SoftAR: Visually Manipulating Haptic Softness Perception in Spatial Augmented Reality

Parinya Punpongsanon, Student Member, IEEE, Daisuke Iwai, and Kosuke Sato, Member, IEEE

Abstract—We present SoftAR, a novel spatial augmented reality (AR) technique based on a pseudo-haptics mechanism that visually manipulates the sense of softness perceived by a user pushing a soft physical object. Considering the limitations of projection-based approaches that change only the surface appearance of a physical object, we propose two projection visual effects, i.e., surface deformation effect (SDE) and body appearance effect (BAE), on the basis of the observations of humans pushing physical objects. The SDE visualizes a two-dimensional deformation of the object surface with a controlled softness parameter, and BAE changes the color of the pushing hand. Through psychophysical experiments, we confirm that the SDE can manipulate softness perception such that the participant perceives significantly greater softness than the actual softness. Furthermore, fBAE, in which BAE is applied only for the finger area, significantly enhances manipulation of the perception of softness. We create a computational model that estimates perceived softness when SDE+fBAE is applied. We construct a prototype SoftAR system in which two application frameworks are implemented. The softness adjustment allows a user to adjust the softness parameter of a physical object, and the softness transfer allows the user to replace the softness with that of another object.

Index Terms—Spatial augmented reality, pseudo-haptic feedback, softness perception, product visualization

1 INTRODUCTION

The sense of softness is an essential haptic cue that significantly affects the impressions of soft objects as well as the assessment of their material qualities. Softness properties should be designed carefully for various soft products, particularly those that must be comfortable for users, such as furniture (e.g., cushions and sofas), clothes (e.g., hats and shoes), and plush toys (e.g., dolls). For soft products that use imitation materials (e.g., artificial leather and fake fur), manufacturers have pursued not only textures but also softness of products that are similar to those of real materials to achieve high-quality products at low prices. The food industry also attempts to optimize the softness of food products, which can significantly affect the taste of the products. In social human-robot interaction, the softness of a robot’s skin plays an important role because it determines the close physical interaction between robots and humans, and the impressions of the robot [1, 2].

The softness properties of the above-mentioned products are generally optimized through trial-and-error processes in which designers compare different soft materials through touch. However, the number of materials that designers can investigate is generally limited because of budget and space constraints. Augmented reality (AR) researchers have tackled this issue, thus allowing designers to explore a larger softness parameter space with a small number of real materials by manipulating the perceived softness of materials based on either physical haptic feedback [3] or pseudo-haptics [4, 5]. The latter approach visually changes the degree of deformation of a soft object while a user touches it, and this visual information is displayed on a head-mounted display (HMD) worn by the user. However, such approaches require users to wear or hold dedicated equipment that prevents comfortable and natural interactions.

In this paper, we introduce SoftAR, a novel spatial AR technique that visually manipulates the sense of softness perceived by a user touching a physical soft object without requiring any special devices. We use a consumer-grade projector to modify the appearance of a user’s hand and a touched object to change the perception of softness by leveraging multi-sensory integration of visual and haptic sensations in human brain. Such visual stimulation affects haptic perception; however, the flexibility of the visual representation of spatial AR is limited. In particular, the proposed method controls only the surface appear-
 sterilized for projection (e.g., they are geometrically complex, colored and textured). Consequently, the potential applications of spatial AR have been expanded considerably, such as virtually restoring damaged or historically significant objects [9], augmenting android robot head impressions [10], enhancing theme park experiences [11], and supporting car design processes [12]. However, even when a sophisticated radiometric compensation technique is applied, the textures of projected surfaces cannot be controlled perfectly and remain visible in most cases because of the limited dynamic range and spatial resolution of projectors [8].

Pseudo-haptics are caused by multi-sensory integration of visual and haptic/tactile sensations in the human brain, which has long been studied in psychology research [13, 14]. Following the pioneering work by Lecuyer et al. [15], several studies on virtual reality (VR) systems have applied pseudo-haptics, which provide haptic/tactile sensations by presenting only visual information that causes inconsistency between visual and haptic sensations [16]. Sensory inconsistencies can be presented with relative ease in VR environments because the graphics of virtual objects are completely controllable. Recently, pseudo-haptics were also observed to occur in AR environments where users’ bodies and/or real objects are visually modified and presented [17, 18]. However, the scope of pseudo-haptics AR research has been limited to video see-through AR that can control the visual information of a real scene. To date, spatial AR has not been a research focus.

