# Aesop: An Expressive and Low-fidelity Approach for Soft Objects Printing

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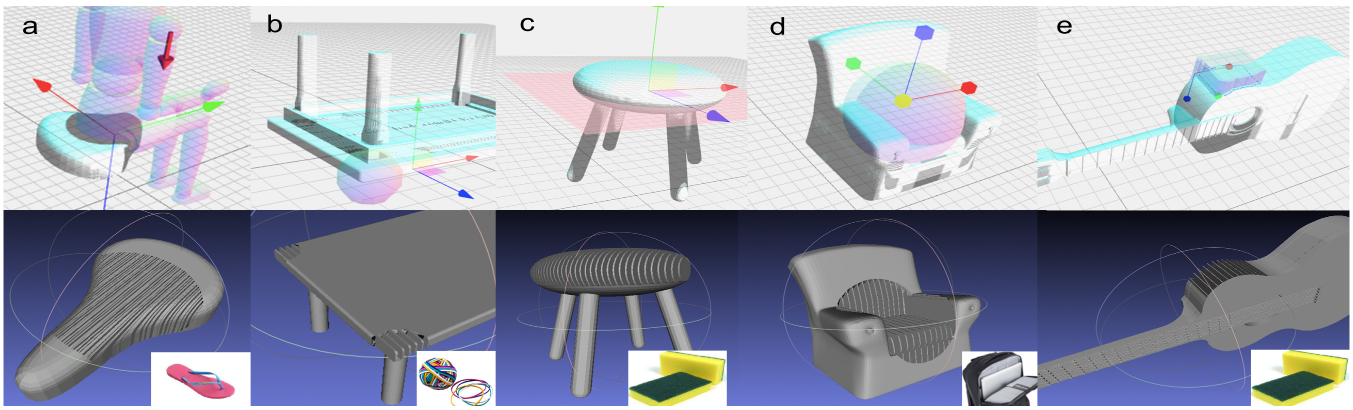


**Figure 1: Aesop is a low-fidelity approach for end-users to expressively model and 3D print objects with customizable softness. Designs created by our study participants: an ergonomic bike seat, baby-proof table, stool and sofa with soft seating, and a guitar with improved comfort. We created openings on the surface to reveal internal structures to produce softness**

## ABSTRACT

Softness is one of the most important factors in human tactile perception. With recent advancements in 3D printing, there has been significant progress in soft objects fabrication. However, these remain largely inaccessible to casual makers due to the requirement of high-end 3D printers, specialized computational software, and the lack of intuitive interfaces for expressing design intent. In this work, we propose Aesop, an expressive and low-fidelity approach to design and fabricate soft objects. Informed by systematic experiments on how printing parameters influence the resultant softness, we develop a simple data-driven pipeline to model softness based on user input. Our studies show that fabricated objects match the user perceived softness levels. We also provide an expressive design tool to specify the contact area, the level of softness by a jargon-free, easy-to-understand, example-based approach. We demonstrate our tool via practical applications created by actual users in an hour-long design session.

## CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**;

## KEYWORDS

Rapid Prototyping, 3D printing, Softness Design

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## 1 INTRODUCTION

From bike handles to seat cushions to shoe soles, soft objects play an important role in our daily lives. As one of the major components in human haptic perception [13], we often rely on softness to determine a material's quality, composition


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and comfort. With the democratization of 3D printers and an increasing selection of material options, it is possible for designers and casual makers to fabricate objects of various softness, which has greatly expanded the range of potential applications of 3D printing. However, designing and customizing soft objects remains challenging. Typically, popular 3D printing techniques, such as Fused Deposition Modeling (FDM), rely on special raw materials to fabricate compliant objects with little variability. If a user instead wants to vary the softness, the only option is to experiment with low-level printing parameters.

To overcome the innate limitations of raw materials, prior works [3, 9, 14–16, 23, 26, 27] have demonstrated that a broad range of material properties and interesting mechanical behaviors can be achieved via carefully designed *metamaterials*—using intricate microscopic structures to enable macroscopic behaviors beyond the raw material's bulk properties. While the potential application of metamaterial is immense, it is not yet accessible to a wide range of designers and casual makers due to the requirement of high-end 3D printers, advanced algorithms and the lack of user friendly design tools.

In this paper, we propose a low-fidelity approach for designers and casual makers to rapidly prototype objects with customized softness using off-the-shelf FDM machines and materials. As shown in Figure 1, our approach achieves customizable softness by a composition of simple infill patterns underpinning a user-specified area. Similar to how low-fi UI prototyping is valuable in the design process of software systems, we envision our softness design and fabrication approach will contribute to the early stages of 3D design. Our design tool, Aesop, addresses the following challenges:

*Computation.* Existing approaches for metamaterial design [23, 26] often require advanced algorithms in order to accurately obtain desired material properties. Such algorithms tend to be computationally expensive and inaccessible by the maker community. In contrast, Aesop takes advantage of human's softness perception [29] and adopts a low-fidelity and simple design that can be readily processed by existing software, such as the CuraEngine.

*Fabrication.* Due to the intricate nature of metamaterials, existing works often require high-end 3D printers for their fabrication. [14, 16, 23, 26] all rely on Stereolithography printers due to the high requirement on print accuracy and resolution. While recent works such as [15] aim to ensure FDM printability, the complexity of the output design makes it very time-consuming to generate and slice.

With Aesop, users can use any FDM 3D printers with various machine settings, such as different nozzle sizes and print bed, using the most common off-the-shelf soft materials (Soft PLA and TPU), under the default slicing and print speed. Advanced users can also expand our data-driven approach to introduce more materials, such as Soft Material composite filament (i.e. PolyFlex).

*Accessibility.* The lack of easy-to-use design tools is another factor that stops designers and makers from adopting metamaterial in their works. Existing approaches require users to communicate their desired softness in scientific quantities such as Young's modulus and Poisson's ratio, which may be non-intuitive for users without physics or engineering backgrounds. Existing tools for metamaterials design also tend to focus on low-level composition of structures, assuming a designer already has ideas of how to align cell structures [9]. Currently, there is a lack of expressive ways for users to: (1) define regions of a 3D model, (2) assign specific softness levels to those regions, and (3) achieve specific functional or application requirements. Aesop incorporates all these considerations into the design process. In our lab study, participants were able to successfully create their own designs using Aesop in an one-hour design session (Figure 1).

