FlexTure: Designing Configurable and Dynamic Surface Features

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ABSTRACT

We present FlexTure, a method for creating pop-up kirigami structures with a selectively bonded bilayer. These surfaces enable a new design space for accessible and rapid prototyping of dynamic surfaces. Using a flexible material selectively attached to a stretched substrate, we can create metamaterial surfaces that change texture. The tactile and aesthetic effects of these surfaces can be tuned through the configuration of cuts in the top layer of material, as well as the selection of the layers themselves. We provide a design workflow and accessible methods to achieve target effects and experimentally measure some mechanical properties of the surfaces. Several application concepts are offered along with a computational design tool.

Authors Keywords

Fabrication; haptics; design tool; wearables; textiles.

CSS Concepts

- Human-centered computing → Human computer interaction (HCI)

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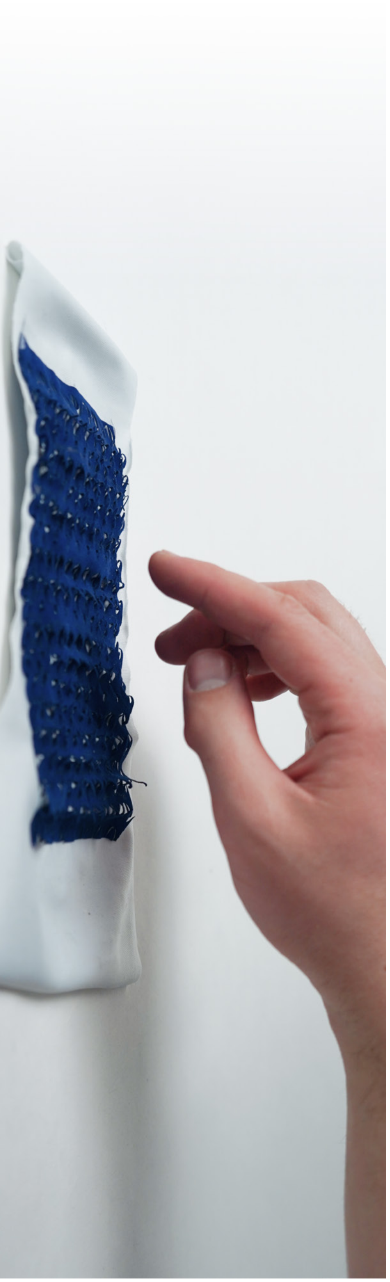
INTRODUCTION

Personal devices and wearable technologies often rely on separate methods such as vibration for haptic response and digital displays for visual affordances. Because of this, there is often an incongruence between how the surfaces of these devices look and how they feel. FlexTure seeks to minimize this gap by creating responsive surface features that change in both visual and tactile experience. These surfaces are created on an elastic substrate with tools such as a laser cutter or 3D printer. By making these surfaces easy and accessible to design and fabricate, the visual and tactile qualities of these surfaces can be rapidly prototyped and tuned.

The primary contributions of this work are:

- The FlexTure design landscape, which allows for the parametric control of the visual and tactile aesthetics of the configurable surface features.
- An accessible workflow for the fabrication and assembly of these surface devices using inexpensive and popular tools.
- A digital node-based design tool that offers pattern controls and export for digital fabrication.



This pictorial is motivated by the following: (i) to enable a new design space with congruent material changes to visual and tactile experience, (ii) to create mechanically reliable, programmable, and deformable surfaces, and (iii) to visually document and share our material-driven exploration into dynamic surfaces. In service of these goals, we developed a system of perforated deformable sheets selectively bonded to elastic substrates. We provide some options for the fabrication, actuation, and integration of these surfaces for use in responsive devices. We hope that these guidelines and methods support future exploration with this system, and provide an open-source design tool and cut-out paper schematics in support of that goal.

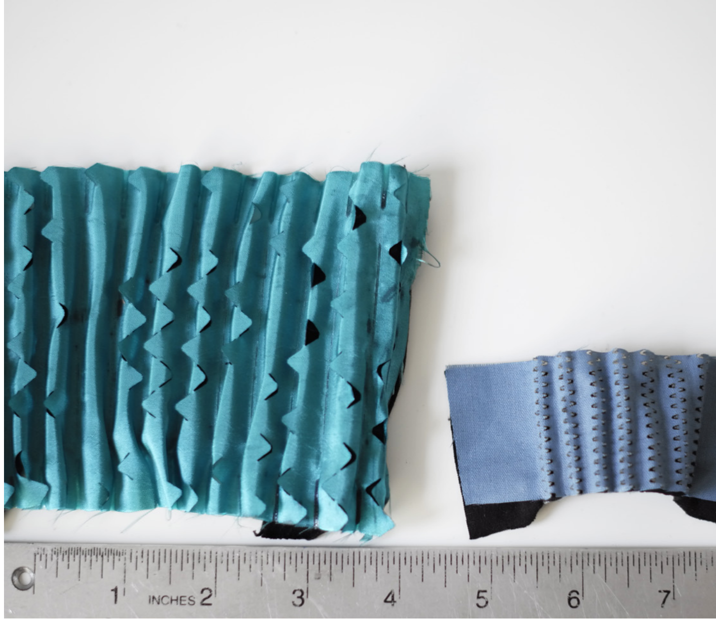
RELATED WORKS

Prototyping Responsive Surfaces

The HCI community has investigated tactile and responsive surfaces using a breadth of methods and technologies. Previous work acknowledges the craft and design process within the development of tangible devices and experiences [4,17]. Technologies like vibrotactile surfaces have been created for precise haptic control, but are limited by their lack of changing visual affordance [3]. Additionally, people prefer physical, material haptics over vibrotactile methods in some virtual environments [8]. As such, FlexTure provides both physical/tactile change and a changing visual affordance of the surface.