This section describes the proposed method, which manipulates the perception of softness using pseudo-haptics has been investigated in VR and AR research. Hirano et al. found that the softness of a touched real object can be manipulated by visually enhancing the three-dimensional dent deformation of the object in a video see-through HMD according to a user’s pushing action on the object [4]. Such three-dimensional virtual deformation of a real object is technically possible in spatial AR based on the stereo rendering techniques used in immersive VR systems [7]. However, this requires the user wear tracked glasses, which degrades the advantage of spatial AR over other approaches. Furthermore, deformation graphics cannot be projected onto surfaces outside the projector’s view frustum; therefore the amount of deformation is limited. An alternative method that manipulates the perceived softness of a two-dimensional texture image displayed on an ordinary computer monitor and mouse-based input [19] has been proposed. That study proposed to apply two-dimensional dent deformation to a texture image and gradually change the color of a hand-shaped mouse cursor from white to red when a user clicks on the image. Achi et al. demonstrated that changing the color of a virtual hand could successfully alter the perception of softness of an elastic handheld device in a three-dimensional VR environment [20].

In this study, we investigate whether pseudo-haptics can occur in a spatial AR environment. In particular, our goal is to manipulate the perceived softness of a touched real object by projections. To achieve this goal, we apply the following projection visual effects: (1) two-dimensional dent deformation of an object’s surface and (2) changing the surface appearance of the user’s hand. As mentioned previously, it has been determined that similar visual effects work well in VR and video see-through AR systems. Additionally, these effects require only the modification of the appearance of real surfaces, thus, they are better suited for spatial AR than methods that require three-dimensional deformation. However, as mentioned above, current radiometric compensation techniques cannot perfectly control the appearance of a real surface by projections. Consequently, users must observe the surface of their hands and the touched real objects even when visual effects are overlaid. In our preliminary informal study, it was suggested that a combination of these projection visual effects had the potential to manipulate the user’s sense of softness in such a non-optimal condition [21]. In this study, we conduct a thorough formal experiment to investigate the detailed relationships among the projection effect parameter, the physical softness of a touched object, and its perceived softness to manipulate the perception of softness accurately with the visual effects. Furthermore, we discuss systems that apply the proposed method and validate them through the formal user studies.

2 RELATED WORK
Spatial AR or projection-based AR allows users to observe augmented real objects directly without requiring them to wear or hold dedicated devices [7]. Because of recent advances in radiometric compensation techniques [8], the surface appearance of real objects can be edited flexibly by projected imagery even when the surfaces are not optimized for projection (e.g., they are geometrically complex, colored and textured). Consequently, the potential applications of spatial AR have been expanded considerably, such as virtually restoring damaged surfaces. This manipulation of the perception of softness using pseudo-haptics is shown in Fig. 2.

Fig. 2. Proposed concept.

To summarize, this paper makes the following contributions:
- We introduce a novel spatial AR approach to manipulate the softness perception of a physical material without any user-worn/hand-held devices based on multi-sensory integration of visual and haptic sensations.
- Through a psychophysical study, we determine that a projected visual effect that changes the surface appearance of a projected hand and a touched object can significantly influence the perception of softness. Additionally, we derive a computational model that estimates a user’s sense of softness when this visual effect is applied.
- We have built a prototype system based on the proposed model that can manipulate user perception of softness, and we confirm its feasibility through user studies.

3 VISUAL MANIPULATION OF SOFTNESS PERCEPTION
This section describes the proposed method, which manipulates the perception of softness of a touched real object using only projected...
imagery. We present detailed information about the proposed visual effects and explain our psychophysical study, which investigated how the effects influence softness perception. On the basis of the results of the study, we propose a computational model that can predict the perceived softness as modified by the effects.

3.1 Visual Effects

When the surface of a textured elastic object is pushed by a finger, the surface texture moves to the pushed point because of its dent deformation. Simultaneously, the appearance of the fingertip also changes [22,23]. On the basis of these observations, we propose two projection visual effects, which are surface deformation effect (SDE) and body appearance effect (BAE) to induce visuo-haptic sensory inconsistency, and consequently, pseudo-haptics of softness perception. These effects are dependent on pushing force $F$ applied to the surface and softness parameter $K$ of a pushed real object. In this paper, $K$ is defined by a softness standard, TYPE E/ISO 7619 using a durometer (TECLOCK GS-721N), which is generally used for relatively soft elastic materials such as soft rubber and sponge. Note that when $K$ is small, an elastic object is soft, and vice versa.

3.1.1 Surface deformation effect (SDE)

Considering suitability for spatial AR, we apply a two-dimensional deformation effect rather than a three-dimensional effect. This effect synthesizes a deformation image by simulating elastic deformation of a pushed real object viewed from its normal direction (i.e., the direction from the top view), which is then projected onto the object’s surface. The deformation simulation depends on the softness parameter $K$ and applied force $F$. In this study, using our computer-vision-based deformation measurement technique [24], we measure the two-dimensional displacement vector $d(p,K,F)$ of each surface point $p$ with different combinations of $K$ and $F$ in advance. We then compute displacement vector maps for other combinations of $K$ and $F$ by interpolating the measured results. This calibration process is required once in advance. At run time, the deformation image to be projected is synthesized in real time by a simple texture mapping process using the surface appearance of the object and the displacement vector map.