In this work, we define *softness* in the same manner as the seminal work [29], where softness measures a material's deformability under force. Specifically, we employ a standard softness measuring principle using the Shore A hardness scale [12], which measures the resisting force against a predefined displacement by a user's contact with and actions against an object. Our approach allows users to express a wide range of softness levels at specific target regions. Users can get feedback on the material softness, measured in Shore A scale, by specifying a common soft objects as reference. We then map user-defined softness values to design parameters by extending the existing notion of infill patterns to enable region-specific, user-customized softness. Specifically, by varying the density of an infill pattern, our experiments demonstrate that we can programmatically control softness as specified by the user.

Our specific contributions are as follows:

- A design tool for users to specify softness using familiar reference objects on a standard scale— the expressive user interface is compatible with other types of materials and microstructures to create soft objects
- A low-fi approach that fabricates softness by varying an object's infill density—our systematic experiment and user studies found that our generated softness closely matched users' desired softness, and specified softness by reference materials is reproduced using our fabrication method;
- An experimental pipeline for modeling the relationship between softness levels and the printing parameters—this pipeline allows experts to replicate our approach.

The limitations of our current approach are as follows:

- As a reasonable starting point, we decided to focus on one of many possible infill patterns (Figure 1); we printed our infill structures in the most optimal way, i.e., aligning them with the vertical printing direction;
- Different infill patterns may involve other factors that contribute to softness (binding strength between vertical cross-sections in honeycomb or concentric patterns), while we focus on the most significant parameter—infill density;
- Generalizing our approach to different FDM printers and filaments requires a one-time calibration process, which we have documented and open-sourced[1].

## 2 RELATED WORK

We start by discussing recent interactive design tool to support personal fabrication and existing techniques to design metamaterials to manipulate properties of objects. Then we discuss our inspirations drawn from latest research, to think about perception aware applications design.

### Design Tools for Personal Fabrication

Recent work in personal fabrication research found interactive tools for end users to explore design space earlier useful when they design features [4]. With a goal of enabling rapid prototyping, speeding up iteration became the first class challenge, leading approaches to address such issues by enabling users to validate results quickly (i.e., [21]). Instant visual feedback takes significant role in this case, so a user can estimate the shape before physical manufacturing (i.e., [5, 10]), and predict mechanical behaviors (i.e., [17]). As these tools focuses and rely on in visual features, namely shape and mobility, designing non-visual properties (e.g., softness) has been unavailable in most design tools.

### Metamaterial Design

At a sufficiently small scale, almost all material properties are the result of different structure arrangements at the molecular or crystal level. Scientists have been intrigued by how such microscopic structure influence a material's overall properties for decades. Large quantities of theoretical studies have been published (e.g. [8, 18, 19, 28]). However, most of these microstructure designs are either difficult or impossible to fabricate at the time.

With the rapid advancement in fabricating technologies, manufacturing highly complex structure in fine resolution becomes feasible. In laser cutting [32] and weaving [1], researchers have used creative metamaterial designs to overcome the innate limitation of the raw material. In 3D printing, Bickel et al. has proposed a data-driven approach to stack a small set of layer structure to achieve a target deformation behavior [3]. More recently, different classes of periodically tiled cellular structures are combined to obtain desired spatially varying material or mechanical properties [9, 23, 26]. In addition to regularly tiled patterns, a number of works explore the potential of using variations of Voronoi-like structures for achieving target material properties [14–16]. While these works demonstrate the feasibility of fabricating metamaterial that matches target material properties, the structures used often require specific printing technology and printer settings. A small change in the printer setup may result in completely different macroscopic material properties. Furthermore, with the exception of [9], designing an easy-to-user interface for conveying user's design intent is often overlooked, which hinders the wide adoption of metamaterials by the maker community.

### Perception Aware Fabrication

Research in haptic interfaces, especially haptic input devices, is increasingly concerned with user perception. Haptic devices are a proposed mechanism for users to express their intent. In the context of digital fabrication, by identifying fabrication parameters that affect perception [24], we can enable designers to consider the user's perception as a design parameter. Compliance perception is a complex phenomenon, affected by different cues, ranging from kinesthetic and cutaneous tactility [6, 30]. Awareness of the perception space lets researchers understand what to regard when fabricating objects, especially to create elastic object [25]. While this approaches by simulation and optimization of constructing kinesthetically tactile 3D object, HapticPrint provides tools for end users to design external (surface textures) and internal (weight and resistive force alongside the direction) tactility of a 3D printed object [31]. The results only show that changing infill density (20%-80%) in printing TPE presents linear relation between deformation degree by applied force, missing to convey how this information (displacement by pressure in N scale) can be used by end users.

In this work, we are concerned with the kinesthetic cues with applied force and force distribution by region, taking our attention away from visual validations and external design features (cutaneous tactile information) of the most common CAD tools.

## 3 EVERYDAY SOFT OBJECTS

Tactile overlay buttons are known examples that help blind people to access the flat buttons often found on home appliances [7]. With the Aesop design tool, users can transform their environments to become more accessible, with preferred comfort and pressibility. Improving the grip of everyday objects, such as a bike handle and a vinyl bag gripper, can greatly improve the quality of life of people with motor

[1]URL anonymous for review

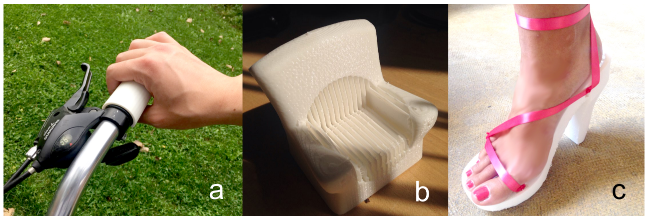


**Figure 2: Our tool, Aesop, enables novice users to create a personal grip handle cover, an ergonomic furniture, and a customized shoe with comfort.**

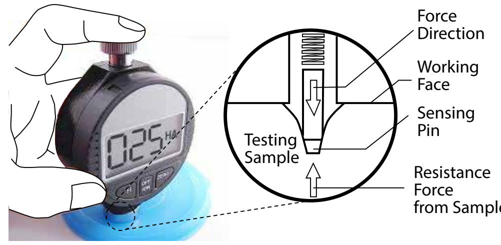


**Figure 3: A Shore-A Durometer is a device that measures softness as a function of resistance force from the material**

impairments [4] (See Figure 2a). There have been a lot of attempts to prototype ergonomic furniture using 3D printing, such as arm chair (See Figure 2b). Aesop will enable even a novice user to design and fabricate furniture (as shown in non-experts designs in Figure 1) and a highly customized wearable, a high heel with soft toe and heel while keeping the tip of the heel rigid so it can fully support a person's weight (Figure 2c).

