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HapticPrint: Designing Feel Aesthetics for 3D Printing

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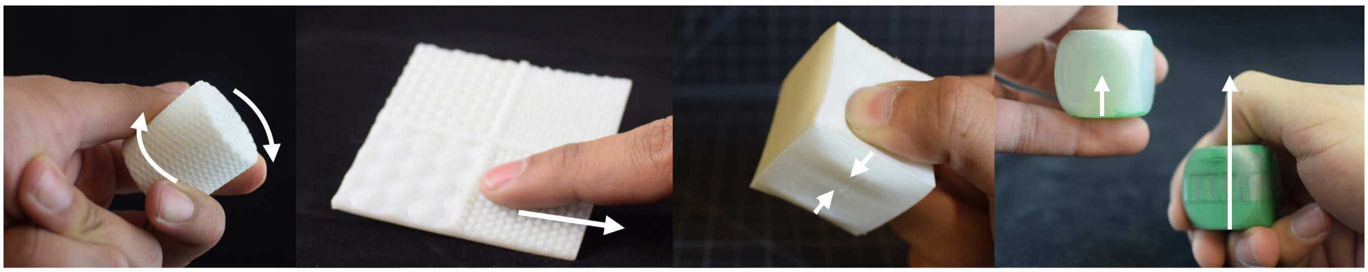

Figure 1. Example objects created with HapticPrint. *External* and *Internal* tools allow users to easily add tactility, flexibility, and weight to objects.

ABSTRACT
Digital fabrication has enabled massive creativity in hobbyist communities and professional product design. These emerging technologies excel at realizing an arbitrary shape or form; however these objects are often rigid and lack the *feel* desired by designers. We aim to enable physical haptic design in passive 3D printed objects. This paper identifies two core areas for extending physical design into digital fabrication: designing the external and internal haptic characteristics of an object. We present HapticPrint as a pair of design tools to easily modify the feel of a 3D model. Our external tool maps textures and UI elements onto arbitrary shapes, and our internal tool modifies the internal geometry of models for novel compliance and weight characteristics. We demonstrate the value of HapticPrint with a range of applications that expand the aesthetics of feel, usability, and interactivity in 3D artifacts.

Author Keywords
digital fabrication; haptics; design; texture; deformation

ACM Classification Keywords
D.2.2 Design Tools and Techniques: User interfaces (H.5.2, H.1.2, I.3.6)

INTRODUCTION
In current digital fabrication practices, 3D modeling has often been seen as a medium concerned with the *look* of an artifact. Yet designing the *feel* of an artifact is highly critical to the usability, accessibility, and perception of physical artifacts [15].

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The *feel aesthetic*, or the choice of haptic characteristics given to an object, contributes to both the functional and aesthetic value of an artifact such as adding a knurl[1] texture to a simple knob. Albeit subtle, these cues are a part of the design of everyday objects.

Primarily influenced by form-first design tools and limited access to multi-material 3D printers, today's artifacts are produced as rigid, smooth plastic parts. We see this as an opportunity to enable the design of haptic characteristics and expand the feel aesthetic of printed artifacts using current 3D printing techniques. While several methods have been developed for expanding the range of haptic properties in digitally fabricated artifacts [1, 4, 19, 21, 22], synthesizing these haptic characteristics in a design tool remains underdeveloped.

We introduce HapticPrint, a pair of design tools that enable users to easily design the *feel aesthetics* of an object using Fused Filament Fabrication (FFF). In both tools, we distill the 3D design problem into a 2D design task for users. Our *external* tool overlays textures derived from 2D raster graphics to generate tactile models on a variety of surfaces. Our *internal* tool controls a 3D model's stiffness and mass distribution by partitioning it into "chambers" which can then be ascribed special haptic infills. Features of infill and texture patterns were parametrized to enable users to control specific cues of haptic exploration (Figure 2). Lastly, to aid users with haptic selection and facilitate an iterative design practice, we created an online library of printable reference designs, or palettes.

We motivate HapticPrint with a review of related work in haptic perception, digital fabrication, and the physical design space. We then outline the implementation of the two HapticPrint tools and evaluate each *Feel Aesthetic*. Finally applications with HapticPrint show how the synthesis of haptic design produces novel artifacts and interactions.

[1]Knurl is a pattern of angled cut lines given to machined parts for user grips.

RELATED WORK

Our work aims to connect research on feel aesthetics and prototyping tools for more expressive and usable objects. We reviewed literature on haptic perception, prototyping in design, and 3D printing tools and techniques.

Prototyping Feel

Houde & Hill's work on iterative design identifies *look & feel* as critical properties of successful prototypes [11], referring to both the interactive feel of virtual interfaces and the physical feel of tangible prototypes. Despite the importance of haptic characteristics in an object's design, haptic design remains an underdeveloped area. Instead, design language for feel largely borrows from visual design [29]. In seminal work on Haptic Exploration, Lederman & Klatzky showed that users identify objects by six exploratory procedures: lateral motion (texture), pressure (hardness), static contact (temperature), unsupported holding (weight), enclosure (volume), and contour following (global shape) [16]. We use this haptic exploration space to guide the design of HapticPrint (Figure 2). While 3D printing for prototyping largely captures the global shape of an artifact, we seek to develop techniques for addressing a larger breadth of haptic exploration language, or feel, of a 3D printed artifact.

