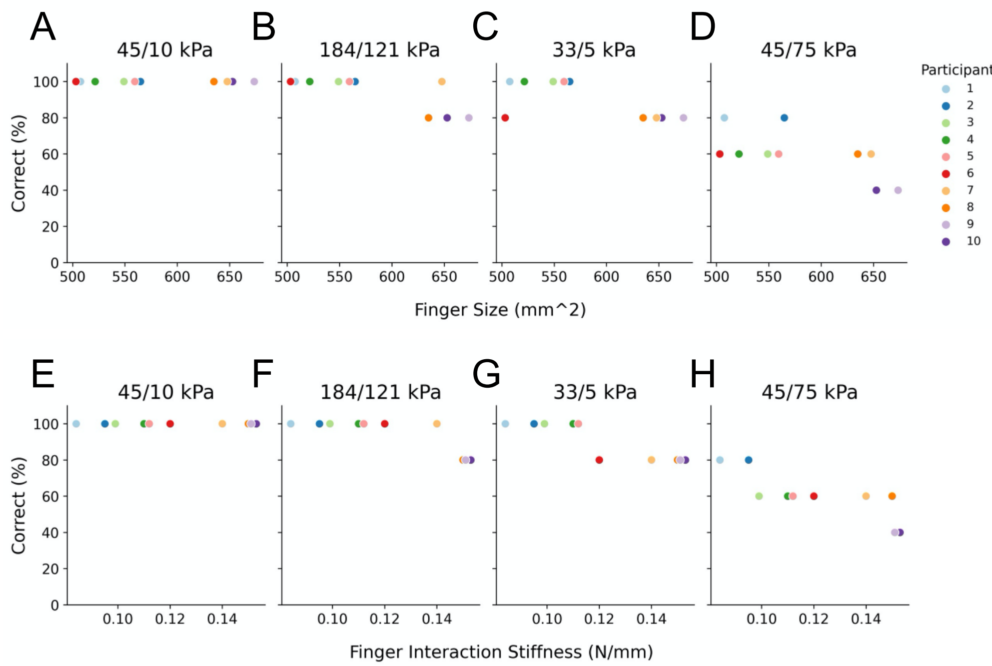

Figure 3. Psychophysical results of pairwise comparison of stimulus compliances with finger size (above) and stiffness (below). A) All ten participants exhibit a 100% correct rate in differentiating the 45 and 10 kPa stimuli. **B)** The finger size is inversely correlated ($r = -0.78$) and significant (ANOVA, $p < 0.001$) with detection rates for 184/121 kPa stimuli. For example, participant 10 has the largest finger size but the lowest detection rate. **C) – D)** Same correlation and significance hold for 33/5 kPa ($r = -0.72$, $p < 0.001$) and 45/75 kPa ($r = -0.65$, $p < 0.001$) stimulus comparisons. **E) – H)** A strong and significant correlation between the finger interaction stiffness and detection ability is shown, 184/121 kPa ($r = -0.81$, $p < 0.001$), 33/5 kPa ($r = -0.88$, $p < 0.001$) and 45/75 kPa ($r = -0.82$, $p < 0.001$).

