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SoftPrint: Investigating Haptic Softness Perception of 3D Printed Soft Object in FDM 3D Printers

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Abstract. *FDM 3D printers allow massive creativity in personal products, but their potential has been limited due to inability to manipulating material properties. Previous work had demonstrated that the desired roughness could be presented simply by controlling the spatial density of tiny pins on a printed surface. This article offers a means of providing the desired softness perception of a printed surface and the desired roughness to expand the haptic dimension over which a user can exert control. Specifically, we control the softness by manipulating the infill structures of a printed surface. However, it is known that a skin contact area affects softness perception. The roughness, which is controlled by pins' density, may also affect the perceived softness of a printed surface. Therefore, we investigate how the internal structures and the density of the pins affect softness perception. Through psychophysical experiments, we derive a computational model that estimates the perceived softness from the density of the pins and the infill density of a printed surface.*
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1. INTRODUCTION

Recent FDM 3D printers (i.e., consumer-grade 3D printers) have enabled amateurs to create a personal product [1]. Along with advancements in machinery, there has been a growing desire for a variety of computational 3D printing techniques that enable complex shapes [2] and desired color appearances [3–5]. These techniques allow users to fabricate objects that visually meet personal requirements. However, the FDM 3D printers face several challenges in fabricating an object with desired haptic properties both due to the hardware form factors and affordability. For example, the current FDM 3D printer only allows two nozzles to extrude filaments. Thus, a user can use only two materials for each printed object, making it difficult to print it with various haptic properties. The printable haptic space limitation hinders a user from designing an object with the desired haptic sensation.

Adding the haptic sensation of 3D printed objects contributes to the functional and aesthetic values of the 3D printed objects as artifacts. Therefore, researchers have developed several computational 3D printing techniques by which rich haptic sensations can be presented [6–8]. These techniques rely on high-end 3D printers or active components such as an actuator. However, consumer-grade FDM 3D printers print an object less precisely and with fewer materials than high-end 3D printers. Additionally, the active methods require additional hardware or post-fabrication process, and thus, are difficult for personal use when a user has limited skills and does not have access to the supplies required by the additional hardware. Therefore, most of the previous studies do not fit our target user scenario, although one study does present a haptic printing technique that can be used in FDM 3D printers and does not require external active components [9]. Specifically, it demonstrated that the desired *roughness* could be presented simply by controlling the spatial density of tiny pins on a 3D printed surface.

This article focuses on providing the desired *softness* perception of a printed surface and controls desired roughness at the same time to expand the controllable haptic dimension (Figure 1). Our basic strategy to control the perceived softness is to adjust the internal structure of printed objects, specifically to infill density. Although this strategy sounds straightforward, it becomes complex when we focus on reproducing both desired softness and roughness perceptions. A previous study revealed that the contact area between a finger of the user and a surface significantly affects its perceived softness [10]. This finding suggests that the pins density control needed to reproduce the desired roughness could also modify the perceived softness of the surface. Therefore, the primary contribution of the article is investigating how the density of pins and infill density affect the perceived softness. Particularly, we conduct a psychophysical study to derive a computational model that estimates the perceived softness of a 3D printed surface from the infill density and pins density of the surface.

2. RELATED WORK

Our work is related to the passive haptics in 3D printed objects, and various fabrication techniques that address the limitations of FDM materials. For 3D printing techniques that aim to improve the mechanical properties of 3D printed material or enable tactile effects on the touch surface, please refer to [11–13].

2.1 *Increasing Needs in Haptic Experience in 3D Printing*

One of the benefits of 3D printing is that it allows the user to fabricate the appearance of an object (e.g., color and shape) and its haptic properties [4, 8, 14–17]. This function