Material Prototyping

In order to expand the range of producible 3D printed artifacts, recent research explores controlling or simulating material properties other than thermoplastics. Bickel et. al. used a multi-material printer to synthesize target material behaviors by layering two or more base materials [1]. This material "dithering" is used to produce materials with hybrid properties. This work led to the development of OpenFab, a shader-like specification language for the multi-material printing pipeline [32]. Other fabrication techniques work directly with the desired materials, including wool [12] or carbon fiber[2]. While Bickel et al. approaches haptic design from a goal-driven framework, we focus on the iterative and reflective design cycle used by many product designers. More succinctly, *how does a designer choose the right feel*?

Surface Design: On the Skin

3D modeling remains a barrier to many amateur designers, let alone modeling surface textures. Simplified methods such as 2.1D models (i.e., stacked planar slices) have the potential to increase participation in 3D design [24]. Similarly, 2.5D models have been constructed from Shape from Shading (SFS) or sensor-based depth-maps to create tactile paintings [5], graphs [2], and maps [8]. More recently, these techniques have been used to create physical visualizations of data [28]. More sophisticated tools such as ZBrush[3] unwrap a 3D mesh (UV mapping) on a 2D canvas allowing users to specify texture through brush interactions.

Surface textures can also be sampled directly from the environment. Using depth sensors Li et al. reconstructed full body portraits from noisy environments [17]. Furthermore, post-capture refinement algorithms have been used to successfully capture and abstract textures such as hair [4]. However, capturing detailed textures requires high-resolution meshes and introduce a large computational overhead for interactive applications. By generating textures from imported 2D height maps, users can manipulate textures in a real-time environment. Displacement mapping, the equivalent technique in computer graphics, uses a GPU vertex shader to calculate a vertex's 2D position on a screen to later result in a 2D raster graphic; our technique leverages HTML5 WebWorkers to calculate a vertex's 3D displacement and construct a 3D model at interactive speeds.

Internal Design: Under the Skin

Many new design opportunities arise from modifying the internal structure of objects. For instance reducing the need for an internal support structure via skin-frames [33] or wireforms [21] can speed up the prototyping process and decrease print time by tenfold. Stava et al. demonstrated that a combination of thickening, hollowing, and supporting struts increases the structural integrity of a print [27]. Similarly, a hollow honeycomb interior was shown to add to an object's durability [19]. While these techniques generally maintain the *shape* and *form* of an object, we contribute techniques for prototyping the *feel* of a model.

In digital fabrication design, Prévost et al. [23] modify the internal voxel geometry of a 3D model in order to redistribute an artifact's center-of-gravity to achieve balance. More dynamic behaviors have been explored using layered soft composite materials and pneumatic actuation [37].Likewise other internal modifications have been shown to enable output mechanisms with optical light pipes [35], identification structures [36], or internal media-containing tubes [25]. While others have demonstrated it in principle, we look at internal structure design under the lens of interaction design. We explore how weight and compliance might be used in designs as as a mode of interaction and present a method to both redirect the mass and compliance of different areas using standard 3D printing techniques.

THE PHYSICAL HAPTIC DESIGN SPACE

Physical design generally refers to giving shape and external form to an artifact, yet design literature identifies several design parameters like weight, texture, and resilience that are important to the feel, or haptic design, of an object [15]. According to ISO standards, haptics are divided into *tactile or cutaneous touch* referring to mechanical stimulation of the skin, and *kinaesthetics* referring to that sensation of movement, force, and position of the body with respect to an object [31]. Loomis and Lederman further distinguish haptics based on a) active/passive touch i.e. the presence or absence of motor control, and b) the afferent inputs used i.e., cutaneous, kinesthetic, and haptic[4] [14, 18]. In this paper, we restrict our exploration to active touch. In this section, we describe the haptic design elements used in HapticPrint and how they are utilized to expand the physical haptic design space.

[2] `http://www.markforged.com`

[3] `http://www.pixologic.com/`

[4] Haptic in this context is used to refer to combined inputs from the cutaneous and kinesthetic touch

Cutaneous Tactility

Tactility refers to the sense of touch derived from skin's physical contact with the environment [31]. Tactile perception is limited by spatial sensitivity (≈ 1.5–2.5 mm periods, dependent on force exerted on the skin) and temporal sensitivity (≈ 20, 40, 250 Hz bandpass mechanoreceptors); optimal information transfer can be achieved by matching the spatial and temporal display parameters to sensing limits [18]. Atomic perceptual models from psychophysics reveal a feature space for tactile surfaces across three dimensions: roughness & smoothness, hardness & softness, and elasticity (springiness) [10]. These haptic feedback mechanisms are often used to communicate affordances i.e., cues to a user that signal opportunities to perform an action [22]. For example, a ridged texture around a camera lens conveys where a user should grip and twist for manual focus. We divide the space of tactile design under physical characteristics and semiotic characteristics.