## 4 OVERVIEW OF DESIGN & FABRICATION

Underpinning Aesop's low-fidelity softness fabrication approach is a data driven pipeline that models the softness of 3D printed objects and a computational design tool to support the design of fabrication-ready soft objects. According to the type of application that a user wants to create, there are various factors that the user needs to consider.

*Softness Level.* Although natural language best represents human's *perception* to explain feeling, the ranges of expressions are limited (i.e. Soft - Medium - Hard). However, natural language lacks precision, for example, it is hard to describe the softness preference of a mattress, unless a user touches it in action and compares the feeling with other objects. Also the expected softness-hardness level may also different by different individuals as it relies on subjective understanding and perception. Someone may expect as hard as rock from 'the hardest', while the other may expect as hard as a car tire with full air-pressure. It will benefit users to correctly specify subjective softness depending on their own feeling– personal perception on the materials by directly touching and feeling. How to model and enable users to specify softness will be detailed in section 5.

*Region and Direction of Force.* Human's perceived softness of objects is dependent on the use cases of fabricated objects. For example, an object's softness level a person feels may vary if the object is pressed by a finger, stepped on by a foot, or sat on by one's posterior, etc. Aesop enables users to directly specify the type of interaction, which allows our system to automatically retrieve the pre-defined force direction that matches the interaction type.

In many cases, these can be also specified by two factors: soft region and direction of force applied. For example, when designing a shoe with ergonomic softness distribution, a user may select soft regions by drawing the toe parts on the shoe's surface or by overlaying an elliptical-sphere to include the toe parts. Then, after soft regions are selected, the user can specify the expected direction of the force. In this case, the force is from the top to the ground and the user simply rotates the associated arrow to indicate that. Knowing that the force comes from above, our system automatically keeps the surrounding regions rigid, so the heel tip does not collapse when being worn. Details on how user can specify these factors will be described in Section 6.

## 5 MODELING SOFTNESS FOR FABRICATION

In this section, we detail how to create an object with different softness, and how we measure softness of these objects to model the correlation between softness as output and parameters to reproduce the softness.

### Softness Scale and Measurement

We take an experimental approach to investigate the correlation between printing parameters and the resultant softness by measuring printed objects'. We used a Shore A scale to measure hardness(softness), which is defined as the resistance to *indentation*, determined by measuring the depth of the indentation as shown in the Figure 3.

When using a fixed load (force applied to the sample), the larger the indentation, the softer the material [2]. Shore A scales and Durometers measure softness empirically and are commonly used in the plastic industry to assess objects such as rubbers, vinyls, etc. Shore A scales can measure the softness difference between a wide array of plastics and elastomers, and the device is affordable for personal use. Another benefit of using the Shore-A hardness scale is, if the material's own Young's modulus is known, it is possible to convert the number into the range of 30 - 95 values [11].

### Creating Metamaterial by Printing Parameters

Although there are existing algorithms to create compliant objects, these are typically either not compatible with low-cost FDM printers [23], or computationally expensive as they need many iterations to optimize a complex structure [15, 26]. Moreover, structures with a complex geometry can take a lot longer time to slice for processing and 3D print (15% slower than regular line based infills in [15]. In contrast, printing parameters are fast to set and directly influence the quality and property of a 3D printed object. These are factors that interweave the gap between a design file that describes a 3D model digitally and a machine language that interprets the model physically. Even with the same 3D model, different printer settings will generate physical models with different properties, such as strength and weight. With the understanding of printing parameters and challenges from existing solutions, we propose the following research question:

**RQ:** Can changing printing parameters operate as serve as a low-fi approach to create softness similar to generating metamaterial and how?

### Quantifying Factors to Manipulate Softness

With off-the-shelf flexible materials (eSUN Soft PLA and NinjaFlex TPU) using FDM process, users can differentiate softness by changing infill density of the same model. When a user prints a model in >80% density, the resulting in an object as firm as one printed in regular PLA—a rigid plastic. First, we experimented softness changes by changed printing parameters. Within Cura, one of the most common mesh slicers, expert settings mode exposes more than 13 parameters affecting print quality and property of results. To evaluate the effect of these parameters, we varied factors and generated apparatus to measure softness. Among these parameters, to find the most significant factor that affects softness, we set three criteria as follows:

- **Printability (P):** changing parameter should ensure fine quality of final outcome
- **Range of softness (R):** changing parameter should be able to generate a wide range of softness
- **Adjustability (F):** softness should be granularly adjustable by fine-tuning the parameter.

To model softness, printability using FDM with off-the-shelf materials, the wide range of softness and fine-grain control of softness should be assured. With these in mind, the following summarizes our experiments settings and experiment results about how these printing parameters affect softness. We modeled a 30 by 20 by 10 cuboid sample and varied factors as follow. Then measured the softness using a Durometer at three different locations of the top surface.

**Layer height** (from 0.1mm to 0.3mm by 0.05mm changes) has only little effects on softness. Also increasing it over 0.25mm loosen layer binding strength.

**Shell thickness** (from 0.2mm to 1.2mm by 0.2mm changes) only affects the thickness of outer walls, except top/bottom covers and infill walls as shown in the Figure **??**[2]. The effect on softness is ignorant.

**Retraction** (enable/disable) tested from may cause constant retracting and extruding so underextrude when printing with soft materials. In some cases, the printer could even grind the filament, or tangling between gears. Thus, users have less choice (disable retraction) to ensure printability.