These physical haptic prototype devices leverage a breadth of methods and materials such as films [10,16,30], fully 3D-printed structures [14,18,22,23,24,26,27], fibers [15], papers [25,28], and textiles [7,11,20]. FlexTure seeks to supplement these methods with an accessible method that enables response and configurability that previous methods don’t.

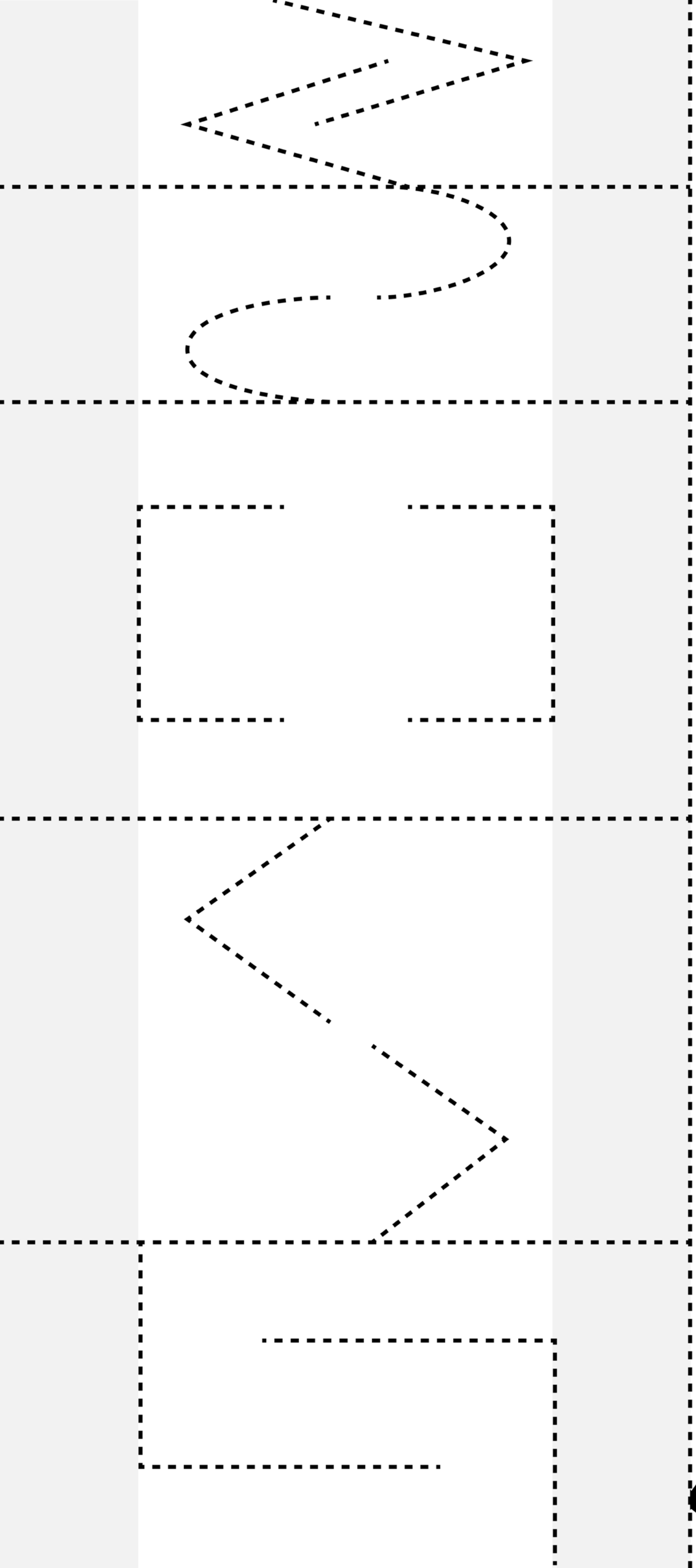
Our work particularly draws on Ion et al.’s Metamaterial Textures, which investigates tunable surfaces from perforation patterns [12]. Their method takes a complex monolithic 3D-printed metamaterial approach, whereas ours focuses on establishing a comprehensive design system with the possibility of using faster and more accessible techniques for prototyping.



Kirigami

Actuated kirigami and origami structures have been deployed for the creation of variable mechanical surfaces [19,21] as well as tangible interfaces and displays [13,28]. Existing patterns inspired our investigation of FlexTure’s tunable kirigami for new interaction designs [12,29]. These works use primarily extension-based designs, whereas our method uses contraction-driven effects that exhibits a greater surface texture in the contracted state, which we take as the default.

Although research has been done into both the mechanical understanding of kirigami structures [5] as well as their integration with computational control and sensing [28], FlexTure contributes an integrated design and fabrication method that enables these structures to be used as a medium in interaction design.



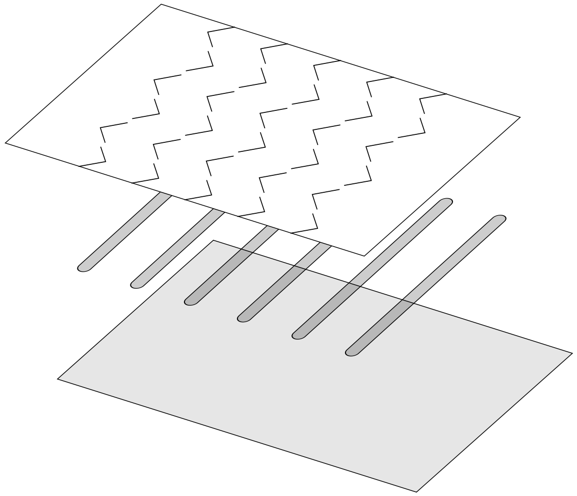
MECHANISM

In nature, animals employ node-based surfaces such as hairs, scales, and spines. These surface features are frequently actuated by changing skin surface length through methods such as muscle flexion, air bladders, or other swelling mechanisms. In natural contexts, the visual changes of these surfaces are synchronous with changes to the animals state or behavior such as aggression, arousal, or fear. For example, porcupines use quills that change angle when threatened, changing both the visual communication to predators and the mechanical performance of the quills, allowing them to more easily contact a predator.