Physically, surface geometries and material properties largely contribute to tactile sensing: for cutaneous interactions, haptic slip and torque feels has been linked to skin-stretch and slip-direction [26]. These surface geometries can be characterized by *feature-size* and the gap between features, or *feature-gap*. Other derivable dimensions include fill-density and volume-factor. The *arrangement* of the features within a texture also affects the user's perception. Grids communicate order, honeycombs denote more natural formations, and "randomness" is closely associated with a digital aesthetic. Dynamic textures, or those that change over time, have been explored in materials like leather that develop a patina. Certain textures need to retain a specific size and density in order to convey its message (e.g., *snake scales*). We draw from semiotics in order to characterize these types of textures:

- *indexical* - references real world stimuli e.g. cloth;
- *iconic* - abstracted stimuli e.g. studded scales, knurl;
- *symbolic* - does not reference any real world stimuli, must be learned e.g. braille, letters.

Kinesthesia

Kinesthetics is also referred to as proprioception and refers to sensory inputs from mechanoreceptors in the body's muscles, tendons, and joints; however the ways these receptors mediate perception is less defined than cutaneous touch [3, 14].

In haptic design, kinesthetics are integral to haptic exploration; the ability of a body to exert forces and evaluate how an object alters normal body motion allows us to gain an understanding of the kinesthetic properties of that object. For instance, a user applies pressure to a flexible object to understand how it should be held or attached. The *visibility* of the inner structure provides visual feedback of the mechanics of the object. For example, corrugation patterns in cardboard convey the grain of flexibility, while the fine mesh of Styrofoam in foamboard conveys a softer more impressionable interaction.

Other properties such as weight plays an important role in the trustworthiness of an object [29]. For instance, a light drill is perceived as less trustworthy and powerful than a heavier drill. The distribution of weight is also an indicator of stable states - how an object sits or rests in the hand implies interaction points and modes. For instance, many objects have a single base weight pattern where the weight distribution "grounds" the object, inviting a user to interact from the top or merely implying a decorative "statue-esque" role. A weight distribution could convey how interfaces should be held, such as placing batteries in the lower cavity of a remote control to act as a cantilever for pressing buttons in the upper segment. Axial weight configurations encourage users to rotate objects around an axis. Polycentric centers-of-mass such as the loose pebbles in a rainstick encourage interaction by influencing the user to switch between states.

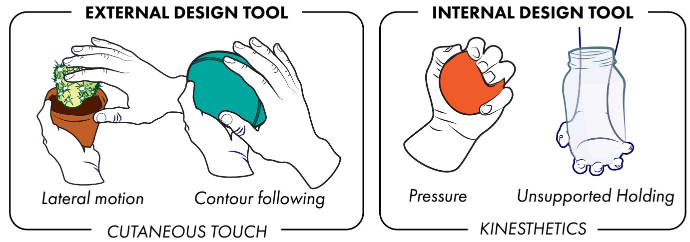

Figure 2. HapticPrint divides *feel aesthetics* into external and internal tools and in order to design haptic exploration [16] in physical design. Enclosure (not pictured) is supported by current modeling tools. Static contact is left for future work.

We implemented specific subsets of this broad haptic design space into our HapticPrint tools which are detailed in the next section.

DESIGN TOOL IMPLEMENTATION

With HapticPrint, we implemented two physical design tools for adding feel aesthetics to models. Each tool addresses elements of the exploratory haptic space depicted in Figure 2. The *external tool* overlays patterns on models allowing users to specify tactile cues (lateral motion) or seams to follow (contour following). The *internal tool* allows a user to specify compliant infill patterns (pressure) in specific regions, including an infill pattern for injecting weight post-print (unsupported holding). In this section, we detail the technical implementation of each tool and the process used to create a library of 25 feel textures, 5 structural infills, and 6 weight profiles, each of which spans the feel design space. Figure 1 shows shape primitives with example feel aesthetics.

EXTERNAL DESIGN TOOL

The primary goal of the external tool is to easily modify the surface of a model with texture. In particular, the tool should be capable of expressing a broad range of textures on a given form. With this tool a designer can either import, create, or specify an existing texture. While selection is fairly trivial in a digital design scenario, physical design is better facilitated with tangible references. As such, we see such a design tool that supports capturing textures from the environment, designing textures virtually with physical perception feedback, and specifying unknown textures guided by similarity to other known textures.

