Unveiling users' perception of soft robotic UIs: Impact of surface softness on users' perception of surface curvature

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User interfaces (UIs) made with soft materials (soft UIs), such as elastomers, offer many opportunities for HCI. Examples include safe, compliant UIs worn on the body, and entirely new shape- and stiffness-changing UIs adapting to users, their tasks, and the context of interaction. While soft robotics technologies based on experimental material structures enable the implementation of shape- and stiffness-changing UIs, we do not know yet **which materials are best suited for which interactions** (*Transfer* research area of the workshop). This position paper proposes to address this problem. In particular, while previous work studied shape perception of rigid surfaces, we do not know yet how well users can perceive the shape of soft surfaces through touch and whether the softness of the surface will impact users' perception of the surface shape. Such information is crucial for the development of future soft UIs, e.g., for the feedback of the system to match users' perceptive capabilities. We conducted an experiment to study whether the softness of the UI will impact users' perception of the UI shape. For our experiment, we consider that the local curvature describes the shape of UIs. We thus conducted a psychophysical experiment to determine the just noticeable difference (JND) and the point of subjective equality (PSE) in curvature and the impact of the softness of curved surfaces on these measures. The results will help to lay the foundation for soft surface shape perception and provide a guideline for the design and implementation of shape- and softness-changing UIs.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**.

Additional Key Words and Phrases: Soft robotic UIs, shape-changing UIs, Psychophysics, Experiment, Just Noticeable difference.

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1 INTRODUCTION

Soft materials gained a lot of attention in the past decades in HCI [9]. User interfaces (UIs) made with soft materials (soft UIs) offer novel opportunities for HCI. For example, soft material like elastomer make UIs inherently safe, in particular wearable UIs (e.g., [5]), thanks to their softness and body compliance. Novel technologies from Soft Robotics (e.g., [12]) and emerging soft programmable material (e.g., [13]) make it possible to actuate the shape of soft materials, thus offering the potential to construct shape-changing soft UIs. Furthermore, combined with stiffness changing technologies, such as jamming [3], soft UIs can also change from soft to rigid. This widens the opportunities to provide feedback to users. Stiffness change enable UIs to benefit both from shape flexibility and body compliance when soft, and from resistance to external forces and shape stability when rigid.

While technology is progressing, we do not know yet which material is best suited for which interaction. It is not clear yet which levels of shape and softness can be used to provide feedback to users. This position paper proposes to

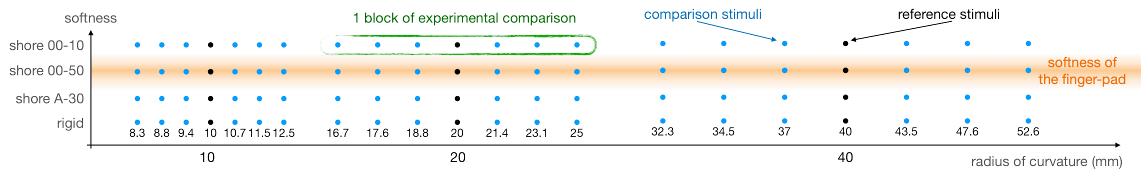

Fig. 1. The experimental variables and their levels. We have stimuli with four different levels of softness, and three different levels of curvature references. In each block of experimental comparison (one softness and one curvature reference condition), participants were presented with 1 reference stimuli with 6 comparison stimuli (3 more curved than the reference stimuli, and 3 less curved).

address this problem. The shape of UIs can provide crucial haptic feedback when we touch them [1]. To leverage novel technologies from soft robotics, it is essential to know users' shape perception ability of UIs made of different materials.

Prior work only partially addressed this problem. Norman et al. shows that users, touching and exploring the shape of objects' surface, can have the same distinguishing accuracy as if they used vision alone [7]. While prior work studied shape perception of *rigid* surfaces [16], we do not know yet how well users perceive the shape of *soft* surfaces, and whether the softness impacts the perception of the shape. We started to conduct a psychophysical experiment to answer these questions. The shape of an object can be defined in terms of its local *curvature* [11]. Our experiment therefore studies the just noticeable difference (JND) and the point of subjective equality (PSE) in *curvature*, and the impact of the softness of the surface on these measures. This position paper presents our experimental design and preliminary findings from our pilot study. We then discuss the possible impact of this experiment on the design of soft robotic UIs.

2 STUDY DESIGN

The goal of our experiment is to explore whether the softness impacts participants' ability to discriminate between different surface curvatures. More specifically, we measured the just noticeable difference (JND) and the point of subjective equality (PSE) in curvature with stimuli showing different softness.