Our mechanical method follows this biological inspiration. The system is comprised of three major elements:

- a thin, buckling top sheet, such as paper, plastic, or fabric, which becomes the contact surface
- the bonding regions used to secure the top sheet
- an elastic substrate sheet that provides the compressive force that, in conjunction with the selective bonding and perforations, actuates the uniform surface change

Each of these three elements can be tuned and created with a range of materials and processes, yielding different results.



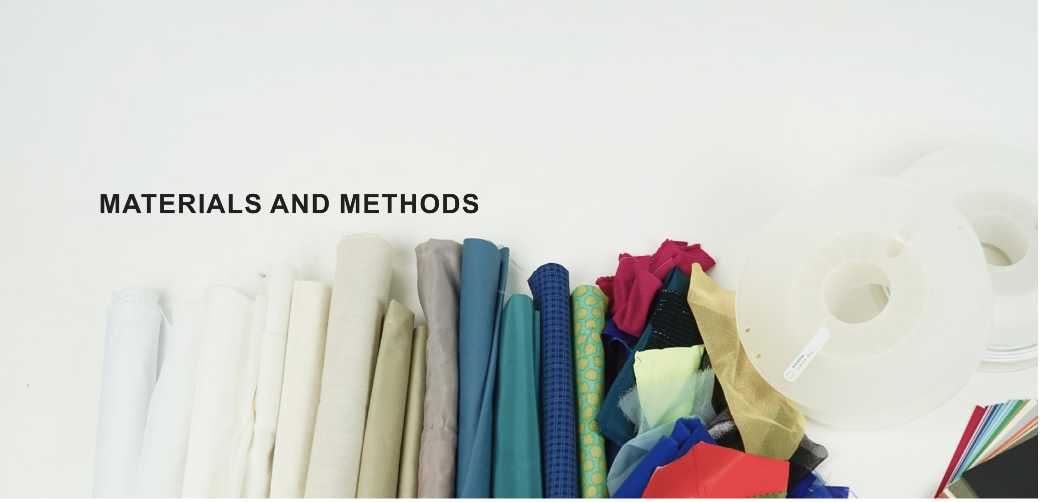
At a fundamental level, the ‘pop-up’ or shape-changing behavior occurs due to the differential compressive forces on the two layers. The pre-strained elastic substrate forces the thin, deformable top layer to buckle. Selective attachment of the top and bottom layers in the pre-programmed rows limits the buckling to localized rows of material.

These surfaces are assembled with the substrate layer stretched, such that their default state after fabrication is as an actuated, ‘pop-up’ surface.

After that, the surface can be tuned by re-straining the elastic substrate. If the substrate is stretched fully back to the as-fabricated length, the surface will return to flat; a linear actuation system could target either discrete levels of actuation or a continuous and gradual surface change. This can be achieved with a motor or other electronic actuator.

Try it! To try out one of these surface features yourself, print out this document, cut along the dotted lines, place it on a flat surface, and push the shaded areas together. You can try shaping or modifying the cut line and shape to see the different possible visual and physical effects!

MATERIALS AND METHODS



Top Layer

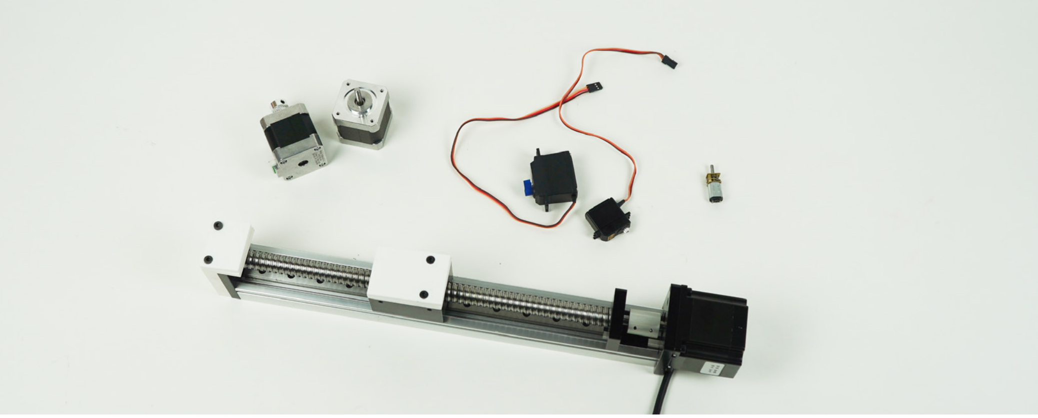
The top buckling layer requires a thin sheet material that can be easily and precisely perforated. The sheet requires some stiffness: too deformable of a material prevents the perforated features from actuating and a linear wrinkling will occur. Our explorations used laser-cut fabrics, papers and plastics, as well as 3D-printed TPU and PLA sheets. We found that thin, stiff fabrics fabrics that were either composed of or coated with synthetic polymers, such as polyester or TPU-coated fabric tended to cut and deform well, whereas most papers that we tried would permanently deform after a few actuation cycles or hand contact.

Bonding Layer

For bonding the top and bottom layers together, we found that heat sealing and manual adhesive application (cyanoacrylate glue) were most successful. Due to the plastic content in elastic fabrics, they can be heat sealed to a range of top sheet materials. For textile applications, sewing along the bonding lines is recommended.

Contracting Layer

Uniform contraction of the bottom layer is needed for an even and successful actuation of the surface features. We found that elastic materials such as elastic fabric and silicone worked particularly well. Although not explored in this work, organic surfaces that undergo universal contraction, such as skin, might also be used.