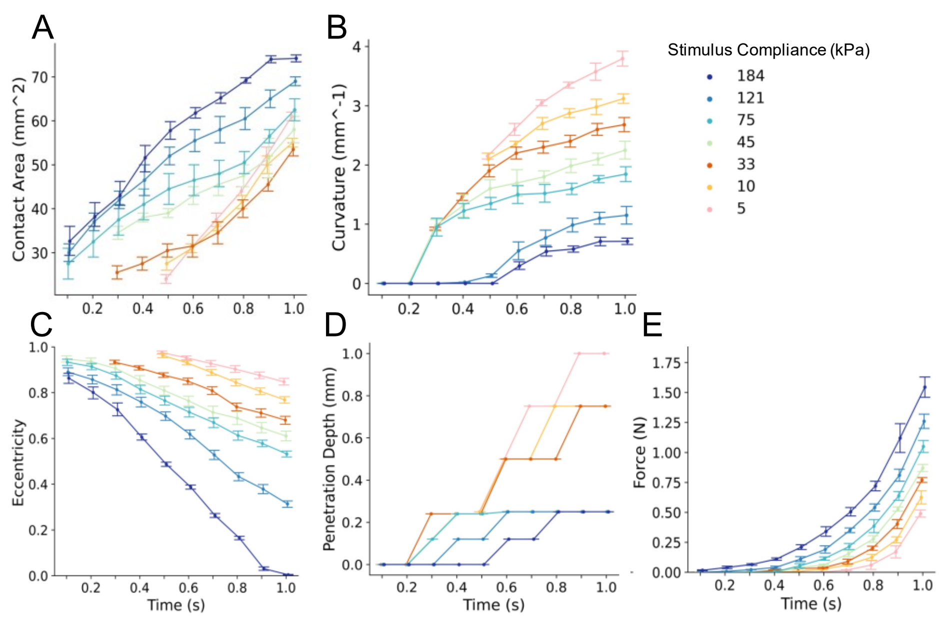

Figure 4. With data from all ten participants aggregated, a comparison of the five skin deformation cues for each of the seven compliant substrates. Data points show the analysis was done every 100 ms from 0.1 to 1.0 sec. The error bar represents 2 standard deviations of the sample mean.

average change rate and terminal values for each skin deformation cue (Fig. 5). In this way, an individual participant's skin deformation cues were compared with their discrimination performance. As finger stiffness increases, the change rate and terminal value of contact area (Fig. 5F, K) and eccentricity (Fig. 5H, M) decrease for 184/121 and 33/5 kPa stimulus pairs, in correspondence with a decrease in discrimination performance. However, finger stiffness impacts neither the change rate nor the terminal value of curvature (Fig. 5G, L) or penetration depth (Fig. 5I, N). Furthermore, stiffer fingers generated a larger difference in force change rate and terminal force, most notably for the stiffest pair (184/121 kPa) (Fig. 5J, O).

IV. Discussion

This work evaluates the impact of individual differences on the ability to differentiate surfaces that vary in compliance. Within a younger cohort of ten participants, we investigated the relationships between an individual's finger size and stiffness, evoked patterns of skin deformation, and performance in