3.1.2 Body appearance effect (BAE)

The BAE changes the surface color of the user’s body according to pushing force $F$. We prepared four types of BAEs, each of which changes the color of a different part of the hand, such as a finger or blood vessels, and we investigated the most effective BAE in a subsequent psychophysical study (see Sec. 3.3). Each effect changes the color of a specific part of the hand by projection such that it gradually changes the projected color from gray to red by increasing the saturation value in the HSV color space in proportion to the current pushing force $F$ while fixing the hue as red and the brightness as the mean brightness of the SDE. We apply a simple linear relationship between the saturation value of projected color $S$ and $F$ as $S = \frac{F}{F_{M}} S_{M}$, where $S_{M}$ and $F_{M}$ represent the maximum displayable saturation value and the maximum measurable force, respectively. Figure 5 shows the four effects: nBAE, fBAE, vBAE, and hBAE. nBAE changes the fingernail color of a pushing finger uniformly (Fig. 5(b)). fBAE changes the color of a pushing finger (Fig. 5(c)), in which the color change does not occur uniformly over the finger area but gradationally from the fingertip to the base of the finger. vBAE uniformly changes the color of the blood vessels in a hand (Fig. 5(d)). hBAE uniformly changes the color of the entire hand area (Fig. 5(e)).

These effects are realized by the following computer vision techniques. First, we extract the hand area using an overhead near infrared (NIR) camera with uniform NIR lighting such that the measurement is not disturbed by projections. We extract a user’s hand area by a simple threshold process based on the assumption that human skin absorbs more NIR light than the pushed real objects. We informally confirmed that real elastic objects used in our potential applications generally met this assumption. The subsequent process is different for each effect. For nBAE and fBAE, we apply a simple fingertip detection method by assuming that a user pushes a real object’s surface using only their index finger. In particular, we compute the convex hull of a simple polygon covering the extracted hand area [25] and detect the fingertip of a pushing index finger as the vertex of the polygon that is the furthest from the center of the hand area. For nBAE, an additional fingernail detection process is applied. We set a region-of-interest (ROI) of $m \times m$ pixels around the fingertip, apply the canny edge operator to extract edges, and fit an ellipse to the edges to detect the fingernail region. For vBAE, we apply adaptive histogram equalization (CLAHE) and a low-pass filter similar as to those method in [26] to the hand area to extract blood vessels that exhibit the darkest intensities in the hand area because of the NIR light absorption by hemoglobin. Note that we could replace these computer vision techniques with more sophisticated techniques to relax the above mentioned assumptions. However, these techniques worked well in our experiments and improving them is beyond the scope of this study.
3.2 SDE Calibration

The measurement of a displacement vector $d(p, K, F)$ for SDE was performed using the system shown in Fig. 3. We placed an elastic object with a known softness parameter on the workspace of the system and attached circular visual markers to its surface. The displacements of the markers were measured using the overhead NIR camera and the NIR light source. We installed a force sensor (WACOH-TECH Dynpick 6-axis WEF-3A20-0.2-UA) under the object to measure the pushed force value $F$. A stick held above the surface was used to apply constant force to the object throughout each measurement. Note that the value of $F$ could be varied easily by adjusting the stick holder.

The camera used in this experiment (PointGrey Flea3 FL3-U3-13S2M-CS with an IR pass filter, 1024×768 pixels) was installed 800 mm above the surface (Fig. 3(b)). We prepared three elastic objects (Exseal Hitohada Gel 0, 5, and 15; 300×300×35 mm) with different softness properties ($K = 0, 5, and 15$, respectively). Forty-eight circular markers (2 mm radius) were distributed on the surface, as shown in Fig. 3(a). Using our deformation measurement technique [24], we measured the displacements for all combinations of the three different objects ($K = 0, 5$, and 15) and 11 different force values ($F = 1, 2, 4, 6, 8, 10, 12, 14, 16, 18$, and $20$ N). In subsequent experiments, the measured data were linearly interpolated to compute displacement vector maps for unmeasured combinations of $K$ and $F$. The results of the deformation measurement for each elastic object (i.e., $K = 0, 5$, and 15) are shown in Fig. 4.

3.3 Psychophysical Study

We conducted a psychophysical study to investigate how the softness parameter $K$ affects the perceived softness. Furthermore, we conducted other studies to identify the most effective BAES, and investigated how the combination of SDE and the most effective BAE influences the perception of softness.