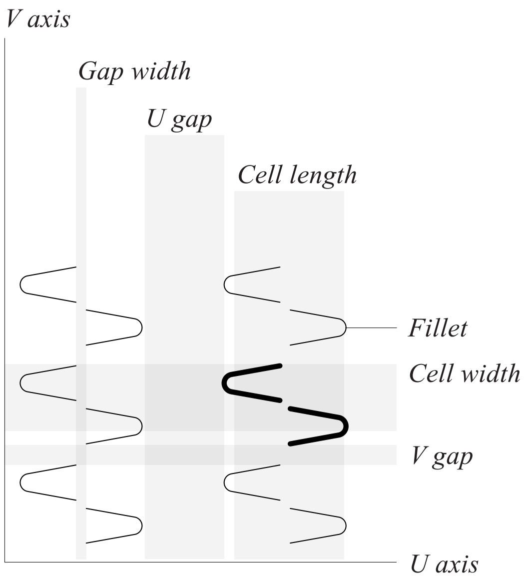


Actuation

The primary methods that we found successful during our exploration included motorized linear stages and motorized spindles/drums. These can be easily controlled and integrated with a microcontroller and power supply. Other lower-profile methods can be used, such as integrated fiber actuators [2].

DESIGN PRINCIPLE

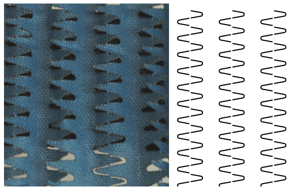
Along with the materiality of the surfaces, the perforations are crucial for designing a visuo-haptic experience. The appearance and hand feel of these surface features combine to create a textural aesthetic. We provide some factors that inform the mechanical and visual performance of these surfaces.



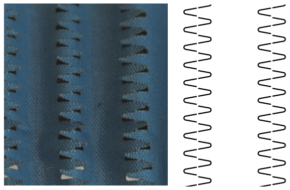
The proportional value of these different measurements, in conjunction with the material selection, allow for the precise tunability of the visuo-haptic experience. The numerical values listed by the patterns can be used with the following digital design tool to replicate and modify the surfaces shown here. We use the axes *V* and *U* to describe dimensional changes in two directions, with the shaded regions representing the dimensioned areas.

Row width

The spacing of node rows and columns can create more sparsely or densely populated surfaces.



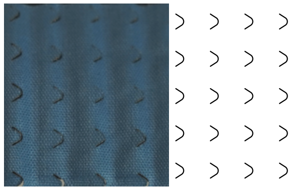
Small spacing
Triangular
U gap:0
V gap:0.3
Cell length:9.7
Cell width:3.5
Gap width:0.5
Fillet: Uniform, 1.1



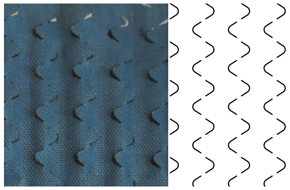
Large spacing
Triangular
U gap:6.2
V gap:0.3
Cell length:9.7
Cell width:3.5
Gap width:0.5
Fillet: Uniform, 1.1

Directionality

The proportional sizing and quantity of nodes going in each direction can create variably symmetric or asymmetric surface forces.



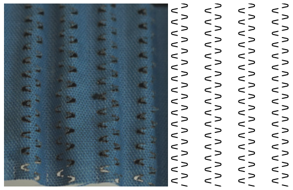
Directional
Triangular
U gap:1.5
V gap:0.3
Cell length:6.4
Cell width:8.2
Gap width: 1.1
Fillet: Uniform, 3.0



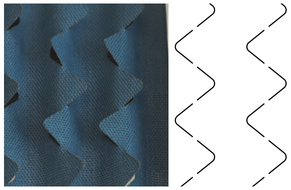
Symmetrical
Triangular
U gap:1.5
V gap:0.3
Cell length:6.4
Cell width:8.2
Gap width: 1.1
Fillet: Uniform, 3.0

Scale

The size of each textural node in relation to the interaction scale and material thickness contribute to more fine or coarse hand feel.



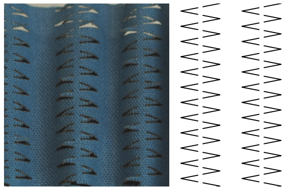
Small
Triangular
U gap:2.5
V gap:0.3
Cell length:6.4
Cell width:2.7
Gap width:1.1
Fillet: Uniform, 3.0



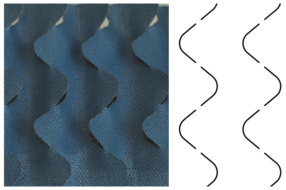
Large
Triangular
U gap:5.7
V gap:0.0
Cell length:10.1
Cell width:16.2
Gap width:1.1
Fillet: Uniform, 1.2

Affect

Describes the qualitative relationship between perception and expectation of comfort (ex. Bouba/Kiki effect)[6].



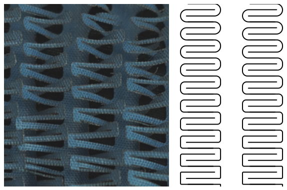
Spiky
Triangular
U gap:5.7
V gap:0.0
Cell length:10.1
Cell width:3.4
Gap width:1.3
Fillet: Uniform, 0.0



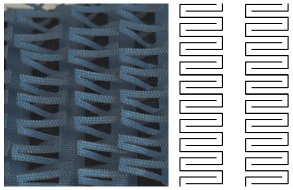
Comfortable
Triangular
U gap:2.3
V gap:0.0
Cell length:10.1
Cell width:16.8
Gap width:1.1
Fillet: Uniform, 3.0

Variation

Individually or parametrically modifying the nodes can create irregular surfaces that create larger visual patterns or represent information values.