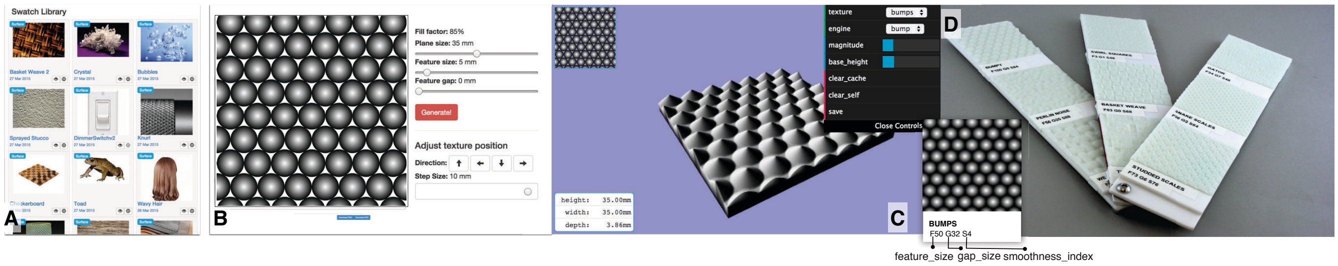

Figure 3. The external design tool. (a) Library of textures, interactive patterns, and infill samples. (b) A height map generator patterning a "spike" feature. (c) A 2D height map is converted into a 2.5D tactile mesh using WebGL. (d) Example textures on swatch palettes.

Using `three.js`[5] we created a web application to generate a 2.5D model from a raster graphic (Figure 3c). 2.5D refers to models that are 3-dimensional in appearance but only vary along a single dimension; they can be represented by the height field function of $z = f(x, y)$ [24].

The external tool first converts a raster image into a heightmap based on the corresponding grayscale value of each pixel. Our tool then uses height displacement – a common computer graphics technique – to modify points on the mesh. The 2D raster graphic is UV mapped, or projected onto the mesh, and used to bind the heightmap to mesh vertices.

To obtain high resolution height displacement, the heightmap needs to be assigned to a high-resolution triangular mesh surface. For 2D rendering, this operation is offset to a vertex shader on the GPU; this unfortunately only calculates the 2D displacement of vertex coordinate on the screen. In order to produce a 3D mesh, we used a map-and-reduce routine with HTML5 WebWorkers to calculate vertex displacement. For reference, operating on a mesh with 45K vertices, we report the following performance values: GPU vertex shader (`5ms`, 2D graphic only), iterative (`11-12s`, mesh), and WebWorker map/reduce (`140ms`, mesh).

In our implementation, we exposed the vertex-shader image to the user and computed the full mesh displacement in the background. Height displacement occurs with respect to the direction of the surface normal at each vertex. Finally, the tool stores the resulting mesh as an STL for 3D printing.

A clear advantage of a height displacement approach is the decomposition of a 3D surface task into a 2D graphic task. Texture as a 2D input allows inspiration to come from existing images rather than solely designing in a 3D modeling environment. Furthermore, many 2D graphic tools support tools such as gradients and opacity, which can be used to create bumps, seams, and levels of elevation - a trait we exploit to enable tactile user interface (UI) design.

Importing, creating, and selecting a texture

The external tool takes textures in the form of a raster graphic or Support Vector Graphic (SVG). Raster images were sourced from simple image searches as well as repositories of bump maps[6] in the graphics community. Parameterizable height maps were generated using a custom `paper.js` application shown in Figure 3a.

[5] **`http://threejs.org/`**

[6] **`https://www.filterforge.com/filters/`**

A user can specify the individual feature element in a texture (i.e. a single cell of honeycomb), and the tool lets the user pattern and scale the texture based on feature size, feature gap, and arrangement.

The arrangements are a rectilinear grid, a honeycomb grid, or a honeycomb with added perlin noise for more natural formations. For prototyping many textures, a designer can construct haptic swatches as 70 mm x 70 mm 2.5D layers and place them on a "swatch palette" similar to a paint swatch (Figure 3d). We contribute printable STL palettes of 25 textures we found in an examination of this design space.

INTERNAL DESIGN TOOL

Printing models as completely solid objects is prohibitively costly in both material and time. In additive manufacturing processes such as Fused Filament Fabrication (FFF)[7], slicing software converts a 3D model file into correctly sized layers and toolpaths for printing. In the slicing stage, models are commonly hollowed and filled with a structural support called infill. Our internal design tool uses the open-source Ultimaker CuraEngine[8] - itself a slicer - to generate custom g-code toolpaths. We exploit the infill to control the kinaesthetic characteristics of an object and develop an interface for designing these elements into 3D models.

Internal fill patterns

Five infill patterns were used to control the compliance along each dimension of the 3D model: *line*, *grid*, *concentric*, *grided spiral*, and *weighted chamber*. The first three patterns are provided by the CuraEngine project. Figure 5 shows each infill pattern and the corresponding directions of compliance. The concentric pattern, for example, is unsupported in X and Y but stiff in the Z direction. Since infills typically have thinner walls and are printed at faster speeds, patterns typically are homogenous along the z-dimension. For the *grided spiral*, we achieved compliance in 3 dimensions by rotating the grid infill with each layer at a rate of 0.17 rad/mm. The weight chamber infill (Figure 4B) was designed to provide both support but also a permeable structure. This is used so that a user might fill the model post-print with a material and prototype the weight characteristics *in situ*. The fillable portion, or distribution, of the weight infill can be specified to be: offset, centralized, or completely fillable.

[7] Fused Filament Fabrication is synonymous with Fused Deposition Modeling (FDM), a process patented by Stratasys Ltd.