3.3.1 Experimental setup and participants

This experiment was conducted in a dark room (4.5 lux without projection). We used the same equipment described in Sec. 3.2 and a projector (NEC NP-L51WD, 1280×800 pixels, 70 Hz, 500 ANSI lumens), which was installed close to the NIR camera so that it faced down onto the workspace. The system hardwares are controlled by a PC (CPU: Intel Core i7 950 3.07 GHz, RAM: 6GB, GPU: NVIDIA GeForce GT520 2GB). The chromaticity and illuminance of the projected light measured at the work space was $x = 0.6326$, $y = 0.3296$ (CIE 1931 xy value) and 322.3 lux, respectively, when the most saturated red color (i.e., $S = S_M$) was projected. Note that, the chromaticity of projected gray color (i.e., $S = 0$) was $x = 0.3248$, $y = 0.3443$. We used the three elastic objects described in Sec. 3.2. In the remainder of this paper, $K_o$ denotes the softness parameter of the objects. As described above, these objects have different physical softness properties ($K_o = 0, 5$, and 15). As shown in Fig. 5, we applied a black and white checker pattern (8.5×8.5 mm) as the projection texture because the physical objects did not exhibit any visual textures. The pixel size of the ROI in the fingernail extraction process was set to $m = 15$.

Seventeen unpaid participants (13 males, and 4 females; age 22 to 26) were recruited from a local university. All participants were naïve to the purpose of the experiment and had normal or corrected to normal vision. We asked each participant to stand in front of the experimental setup, place a right index finger onto the elastic object placed above the center of a force sensor, and look at the object. Note that no specific instructions regarding viewing angle were given to the participants.

3.3.2 Effect of SDE on softness perception

We investigated the perceived softness of each physical elastic object when the SDE was applied. In the remainder of this paper, $K_e$ denotes the softness parameter of SDE. We applied parameters that are the same as those of the physical objects (i.e., $K_e = 0, 5$, 15). There were nine experimental combination of $K_o$ and $K_e$ employed in this experiment. Note that $K_o$ and $K_e$ were identical in three conditions in
which the deformation movement of the projected checker pattern was the same as that of the physical surface. Under these conditions, the SDE simply visualized the actual deformation, thus, no meaningful effects were applied. Therefore, we regarded these three conditions as baseline conditions. These baseline conditions are referred to as $BC_0$, $BC_5$, and $BC_{15}$, respectively.

We applied a magnitude estimation method to investigate how the perceived softness was changed by the SDE. In each trial, we placed a reference (an elastic object of $K_o = 5$ without projections) next to our stimulus (one of the elastic objects under projection effects). We asked each participant to push the reference and the stimulus repeatedly with the same index finger and rate the perceived softness of the stimulus assuming that of the reference was 100. If the perceived softness of the stimulus was softer than the reference, a score greater than 100 was given, and vice versa. To ensure that the experiment was conducted with largely varying pushing forces, we conducted two trials for each condition in which different forces were applied. We asked each participant to push the stimuli and the reference with strong force in one trial and with weak force in the other trial. We allowed participants to determine subjectively how strongly they applied forces. Each trial was conducted in randomized order among participants and took approximately two minutes on average.

**Result** The forces applied in the experiment, which were measured by the force sensor, ranged from 1 to 4 N (2.07 N on average) in the weak force trials and from 7 to 10 N (9.21 N on average) in the strong force trials. We examined whether the different amounts of pushing forces influenced the assessment of softness significantly. We applied a two-tailed paired $t$-test for a pairwise comparison between the mean subjective magnitude of the strong force trial and that of the weak force trial for each of the nine conditions. We found that there was no significant difference under any conditions. Therefore, we conducted subsequent data analysis without discriminating between the magnitudes of the strong force and weak force trials.

Figure 6(a) shows the means and interquartile ranges of the participants’ subjective magnitudes. Because the goal of this study was to investigate the influence of the SDE, therefore, we focused on comparing results among conditions in which the same physical objects were used. We separated the experimental conditions into three groups in terms of the softness parameter $K_e$ and applied one-way analysis of variance (ANOVA) for each group. The analysis showed the following main effects in all groups: $F_{2,48} = 73.4$, $p < 0.01$ in the $K_e = 0$ group, $F_{2,48} = 25.3$, $p < 0.01$ in the $K_e = 5$ group, and $F_{2,48} = 25.3$, $p > 0.01$ in the $K_e = 15$ group. Post-hoc analysis was performed using Bonferroni’s method for pairwise comparisons among the means of each group.

As shown in Fig. 6(a), the results of analysis suggest that the SDE with smaller softness parameter $K_e$ generally provides significantly softer perceptions, and vice versa ($p < 0.01$ in seven pairs out of nine). By focusing on the differences from the baseline conditions, significant differences were determined for all three cases of $K_e < K_o$ (i.e., softening manipulation). However, no significant difference in the case of $K_e > K_o$ (i.e., hardening manipulation) was determined. Therefore, although we confirmed that softness perception of an elastic object can be manipulated with the SDE by adjusting the softness parameter $K_e$, this visual effect can manipulate human perception of softness only for the softening direction.