Gradient fillet
Rectangular
U gap:5.6
V gap:0.0
Cell length:10.2
enter thickness:1.6
Cell leg width:1.5
Fillet: Gradient along V, 1.9

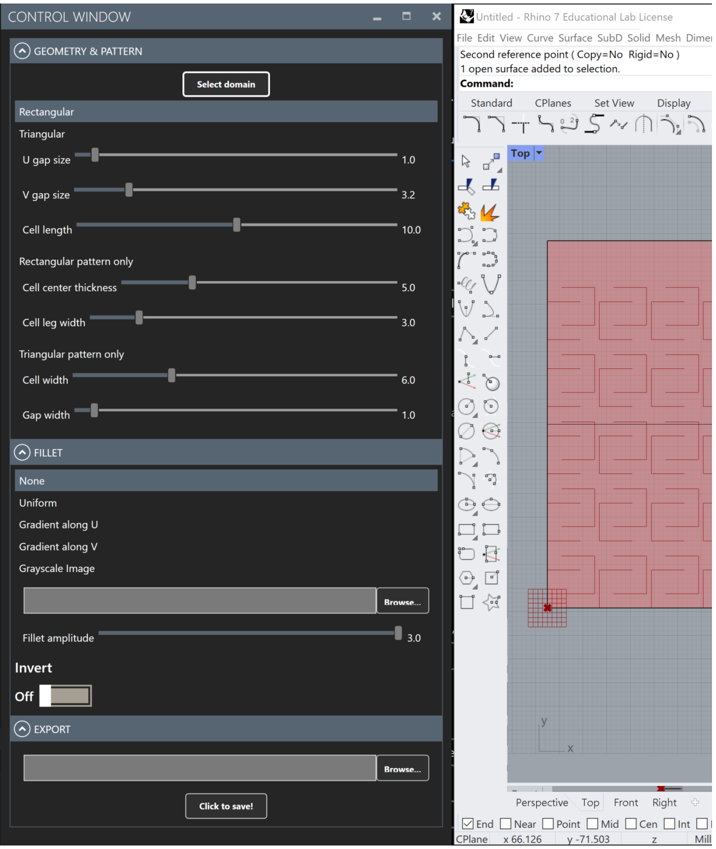


Fixed fillet
U gap:5.6
V gap:0.0
Cell length:10.2
Center thickness:1.6
Cell leg width:1.5
Fillet: 0

PROTOTYPING TOOLS

The large number of parameters leads to a design space that can be hard to conceptualize, making design decisions difficult as well. In our development of these surfaces, we found two basic approaches to be effective: paper single-node prototyping (as provided in the Mechanism section) and digital design tools.

By manually cutting individual nodes out in paper, they can be hand-actuated and quickly assessed. These single nodes can be easily and accessibly created to validate design decisions. Measurements and proportions from those features can then be brought into a digital editing environment for tuning and preparation for fabrication.



Rectangular
Triangular
U gap size 1.0
V gap size 3.2
Cell length 10.0
Rectangular pattern only
Cell center thickness 5.0
Cell leg width 3.0
Triangular pattern only
Cell width 6.0
Gap width 1.0

None
Uniform
Gradient along U
Gradient along V
Grayscale Image
Fillet amplitude 3.0
Invert
Off

Untitled - Rhino 7 Educational Lab License
Second reference point (Copy=No Rigid=No)
1 open surface added to selection.
Command:

☑ End ☐ Near ☐ Point ☐ Mid ☐ Cen ☐ Int
CPlane x 66.126 y -71.503 z Mill

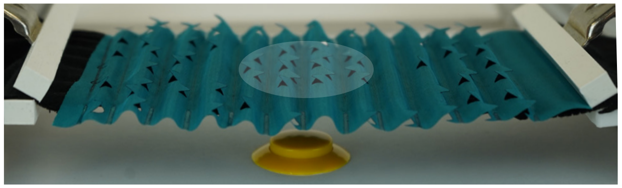
To aid the creation of these surfaces, we provide a digital design tool (shown at left) with parametric control for two pattern tilings: rectangular and triangular. The parameters are taken from the method described in the Design Principle section. The rectangular and triangular pattern types can be adjusted across a repeated custom plane using the Grasshopper plugin for Rhinoceros 3D [1] and then exported as a DXF/STL file for digital fabrication using a laser cutter or 3D printer.

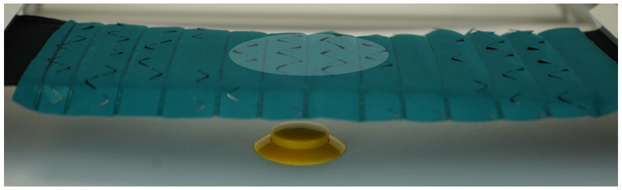
Additional functionality includes a filleting option, where users can select different control parameters to apply uniform or variable fillets to each node. The 'Grayscale Image' field, for example, allows the contrast values in different regions of an image to be converted to variable fillet values in the corresponding regions of the pattern.

We provide this tool to the community at https://github.com/morphing-matter-lab/FlexTure. For many of the textures in this paper, we provide the tool parameters in captions to replicate our examples. Some of the surfaces were created prior to the completion of the tool by manually dimensioning and repeating the nodes in a DXF editing software. We hope that this tool serves as inspiration for further possibilities of the computational design of these shape-changing surfaces.

Non-actuated

Actuated

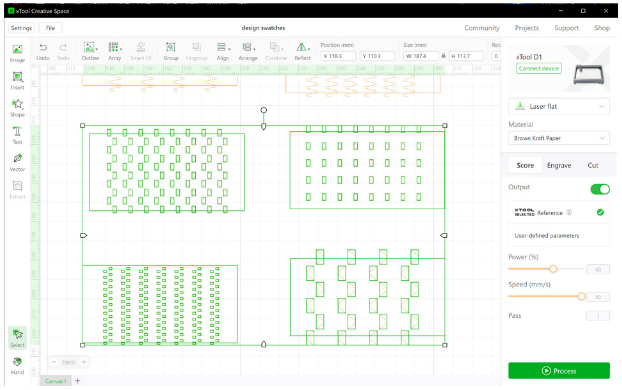




In the above scenario, a FlexTure surface prompts user interaction with a hidden button below. We created an initial surface with the design tool, then manually edited it to add focus to the button area.