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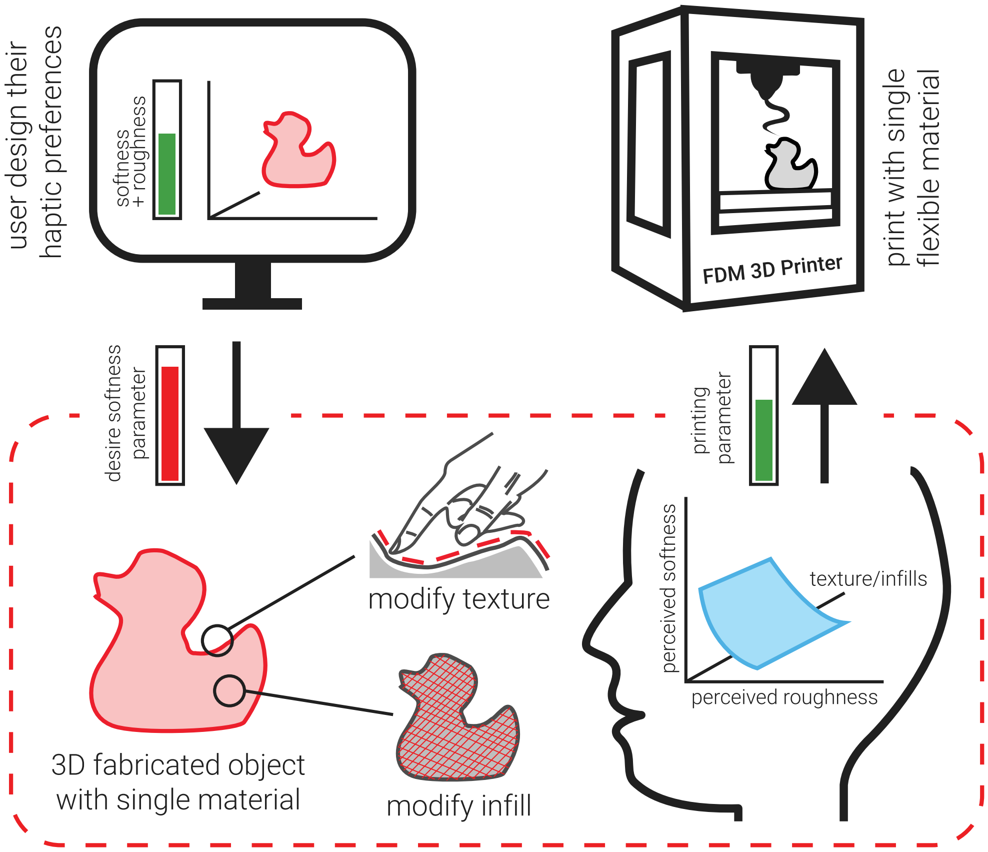

Figure 1. Our proposed concept could allow the user to design the desire to perceived softness and roughness as an input for 3D printing. The system then determines the 3D printing parameters such as infills and surface textures according to the target perceived softness. Then, generate the printing parameters to print with an FDM 3D printer.

is generally important for applications from designing comfortable clothing to medical phantoms for surgeons and doctors. However, the material used to generate meaningful haptic sensations is limited, causing unintended changes to the haptic perception of a 3D printed design.

Since an FDM 3D printer allows the user to control specific printing patterns at a relatively reasonable resolution, researchers have started to vary its properties with methods such as directly infusing special pigments into standard plastics and adjusting the printing commands to directly control the printer [2, 18, 19]. *CurviSlicer* [20] introduced an optimized printing command to manipulate the haptic representation from the printed curved part. *3D printed fabric* [21] presented a similar method for fabricating a flexible fabric without additional hardware. *CrossFill* [7] presented a method to indirectly manipulate 3D printed objects' weight perception by controlling the infill regions and their density. *HapticPrint* [22] manipulated 3D printed object's weight sensation by infusing special material that exhibits weight changed after fabrication. Our work focuses on the softness and roughness perception of 3D printed objects and therefore adds to this space the haptic softness and roughness experience of 3D printed objects.

2.2 *Softness and Roughness Perception in 3D Printing*

Prior works have investigated the effects of indentation depth and contact area aiming on manipulating either the appearance [23, 24] or tactile properties [6, 10, 25] of fabricated objects. Han and Keyser [26] examined the influence of material appearance on deformation perception and demonstrated that appearance could influence the judgment of softness based on visual properties. Previous work in digital fabrication has used a mechanical metric to quantify differences in softness and roughness properties. Piovarči et al. [27] introduced a method that modifies the softness of 3D printed objects by computing perceptual aware models through elastic modulus, and Bickel et al. [28] applied a finite-element method to design a specific softness (e.g., deformation properties) of the 3D model. However, such metrics require high-resolution industrial 3D printers.