3.3.3 Most effective BAE

We investigated how the proposed BAEs influence perceived softness to identify the most effective BAE. We investigated perceived softness of the three elastic objects ($K_e = 0, 5$, and 15) with the four BAEs (i.e., vBAE, hBAE, vBAE, and hBAE). Thus, there were twelve experimental conditions, which we refer to as BAE conditions in this section. We applied the same experimental procedure as the previous experiment described in Sec. 3.3.2. We conducted two trials with different forces (strong and weak) for each condition. To visualize the actual surface deformations on the non-textured elastic objects, we applied the SDE with a softness parameter that was equal to the actual deformation (i.e., $K_e = K_o$).

**Result** The forces applied in the experiment ranged from 1 to 4 N (2.00 N on average) in the weak force trials and from 7 to 10 N (8.58 N on average) in the strong force trials. A two-tailed paired $t$-test showed that there was no significant difference between the mean subjective magnitude of the strong force trial and that of the weak force trial for each of the twelve conditions. Therefore, we conducted data analysis without discriminating the magnitudes of the strong force trials from those of the weak force trials.

Figure 6(b) shows the means and interquartile ranges of participants’ subjective magnitudes for the BAE conditions. We compared the results with those of the baseline conditions (i.e., $BC_0$, $BC_5$, and $BC_{15}$ in the previous experiment) to investigate the influence of the BAEs. Specifically, we applied a two-tailed paired $t$-test to compare...
the mean subjective magnitude of a BAE condition with that of the corresponding baseline condition. Note that, these conditions shared the same elastic object. The statistical analysis showed that only fBAE provided significantly greater perception of softness than the baselines for all elastic objects \((p < 0.05)\). The other BAEs provided significantly different softness perceptions for only a part of the objects. Therefore, we confirmed that fBAE was the most effective among the proposed BAEs. We propose to combine the fBAE with the SDE to boost the perceived softness manipulation ability of the SDE, particularly in the softening direction.

3.3.4 Effect of combined SDE and fBAE on softness perception

We investigated how the combined SDE and fBAE influences the perception of softness compared with the SDE only. In the remainder of this paper, we refer to this combination as SDE+fBAE. In this experiment, we asked participants to assess the softness of elastic objects \((K_o = 0, 5, \text{ and } 15)\) when SDE+fBAE with different softness parameters \((K_e = 0, 5, \text{ and } 15)\) were applied. Although there were nine experimental conditions \((3 \times 3)\), we already tested three conditions where \(K_o = K_e\) in the previous experiment. Thus, there were six conditions to investigate. We applied the same experimental procedure used in the previous two experiments. Therefore, we collected the participants’ perceived softness as their subjective magnitudes through two trials with different forces (strong and weak) for each condition.

**Result** The forces applied in the experiment ranged from 1 to 4 N (2.17 N on average) in the weak force trials, and from 7 to 10 N (8.35 N on average) in the strong force trials. A two-tailed paired t-test showed that there was no significant difference between the mean subjective magnitude of the strong force trial and that of the weak force trial for each of the six conditions. We then conducted data analysis without discriminating the magnitudes of the strong force trials from those of the weak force trials.

The means and interquartile ranges of the participants’ subjective magnitudes for all conditions, including those for \(K_o = K_e\), are shown in Fig. 6(a). As described in Sec. 3.3.2, we separated the experimental conditions into three groups in terms of softness parameter \(K_o\) and applied one-way ANOVA to each group. The analysis showed the main effects for all groups: \(F_{2, 48} = 39.0, p < 0.01\) in the \(K_o = 0\) group, \(F_{2, 48} = 58.1, p < 0.01\) in the \(K_o = 5\) group, and \(F_{2, 48} = 16.3, p < 0.01\) in the \(K_o = 15\) group. Post-hoc analysis was then performed using Bonferroni’s method for pairwise comparisons among the means of each group.

As shown in Fig. 6(a), the results of the analysis suggest that SDE+fBAE with smaller softness parameter \(K_e\) generally provides significantly softer perceptions, and vice versa \((p < 0.05 \text{ in seven pairs out of nine})\). To compare these results with those of the SDE only, we applied a two-tailed paired t-test for a pairwise comparison of each pair. The results are also shown in Fig. 6(a). As can be seen, SDE+fBAE provided significantly softer perceptions than the SDE only \((p < 0.05 \text{ in eight pairs out of nine})\). From these results, we confirmed that the combined SDE+fBAE had stronger effect on perceived softness for the softening direction of an elastic object than the SDE only. Thus, we selected SDE+fBAE as the visual effect for our system.

3.4 Computational Model to Estimate Perceived Softness

We created a computational model that estimates how perception of softness changes when an elastic object with a softness parameter \(K_e\) is pushed while SDE+fBAE is applied with a softness parameter \(K_o\). Using the model, we can visually manipulate a user’s softness perception of an elastic object such that they perceive different target softness rather than the physical softness.