2.1 Experimental design

We used four different softness levels among all stimuli (Figure 1). One was rigid and three soft: shore 00-10, shore 00-50, shore A-30 [4]. We chose these soft levels based on an existing measurement of the index finger-pad hardness [2]. The softness of our soft stimuli was designed to be (1) softer (shore 00-10), (2) as soft (shore 00-50), and (3) harder (shore A-30 ≈ shore 00-80 [10]) than our index finger-pad. To investigate perceptual sensitivity over a broad range of UI curvatures, we used 3 different curvatures as references, as in [8] (Figure 1): 10, 20 and 40 mm. For each curvature reference (one block in Figure 1), participants were presented with stimuli whose curvature clustered around this reference.

2.2 Setup and procedure

As shown in Figure 2 (A), participants sat at a table while their arms rested freely on the table. They freely explored the curvature of the stimuli with the index finger of their dominant hand. A box prevents participants from seeing their finger and the stimuli. The pilot experiment used a two-alternative forced-choice procedure and followed the method of constant stimuli [15]. I.e., in each trial, we presented participants with two stimuli successively: one reference stimulus and one comparison stimulus. S·he had to indicate which of the two presented stimuli felt more curved (as in [16]) by answering "first" or "second". Every participant experimented with all four softness and three curvature conditions. We used a fully-crossed, within-subjects factorial design with repeated measures.

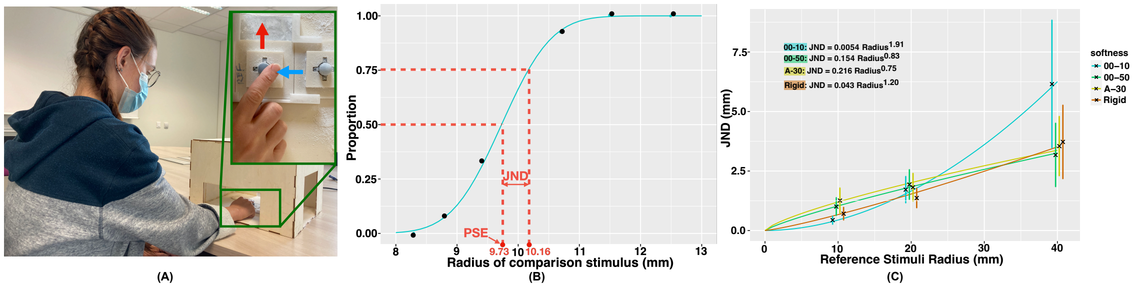

Fig. 2. (A) A participant exploring our stimuli. Stimuli were installed on 3D printed support, which can quickly slide over the 3D printed slide to ensure the quick switch between the stimulus of reference and stimulus of comparison. The first stimulus exits following the direction of the red arrow and the second stimulus enters following the blue arrow. (B) An example of psychophysical data –softness Shore 00-10 and radius of reference 10mm– and corresponding psychometric function fit for the proportion of times participants reported the comparison stimulus as the less curved than reference stimulus. The 50% point on the psychometric curve indicates the point of PSE and the distance between the 50% point and 75 % point on the psychometric curve indicates the JND. (C) JND results fitted by a power curve as suggested by Steven's Power Law [14]. Data points are slightly jittered horizontally to avoid overlap.

3 PRELIMINARY FINDINGS

4 participants (3 female and 3 right-handed) from the local university participated our pilot study. We computed the JND and PSE values in different softness and curvature condition using the MixedPsy R package [6][1]. The major calculation process is to firstly use psychometric functions [6] to fit the proportion of times participants reported the comparison stimulus as the least curved, as one example presented in Figure 2 (B). Then, we estimated the JND and PSE values based on the fit functions. We calculated the confidence intervals (CI) of our estimation using the Delta method [6]. In the remaining of the paper, unless otherwise mentioned, all error bars indicate 95% confidence intervals (CI).