**Flow rate/Feed Speed** (from 80% to 120% by 10% changes) Increasing flow rate extrudes more materials, harder object. However, to ensure printability and the quality of wall finishing, the range of safe flow rate cannot be diversed from 100% to around 120%, resulting in a narrower range of softness to produce.

**Printing speed** (from 5mm/s to 30mm/s by 5mm/s changes) cannot go beyond 20mms to ensure printability of flexible material, so that users cannot model a wide range of softness.

**Number of top layers** (from 1 to 5 by 1 changes) is modeled by top/bottom thickness, as a multiple of the layer height, otherwise slicing algorithm round it up. (i.e. Setting 0.8mm thickness with 0.2 layer height results in 4 top/bottom layers) Increasing 1 layer increases the level softness 10 15, makes it hard to fine tune softness difference under 10.

**Infill type** is limited in number as there are only certain types of infill patterns available. Changing infill pattern currently enables 8 different softnesses.

**Infill density** (from 5% to 100% by 5% changes) yields the widest range of softness with fine granularity of softness, guaranteeing printability.

Table 1 summarizes characteristics of printing parameters. Other than those listed, other parameters (e.g. platform adhesion type, support type, etc.) have no significant effect on softness. From this experiment, we can conclude that there are number of factors affecting softness of the object, but infill density is the most significant variable that lets us programmatically control softness.

### Modeling Softness

From our experiment, we found infill density the most significant, that can produce a wide range of softness, enabling fine tuning softness with stable printability.

Infill density is defined by the percentage of solid volume per the entire volume. The denser, the less empty space left inside the object. It is affected by the number of interior structures created, and the thickness of each of these structural

[2]Empirically, the shell thickness changes the infill wall thickness if it is set to the smaller than the nozzle diameter. Detailed in the 'replicability' section

| | Printability | Range | Granularity |
|---|---|---|---|
| Layer height | ○ | | |
| Shell thickness | ○ | | |
| Flow rate | | ○ | ○ |
| Print speed | | | ○ |
| # of top covers | ○ | ○ | |
| Infill type | ○ | | |
| Infill Density | ○ | ○ | ○ |

**Table 1: Among the most important printing parameters, infill density fulfill three criteria to model softness for 3D Printing.**

walls. Often, wall thickness of infill structures are fixed to the nozzle diameter, not able to be altered unless hacking. Assuming a vertical line-fill, which is one of the most common infill pattern, and fixed shell thickness, we modeled the infill density by intervals, line distance[3] between the infill walls. In turn, we can compute the number of interior walls in the square mesh as follows:

$$N_w = \frac{W_o}{(L_d + T_s)} \tag{1}$$

Where $N_w$ (integer) denotes the computed number of internal walls to support the top, $W_o$ refers to the width of the object, $L_d$ refers to the spacing between two adjacent walls, and $T_s$ refers to the thickness of each wall, currently set as default to the nozzle diameter.

With this equation in mind, we created 15 samples with the same cuboid shape and dimensions (30mm by 20mm by 10mm) and varying interior wall spacing, using a MonoPrice Maker MK11 with 0.4mm nozzle[4]. We kept all printing settings constant for these tests, but iterated twice with two the most commonly used flexible materials using FDM, Soft-PLA(eSUN) and TPU(NinjaFlex). Then we measured softness of each sample under a vertical, downward force, because printed outcome naturally presents orthotropic characteristics. Then we plotted the relationship between wall spacing and softness to see the correlation as shown in Figure 4, and found a trend line by various data fitting methods.

Here we get three equations that explain the data correlations better, with higher $R^2$ than others. For example, the equation derived by the power series fit is as follows:

$$S = \alpha \times L_d^{-\beta} \tag{2}$$

[3]https://ultimaker.com/en/resources/52670-infill

[4]The most common size nozzle for FDM printers

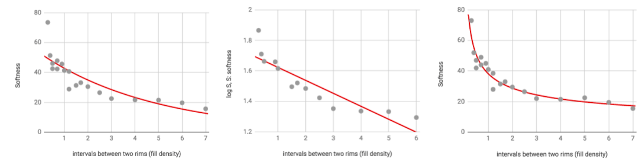

**Figure 4: Finding trend lines using an exponential model, linear model (by taking logs on exponential model), and power series model.** $R^2 = 0.728, 0.792, 0.926$**, respectively**

Where $L_d$ denotes our variables, line distance (wall spacing), and $S$ denotes produced softness by given variable values ranging from 0.3mm to 6mm. For Soft PLA, $\alpha = 38.2$ and $\beta = 0.408$, while for TPU, $\alpha = 43.9$, $\beta = 0.415$.

Our goal is to enable the system to compute an exact interval given a user specified softness level. When a user enters their desired softness level ($S$), the system needs to calculate the line distance ($L_d$) to leave gaps between vertical walls. This gives us the following by inverse of the Eq.(2):

$$L_d = e^{-\frac{1}{\beta} \times (\ln S - \ln \alpha)} \tag{3}$$

For example, to fabricate an object with softness 35 using Soft PLA, infill wall spacing is calculated by $e^{-\frac{1}{0.408} \times (\ln S - \ln 38.2)}$, which is 1.2391mm. Then this gap is used to build a number of walls inside of the object by equation (1) in the system.

*Validation.* Even with the intuition that a model with the highest $R^2$ would best describe the data among three data mapping options, we need to validate whether the inverse model can physically reproduce the desired softness (input) by computing line distance and whether it over-fits.

Thus, we reprinted samples with wall separation distances that are computed using desired softness as input, by three models. Table 2 summarizes computed wall separation by input softness, and generated softness by Durometer measure. We created the same samples with same dimension (30by20by10 cuboids), and measured softness in three different location and averaged as instructed by the Durometer manual.

Having all validations, we conclude that power series model best replicates desired softness, by computing intervals precisely without over-fitting.

