3D-Printed Cells for Creating Variable Softness

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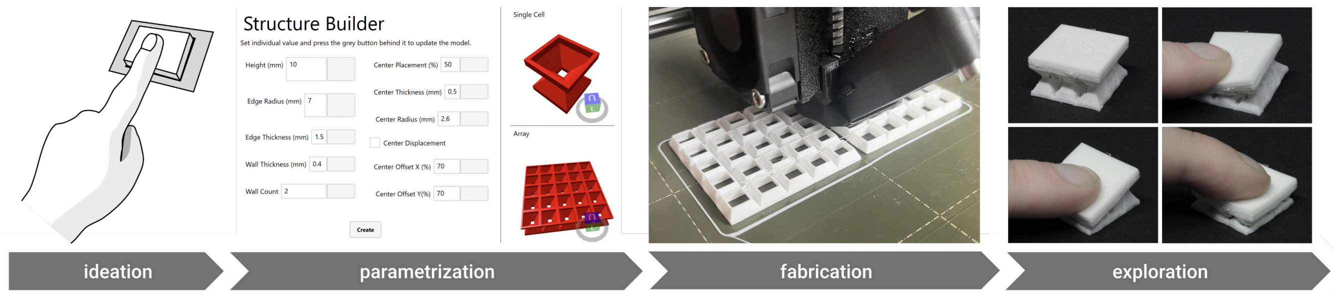

Figure 1: Process from intended compliance to manufactured prototype.

ABSTRACT

We present a method for 3D printing objects with variable softness inspired by mechanical metamaterials. These printed cellular structures can provide users with varying experiences of compliance across different scales through changes in their parametrized cell geometries. With our approach and tool, we want to enable designers and makers to rapidly prototype objects with variable softness as a base for diverse applications. The hereby generated structures are adaptable for fabrication on both high-end and commodity 3D printers. Four participants engaged in hands-on exploration with such 3D printed samples, providing initial data on how cell-parameters might affect the subjective/qualitative experience of compliance. In future research, we will systematically investigate such relationships to better understand how these structures can be designed to achieve desired perceived properties.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; Mixed / augmented reality.

KEYWORDS

metamaterial, 3d printing, fabrication, haptic experience

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1 INTRODUCTION

Compliance is a key property of many devices and mechanisms. It might be used for comfort as seen in shoe soles [1], compliance might provide a key indicator for potential interactivity as seen in buttons (e.g., [15, 22]), or it might be an important mechanical element, for example to dampen vibration [20].

When prototyping new designs, 3D printing has become one of the defacto standard approaches, with fused deposition modeling (FDM) printing still being the most accessible method. While this enables detailed representation of the object's geometry, representing the material qualities, such as the softness of an object, is comparatively difficult. Even though a range of elastic filaments enables FDM printers to produce objects with elastic materials, more room for the adjustments of compliance can be found in the geometry itself, for instance using mechanical metamaterial structures (MMMS) (e.g., [8, 12, 13, 17]). Some other methods have shown the ability to create objects with properties that differ from those of the raw filament materials used for 3D printing [4, 14].

We present a technique, which enables creating elastic cellular structures with varying compliance. By manipulating the geometry of *unit cells*, we can create a desired change in the deformation behavior of the resulting object, either globally or locally. With this method and the provided tool, we aim to enable users to generate customizable, functional structures, ready for printing on conventional FDM 3D printers. Furthermore, we provide an initial qualitative evaluation of printed samples with considerations towards future studies at a larger scale (number of participants and parameter levels) as well as quantitative evaluations, for instance to characterize the physical properties of such 3D-printed objects.

2 RELATED WORK

There has been significant interest within the Human-Computer Interaction (HCI) community in 3D printed interfaces for a variety of applications, including 3D-printed hair [14], utilizing under-extrusion to print fabric-like materials [4], and pop-up Kirigami structures that create haptic experiences[10]. These innovative approaches demonstrate the versatility and potential of 3D printing technology in HCI design. We add to this literature by presenting a method of *manufacturing mechanical haptic devices* inspired by *mechanical metamaterial mechanisms*. A stand-out feature of our method is that it supports *procedurally designed* variable tactile experience. We structure the related work along these themes.