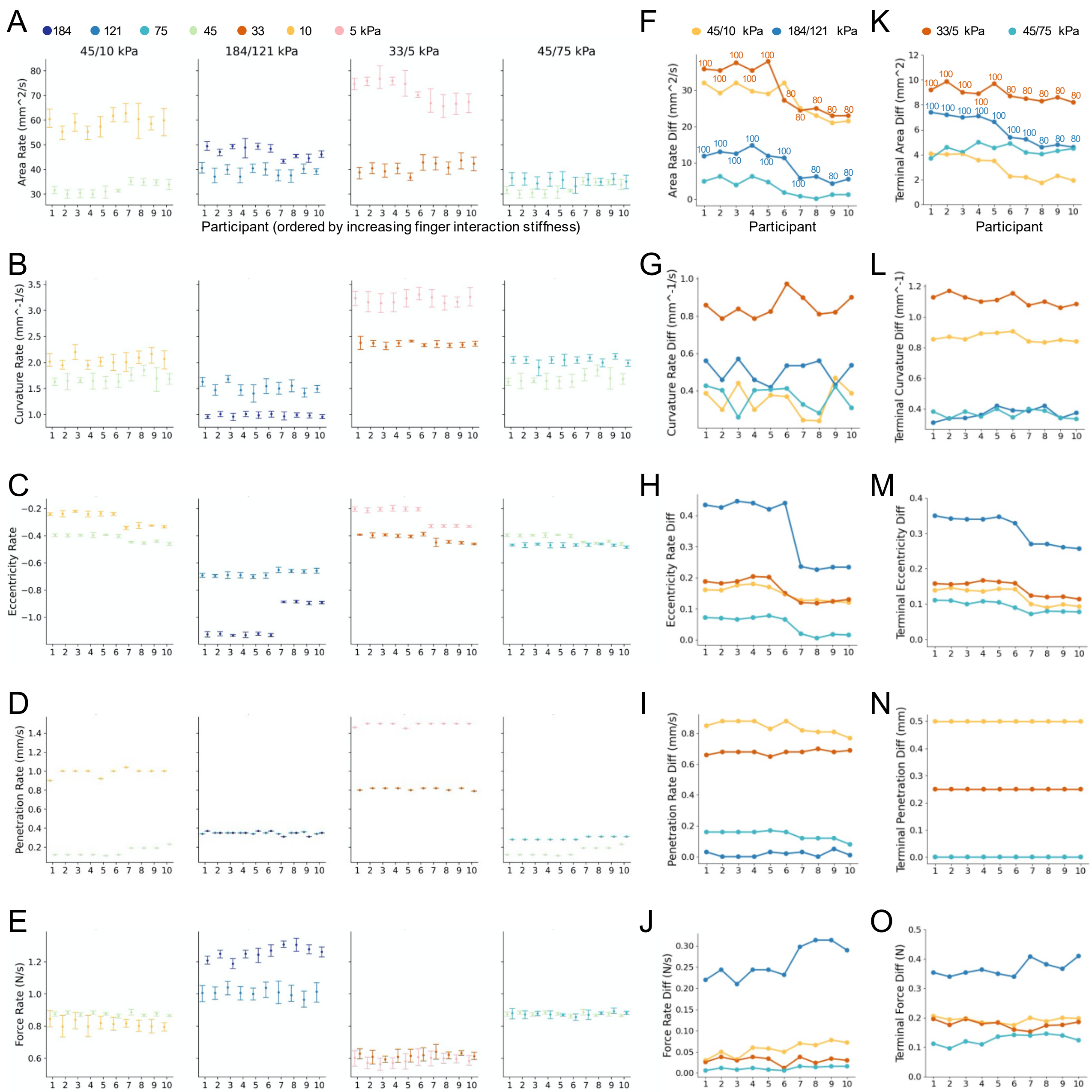

Figure 5. Individual differences for the skin deformation cues shown as average change rates and terminal values. Each error bar represents the change rates for each 100 ms analysis window averaged from 0.1 to 1 s for the five stimulus repetitions, with 2 standard deviation of the sample mean. **A) – E)** compare the average change rate of contact area, curvature, eccentricity, penetration depth, and force between two stimulus compliances, where 45/10 kPa is the most differentiable comparison and 45/75 kPa is the least differentiable. **F) – J)** describe the mean difference in the change rate of each cue between two stimuli. The numerical numbers in **F)** represent the corresponding correction rates from the psychophysical results in Figure 2. Note that in this figure those performing at 80% for 45/10 kPa and 33/5 kPa pairs show a drop in this skin deformation cue compared to those who perform at 100% discrimination, with a similar observation for the eccentricity cue. **K) – O)** show the mean difference in the terminal values between two stimuli at 1 sec.

discriminating compliant surfaces. There were several important findings. First, the individuals exhibited a range of finger size and stiffness and we found a positive correlation between these variables. Second, individuals with stiffer/larger fingers were worse at discriminating the compliant surfaces compared to the participants with softer/smaller fingers. Third, for those individuals with stiffer/larger fingers, who perceptually performed worse, we observed less distinguishable contact areas and eccentricities, compared to softer/smaller fingers. These particular cues well predicted individual differences observed in perceptual discrimination. In comparison, with two other cues, curvature and penetration depth, the imaging readily distinguished the compliant surfaces irrespective of finger stiffness/size, not aligned with discrimination.

Contact area and force cues are commonly thought to be important in encoding compliance. Here, we evaluated another cue tied to contact shape, eccentricity. The results show that hard stimuli generate more a circular contact shape while soft stimuli are more elliptical. The change of contact shape may ultimately impact afferent recruitment and firing [20], [21]. Moreover, the finger pad deforms differently depending on the compliance of a substrate. To differentiate hard stimuli (184/121 kPa), penetration and contact area become less useful because the finger flattens out immediately with little penetration into the substrates. In contrast, the finger tends to retain its original shape when substrates are soft (33/5 kPa), which makes cues penetration and curvature more distinguishable. Eccentricity remains distinct across all stimuli and force only is differentiable for hard stimuli or stiffer fingers. It is highly likely that we exploit the cues available given a stimulus comparison, so each of the cues is situationally useful.

Finally, individual differences in either finger size or stiffness were intertwined. Smaller fingers seem to align with a denser distribution of afferents [4], and finger stiffness might affect skin elongation. Additional participants will be needed to decouple these factors.

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