Recently, Tymms et al. [9] created a roughness perception model based on pins density at which it is possible to print with an FDM 3D printer. Similarly, Dhong et al. [10] investigated the effect of pits on the roughness and softness perception. Giving pits as concave shape and pins as convex shape affects human perception in the same way. While increasing the intensity of pins could increase the contact area and affect perceived roughness and softness, decreasing the intensity of pits could also increase the contact area. While pins density potentially modifies the perceived softness, it is missing in the previous efforts to fabricate a haptics sensation with 3D printers. As a reminder, this study aims to add the softness sensation and a given roughness parameter. We expand the roughness perception model from previous works [9, 15] because modifying the perceived softness is unavoidable when combining with infills, and estimate the different perceived softness using an FDM 3D printer.

3. HAPTIC SOFTNESS PERCEPTION IN FDM 3D PRINTER

Although various infill densities (i.e., the volume inside the 3D printed object) can modify the perceived softness, it is unclear whether the indentation and contact area of pins that modify perceived roughness could also contribute to the softness sensation. On the other hand, modifying the contact area used in the roughness perception model may change the perceived softness, but no such investigation has been conducted so far. Our work is the first to explore haptic softness perception from a given roughness perception in an FDM 3D printer. Thus, we aim to allow both roughness and softness sensation for 3D printed objects.

We conducted the first experiment to investigate the best infill structure that would allow us to change the softness of fabricated 3D objects in the widest softness perception range. Then, we conducted the second experiment to investigate the effect of contact area on softness sensation by controlling pins density in addition to infill density.

3.1 *Method: 3D Printed Pins and Slab*

From previous work that sought to control roughness perception by manipulating pins density [9], we add a new domain—softness to cover both the haptic roughness and softness sensation of 3D printed objects. Our work combines the infills for slab and pins density derived from the roughness model using an FDM 3D printer (Fig. 1). We hypothesize that if the pins are sparser (i.e., a progressively longer distance between each pin), the contact area between the finger and the slab changes affects both roughness and softness sensation. In other words, we believe that when the pins are denser, it might affect the perceived roughness more than softness. By combining this with 3D printing infills, such as infill density and infill patterns, we explore the perceived softness for each range of parameters.

Unlike previous work, our pins and slab were made by an FDM 3D printer (Ultimaker 3, 0.4 mm nozzle resolution) using TPU material (Ultimaker TPU95A filament, 2.8 mm diameter). Since the previously investigated pins model for roughness perception was fabricated using a high-resolution industrial 3D printer, we set the pins resolution at one compatible with that of the FDM 3D printer from our preliminary experiment. The mechanical softness of 3D printed objects was measured by a standard elastic SHORE TYPE A/ISO 7619 using an off-the-shelf durometer (TECLOCK GS-09N). As shown in Figure 2, the results are compared with the magnitude estimation test in Experiment 1. The 3D printed objects were made without modifying the 3D printing parameters or enhanced the printer except for the infill density parameter.

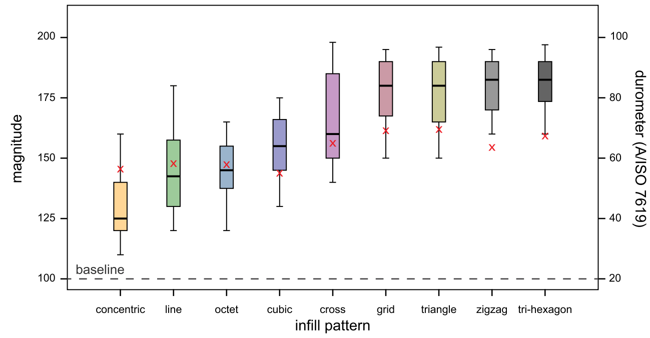

Figure 2. Boxplot of subjective magnitudes of perceived softness for each infill pattern compared with the mechanical test using durometer SHORE A/ISO 7619. The whiskers represent the highest and lowest values within 1.5 and 3 times the interquartile range without outliers. The baseline shows the magnitudes of perceived softness for the reference object.