2.1 Manufacturing Mechanical Haptic Devices

While a large portion of HCI work explores active haptics in the form of vibrotactile actuation (e.g., [15, 20]) an important area of haptic is the mechanical tactile design of an object. For instance, Zheng and Do [22] designed *Mechamagnets*, a method for rapid prototyping haptic and functional tangible user interfaces (TUIs). They used simple FDM 3D-printing techniques with embedded magnets to create physical properties such as snapping toggle switches or springy push buttons [22, 23]. Similarly, van Oosterhout et al. [19] investigated knob interfaces constructed of shape changing cells, that provide distinct haptic forces. We are inspired by the simplicity and effectiveness of such approaches and aim to also create interesting object properties by modifying their compliance (i.e., compression behavior) which designers and makers can easily utilize for creating TUIs or other interactive objects.

Furthermore, Ballagas et al. [2] surveyed a large corpus of work related to 3D printed interactivities and provide a design space based on parameters like interaction primitives, designed affordances, and mechanism. For metamaterial mechanisms, their survey revealed that common affordances are pressing and squeezing [2].

An important haptic cue is the compliance of objects. A simple but yet effective approach to create objects of different softness is to only adjust printing settings in the slicer software. Kim et al. [11] concluded that *infill density* is the only parameter which meets their criteria, i.e. printability, high range of achievable softness, and fine-tuneable softness. Inspired by this idea, we utilize parametric modelling to generate customizable structures with controllability beyond what is found in common slicer software (used to prepare objects for 3D printing), e.g. by applying varying infill densities. In terms of accessibility, we aim for simplicity and ease of use for a wide range of users.

2.2 Mechanical Metamaterial Structures

Metamaterials can be defined as: “a novel class of complex composite materials [with the] ability to exhibit any desirable electromagnetic, acoustic, or mechanical property such as negative mass, stiffness, or Poisson’s ratio” [18]. Following this definition, mechanical metamaterial structures (MMMS) exhibit unique mechanical characteristics that deviate from those typically observed in conventional materials. For example, flexible filament for 3D printing cannot necessarily be compressed to create soft objects. MMMS have been used in a diverse range of applications such as proxy objects in VR [3], adding capacitive sensing capabilities to interactive devices [6], creating functional movements (e.g., door latch) or tools like pliers [7, 8] or even encode digital information using bistable springs [9]. Data driven approaches have been incorporated as well, for instance, to design personalized shoe soles [1]. Feick et al. [3] also used low cost FDM 3D-printing to create MMMS that alter properties like roughness or hardness under lateral compression. They found significant increase of perceived roughness while increasing lateral compression, however, for hardness they did not find such a significant trend [3]. In our approach, we try to harness the diverse potential of mechanical metamaterials and their embedding in complementary technologies and aim for a set of parameters to precisely control compliance properties.

2.3 Procedurally designed MMMS

There are methods available to procedurally design cellular metamaterials with an extensive set of parameters that can be defined in a custom software [12], or simply modifying printing parameters [11]. However, designers and makers might prefer solutions that can be integrated in their tool chain and workflow. For instance, Sun et al. [17] proposed a tool to create objects with tunable compliance using Triply Periodic Minimal Surfaces (TPMS). They built their tool in Rhinoceros and Grasshopper, a very common tool chain in the design community, and provide adjustable high-level parameters in a GUI [17]. The resulting structures can be exported as STL[1] file, which is widely used for 3D printing. For our tool, we take inspiration from this approach, as it suits our goal to make such generative designs accessible for designers and makers. In addition, we aim for objects that can have varying local compliance with gradual changes between them. This has been demonstrated using dynamic Voronoi patterns to continuously alter cell size and geometry [13]. We provide an alternative approach, as we keep the basic size and shape of each cell consistent, while varying the internal properties of each unit cell.

3 DESIGN RATIONALE

This project arose from a desire to design and fabricate objects with variable, non-uniform and fine-tuneable compliance, for example interactive UI prototypes, body-conforming shoe insoles, or data visualizations requiring active exploration. These objects should have either a uniform compliance or variable compliance with localized gradients. To achieve this, we take inspiration from MMMS, which offer unique opportunities for designing objects with tailored properties.