[8] **`https://github.com/Ultimaker/CuraEngine`**

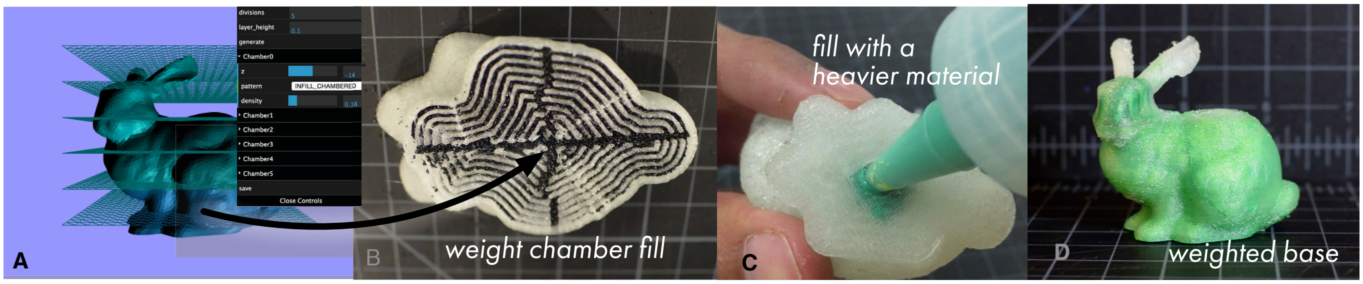

Figure 4. The internal design tool. (a) A model is divided into chambers. Users can specify what type of infill each chamber should have. (b) A cross section of the bottom weight chamber of the bunny; filled with black sand for contrast. (c) The user manually injects the infill with a heavier material. (d) The final bunny artifact weighted down by green acrylic medium.

Selecting infill

Our internal tool first loads a user-provided `STL` model file, identifies points of interaction, and specifies the desired print direction. This is then used to split the model into z-chambers, which a user can then use to specify infill properties (Figure 4A). Users have control of the fill pattern, fill density, and in the case of the *weight chamber*, distribution.

Kinaesthesia

In our internal design tool, a model is separated into equal sized chambers (Figure 4A). A user can alter the chamber boundaries to correspond with semantic boundaries (e.g. the tail of a bunny). A user can then select an appropriate haptic infill that is parametrized through infill density. Though a percentage fill is common in existing slicers, this allows our infill patterns to change stiffness. We printed each infill in a range of percentages and then tested their compliance on a custom stress-strain fixture (Figure 9). We then mapped each infill percentage to the measured compliance. Thus a user can specify an estimated stiffness and direction(s) of flexibility which is then used by the internal tool to generate the appropriate infill and density.

To achieve a desired weight and mass distribution, materials can be injected into objects post-print using the *weighted chamber* infill. This infill functions in its primary capacity i.e. supporting outer walls during print-time, but also leaves a relatively hollow chamber that allows fluid materials to fill a chamber of the model through a small pipe. This is achieved by routing the liquid through channels in between support walls (Figure 4C). This provides unique opportunities for the user to alter the balance and kinesthetic properties of the object. A user might for instance wish to create a stabilizing base. The bottom chamber of the model can be filled with a heavier material (Figure 4D). An artifact may have multiple weight chambers or other infill chambers; to prevent interference between chambers, a 0.8 mm solid chamber wall exists around chamber boundaries.

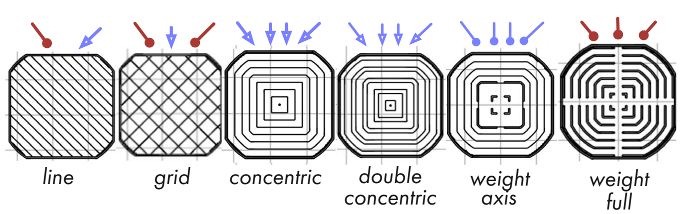

Figure 5. Various patterns of infill provide different types of compliance along dimensions orthogonal to the build direction. Red arrows indicate resistive (less compliant) points whereas blue arrows designate compliant directions. The weighted infill is designed such that a medium is able to be injected post print.

FABRICATION TECHNIQUE AND EVALUATION

In this section we describe our printing techniques, evaluation, as well as example physical artifacts produced by each tool. We discuss the potential and limitations of each method.

Tools and Materials

For fabrication, we used a Type A Series 1 Machine (TAM) with a G2, 0.4 mm extruder. Two types of filament were used: 1.75 mm PLA, a strong and durable plastic, and 1.75 mm NinjaFlex TPE, a flexible thermoplastic elastomer. All artifacts were printed at maximum resolution (0.10 mm layer height). TAMs share a common architecture with most FFF machines; it extrudes thermoplastic filament through a heated nozzle and motion is derived from a 3-axis gantry. Stereolithography (SLA) and PolyJet printing differs from FFF by jetting or curing polymer resin in successive layers to build up a model; although not explicitly tested our approach is extendable since it modifies common procedures (i.e. support and infill material) typical of most additive manufacturing process.