3.1.1 *Slab*

The slab was printed with a square shape, W35 mm × H35 mm × D20 mm in size. The infill density was set at 5% after considering the standard FDM 3D printing recommended minimum. The infill structure was varied; cubic (CU), line (LI), octet (OC), concentric (CO), grid (GR), cross (CR), triangle (TR), tri-hexagon (TH), and zigzag (ZI) (Figure 3). We selected the infill structure patterns from the standard set of pattern frequently used by FDM 3D printers and considering the printable structure without any support materials.

3.1.2 *Pins*

We prepared five sparse pins by adapting the distance between each pit λ parameter from previous findings on roughness perception in 3D printed objects [9]. Each pit was printed as a cone shape, 0.3 mm in diameter and 0.5 mm in depth. We conducted the pilot study to verify the adapted λ was compatible with the FDM 3D printer [29, 30]. We decided on λ values of 0.685 mm, 0.815 mm, 0.935 mm, 1.063 mm, and 1.250 mm, respectively, for this study.

In the following section, we explore infill structures that provide a soft perception (Experiment 4). Then, we used these results to expand the softness domain to the roughness perception model (Experiment 5).

4. EXPERIMENT 1: EXPLORING INFILL STRUCTURES

In this experiment, we investigated the effect of infill structure on haptic softness perception to allow the widest change in softness perception. We recruited twelve naïve participants (seven male and five female) aged 22–24. All participants were right-handed. We screened all participants

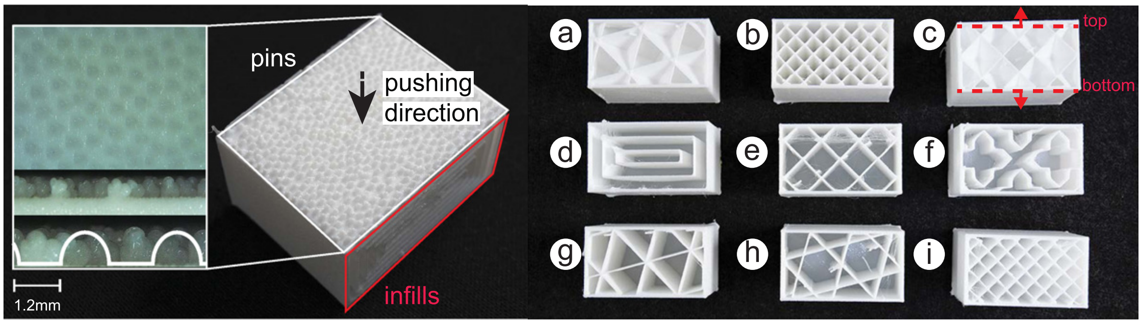

Figure 3. A sample 3D printed object with pins and concentric infill structure is used in the experiments 1 and 2. We prepared (a) cubic (CU), (b) line (LI), (c) octet (OC), (d) concentric (CO), (e) grid (GR), (f) cross (CR), (g) triangle (TR), (h) tri-hexagon (TH), and (i) zigzag (ZI) infill structures as the stimuli to explore the perceived softness. The samples show cut 3D printed object to display the internal structure on sides (i.e., user touch the object from the top as shown in white line). In the experiments, the internal structure was not visible to the participants.