To outline our approach, we set three goals. The first design goal is to *enable makers and designers to explore compliance through a set of controllable parameters*, giving them the opportunity to emulate known and create new experiences. Therefore, we approached the creation of cellular structures with controllable compliance, focusing initially on compression in the vertical direction. Second, we

[1] Objects are represented as triangulated surfaces.

strive for a *simple and convenient manufacturing process to support repeatability of the process and accessibility* to our approach. We chose to focus on FDM printing as this is the most common and accessible 3D printing technique, with relatively low cost and high public availability. Our third design goal is to provide *a workflow, which is as accessible as possible throughout different levels of 3D modeling skills*. Therefore, we want to provide a tool for the generation of printable geometry, which is available with a simple GUI as well as a customizable definition in commonly used modelling software like Grasshopper 3D (for advanced users).

4 DESIGN PARAMETERS

Our method is grounded in the concept of the *unit cell* serving as the smallest entity of the metamaterial-inspired structure. The geometric characteristics of the cell play a crucial role in determining the properties of the overall object, making it essential for us to select an arrangement that accommodates both variability in stiffness/compliance and ease of printing. While FDM 3D printing offers vast freedom in design, the main obstacle are the cells overhangs, which should not exceed 60 degree [21], as especially flexible FDM prints struggle with those geometries.

To achieve a variable compliance of cellular structures, we define the construction of a cell as a vertically stacked and interconnected array of concentric polygons (Figure 2). These form an hourglass like shape with predefined folds, when manipulating their dimensions and relative position. To explore the resulting design space, we chose to focus on the following set of parameters and their effect on compliance:

Cell Height: The vertical size of a cell mainly influences the maximum travel of compression (Figure 2B).

Center Radius: This defines the waistline of the cell, i.e. how thin the center part is (Figure 2B). For instance, as the radius of the middle polygon falls below the radius of the base polygons, the cell starts to develop hourglass like folds in the middle. Those folds deform when vertical stress is applied. If the value is equal to the *edge radius*, the cell forms a hardly compressible cuboid.

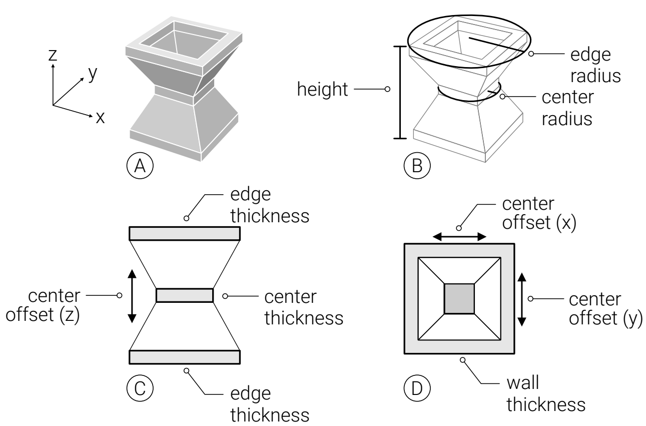

Figure 2: We construct compliant objects based on tiled A) unit cells. The object's compliance can be modified by setting various parameters of these cells, as illustrated in B), C), and D).

Center Thickness: This defines the height of the cell's "waist" which influences the maximum deformation and can be used to limit the travel of an interaction. Since this parameter does not change the cell height, the parameter value is limited by the printable overhang (should not exceed 60 degree [21]).

Center Offset (X,Y,Z): The center (waist) can be offset in all three axes. For example, an offset in z-axis results in a different height of the top and bottom half, and hence creates different travels when the object is pressed (Figure 2C,D). An offset in x- and y-axis can support a directional deformation.

Edge Radius: This defines the distance of the polygon's corner points to its center and thereby the cell's x and y dimensions. This parameter is nearly unrestricted as long as the other parameters can adapt proportionally.

Edge Thickness: Thickness of the top and bottom of a cell (Figure 2C). This parameter is important for the connection of tiled cells, as the thickness directly influences their contact area. Additionally, this parameter potentially influences the deformation behavior of the interconnected structure.