## Radial walls

For spherical/cylindrical objects where user's force is applied around the curved surface, internal structures that support surface around the contact area is by radial distribution of the walls. To test the softness of these shape, we computed arc length by projected angles. As walls around spherical or cylindrical objects shapes are distributed around the arc length, we can calculate the projected arc length. To produce samples and measure the correlation between arc length

| Softness Input | Linear $L_d \Rightarrow \mathbf{S}_p$ | Exponential $L_d \Rightarrow \mathbf{S}_p$ | Power Series $L_d \Rightarrow \mathbf{S}_p$ |
|---|---|---|---|
| 15 | 6.74 ⇒ 18.83 | 6.19 ⇒ 18.83 | 9.88 ⇒ 15.66 |
| 25 | 3.77 ⇒ 20.33 | 3.64 ⇒ 22.33 | 2.82 ⇒ 25.5 |
| 35 | 1.81 ⇒ 35.83 | 1.96 ⇒ 34 | 1.23 ⇒ 35.83 |
| 40 | 1.04 ⇒ 42.5 | 1.29 ⇒ 43 | 0.89 ⇒ 41.16 |
| 45 | 0.35 ⇒ 61.6 | 0.70 ⇒ 47.83 | 0.66 ⇒ 47.83 |

**Table 2: Softness reproduction validation by random sampling of target softness. Power series fit generates the least gaps between input softness and produced softness**

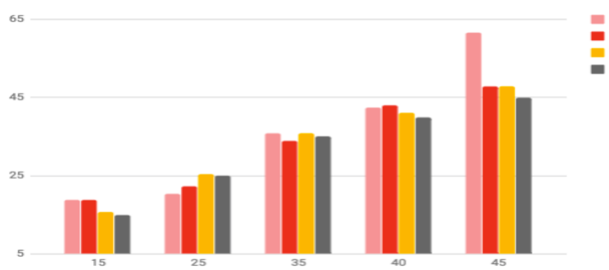


**Figure 5: Produced softness by input softness show less discrepancy when $L_d$ is computed by inverse power series model (3rd, yellow bar), compared with the actual data (last, gray bar)**

and softness, we varied angles between two walls diversed in given angle. Then, we measured produced softness to find $\alpha$, $\beta$ parameters of Eq. (2)-(3), that explains the relation between softness and spacings; using Soft PLA, $\alpha = 152$, and $\beta = 0.852$, and using TPU, $\alpha = 151$, and $\beta = 0.792$. In radial infills, $L_d$ of Eq.(2) and (3) denotes arc length $L_arc$, as arc length is linearly computed by the angle $\theta$ between two walls. The equation can be translated into the correlation between angle $\theta$, (i.e. $L_{arc} = 2\pi r * \frac{\theta}{360}$) and the produced softness $S$:

$$\theta = \frac{180}{\pi r} \times e^{-\frac{1}{\beta}(\ln S - \ln \alpha)} \tag{4}$$

Where $r$ denotes the radius of a spherical/cylindrical object.

## Replicability

To validate if our approach is extensible and reproducible using different types of machines with different dimensions and form factors, we further iterated our experiments using three commodity FDM 3D printers; Monoprice, Printrbot, and Lulzbot with 0.4mm nozzle and 0.6 nozzle. Other than the type of printer and nozzle size, we unified the printing profiles for parameter settings (layer height 0.25mm, shell thickness 0.2mm, bottom/top thickness 0.4mm, print speed 20mm/sec, printing temp 220, flow rate 110%). Same samples are printed and generated softness are similar without heated bed in PritrBot, with heated bed in 40 in LulzBot, and both cases in MonoPrice, resulting in similar softness (Softness STD=0.94, less than softness difference of 1)

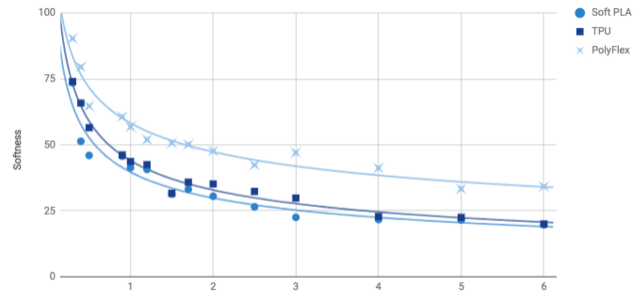


**Figure 6: Our approach expands printing material's innate range of softness: two materials with the same original Shore A softness (SoftPLA and TPU, 85A) shows very close tendency in wall spacing-softness correlation. Even a new material with higher Shore A softness (PolyFlex, 91-5A) shows similar tendency, but with stiffer $R^2 = 0.95, 0.98, 0.95$, respectively**

## Expanding to New Materials

Our models are material specific, validated using two of the most widely used off-the-shelf flexible materials (Soft PLA(TPE) and TPU) for FDM, and one more experimental material (PolyMaker PolyFlex, 90% TPU + 10%PLA). Figure **??** shows all materials show similar tendency around relationship between wall spacings and softness; the wider spacing, the softer.

Material experts and researchers, including a new algorithm to generate microstructure based metamaterials (i.e. [15], who want to model softness for end users, can iterate our pipeline: (1) print samples with various wall spacing, (2) measure generated softness, (3) find the correlation. We open sourced the process to model softness in numerical scale (Anonymized for Review), with a suggested settings to ensure printability of soft materials. We provide sample models in STL with various infill wall spacings, and interface to enter measured softness of each. The system then generates a new equation to define correlation between input softness and computed line distance. Once the relation is identified, our front-end design process remains universal for end users; they are still able to specify desired softness to generate 3D-printable files using a new material.

## 6 EXPRESSING PERCEIVED SOFTNESS

Computing intervals to reproduce desired softness requires users to input this number. It is beneath the assumption that users feel softness similarly as scale indicates; the lower the number, the softer.

### Measured Softness vs. Perceived Softness

To validate the assumption, first, we need to compare if measured softness in scale can represent user's felt softness.

*Method and Apparatus.* We conducted the first user study to see if user's softness perception closely matches the softness measured using the standard scale. We recruited 20 participants (Female=8) internally, age varying from 21 to 32. We first ranked stimuli that we produced to see correlations between line distance of walls and softness, based on measured softness scale. When ranked, softness difference in scale between two adjacently ranked stimuli are different, ranging from 0.1 to 22 (See Figure **??**). We then let users order stimuli from the softest to hardest, and compared results with the scale.