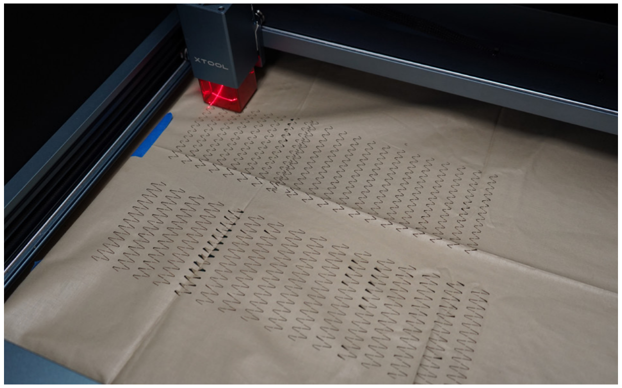
FABRICATION

Due to the broad applicability of the FlexTure system, there are many possible methods for each step of the fabrication process. At a high level, the top sheet of material needs to be controllably perforated and then selectively attached to the elastic substrate while the substrate is held at a fixed stretch rate. Both of these processes need to be done accurately for a successful FlexTure surface. We offer a description of the fabrication process of many of the FlexTure surfaces in this work.



Position (mm) X 118.3 Y 110.3
Size (mm) W 187.4 H 113.7
Material: Brown Kraft Paper
Output: on
Power (%) 60
Speed (mm/s) 80
Pass 1

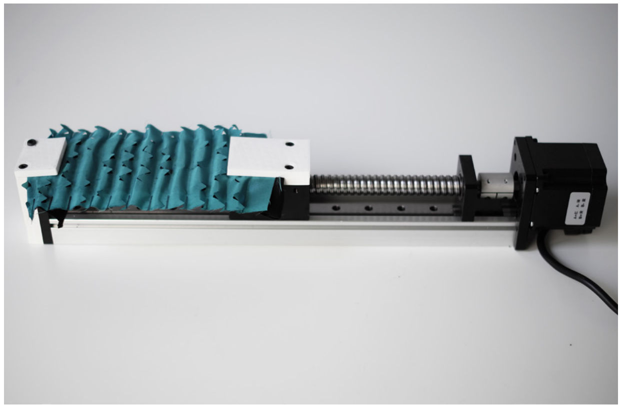
1) After outputting a DXF file from our Rhino3D tool, the paths can be placed and scaled in a manufacturing program. In this case, we used xTool Creative Space to generate machine files for laser cutting.



2) The top sheet is manufactured using a laser cutter, 3D printer, CNC cutter, or similar. We used an xTool desktop laser cutter for many samples in our exploration.

3) The elastic bottom sheet is stretched to the desired stretch rate and clamped. Once the perforated top sheet is aligned the two sheets can be bonded or sealed together. We assembled a rig using aluminum extrusion to fix the sample surface in place.

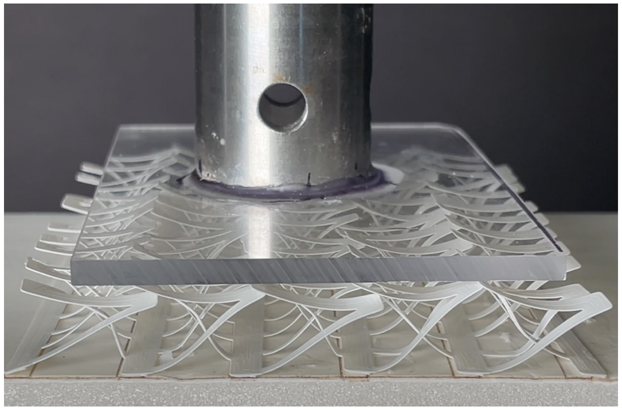
4) Our exploration used a row-by-row heat sealing system, with the sealer able to translate side-to-side along rails. In situations where more precise adjustment is necessary, a CNC adhesive application or heat sealing could improve the speed, precision, consistency, and strength of the attachment.



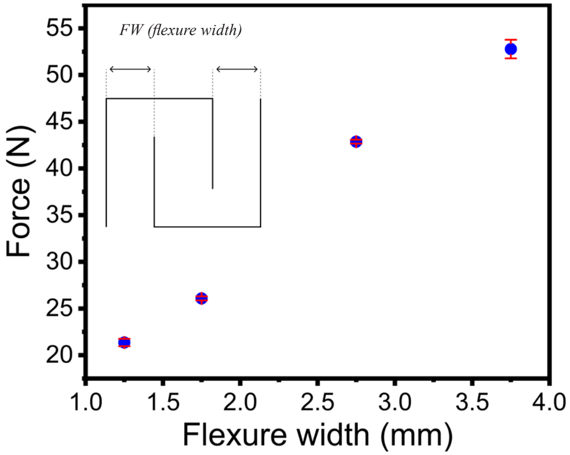
5) The sample is then fixed at the ends for its intended use, allowing the surface's overall contraction to be controlled, tuned, and/or automated. In this example, the sample is attached to a lead screw driven by a DC motor, with 3D-printed clamps to fix the sample ends to the actuator stages.