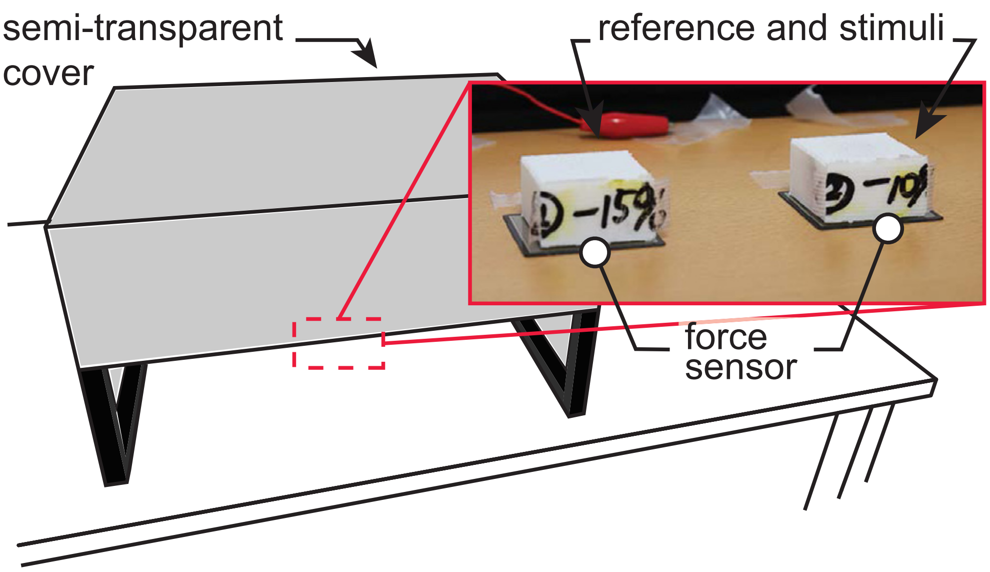

Figure 4. Experiment setup: a semi-transparent cover set over the experiment to prevent participants from seeing the stimuli while still allowing them to estimate the touch location.

to ensure that they were not depressed or excessively tired as physical or emotional states can alter perception.

4.1 *Apparatus and Stimuli*

As shown in Fig. 3, we prepared nine sample objects printed with 20% infill density using infill patterns shown in Section 3 as haptic stimuli. For the references, we used a standard elastic object (Exseal HITOHADA Gel Type 15) with the same dimension as the stimuli. We prepared a semi-transparent cover to prevent participants from seeing the stimuli, but they were still able to estimate the touch location of the stimuli. Furthermore, we attached the force sensor at the bottom of the stimuli to measure the force of touch exerted when participants explored the 3D printed objects (Figure 4).

4.2 *Procedure*

The participants were instructed to touch about 15N on the surface of the reference material (elastic object) for five seconds, then touch the stimuli (3D printed objects) for another five seconds and answer the questionnaire after each trial. Before starting each trial, the participant sat in front of the experiment setup and placed their dominant hand on the reference material. At the sound of a beep, participants started their haptic exploration with the reference object. They stopped their exploration during another beep (after five seconds) and moved to explore the stimuli. They stopped the trial when another beep was sounded (after five seconds). The questionnaire was presented on a monitor screen located to the right of the participant. We asked the participant to estimate the softness perception of the stimulus compared with the reference object using *magnitude estimation* method [31, 32]. They were instructed to indicate softness value as less than 100 if they felt the stimulus was softer than the reference and vice versa. Each trial lasted for about 15 min and included a total of nine stimuli. Each participant was asked to comeback to the experiment room the next day to perform a second measurement (called the *intervention task*).

Table I. Result of post hoc analysis on infill patterns using Tukey's HSD (significant difference: $p < 0.05$).

	CO	LI	OC	CU	CR	GR	TR	ZI	TH
CO	1.000	0.231	0.231	0.003	0.001	0.001	0.001	0.001	0.001
LI	0.231	1.000	1.000	0.825	0.024	0.001	0.001	0.001	0.001
OC	0.231	1.000	1.000	0.825	0.024	0.001	0.001	0.001	0.001
CU	0.003	0.825	0.825	1.000	0.009	0.009	0.010	0.002	0.001
CR	0.001	0.024	0.024	0.631	1.000	0.640	0.658	0.320	0.658
GR	0.001	0.001	0.001	0.009	0.640	1.000	1.000	1.000	0.998
TR	0.001	0.001	0.001	0.010	1.000	1.000	1.000	1.000	0.997
ZI	0.001	0.001	0.001	0.002	1.000	1.000	1.000	1.000	1.000
TH	0.001	0.001	0.001	0.001	0.998	0.998	0.997	1.000	1.000

4.3 *Result*

The result in Fig. 2 shows the average perceived softness of each stimulus (e.g., the 3D printed objects with various infill patterns). The participants felt softer with *concentric* (avg. 128.33) infills than *line* (avg. 144.16), *octet* (avg. 144.16), *cubic* (avg. 153.91), *cross* (avg. 165.67), *grid* (avg. 177.33), *triangle* (avg. 177.16), *zigzag* (avg. 180.41) and *tri-hexagon* (avg. 182.00), respectively. We performed a repeated measures ANOVA and found the main effect of infill density (F (8, 88) = 19.362, $p = 0.001$). The post hoc analysis using Tukey's HSD found the significant difference shows in Table I. Compared with the mechanical softness experiment using a durometer, the results corresponded with our perceptual study results. However, we also found that the participants felt softer of the object with concentric infill compared to mechanical measurement.