Wall Thickness: Thickness of the 3D printed wall. Thicker walls increase the cell's stiffness, thereby giving it more resistance to compression. Note, especially for thin walls (e.g. below nozzle diameter) the print quality depends on the 3D printer and filament. One might set this parameter in multiples of the *line width* parameter, which is set in the slicing software.

5 IMPLEMENTATION

We created our tool in Rhinoceros 3D (Rhino 7), a common CAD software, utilizing its embedded parametric modeling environment Grasshopper 3D. We chose this software stack, because it is well established across design communities. In Grasshopper, generated geometry is not defined as a rigid body, but rather as a combination of basic geometries and their interdependencies. This enables precise customization of individual property settings for each unique unit cell, and also facilitates the creation of inhomogeneous cell arrays featuring gradual variations in geometry.

The Grasshopper definition we developed (Figure 3A) offers the ability to assign numerical values as static inputs for each cell geometry parameter (see section 4) and those of the array. Furthermore, it allows creating new dependencies by linking these parameters to various input sources. When applied to a cell array, this functionality can be utilized, for example, to establish a correlation between the middle radius of individual cells and their relative distance from a designated reference point. The basic geometries, defined by inputs depicted in block B (red) of Figure 3A, are subsequently connected first to planar surfaces and then later to 3-dimensional solids.

As the labeled and color coded Grasshopper definition (Figure 3A) aims to enable further engagement and adaption (for experienced users), we complemented it with a simple GUI (Figure 3B) utilizing the Human UI plugin[2]. The GUI has controls for all parameters of the unit cell and provides a preview of the current configuration. This allows designers and makers without extensive

[2]https://www.food4rhino.com/en/app/human-ui, last accessed October 23, 2023

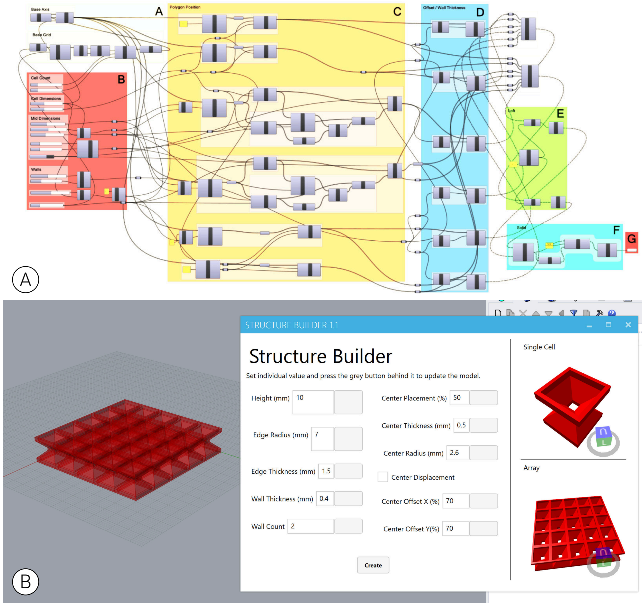

Figure 3: Implementation of the tool A) in Grasshopper 3D (Rhinoceros) and B) a simple GUI with parameters to create tiled cell samples.

knowledge of Grasshopper to customize and generate printable sample structures (i.e., tiled cells). The GUI as well as the Grasshopper definition generate a closed solid polysurface in Rhinoceros, which then can be exported as STL file and opened in any conventional slicer software to prepare the file for 3D printing.

Even though we tried to make our approach as accessible as possible, replicating the manufacturing with FDM will need some individual adjustments. Printing complex geometries with flexible filament can be challenging, as the process is different for each printer and filament as well as environmental conditions. A good point to start is to find the right preset for printer and filament in the slicer software like Prusa Slicer or Ultimaker Cura[3]. When struggling with replication, some general measures that helped in our case were: lower print speed, slightly higher extraction rate and disabled retraction (can lead to stringing). For more surface adhesion, we used a brim. This and possibly occurring stringing were removed afterward.