Tactile Evaluation

To evaluate our external design tool, we printed a diverse set of reference objects and evaluated print quality. A chief concern of the FFF process is that print quality is highly dependent on planar orientation. A *grain* in Fused Filament Fabrication, for instance, results from small ridges between layers.

The printed set consisted of: a) the library of 25 tactile surfaces in PLA on 70 mm x 70 mm squares with a 2 mm base, and b) three representative textures printed on cones, spheres, planes, and cylinders primitives, shown in Figure 6. These primitives were chosen as to cover all 3D planar orientations. Furthermore, these primitives explore how these textures feel on various common objects through different exploratory haptic interactions (e.g., pinch, stroke, enclosure). All features were displaced less than 3 mm from the surface normal.

We found that printing objects with textures had the practical benefit of masking the grain of 3D printed artifacts. This technique was limited by retraction errors, where extruded material was not properly retracted and resulted in cobweb traversals (e.g. traveling between peaks in spiky textures).

Figure 6. 3 cylinders and 3 cones printed with alligator (indexical), bump (iconic), and arrow (symbolic) textures, respectively.

This could easily be improved with some post-print cleaning. As perceived by the authors, small features sizes (< 0.5 mm) and feature gaps (< 0.1 mm) produced smoother surfaces. Print times for these parts increased from 5-15%, depending on feature-area. Textures with smaller features than the layer resolution (< 0.1 mm) - like knurl, or alligator - printed best in all planes and obscured the artifact grain. However these textures were less easily identifiable. Textures with larger features - like corn or arrows - did not hide the layering but were more easily identifiable. In future work we will investigate layering large features with a smoothing noise texture to produce both visually and tactually pleasing objects.

Kinaesthetics Evaluation

Our goal in printing and evaluating the various infill patterns was to understand and control how each pattern varied along each axes for artifacts printed with flexible filament (TPE). Since TPE agglomerates at narrow points like cones and spheres (Figure 6), each infill pattern was printed in 30 mm cubes.

More formally, the compliance of a material is its elastic modulus, where the material deforms under stress yet returns to original position[9]. We modeled each object as a linear spring and report the spring rate as $\frac{\Delta F}{\Delta y}$ in units of $\frac{N}{m}$. The measurement system was built with a linear displacement gauge, a digital scale, a drill press, and a custom bracket to connect the components; the setup is shown in Figure 8. The drill press applied load to the sample piece while the distance gauge measured deflection and the scale measured load.

We show the compliance testing for an infill pattern that is compliant in two-axes - results shown in Figure 9. We printed four cubes varying in fill density from 20% to 80%, took >5 data points, and found the linear regression with the y-intercept set to $y = 0$. In all cases the $r^2 > 94\%$ when depressed by 50%, meaning we can reliably predict deformation

[9] This is the linear region of the stress-strain plot. Plastic deformation is permanent strain to a material. We only measured the compression since most UI elements are rarely in tension.

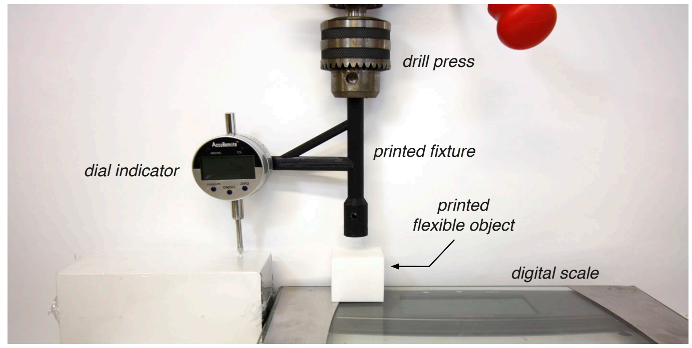

Figure 8. Our compliance testing setup measured force with respect to applied displacement. The drill press was manually operated.

to half an object's height. We also found that 80% and 100% infills were effectively rigid, so flexibility and rigidity can be printed into a single part. For reference, overall pinching strength varies from 50 to 100 N for average adults [20], thus a 20% infill would feel completely deformable while 80% infill would feel nearly rigid. In our design tool, this measure was linearized for user-selection.

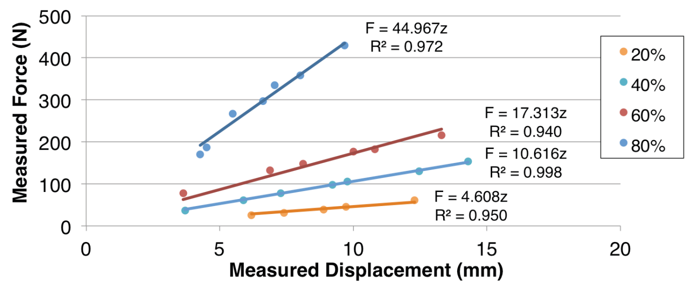

Figure 9. Linear regressions for various percentages of infill and their corresponding compliance. Spring rates require a y-intercept at 0.