From the experiment result, we found that *concentric* the infill pattern (Fig. 3d) provided softer perceptions compared to other infill patterns. From our observation, the contact points between slab and infill corresponding to the perceived softness. Since the CO has fewer contact points when pressed with 15N, it provides a softer sensation than other infill structures. Therefore, we will use CO as the internal structure in the following experiment.

5. EXPERIMENT 2: EXPLORING SLAB AND PINS

In the second experiment, we investigated the effect of pins on perceived softness in addition to the roughness sensation when attached to the surface of the slab with a certain infill pattern. We recruited ten new naïve participants (seven males and three females) aged 21 to 32. All participants were right-handed. As in the previous experiment, we screened all participants to ensure that they were not depressed or excessively tired as physical or emotional states can alter perception.

5.1 *Apparatus and Stimuli*

As mentioned in Section 3, we prepared five 3D printed slabs with pins as stimuli. The infill structure of the slab was a *concentric pattern* (CO) based on its designation as providing softer perception in Experiment 4. We measured the mechanical elastic properties of stimuli produced with the same infill density and confirmed that the pins do not affect the mechanical softness. We used a standard elastic object (Exseal HITOHADA Gel 15) as the reference object. As in Experiment 4, we prepared a semi-transparent cover to prevent participants from seeing the stimuli, although they were still able to estimate the touch location of the stimuli. We also attached the force sensor to the bottom of the stimuli to measure the force of touch exerted when participants explored the 3D printed objects (Fig. 4).

5.2 *Procedure*

The participants were instructed to touch about 15N on the surface of reference material (i.e., the elastic object) for five seconds, then touch the stimuli (3D printed objects) for another five seconds and answer the questionnaire after each trial. To control the touch force, prior to the session, we asked the participants to touch the sample soft object before the session and measured the touch force. We recorded the touch force of each trial to the experimental computer, where each participant touched the objects. The participant sat in front of the experiment setup and placed their dominant hands on the reference material. At the sound of a beep, participants started their haptic exploration of the reference object. They stopped their exploration when another beep sounded (after five seconds) and moves to explore the stimuli. They stopped the trial when another beep sounded (after five seconds). The questionnaire was presented on a monitor screen located to the right of the participant. As in our previous experiment, we asked the participant to estimate the softness perception of the stimuli compared to the reference object by using the magnitude estimation method to assume the softness of the reference object as 100. If they felt the stimuli were softer than the reference, they would answer the magnitude of less than 100 and vice versa.

Each session included five stimuli (i.e., five pins), and each session took about 15 min. Each participant performed each session twice and was asked to comeback to the experiment room the next day to perform the intervention task. In total, we conducted five sessions (i.e., 5 infills) × 2 tasks × 5 stimuli = 50 trials.

Table II. Average results from magnitude estimation of perceived softness in experiment 2.

λ (mm)	Infill density (%)				
	5%	10%	15%	20%	25%
1.25	118.0	162.0	218.0	203.0	219.0
1.063	119.5	187.0	189.0	239.0	219.0
0.933	133.5	174.0	214.0	201.0	202.0
0.873	139.5	172.0	184.0	246.5	170.5
0.688	159.0	204.0	233.0	197.5	226.0

5.3 *Result*

The result in Table II shows the average perceived softness of each stimulus from two tasks. The participants felt stimuli softer with 5% infill and $\lambda = 1.25$ (118.0) than 1.063 (119.5), 0.933 (133.5), 0.873 (139.5), and 0.688 (159.0), respectively. Similarly, for the 10% infill, the participants felt the stimuli softer with $\lambda = 1.25$ (162.0) than 1.063 (187.0), 0.933 (174.0), 0.873 (172.0), and 0.688 (204.0), respectively. However, from the result, we could not find a clear relationship between softness perception and pins parameters with 15%, 20%, and 25% infills.