3.1 Just noticeable difference (JND)

The JND estimates participants' discrimination threshold (i.e., the larger JND means a higher threshold). Figure 2 (C) shows that participants' JND increased as the stimuli become flatter (i.e., reference curvature radius from 10 mm to 40 mm). We surprisingly found that in the most curved condition (i.e., reference curvature radius being 10 mm), participants showed the lowest discrimination threshold (i.e., smallest average JND) in the softest condition (00-10), even better than in the rigid condition. Users' discrimination threshold with the other two soft stimuli was similar and worse than with the rigid stimuli. In the middle curved condition (i.e., reference curvature radius being 20 mm), participants showed a similar discrimination threshold for the three soft stimuli and a slightly better lower threshold with the rigid stimuli. In the flattest condition (i.e., reference curvature radius being 40 mm), participants had the highest threshold in the softest condition and had similar threshold in the other three softness conditions. The power-law fit result shows that the curve in Shore 00-10 condition had an exponent value (i.e., 1.91) much larger than the other three softness conditions. This suggests that, in this Shore 00-10 softness condition, participants' curvature discrimination threshold may strongly increase as the surface becomes flat. The two other soft stimuli (Shore 00-50 and Shore A-30) and the rigid stimuli yield power functions having exponent close to 1 (0.83, 0.75 and 1.2 respectively). This suggests that participants' discrimination threshold increased slower in the two other softness conditions than in the rigid condition.

[1] https://rdocumentation.org/packages/MixedPsy/versions/1.1.0

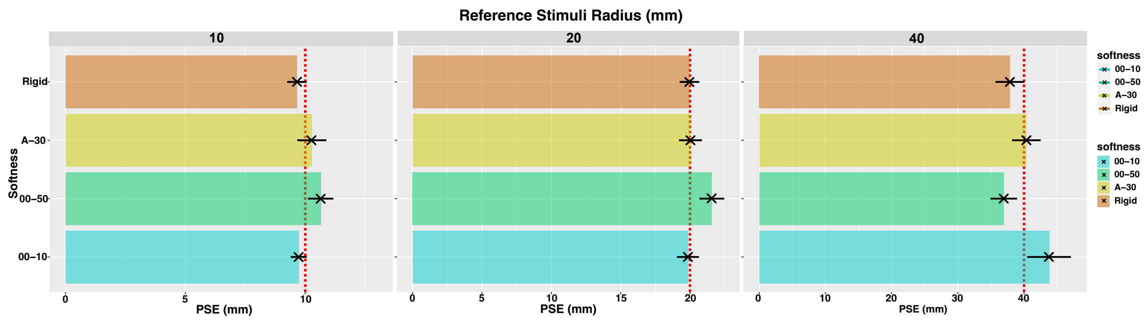

Fig. 3. PSE results in each curvature and softness condition, red dash line present the radius of reference stimuli.

3.2 Point of Subjective Equality (PSE)

The PSE presents participants' estimation accuracy. A PSE closer to the reference curvature means better accuracy. We first notice in Figure 3 that when a stimulus was as soft as our index finger-pad (Shore 00-50), participants' estimation was further away from the reference curvature, compared to other softness conditions. The loss of accuracy apply to all 3 curvatures. Second, we notice that in the flattest and softest condition (40 mm and Shore 00-10), participants were also less accurate. For all other conditions, the 95% CI include the reference, meaning that participants were accurate.

4 PRELIMINARY LESSONS FOR THE DESIGN OF SOFT ROBOTIC UIS

This pilot experiment provides preliminary quantitative data to design adequate haptic feedback with soft robotic UIs. First, participants performed with low discrimination threshold and high accuracy with the softest stimuli in the most curved condition. This suggests that soft material can precisely and accurately transfer shape information. Very soft (00-10) and very curved UIs (radius 10mm) may enable the display of the most precise and accurate information to users. On the contrary, soft robotic UI designers should avoid using very soft material (e.g., softness similar to Shore 00-10) when UIs are nearly flat (e.g., with a radius more than 40 mm).

Second, participants were less accurate in estimating the curvature when the stimulus had a softness similar to our index finger-pad. The estimation was flatter when the curvature was 10 and 20 mm, and more curved when the curvature was 40 mm. If our final experiment confirms this pilot data (e.g., confirmed by ANOVA), this phenomenon should be compensated for, when designing soft robotic UIs. During the discrimination with stimuli harder than our index finger-pad (i.e., Shore A-30 and Rigid), the inaccuracy did not occur. During the discrimination with stimuli softer than users' index finger-pad (i.e., Shore 00-10), the inaccuracy occurred only when discriminating our flattest stimuli, not in the cases of more curved stimuli. This suggests that participants can have better discrimination accuracy when touching and exploring a surface whose softness differs from the softness of their finger pad.

5 CONCLUSION AND FUTURE WORK

We presented the design of a psychophysical experiment to determine the point of subjective equality (PSE) and the just noticeable difference (JND) in curvature depending on the softness of the UI. We also presented some preliminary findings based on our pilot data. We will now conduct the actual experiment (i.e., with 12 participants) to provide the HCI and soft robotics communities with accurate JND and PSE, and to determine whether softness has a significant effect on the curvature JND and PSE. This experiment will allow us to provide design guideline for shape- and softness-changing UIs.

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