For weighted artifacts, we injected a variety of materials post-print including: hot glue, epoxies, sands, and acrylic medium. A pipette was used to pipe liquid mediums into appropriate weight chambers, shown in Figure 4C. Hot glue was used to close the resulting hole. Epoxies were allowed to cure before closure. Due to imperfect layer fusion from FFF, we found that chambers needed to have wall thicknesses of at least 0.8 mm in order to contain less viscous fillers. Filling these cavities with conductive materials may be utilized to provide interactive properties to otherwise passive prints.

FEEL AESTHETICS IN EXAMPLE OBJECTS

In order to evaluate how our tool expands the current *feel aesthetic* of 3D printed objects, we designed a set of four prototype objects using both internal and external HapticPrint tools. Each object explores how haptic properties can be utilized and prototyped in an iterative design process.

Affordance Design for User Interfaces

The physical affordances, or cues that convey potential action, are a powerful design property; however, capacitive touch surfaces have few physical affordances. Harrison et al. explored pneumatically actuated latex templates to provide some tactile information [9]. We created a set of three passive UI interfaces that offer a higher resolution of haptic information. These UIs are used in a common interface

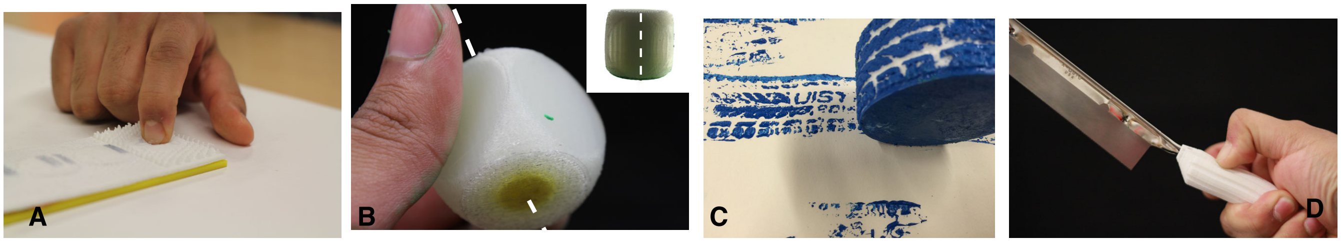

Figure 7. (a) A fan control board. A multi-button pattern is attached to a capacitive layer (bottom) and a raised texture-enchanced surface is placed to give the interface tactile cues and affordances. (b) A weighted die. Acrylic medium is pipetted into an axial chamber. (top) The die backlit. (c) A printmaking wheel with texture, compliance, and weight. (d) A blade handle with additional pressure cues to indicate correct finger placement.

control problem of device controls. Notably, we created the designs using 2D graphics and SVG editors.

To showcase how haptic design can be used to enhance interactive artifacts, we built a capacitive touch sensing layer using an MPR121. A TPE texture layer (dielectric) was placed over copper tape (capactive layer) to give tactile cues to the user (Figure 10). The dielectric was fabricated at a 15% infill, which we found as a usable button stiffness. For displacements less than 4 mm from the copper electrode, we found that two or more discrete events such as "touch" and "press" could be reliably detected.

This technique was applied to a simple four-button control board to control an connected 3-speed fan (Figure 7a). The buttons are circles with radial gradients, displaced 4mm from a planar surface, and constructed with a compliant infill. The icons were overlaid on the buttons and then textures were clip-masked around two conceptual control areas to aid with identification. A spiky texture was customized by looking up feature-size and feature-gap to obtain a desired roughness using the HapticPrint texture palette. The same design was then used to vinyl cut copper traces, which were affixed to a laser-cut acrylic backing (Figure 10).

For interaction, we formatted the buttons to have two degrees of "actionability". We utilized our capacitive displacement technique to turn off the fan *gradually* from a light touch, or *immediately* with a hard press. Thus, the affordances of the button were used to communicate multiple physical interactions. We created a second interface that used striated marks to guide the finger up and down to communicate the affordance of slide-ability. In lighting control situations, custom tactile patterns could be derived from building floor plans, providing a spatial aid.

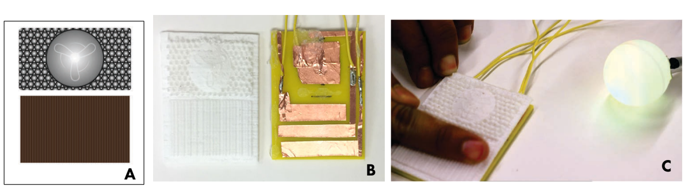

Figure 10. a) An interface design with "spikey" button and "striated" slider elements. b) The printed design in NinjaFlex, with its corresponding copper traces affixed to support three discrete slider positions. c) The sliding mechanism detected touch which triggered an LED.

Weight as function

Weight is regularly used to create stable configurations for objects, however it can also be leveraged to provide additional functionality to objects. Figure 7b depicts a weighted die that has been applied an axial weight pattern. This biases weight (and more literally a craps game) to favor rotary interactions. We then utilized these haptic properties together in a printmaking tool that maps a 2D texture of a tire pattern around a cylinder. We applied a texture to the wheel, then applied a compliant infill to the exterior of the wheel with a weighted axial chamber. We injected the wheel with an acrylic medium for a more realistic moment-of-inertia. Figure 7c shows the final product.