We intentionally performed a Tukey's Hinges method to identify and remove outliers. Therefore, the following analysis was performed on the data that did not include outliers. We also conducted a Shapiro–Wilk test to verify normality and a Mauchly's test to check the sphericity criteria ($p < 0.05$) before identifying the effect of infill and pins conditions in both tasks. Then, we performed a two-way repeated measures ANOVA with the factors of infills and pins for each exploration task to identify the interaction effect between the initial and intervention tasks. The results show that there was a significant main effect of the infills and pins conditions in the initial task (F (24, 239) $= 5.834$, $p = 0.003$) and a significant main effect in the intervention task (F (24, 239) $= 5.061$, $p = 0.002$). There was no significant interaction effect between the two tasks (F (576, 239) $= 1.013$, $p = 0.451$). Therefore, we analyzed both tasks together.

We used a dependent t test to identify the significant effect of pins among the same infills.

As shown in Figure 5, we found significant differences in the following conditions. For 5% infills: 0.688 mm–0.873 mm ($t = 2.847$, $p < 0.05$), 0.688 mm–0.938 mm ($t = 3.484$, $p < 0.01$), 0.688 mm–1.063 mm ($t = 3.990$, $p < 0.01$), and 0.688 mm–1.25 mm ($t = 3.993$, $p < 0.01$). For 10% infills: 0.688 mm–0.873 mm ($t = 2.725$, $p < 0.05$), and 0.688 mm–1.25 mm ($t = 2.661$, $p < 0.01$). For 20% infills: 0.688 mm–0.873 mm ($t = 3.011$, $p < 0.05$), 0.873 mm–0.938 mm ($t = -3.362$, $p < 0.01$), and 0.873 mm–1.063 mm ($t = -2.939$, $p < 0.05$). Then, we conducted the Pearson product-moment correlation coefficient (i.e., Pearson's correlation) and performed a regression analysis to predict the value of infill and pins density outside the scale of printing parameters. Since we only found significant correlation

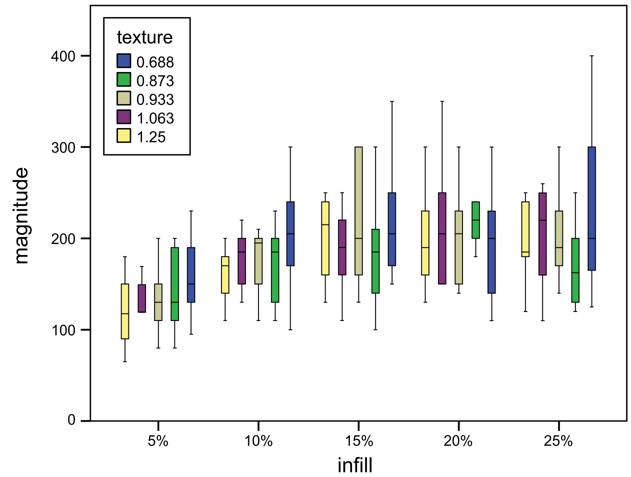

Figure 5. Boxplot of subjective magnitudes of perceived softness for each infill and pit parameter. The whiskers represent the highest and lowest values within 1.5 and 3 times the interquartile range without outliers.

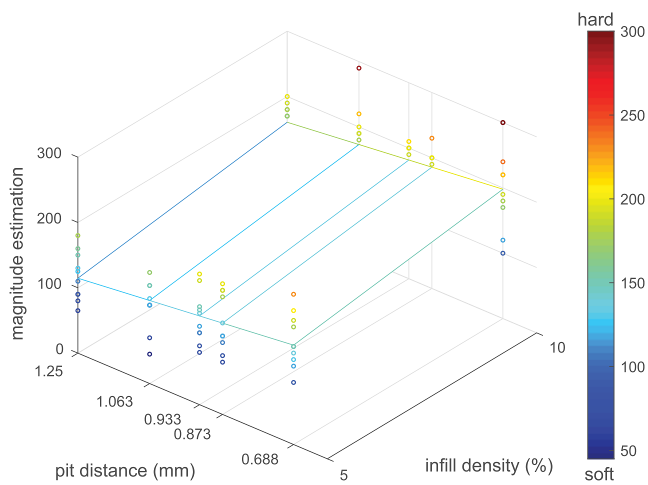

Figure 6. Regression result of raw subjective magnitudes to the perceived softness of infills and pits.