*Result.* Figure 7 shows a confusion matrix between actual rank in scale and users' perceived rank of softness. Rows indicate ranking in measured softness (1: softest, 14: hardest), columns indicate user's ranked softness. Participants' ranks are different from the actual rank by mostly one or two off. The diagonal trend indicates that users' perception of softness is similar to the ranking in number. But as we hypothesized, small differences (stimuli 2 & 3, with 0.1 difference) are not quite noticeable to users, whereas two stimuli with obvious differences (stimuli 13 & 14, with 22 difference) are correctly ordered. It tells us that even if our softness modeling cannot exactly reproduce input softness (STD: XX as shown in Table 2), users would not notice this much difference.

Now we conclude that (1) Human will perceive softness level similarly as standard scale, and (2) Stimuli with very small difference of or with similar softness are barely noticeable, but ordered close together

### Express Softness by Experience

The next challenge is then how to enable users to describe the softness level they want. Although our model can reproduce the right softness that user entered, it needs to be felt by users' own subjective senses, and expressed in numbers. So that the system can generate softness which will be felt similarly. There are existing methods to simulate physical hardness of objects [20, 22], that enable users to have the instant feedback if the results is satisfactory. However, these special devices are often expensive, focus on creating restraining force or shape-changing display, and it is not ideal to think that end users have access to such supplementary devices. Instead, we propose users can remind feeling by previous experiences, touching and sensing ordinary materials.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 7 | 3 | 8 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | 6 | 6 | 7 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **3** | 7 | 10 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4** | 0 | 0 | 0 | 8 | 9 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **5** | 0 | 0 | 1 | 7 | 4 | 3 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **6** | 0 | 1 | 2 | 3 | 2 | 7 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | 0 | 0 | 0 | 1 | 3 | 5 | 10 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **8** | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 14 | 2 | 0 | 0 | 0 | 0 | 0 |
| **9** | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 13 | 3 | 0 | 0 | 0 | 0 |
| **10** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 16 | 1 | 0 | 0 | 0 |
| **11** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 12 | 3 | 4 | 0 |
| **12** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 11 | 7 | 0 |
| **13** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 5 | 9 | 0 |
| **14** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 |

**Figure 7: User's ranked softness and ranking in measure standard softness.**

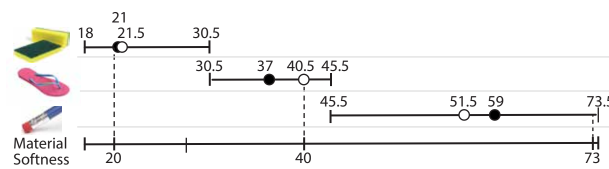


**Figure 8: Perceived softness range of existing objects. Each range shows min/max softness found, the black dot indicates the mean, and the white dot indicates the median of participants' choice. Found mean softness are very close to the actual softness of each objects, except the eraser that has too big gap between the first-second hardest samples**

We collected everyday materials that users might have experienced, or they can grab to feel softness immediately. Then we measured softness using a Durometer to quantify.

*Method and Apparatus.* We conducted the second study to see if reference material can represent their felt softness. We recruited 29 participants (Female=11, Age ranging between 20-49), not overlapping with the first study. We provided three existing objects with different softness, ranging very soft from dish scrubber (S=21), medium, flop-flop platform (S=40), and to very hard, a pencil eraser (S=73). All materials are not specially treated, purchased from commercial stores. Among randomly distributed samples with various softness without order, (same samples with the study 1, but remeasured if softness changed due to several experiments), we then let users compare softness of given materials by pressing with their finger. Then we let them find one sample that match or one with the closest softness. Participants can start searching without any order, however, as their finger may feel tired as the study proceeds, we encouraged them to take breaks when s/he found the match then move to the next object.

| Reference Objects | | S | Reference Objects | | S | Reference Objects | | S | Reference Objects | | S |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hair-roll | 2 | | Mouse pad | 16 | | Bottle nipple | 40 | | Shoe heels | 70 |
| | Make-up sponge | 2 | | Dish scrubber | 21 | | Bath toys | 42 | | Pencil eraser | 73 |
| | Ear plug | 7 | | Art-eraser | 25 | | Door seal | 55 | | Skate board wheels | 78 |
| | Can cooler | 9 | | Laptop protect insert | 30 | | Car tire | 60 | | Leather belt | 80 |
| | Gummy jelly | 10 | | Vinyl toy | 35 | | Screen wiper | 60 | | Shoe sole | 80 |
| | Rubber band | 17 | | Flipflop platform | 40 | | Smart watch Band | 70 | | Garden hose | 95 |

**Figure 9: Existing materials can be used as reference for users to provide instant feedback on softness. The system will retrieve the information to compute object structure**

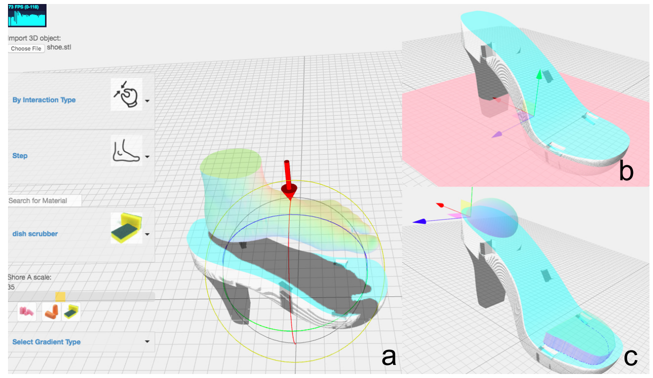


**Figure 10: Aesop design tool that user can select region selection method and softness level (a). User can specify region by projecting the actual body parts directly on the surface of target 3D object (a), by slicing in plane (b), by transforming volume primitives (c, heel) and/or drawing on the surface of the object (c, toe) to create volume.**

*Results.* Figure 8 summarizes the comparison between softness of a reference material and of a found sample. Most of participants were able to find the matched counterpart of a softness object (Softness difference average for flip flop=2.5, dish scrubber=4.1, and pencil eraser=18) P7 used both fingers, feeling the material softness by left finger, while searching the counterpart by right finger, and never validate once selected. Interestingly, most of participants (P3,4,7-9) had hard time to decide the match of the pencil eraser (S=73) between the hardest sample with softness 73.5 and the second hardest sample with softness 51.5, saying felt softness is between the two.