For consistency of units in the model, we define human softness perception using the softness standard of TYPE E/ISO 7619, which is used for representing the softness parameters of \(K_o\) and \(K_e\), rather than the raw subjective magnitudes collected in the previous experiments. In particular, the new perception value, represented as \(K_p\), considers \(K_o\) for the perceived softness of an object whose softness parameter is \(K_e\). We applied regression analysis to estimate the relationship between softness parameter \(K_o\) of physical objects and the raw subjective magnitudes of softness perception in the three baseline conditions. Because of the nonlinearity of human perception, we fit a logarithmic function to this relationship. As a result, we obtain the following equation:

\[
K_p = -9.0241 \log M_p + 47.5471
\]

where \(M_p\) represents the raw subjective magnitude and \(r^2 = 0.836, p < 0.01\). Fig. 7(a) shows the fitting result.

Using Eq. 1, we converted the collected raw subjective magnitudes of SDE+fBAE in Sec. 3.3.4 to \(K_p\). We then created the computational

![Fig. 7. (a) Regression results of converting raw subjective magnitudes \(M_p\) to perceived softness \(K_p\) defined by TYPE E/ISO 7619 using a logarithmic function, and (b) computational model estimating perceived softness \(K_p\) from softness parameters of the physical object \(K_o\) and SDE+fBAE \(K_e\).](image)
model, which estimates perceived softness $K_p$ from the softness parameters of a physical object $K_o$ and SDE+FBAE $K_e$ by fitting a plane function to the converted data. As a result, we obtain the following equation:

$$K_p = 0.6250K_o + 0.1957K_e - 0.4117$$

(2)

where $R^2 = 0.8344$, $p < 0.01$. Fig. 7(b) shows the fitted results.

### 4 Application and Practical Evaluation

We implemented a prototype system to demonstrate potential applications and evaluated how accurately the system can manipulate a user’s perception of softness for each user scenario. The prototype consisted of all hardware used in the psychophysical study, a consumer-grade depth camera (SoftKinetic DepthSense DS325) for force estimation and a single-lens reflex camera (Canon EOS 550D) for capturing an object’s texture.

#### 4.1 Depth-based Force Estimation

In the psychophysical study, we measured pushing forces with a force sensor placed below the elastic objects. Although this method provides accurate measurements, a user must push a specific location on the surface relative to the placement of the sensor. Therefore, it would be inapplicable to many real scenarios. We relaxed this constraint in the prototype system by developing a depth-based force estimation technique inspired by previous depth-based touch detection methods proposed for interactive tabletops [27,28]. In particular, we estimated pushing forces applied to an elastic object from a displacement along a direction normal to its surface.

##### 4.1.1 Force estimation technique

We measured displacement using the depth camera installed above and directed to the surface of an elastic object. Measured depth data at a surface location on which a user pushes is the distance from the depth camera to the upper surface of the touching finger. Therefore, we had to subtract the thickness of the finger from the measured depth data to acquire the distance to the object’s surface. We conducted a preliminary experiment to measure the thickness of seventeen subjects’ index fingers, which was 10 mm on average. In each application, we captured a depth image to measure the distance from the camera to each surface point in advance. The initial distance map is represented as $z(p,K)$, where $p$ and $K$ represent each surface point and the softness parameter of the object, respectively. Then, at run time, we calculated the distance from the camera to a surface point, i.e., the point a user pushes, by subtracting the fingertip thickness from the average measured depth data in the fingertip region (i.e., ROI determined by fingertip detection mentioned in Sec. 3.1.2). The computed distance is represented as $z_p(p,K)$. We computed the displacement along the surface normal caused by the pushing force, denoted as $z(p,K)$, in the following equation.

$$z(p,K) = z_p(p,K) - z(p,K)$$

(3)

We estimated an applied force from the measured displacement by referencing a table that stores relationships between measured displacements and corresponding applied forces. To build the table, we measured displacements under various applied forces. In this calibration process, we placed a force sensor behind the elastic object to measure the applied forces. Note that the force sensor is only required for the calibration. Because the table is material dependent, therefore, calibration is required for each material. Fig. 8(a) shows the relationships among different materials used in the application evaluation in Sec. 4.2.1, which were measured in the prototype.

##### 4.1.2 Evaluation

We evaluated the proposed depth estimation method in terms of accuracy and response time. The object used in the psychophysical study, i.e., an elastic object of softness $K_o = 5$, was also used in the evaluation. For the accuracy evaluation, the object surface was evenly divided into $20 \times 15$ blocks. The evaluation was conducted for each block as follows. After placing the sensor behind the block, one of the authors pushed the surface using an index finger with 20 N and estimated the force using the proposed depth-based technique. We repeated this process ten times, averaged the estimated force values, and computed the error as the difference between the mean force and 20 N. Fig. 8(b) shows the error distribution over the surface. The average force error over the surface was 1.89 N.