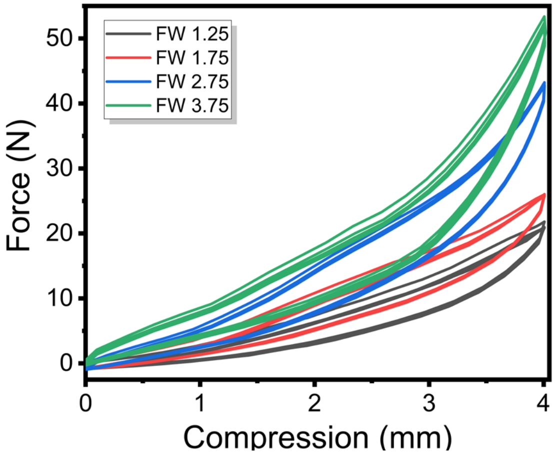
SURFACE FORCES

We assess the tunable tactile qualities of the patterns using an Instron tensile testing machine and a contact plate. The contact plate acts in a similar fashion as a finger or hand moving through the surface, encountering forces as it travels across or into the features. We created 3D-printed sheet samples using a TPU glued to a rigid, fixed-length board at uniform bond intervals. We used the 3D printer for these samples as it allowed us to finely tune the sheet thickness to the force range of our tensile testing machine, in place of acquiring multiple TPU sheets of varying thickness.

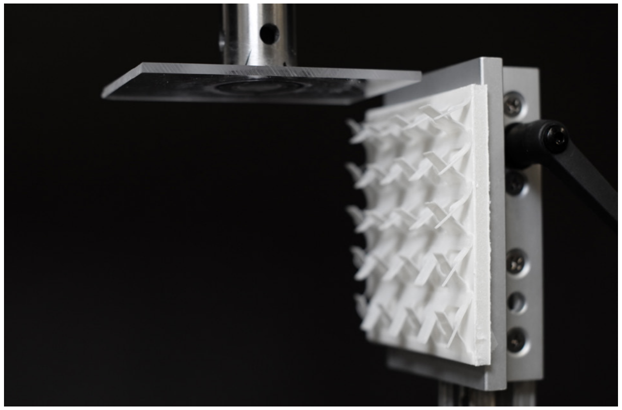


Test 1 (compressive force)

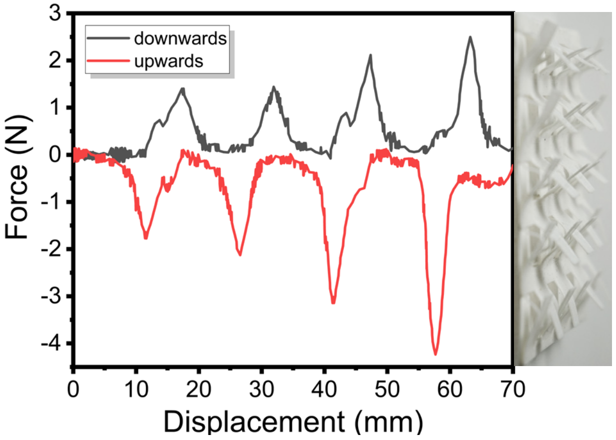


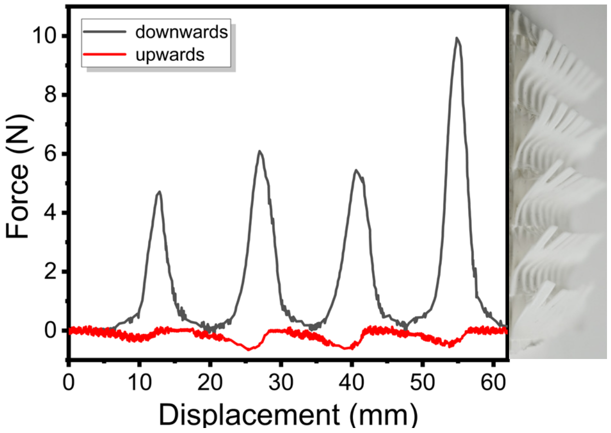


Our first test uses sheets of a pop-up pattern and compresses them to demonstrate the tunable compressive force of the patterns. The 4 samples range in flexural width (FW) from 1.25-3.75 mm. As the flexural width dimension increases, the compressive force of the sample increases at a near linear rate. Peak force values ranged from 21-53 N. We can also observe the strong recoverability of the surface based on the limited variance of the loading and unloading curves.



Test 2 (lateral force)





In our second test, the samples were oriented vertically and the plate was dragged to measure the in-plane forces of different samples. This approximates the forces that a finger may experience as it travels through a surface in an in-plane path. One sample has a symmetrical pattern of pop-up elements while the other only has elements aligned in one direction. The localized increases in force as the plate moves upwards and downwards demonstrates correspond with the number and type of features in the symmetric vs. asymmetric sample.

PROVIDING FEEDBACK ON INPUT DEVICES

These tunable surfaces can be integrated into existing devices and objects. The compliance of their structure allows them to be low profile, ergonomic, and compatible with many surface types and sub-surface geometries.

We integrated a spiked fabric surface using FlexTure onto a Meta Quest 2 virtual reality controller. A single geared motor (ROB-12285, SparkFun Electronics) rotates a 3D-printed drum to vary the tension of the substrate. The motor is only actively powered when moving between states, keeping power consumption low. Actions and events in a virtual space are prompted to the user through changing surface qualities.

As implemented here, the actuation system and materials cost below $20 USD. This surface uses heat-sealed fabric for both the top and bottom sheet, making it robust for hand pressure and moisture.

Rapidly changing between states acts prompts a user to interact with the surface (i.e. picking up the controller). As the user engages with different objects in a virtual space, they may contain classifications that readjust the surface to be ‘rough’ or ‘smooth’ based on their real-life surfaces or a desired experience.