Figure 9 shows the list of materials and representative softness in scale. The values ($S$) will be used in the system to generate meshes of infill walls to calculate projected line distance ($L_d$). Note that there are materials that present similar softness, but we did not exclude them in this list. Therefore, for example, someone may know the feeling of pencil eraser (softness = 40) but not that of bottle-nipple (softness = 40), can still choose one from the potion and express desired softness using their previous experiences.

## 7 DESIGNING SOFT OBJECT FOR 3D PRINTING

In this section, we detail the user-centered design tool, to allow them to explore design space of soft objects creations.

### Design Tool & User's workflow

We present an expressive design tool that facilitate designing soft objects by freely exploring the design space described above.

Our tool is developed using THREE.js, WebGL, and supplementary NPM Javascript libraries for mesh manipulation including ThreeCSG.js. We opensource the tool for future researchers and advanced users to add more design constraints and a wider variety of materials, available at Github (Source Anonymized)

*Step 1. Import 3D Target Object.* First, a user imports a 3D model into the system where s/he wants to design with soft/hard property. It could be any off-the-shelf .stl/.obj file.

*Step 2. Select Region of Interest.* As there could be various ways of selecting region that a certain user feel easy, the system allows user to choose a region selection method at their preference; by (1) overlaying volume, (2) free drawing region on the surface (See Figure 10top), and (3) by the type of interaction the resulting object will be used (See Figure 10 bottom). In the first case, user can switch over different types of shape primitives to overlay with the target objects (sphere, cube, cylinder, and torus), depending on fitting to the original objects. A volume primitive hovers around the target object, calculated by intersection of the raycaster and mouse cursor points, so that a user can easily find surface region. It prevents users from having difficulty to correctly locate the volume, helping the soft region not be blocked by surrounding rigid parts. When a user selects interaction types to select region, the system shows a supplementary menu of interaction list that are associated with certain body parts that will interface with the object (press by finger, step on by foot, sit by hips, grasp by palm, and squeeze by fingers). Selecting an interaction type retrieves 3D representation of body parts and an arrow that show the direction of force applied. It casts a shadow of body part on the surface, so a user can estimate (then later scale to create more comfort) the region. User can scale the body parts, which we load the model in average size of an adults. We will leave an interface for a user can type their hand/foot size so that parts can be automatically scaled for future improvements.

*Step 3. Specify Desired Softness.* Then, a user specifies desired softness level by shopping everyday materials as reference (Figure 9). If a user is not sure what to choose, s/he can select multiple materials to see the ranges of softness and slide between the given ranges. The system visualizes changed gaps in real time as softness value changes.

*Step 4. Select Type of Softness.* In addition to the level of softness, users also can choose the type of softness. A user may want clear separation between soft and rigid regions (e.g. glass frame legs vs. nose support or bike handle grip), while another user may want gradient interpolation between two regions (i.e. arm chair). Based on 3D object application type, user's preference, and the global shape of the object, a user can choose the type of softness among binary, gradient, and radial. The default is set to linear uniform distribution of softness across the entire region.

The system is ready to produce structures along with the softness to export a printable file. It calculates soft region's bounding box size, to computes the number of walls required to fill this space, according to the equation (1). User's specified material informs the system the softness level, used as input to the model for computing a line distance from reference material's softness. The system creates thin walls (0.4mm) to align into the target, then clip by the shape specified region selection method. This soft region is also used to subtract this shape from the target 3D object, regions that will be padded by rigid fill structures.

*Step 5. Export Gcode and 3D Print.* Finally, a user exports the model to 3D print the object. System exports the model in Gcode directly, that incorporates all printing parameters set default to the best profile. Thus, users do not need to care of settings to reproduce softness as s/he indicated. Rigid part is set to 80% infill, which is rigid enough to be as firm as regular PLA print. Internally, the system calls the CuraEngine[5] to generate a final Gcode file with control factors that may affect our softness generation model.

## 8 DESIGN SESSIONS

To validate our design tool, we conducted an hour-long informal, qualitative design sessions with 8 participants. The objective is to let participants create their own soft object using our design and fabrication approach, and elicit their initial reaction and feedback to the system to reveal existing problems and to inform future improvements

[5]C++ console application for 3D printing GCode generation. Available at https://github.com/Ultimaker/CuraEngine

| | | 3D object | Region | Reference objects |
|---|---|---|---|---|
| P1 | F | Bike saddle | Interaction | >Flipflop |
| P2 | F | iPad stand | Drawing | Laptop protector |
| P3 | M | Chair&Handle | Volume | Eraser |
| P4 | M | Stool | Plane | Dish scrubber |
| P5 | F | Headboard | Interaction | Flipflop |
| P6 | M | Helmet | Volume | >Gummy jelly |
| P7 | M | Guitar | Drawing | Dish scrubber |
| P8 | M | Table&Spatula | Volume | >Rubber band |

**Table 3: Participants' 3D object design with region and material specification for softness (> indicates a user changed softness little harder than given softness of the chosen material)**

### Participants, Task, and Procedure

We recruited 8 participants (Female=3). Six of them have no prior experience in 3D modeling/printing, one has a casual experience in 3D printing (P3), and one is an industrial designer with an intensive experience in 3D modeling and printing (P4). First we showed our cuboid samples with different softness and let participants feel, describing how softness is generated across samples (5 min). Then we walked through how to use the Aesop design tool and what functions are supported to design a soft object using the shoe example (10 min). Next, we invited participants to brainstorm their own ideas, and helped them search the example models from online repositories[6] to inspire their ideation process (15 min). As participants started using our tool, we provided help for the tool usage as requested. The screen was recorded by Quicktime player to log participants' workflows for later analysis. Six participants were able to design own applications in less than 30 minuates, as shown in Figure 1. Most of them created one, but two participants (P3, P8) generated two, while the others verbally explained further ideas that they want to make. As our tools requires importing an existing 3D object, participants found existing designs from online repositories (e.g., Thingiverse) or their own collection.