6 EXPLORATION

We intend to formally characterize the parameters and how they link to physical properties of prints and to user experience in future work. Here, we share first initial reactions to printed samples by users naive to our method.

6.1 Setup and Tasks

For this first exploratory session, we selected a subset of six parameters, each with two configurations (Table 1). In total, we printed 12 samples in as 5×5 grid, as shown in Figure 4. All samples were

[3]Both slicing tools are freely available and support a variety of 3D printer models by different manufacturers.

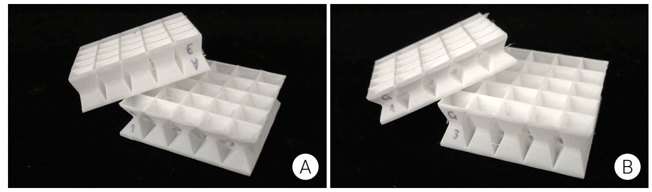

Figure 4: 3D printed samples with two configurations of two parameters, namely A) *center radius* and B) *cell height*.

printed from flexible TPU filament with a shore hardness of 95A (Polymaker PolyFlex 95A) on a Prusa MK3S+ printer using the consistent slicing settings (sliced with Ultimaker Cura).

Four naive participants (1 female, 3 male) volunteered to explore the 3D-printed samples in two tasks. Each participant was presented six samples (3 parameters with two configurations each) for both tasks. In the first task, we asked them to explore each sample separately in a predefined order and encouraged them to verbalize associations with materials or objects and potential applications for such metamaterials. The second task was to assess and compare the perceived softness. In this task, participants were free to explore samples simultaneously and in their preferred order. We asked them to mark the softness of each sample on a soft-to-hard scale, where samples of similar softness are placed closer to each other. These scales only reflect their subjective experience. Participants spent between five and six minutes (approx. one minute per sample) exploring samples in the first task, and the second task lasted between three and four minutes. There was no time limit given for either task. In the following section, we present intermediate results along with anecdotal statements of participants.

6.2 Results

6.2.1 Estimated Compliance. One-by-one comparison of samples with different parameter configurations (second task) produced interesting preliminary results, i.e. highlighting that differences in parameters did indeed affect perceived compliance and also the

Table 1: Variants of parameters for exploration.

parameter	value	sample id
center radius	1.50 mm	A1
	4.50 mm	A3
wall thickness	0.40 mm	B1
	0.80 mm	B2
center thickness	0.67 mm	C2
	2.00 mm	C4
edge thickness	0.20 mm	D1
	1.74 mm	D3
center offset	40.00 %	F1
	60.00 %	F3
cell height	9.00 mm	G1
	15.00 mm	G3

Table 2: Anecdotal perceived difference in compliance per parameter.

parameter	compared parameter values	relative magnitude in perceived difference
center radius	1.50 mm, 4.50 mm	none high relative difference
wall thickness	0.40 mm, 0.80 mm	none high relative difference
cell height	9.00 mm, 15.00 mm	none high relative difference
center thickness	0.67 mm, 2.00 mm	none high relative difference
edge thickness	0.20 mm, 1.74 mm	no clear effect
center offset	40.00 %, 60.00 %	no clear effect

relative difference between the strength of the effect per parameter pair. Table 2 shows the minimum estimated difference in perceived compliance between the tested samples relative to the entire scale; the change in center radius had the largest effect, while the minimal differences for edge thickness and center offset were negligible. Specifically, the chosen values for *center radius* made the samples either *“easy to press” (P1)*, or *“strong [and] hard to squeeze” (P1)*. Participant 4 was not able to compress the sample with the higher middle radius at all. Other parameters and configurations resulted in less variability (Table 2). In contrast, the samples with varying *center thickness* were both rated to be soft, while the sample with thicker center felt more linearly compressing for participant 4. Estimates provided by participants also indicate that different parameters (e.g., *center thickness* and *cell height*) result in similar perceived compliance (Table 2). In contrast, the parameters *edge thickness* and *center offset* did not reveal clear effects, i.e. the compliance of samples with the same parameter values were rated very differently by participants (both parameters) and estimates of the two values overlapped (*center offset*). This needs further and systematic investigation in future work.