Handle for Digital Apprenticeship

In a final application, we looked at how custom tools could be modified to have added usability. We added compliant surfaces to areas of a blade handle that corresponds with areas where pressure was being placed by an expert user (Figure 7d). In this way, a user who downloaded and printed this handle could learn tacit knowledge from subtle pressure cues. A capacitive press sensor could likewise provide feedback to the user to provide feedback or act as a kill switch to prevent user injury if held improperly.

DISCUSSION

Feel aesthetics are critical to the design of everyday objects, but this space is not captured by design tools or easily embedded within the tooling constraints of the fabrication process. Tools like HapticPrint can lead to designs that are more usable (affordances), accessible (improved support for people with disabilities), and aesthetically diverse (beyond smooth and uniform surfaces). However key challenges exist to integrating *physical* characteristics into *virtual* design tools.

Haptic design is inherently a tangible, physical design process. This raises the challenge of integrating haptics into a virtual design environment. HapticPrint addressed this issue by hand-curating a self-referential palette of textures, infills, and weight distributions, reminiscent of current practice with color swatches or color systems. This system however is prefaced on atomic haptic units, whereas real-world objects are a mixtures and layers of tactual and kinaesthetic feels. Dithering the infill, for instance, could create different haptic profiles. Selection tasks could be mitigated by generating small multiples and purposefully generating principled feature representations for data-driven design [30].

For end-user-created feel aesthetics, additional feedback could be provided by performing a similarity search over a corpus of existing textures or developing a higher-level model of expected behavior. HapticPrint found reasonable feel characterizations along feature size, gap, and density; however a formal psychophysics user study is needed to verify this mechanism. Our post-weight print technique provides flexibility for the user to choose the appropriate weight distribution *in situ* for a more reflective design process.

Alternatively, feel can be part of a goal-centered design process where known material behaviors are matched to desired behaviors [1], however the haptic vocabulary even amongst professional designers is limited [29]. Fully communicating multifaceted "feel"' remains a subject for future work.

In the context of industrial-scale fabrication, additive manufacturing (AM) is primarily limited by speed and resolution. Rather than compete with injection molding on speed, AM excels in "mass customization", reducing the cost for one-off designs and trade-offs for added complexity. Though microtextures are common in injection molding (plastic) or electroforming (metal), little work exists for these types of finishing textures (e.g. matte, satin, gloss) in printed parts. Recent work has demonstrated the feasibility of controlling microgeometries to fabricate custom reflectance properties [34]. HapticPrint may apply to custom manufacturing by controlling microtextures without the complex mold-making processes. Additionally, we achieved textures at the resolution of most printing technologies that further helped mask FFF grain leading to more appealing final products. Although our current fill method for augmenting weight is labor-intensive, we see this as a near term solution that will be mediated in the future by multi-material printing.

As multi-material fabrications tools advance, the expanded collection of material properties can be leveraged both structurally (density) and dynamically (viscosity) and lead to unique haptic experiences. HapticPrint contributes a first look towards how these properties might be expressed through a virtual design tool. By enabling haptic design to be more easily designed and produced within 3D designs, we have enabled a broader design space for experts and novices to explore. We are hopeful that this approach will further design tools towards becoming *medium-aware* and engaging with physical design processes.

FUTURE WORK & LIMITATIONS

We evaluated fabrication techniques for expanding the haptic vocabulary of 3D prints. However in order to fully evaluate the haptic characteristics of artifacts, our evaluation was limited by a lack of a formal psychophysics study. Determining elementary measures such as perceptual thresholds, or derived measures such as hardness and smoothness, could better describe the haptic space achievable (and unachievable) using our technique. Alternative approaches include a Gibsonian view of the "haptic system" which conversely eschews atomic characterization of touch and kinesthetics for a more holistic evaluation [6]. This would be a more apt methodology for haptic design since human observers are free to explore, move, or change patterns of touch; this would result in a more subjective report of perception, as would be the case when composing multiple haptic sensations in a design.

This paper addresses a larger breadth of Klatzky's haptic exploration than the state-of-the-art in digital fabrication. HapticPrint provides additional creative handles for controlling haptic information through pressure, contour following and lateral motion, and unsupported holding. We see great value from gaining haptic information from static contact, most commonly achieved through thermal stimulation, which can provide additional cues to users and opportunities for interaction design (e.g. object identification [13]). More interactive haptic cues can be derived through a temporal dimension (such as time-varying textures [7]), or from chemical, electrical, or mechanical stimulation [31].

CONCLUSION

Feel Aesthetics are often lacking in printed designs. In this paper, we identified methods and built tools for easily incorporating *feel aesthetics* into 3D designs. Our HapticPrint interfaces allow a user to easily modify the internal and external haptics through 2D design, which is a medium more widely understood. We evaluated HapticPrint by printing reference artifacts spanning the haptic space and assessed print quality. In a set of example objects, we showcased how tactility and kinaesthetics could be used to design more expressive, usable, and accessible 3D artifacts.

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