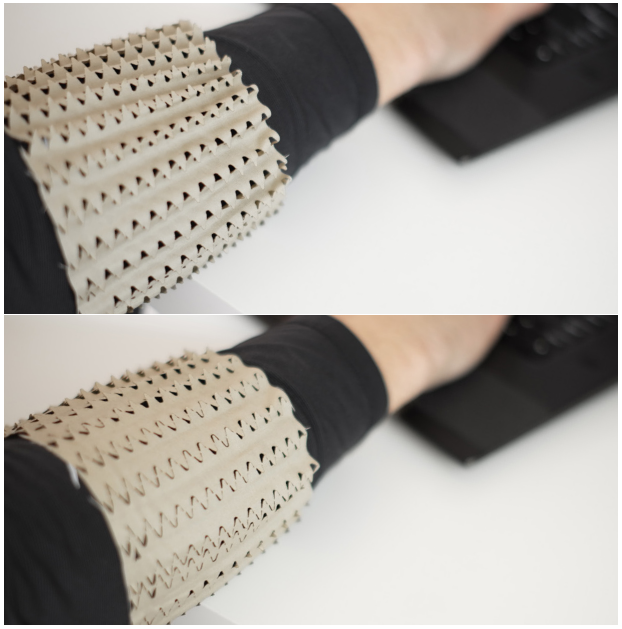
Although not implemented on this device, sensing capabilities can be added to these surfaces through the use of conductive layers or threads. Previous work leveraged the capacitive nature of the changing surfaces, which can directly apply to user inputs during hand exploration or use [28].

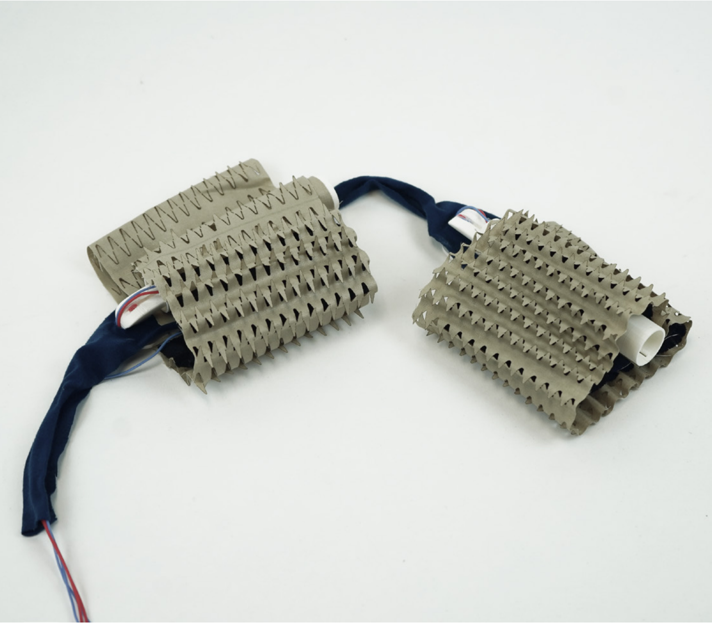
There are many opportunities to integrate these low-profile surfaces into digitally connected systems. As the development of a physically augmented reality continues, we believe that these low-cost and mass-producible materials can be used for the synchronous response of visual and haptic sensation.

COMMUNICATIVE APPAREL

The textile nature of these surfaces means that they are well suited to wearable and fashion applications. The elastic substrate allows for the surfaces to be conformable and fitting to variably sized wearers. While the previous section highlights the tactile use of these surfaces, this device focuses more on the visual affordances, in which the state of the surface provides signaling to peripheral users about the wearer's state or digital interactions.

The automated movement of the device again comes from a geared motor operating a 3D printed drum. The computationally controlled actuation of these surfaces can be combined with the natural extension and compression of human skin, creating an added layer to the embodied behavior of the surface.





Smooth

Textured

Two separately controlled FlexTure surfaces can begin to create some simple logic in their signalling, as the variable surfaces can be actuated in relation to each other. In the example at left, the top surface is linked to the wearer's activity status on their laptop, creating an ambient display of their social state for their cohabitants.

As we described previously with the qualities that contribute to the "affect" of a surface, the FlexTure surfaces can be used to describe variable states of approachability. The left image shows a more relaxed, smooth surface that invites cohabitants to interrupt a user if they aren't actively engaged with a task, whereas the spikier actuated state in the right image deters interaction by appearing and feeling less approachable.

FUTURE WORK

We believe that these surfaces could be durably, cheaply, and effectively mass-produced using apparel and textile manufacturing systems. With mass customization, these surfaces can be tuned based on user preference, data, or other context. Outside of wearables and apparel, we also envision the use of these surfaces for physical data visualization, ambient displays, and kinetic artworks.

From a technical standpoint, there are opportunities to do more thorough mechanical characterization of these repeated kirigami surfaces to create defined mechanical modeling that would allow for the programming of specific surface behavior. Performance characterization could also be done to determine the durability of the structures, their attachment, and their reliability. In contrast to this, the intentional deterioration of these surfaces could also be explored through the lens of interaction design (such as the bottom row of images at right). The surface could also be layered over itself, creating a broader design space with multiple layers and control systems for the perforations, as well as creating more nuanced haptic experiences.

Our exploration covered rectangular and triangular patterning and linear, contraction-based stretch, but there are many opportunities for increased complexity in the pattern and stretch design. Multi-way elastic materials may allow for new interactive and mechanical opportunities. Prior work has integrated 3D-printed elements onto textiles, and the intersection of these methods could further increase the design space [7,20].

In addition to the stretch and pattern, there are many other extension-driven kirigami patterns that were not included in this work that have different visual and tactile effects to be explored. Some of our early experimentation found unique haptic properties in the mechanical bi- and multi-stability of some patterns, which could also be an opportunity for tangible interface design in the creation of pop-up buttons or switches.

CONCLUSION

FlexTure provides a framework and tool with which to explore and create responsive, tactile surfaces. By incorporating a system of design principles, digital design tools, and rapid prototyping, designers can use FlexTure to create low-cost, low-profile, conformable surface features.

Our exploration found these surfaces to be playful, sensorially rich, and customizable. The samples shown at top right demonstrate the breadth of materials, designs, and scales of surfaces that FlexTure can enable. We hope that our method will support prototyping and accessible exploration toward ubiquitous visual/tactile interfaces in everyday surfaces.

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