6.2.2 Associations and Potential Applications. P1 mentioned for sample **A1** that *“this is like, it kind of buckles, which does feel like some buttons in real life. [...] It’s easy to press it and once you press it a bit more and then there is some buckling which could be used as some button I think. And it kind of clicks back when you remove your finger as well.”* Sample **G1** reminded P1 of a computer keyboard, because *“it has that feel like the type of springy”*. In contrast, for sample **C4** P1 experienced that *“this is nice soft”* and *“is more like a bed”*, whereas sample **C2** felt like *“some vegetables or like crunchy fruit”*. P2 expressed some surprising properties of sample **D1**: *“Oh, this guy feels way more solid, more like just a rubber. And it kind of has this weird, let’s say, compression profile, as in it doesn’t give at all and then it just collapses at some point.” (P2)* P2 experienced the same properties with sample **D3**: *“So same, but this one is softer actually. Still more rigid than the first two [**F1** and **F3**].” (P2)*

Sometimes, participants had no clear association or specific application in mind. However, they found them interesting - for instance, P4 mentioned for sample **A1**: *“I don’t have any association in mind, but like my intuition tells me that walking on this would be amazing. Like the feeling that you get would be nice.”* And P3 noticed that sample **D3** *“makes the sound of like a sponge”* when squeezing it and feels mushy.

6.2.3 Other Object Properties. Some samples, which according to participants felt equally soft, may, however, have different mechanical properties. For instance, samples **A3** and **B2** were both rated to be rather hard when applying force vertically (in z-direction). Interestingly, sample **A3** is very flexible and bends easily, whereas sample **B2** barely bends even when applying higher force as shown in Figure 5. This indicates, that certain cell parameters (e.g., *center radius* and *wall thickness*) can be used to generate different flexion while preserving similar compliance. Such properties might be utilized in instrumented shoes to meet mechanical requirements in certain regions of the foot [20].

7 EXAMPLE APPLICATIONS

To provide readers with an intuition of the capabilities of our approach, we have designed a series of demo-objects that highlight how our system might find application.

TUI: The varying compliance of the structure allows us to prototype diverse interactions with tangible user interfaces. This offers opportunities to either emulate conventional inputs like buttons or joysticks (Figure 6A,B), or even envision new forms of compliant interaction in interfaces utilizing compliance gradients (Figure 6C). We created a gamepad dummy (Figure 6A) that demonstrates rapid prototyping of tactile interfaces with easily interchangeable and printable parts. Such parts can also be incorporated with sensing mechanisms (e.g. [6]).

Custom ergonomic Structures: The diverse input possibilities for the Grasshopper definition allow for custom tailored structures for all kind of on-body applications. For instance, we used them to create a custom shoe sole (see Figure 6D) that supports the embedding of electronics for foot augmentations [20]. Hereby, we created 2.5D compliance gradient in the structure by stacking multiple

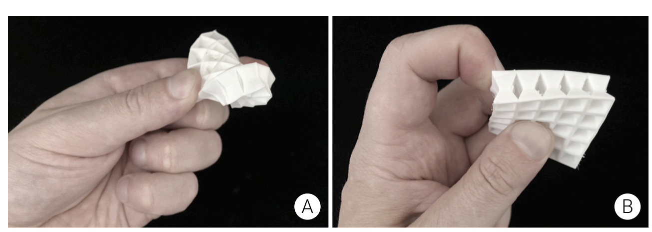

Figure 5: Samples with similar perceived softness but different flexion, as shown for sample A3 (A) and for B2 (B).