coefficients of softness sensation with pins density between 5% and 10% infills ($r = 0.667$, $p = 0.05$), we selected only those two infill parameters in our regression. Our selection is regardless of how deep the internal structure was contacted by the slab when the user pressed the objects with 15N. As a result, we obtained the following equation:

$$[magnitude] = 0.793[pit] + 1.741[infill] - 130.83, \quad (1)$$

where $R^2 = 0.597$, $p = 0.05$. Figure 6 shows the fitting result. From (1), our model estimates the infill density from the given perceived softness (i.e., magnitude estimation) and perceived roughness (i.e., pins density), [*infill density*] = f(*target softness perception*, *target roughness perception*). The target roughness perception derives directly from the roughness perception model [9], and the target softness perception derives from the range of magnitude estimation from our investigation.

6. GENERAL DISCUSSION

6.1 *Contributions*

Our results show that both infills and pins density significantly impact perceived softness and roughness sensations. From our observation, we found that when the contact area increases, the human fingers perceive roughness rather than softness, and at the same time, the perceived softness mainly depends on the pressure of the pushed object rather than the contact area. The psychophysical experiment confirmed that the infills and pins density parameters significantly affect the perceived amount of softness, especially in the range between 5% and 10% infill densities. However, our selection is based on the specific amount of force that is applied to the sample objects (i.e., 15N), and regardless of how deep the internal structure was contacted to the infill structure. Our results correspond to previous findings, which suggested a significant connection between the contact area between the finger and target objects and to the perceived roughness and haptic softness [10, 23, 24]. Furthermore, our work found another dimension—softness perception from the given perceived roughness derived from [9]. Our model can estimate the FDM 3D printing parameter and infill density by giving target perceived softness and target perceived roughness. Therefore, to create the 3D printed objects with a specific desired softness experience, the designer needs to carefully determine the appropriate infill density that will result in the desired softness perception given a target roughness perception.

6.2 *Limitations and Future Work*

First, the density of the pins used in our study relies on the roughness perception model [9] but with only a limited compatible density due to the form-factor resolution of FDM 3D printers. We plan to investigate further different pins models to extend our softness perception model in the future.

Second, our study is only specific to one FDM 3D printer (i.e., Ultimaker3) and with only one flexible filament (i.e., TPU). Although FDM 3D printers usually have a similar printing mechanism, printing speed, temperature, and nozzle size of different printers and different filaments may slightly change the physical properties of the 3D printed objects and modify the softness sensation [6]. Thus, it will be interesting and worthwhile for future studies to pursue a generalization of our exploration.

Furthermore, our selected infill pattern (i.e., concentric structure) does not have a structure that is connected to the shell (e.g., the touched area) and infill. Thus, the contact point between shell and infill does not directly modify the contact ratio inside the shell in case the force applied to the object is less than 15N. This issue limited our perception model to be applicable only when the force is applied to the object at 15N. We will experiment with different infill patterns in order to verify our perception model with the lower amount of applied force to the object.

7. CONCLUSION

This article focused on achieving the desired softness and roughness perceptions of a printed surface using the FDM 3D printer. Our result will help users and designers manipulate both the haptic softness and roughness perception of their target print object with one flexible filament by directly determining target softness perception and target roughness perception. At the same time, our model estimates 3D printing parameters such as infills and surface texture. We conducted two user experiments in which a wide range of infill structures presented different softness sensations and investigated the effect of infills and pins density on modifying the perceived softness. We found that using a concentric pattern as the infill structure resulted in the softest perception of all the prepared infill structures. The second experiment showed that infills and pins density parameters derived from the roughness perception model significantly affect the perceived softness. Finally, we derived the softness perception model from desired softness and roughness to estimate the FDM 3D printing parameters (i.e., infills and pins) from a target haptic softness perception.

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