### Results

Table 3 summarizes design session results. Six participants successfully created a 3D object with desired softness and region as shown in Table 3. P1 created an ergonomic bike saddle(Figure 1a) by selecting sitting part using an expected interaction (sit) and specifying it to be slightly stiffer than the flip flop. She hoped she could even specify the shoe brand to refer specific softness (e.g. Nike running shoe) P2 created an iPad stand with soft flap to protect her device from being scratched. P3 and P8 created furniture, a comfort

[6]https://Thingiverse.com

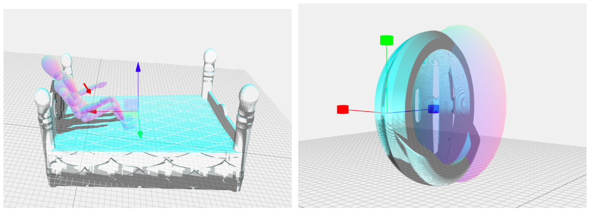

**Figure 11: Examples of failed design trials, because of not supported interaction type (leaning) and alignment issue**

arm chair (d) and a table with baby-proof corners (b) by overlapping spherical volumes to the point of interest. P4 created a stool by slicing the object in two parts, soft cushion over the plane and rigid legs and support under the plane. P5 wanted to created a bed headboard with flip flop platform soft, P6 wanted to create a bike helmet with soft protect inside. P7 wanted the bottom of his own guitar to be soft, as it hurts when playing it longer than an hour; he drew a specific region where he feel it hurts his thigh, and choose a dish scrubber as reference softness (e).

Aesop design tool enabled users to design objects imploying the expected perception and usage, supporting their creativity to think out of the box of 'design for shape'. Participants demonstrated the usability and usefulness of reference objects; they also used various techniques for specifying a soft region, from using a predefined shape to drawing free form paths. The diverse design ideas and outcomes with customized soft regions reveal the expressiveness and practicality of our low-fi approach.

However, we also found several existing limitations. For example, we currently do not support specifying dynamic contact—to design softness on a bike seat, P1 wanted to animate the mannequin's legs as if s/he was riding a bike. Some contacts were unexpected by our tool, e.g., P3 wanted the mannequin to lean on a bed's headboard, which was not considered as we assumed sitting as the only contact when using the mannequin to specify a region. There were also some innate difficulties of direct manipulation with 3D objects: P4 had a hard time aligning an oval sphere inside of a helmet, as the other side of a helmet blocks his view.

## 9 DISCUSSION

In this section, we discuss issues around the Aesop pipeline and design tool, limitations and future work.

### Exploring other infill patterns and Potential Confounding factors

In this work, we focused on finding the effect of density of infill on softness with all other conditions fixed. However, different infill patterns of the same overall density may present different Young's Modulus [15], due to a variety of confounding factors. When there are cross sections between infill walls, as is the case in grid or honeycomb patterns, the infill binds with the exterior shell more strongly than structures without cross sections. Additionally, the bending and bucking behavior of the walls is dramatically changed by the geometry of the infill. One potential future work would expand our experiments to other patterns, possibly to make use of these factors for softness modeling.

### Designing Mechanical Characteristics

We proposed an expressive design and low-fidelity fabrication method to control softness using printing parameters, namely, infill. According to the structure it naturally characterizes mechanical behaviors such as weight and buoyancy; while reducing time and material while 3D printing. One clear benefit of modeling and controlling softness by infill pattern is, it is based on 2D vectors. In the slicer level, to interpret 3D meshes of these structures into paths for printing, the system generates 2D vector patterns. These 2D patterns present interesting mechanical characteristics behaviors, such as orthotropic or isotropic resistance [27]. For example, our chair application naturally presents the orthotropic resistance, as the structures underneath the surface of soft region will deform while the rigid body of chair keep the global shape; so it does not fall down when a user sits. Our future work plan is to visualize expected behaviors by applying physics, and identifying relationship with structures; i.e. restrain movement of the object in certain direction while the force is applied providing a user comfort usage.

### Generating infill patterns along non-axis-aligned directions

FDM printing innately presents limitations on printing direction, where users can 3D print the object with less material and time to build up scaffolding. Our approach to build infill to model softness is based upon structures that are designed to support contact area perpendicular with the direction of force, assuming these structures will be printed vertical from the printing base. When designing aniotropic responses, it could be essential to build infill patterns that are not orthogonal or perpendicular to printing direction. We will leave generating these infills and optimizing them to guarantee printability for future work.

### Potential use of Soft Objects

Other than feelable soft objects to provide comfort and tactile perception, there could be much wider applications where soft object design can be used. Compliant objects are also useful to protect fragile objects and to reduce measurement errors, by creating buffer structures, possibly useful for package box design. Another possibility is to design an soft robotics, by aligning soft and rigid structures adjacent, letting rigid parts to be restraining layer while the soft parts act as actuators. In that case, the design space for users also need to be expanded, to include design of expected motions and behaviors and simulate the results to validate the objects before it is 3D printed by compensating a lot of time and material for testing.

### Automatic suggestion of Reference Materials

Different individuals have different sensitivities. Our tool provides a shopping list for users to select desired softness in level, however, for someone who does not have experiences or is less sensitive to materials' softness, it is possible to suggest preferred range of softness by the application type. This direction could benefit from Ergonomics, knowing what softness range the average people may feel comfort.

## 10 CONCLUSION

For the past decades, research domain on personal Fabrication has been expanded aiming to democritize making experience for casual makers. Nonetheless, the first class challenge that past work tried to solve is to improve efficiency, speeding up the iteration and increase precision. Only a few good user interface is provided with no trial to understand human's perception around the fabricated objects, having them have hard time to struggle with general purpose CAD tools. It is time to incorporate a scientific approach to understand human and human perception. 3D printing hardware needs 3D printing software in addition to the 3D modeling software, which brings parameters and considerations of machines to the designer's attention. We proposed Aesop, an expressive and low-fidelity approach to design and fabricate soft objects, shedding lights upon the relationship between users' expression and expected usage. In this manner, users are able to design and fabricate soft objects, using jargon-free, intuitive interface to convey design intent.

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