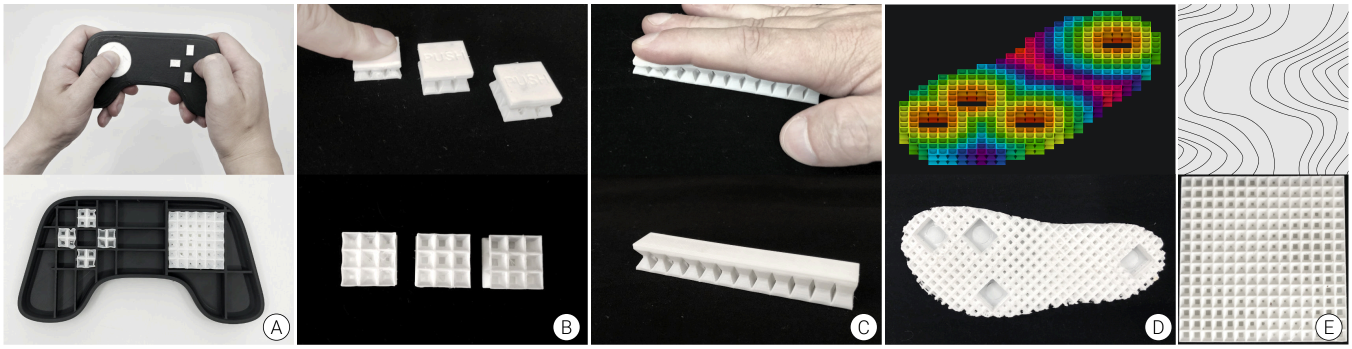

Figure 6: We present potential applications like A) gamepads, B) push buttons, C) compliance gradient, D) shoe soles, and E) a data-physicalization of an elevation map.

individually controlled layers. We envision more personalized on-body applications of this approach like, (prototyping for) wearables, cushioning or prosthetics.

Data Physicalization: Our approach allows for physicalization of different data sets as compliant structures. This could help to display otherwise hard to imagine data. To demonstrate this, we used imaginary elevation data (Figure 6E). The Grashopper definition utilizes image sampling to map the image brightness to the *center radius* of individual cells, which creates varying compliance. Higher areas on the elevation map are now harder to press, with a shorter way of travel, while the lower areas of the map are softer, with more travel. This gives the possibility of feeling the surface relief encoded in the structure.

8 REFLECTIONS

We implemented a method inspired by MMMS that enables us to create objects with varying compliance utilizing a set of cell parameters. Therefore, our implementation offers different levels of controllability; 1) basic (GUI based) parametrization of cell grids, and 2) a customizable Grasshopper definition. We demonstrated the usability of both, by utilizing the GUI to create samples for user explorations, and the Grasshopper definition to create example applications with more complex shapes and variable compliance properties. First explorations of printed samples (printed on commodity 3D printers) indicate that our approach and the chosen cell parameters can create objects of varying compliance (also in different ranges) similar to prior work [11]. Thereby, we achieved our first and second design goal. However, we don't know yet which parameter changes the physical object properties to what extent. This can be achieved using an uniaxial test that gives force-displacement curves [16].

In our initial study, we had limited sample size and scope of testing with just four participants and only a few parameters (and levels) under examination. To address these limitations, future research efforts will involve conducting comprehensive experiments, involve more participants and greater variability across each parameter. For instance, we will conduct experiments such as *magnitude estimation* [5], which will help us to gain a better understanding how the physical parameters affect the perception of compliance [16]. As soon as we understand such relationships, we would like to further extend and explore the design space, for instance with additional cell geometries based on desired deformation behavior.

Introducing other additive manufacturing techniques could increase the choice of possible geometries and materials. Referring to our goal of accessibility, it would be great to evaluate the tool with the target audience, i.e. designers and makers. Especially, investigating how they integrate it in their established workflows. Furthermore, we are interested in how the proposed workflow can be transferred to other parametric modeling environments, e.g. established open-source software such as tools like Blender[4] in combination with Sverchok[5] or FreeCAD[6], or programming based approaches like OpenSCAD[7]. This would allow designers and makers from diverse backgrounds to take advantage of our method for creating objects with variable compliance experiences.

9 CONCLUSION

We presented a method for 3D printing objects with dynamic softness using mechanical metamaterial structures. We also proposed a tool which designers and makers can use to rapidly design objects with variable softness and diverse shapes. Generated objects can be fabricated on both high-end and commodity 3D printers. First hands-on exploration of 3D printed samples, comparing their softness, provided initial data on how cell-parameters affect the subjective/qualitative experience of compliance. Systematic investigation of such relationships in future work will help to better understand how these structures can be designed for desired perceived properties.

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