To evaluate response time, we assessed the delay of the estimated force value from the sensor measurements. We computed the time difference between the time when the sensor measured 1 N and that when the proposed method estimated the same force value. The time difference was evaluated for all blocks. The mean time difference over the surface was 16.2 ms. Fig. 8(c) shows the time series of the estimated and measured force data at a block.

#### 4.2 Application

We consider two application frameworks. The first is softness adjustment in which the perceived softness of an elastic object is adjusted by the proposed technique without requiring a user to change the object. The process of determining suitable softness of an elastic product relies heavily on trial-and-error and requires many materials with different softness parameters. The proposed framework has the potential to shorten the design process and does not require different materials; therefore, it would be beneficial to manufacturers of various soft products such as soft furniture, plush toys, and imitation materials. The second application framework is softness transfer by which a user can replace the softness of an elastic object with that of another object. We assume that there would be some cases where product designers are interested in evaluating the softness of different materials for their products in a designing process.

Figure 1 shows our prototype application called SoftAR, which enables users to perceive differences in softness of an elastic object sim-
In particular, we set \( \hat{K}_p \) softness values for each object for the interface. In the first approach, we set two target softness parameters were prepared for the experiment. As in the psychophysical study, we asked each participant to push a reference to be 100. In this experiment, the participants could push with arbitrary forces (i.e., one trial per condition). The softness of the stimulus by assuming the perceived softness of the reference with our stimulus (a physical objects with SDE+fBAE projection). Each participant pushed the reference and the stimulus repeatedly with the same index finger and then rated the perceived softness for various materials. Physical objects of different materials with different softness parameters were prepared for the experiment. As in the psychophysical study, we asked each participant to push a reference (an elastic object of \( K_o = 5 \) without any projection) and compare the reference with our stimulus (a physical objects with SDE+fBAE projection). Each participant pushed the reference and the stimulus repeatedly with the same index finger and then rated the perceived softness of the stimulus by assuming the perceived softness of the reference to be 100. In this experiment, the participants could push with arbitrary forces (i.e., one trial per condition).

According to the proposed frameworks, we set target softness \( \hat{K}_p \) using the following approaches. In the first approach, we set two target softness values for each object for the softness adjustment framework. In particular, we set \( \hat{K}_p = 6 \) and 5 for a fabric doll (\( K_o = 8 \)), \( \hat{K}_p = 6 \) and 5 for a towel (\( K_o = 8 \)), and \( \hat{K}_p = 7 \) and 6 for a cushion (\( K_o = 10 \) assuming the softness design process of soft products. These objects are shown in Fig. 10. Thus, there were six experimental conditions in the first approach.

In the second approach, we prepared three experimental conditions for the softness transfer framework. Note that we refer our softness transfer as we applied the softness parameter of the reference object to those of target objects. First, the softness of a human hand \( K_o = 8 \) was transferred to artificial human skin \( K_o = 15 \) assuming a robot skin design process. Second, the softness of bread \( K_o = 3 \) was transferred to a sponge \( K_o = 6 \) assuming a soft toy design process. Finally, the softness of a chair \( K_o = 5 \) was transferred to another chair \( K_o = 7 \) assuming the softness design of a chair.

We used the surface textures of physical objects for the SDE rather than the checkered pattern used in the psychophysical experiment. The textures were captured in advance by a single-lens reflex camera (Canon EOS 550D) under uniform white illumination. Except only the checkered pattern used in the psychophysical experiment. The textures were captured in advance by a single-lens reflex camera (Canon EOS 550D) under uniform white illumination. Except only the surface texture for an artificial human skin was taken from the synthesized image because a physical object does not has any texture. Figure 11 shows an example of the SDE applied to the surface textures of the physical objects. Eighteen unpaid participants (15 males and 3 females)
males, age 24 to 27) were newly recruited from a local university. All participants were naïve to the purpose of the experiment, and had normal or corrected to normal vision. We asked each participant to stand in front of the experimental setup, place their right index finger on the object, and look at the object. No specific instructions about viewing angle and pushing position were provided.

Result Figure 9 shows the means and interquartile ranges of participants’ perceived softness converted from raw subjective magnitudes using Eq. 1. For each condition, we computed the error of mean perceived softness from its target. In the conditions for the softness adjustment framework (Fig. 9(a)), the errors were 0.33 ($\sigma^2 = 0.29$) and 0.55 ($\sigma^2 = 0.98$) for the fabric doll ($K_p = 6$ and $K_p = 5$, respectively), 2.17 ($\sigma^2 = 0.66$) and 0.86 ($\sigma^2 = 0.41$) for the towel ($K_p = 6$ and $K_p = 5$, respectively), and 0.54 ($\sigma^2 = 0.37$) and 0.09 ($\sigma^2 = 0.56$) for the cushion ($K_p = 7$ and $K_p = 6$, respectively). In the conditions for the softness transfer framework (Fig. 9(b)), the errors were 0.14 ($\sigma^2 = 1.35$) for the artificial human skin, 0.74 ($\sigma^2 = 0.37$) for the sponge, and 0.50 ($\sigma^2 = 0.34$) for the chair, respectively. The average error for all conditions was 0.44 and the occurred variance among the participants were less than 1.00 except for the artificial human skin condition that assuming the softness transfer framework.

From these results, we confirm that on average, the proposed technique can manipulate perceived softness for various materials with an accuracy of less than one-half of the softness parameter space unit. In addition, we conducted a preliminary informal study to investigate whether the average error is smaller than the just noticeable difference (JND) of softness perception. Fourteen participants recruited from our laboratory were asked to compare the two balloons with different softness, i.e., $K_p = 5.0$ and $K_p = 5.5$, respectively, and then choose the softer one on the basis of the two-alternative forced choice (2AFC) method. The result showed that 47% of the participants selected the correct one, which was close to the chance level (i.e., 50%). From these results, we confirmed that the proposed method provided the perceived softness with an average error of less than the JND of softness perception.

5 Discussion
This section discusses the contributions and limitations of the proposed method.

5.1 Contribution
The application evaluation results suggest that we can manipulate perceived softness with an accuracy of less than JND. Considering the advantages of spatial AR over other AR approaches, we believe that the proposed technique can provide a promising framework for softness manipulation in various application fields, particularly for the design of soft products. In particular, this research provides the following two main scientific contributions.

First, to the best of our knowledge, this work is the first attempt to explore the applicability of a projection-based approach to pseudo-haptics by assuming final application scenarios. Except for a small number of psychophysical studies [29], little effort has been applied to that issue because of the relatively limited capability of visual manipulation even though spatial AR has several advantages over other AR approaches (e.g., wide field of view and no requirement of user-worn/hand-held devices). In this research, we show that projection-based pseudo-haptics have potential applications in various fields.

Second, we also analyzed the outcome of our visual effect on perceived softness and investigated a synthesis framework for the visual effect based on a computational model (i.e., Eq. 2) to control softness perception. This framework can be used by product developers and for emerging research as a system design guideline.

5.2 Limitation
There are three known limitations of the proposed technique. First, the force sensing method based on the depth measurement described in Sec. 4.1 requires calibration for each physical object. Thus, the user must perform calibration every time a new material is used. However, we assume that pushing materials would not be changed frequently because one advantage of the proposed technique is to provide different softness perceptions for a single material. In the future, we plan to collect and store the calibration results for different materials in a database to eliminate the need for repeated calibrations. So that the user applies a calibration data just by copying from the database rather than performing the calibration.

Second, the vision-based deformation measurement method [24] for the SDE was developed with the assumption that the softness property of a measured soft object is spatially uniform. Although many soft products consist of a single material, there are also soft objects with mixed materials with different softness properties. An existing solution for this problem is to apply a finite-element method (FEM) to estimate the deformation of such mixed materials [30]. However, in general, such techniques are computationally expensive, and are thus not applicable to interactive systems that require real time computations.

Third, although the proposed technique can make the perceived softness of an object softer with an accuracy of less than the JND, it is not designed to change the perception of hardness. An important next step of this research will be to find a visual effect that can alter both softness and hardness perceptions.
6 Conclusion

We have introduced SoftAR, a novel spatial AR technique based on a pseudo-haptics mechanism in the human brain that visually manipulates the sense of softness perceived by a user pushing on a soft physical object. Considering the limitations of a projection-based approach that only changes the surface appearance of physical objects, we have proposed two types of projection visual effects, SDE and BAE, that were determined according to the observations of people pushing a physical object. Through psychophysical experiments, we confirmed that the SDE could manipulate softness perception such that a participant perceived significantly more softness than the actual softness of an object. Furthermore, we confirmed that fBAE, in which BAE was applied only for a finger area, heightened the perception manipulation significantly. On the basis of our experimental results, we have created a computational model that estimates perceived softness when SDE+ fBAE is applied. We have constructed a prototype system in which two application frameworks are implemented, i.e., the softness adjustment and softness transfer frameworks. Through a user study of the prototype system, we confirmed that perceived softness could be manipulated with accuracy that is less than the JND of softness perception. SoftAR does not require any user-worn/hand-held equipment and allows users to experience significantly different softness perception without changing the soft materials. Therefore, we believe that it will be useful in various applications, particularly, in the design process of soft products, such as soft furniture, plush toys, and imitation materials. Currently, the proposed method is designed to work within a limited softness parameter space range (i.e., $K \in [0, 15]$). We intend to investigate the applicability of the proposed method to a broader parameter space as a future work.

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