PunchPrint: Creating Composite Fiber-Filament Craft Artifacts by Integrating Punch Needle Embroidery and 3D Printing

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Figure 1: PunchPrint supports the creation of programmable and robust 3D-printed foundation textiles that are compatible with punch needle crafting. We present a design tool and fabrication workflow that reduces labor while supporting the production of detailed composite artifacts. Here we show how PunchPrint enables crafting small detailed designs. (a) We provide a parametric design interface for fabricating a flexible, filament-based textile substrate with design guides and hooks to facilitate assembly; (b) The craftsperson inserts fiber elements using standard punch needle embroidery methods on the 3D-printed foundation fabric; (c) The assembled final artifact with earring hooks and beads.

ABSTRACT

New printing strategies have enabled 3D-printed materials that imitate traditional textiles. These filament-based textiles are easy to fabricate but lack the look and feel of fiber textiles. We seek to augment 3D-printed textiles with needlecraft to produce composite materials that integrate the programmability of additive fabrication with the richness of traditional textile craft. We present PunchPrint: a technique for integrating fiber and filament in a textile by combining punch needle embroidery and 3D printing. Using a toolpath that imitates textile weave structure, we print a flexible fabric that provides a substrate for punch needle production. We evaluate our material's robustness through tensile strength and needle compatibility tests. We integrate our technique into a parametric design tool and produce functional artifacts that show how PunchPrint broadens punch needle craft by reducing labor in small, detailed artifacts, enabling the integration of openings and multiple yarn weights, and scaffolding soft 3D structures.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**.

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KEYWORDS

3D Printing; Textile Craft; Punch Needle Embroidery

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1 INTRODUCTION

Digital fabrication offers the opportunity to extend non-digital craft practices. Personal fabrication presents a vision for digital fabrication where people fabricate personal products and devices through digital tools [9]. One particularly exciting intersection of personal fabrication and 3D printing is the development of methods to produce textiles using fused-deposition modeling (FDM). Such techniques enable the fabrication of woven [36], flexible [8], and soft [27] materials and structures through a variety of methods that leverage the versatility of additive 3D printing toolpaths. These approaches have added benefit of being compatible with relatively inexpensive 3D printers and materials [4].

Existing 3D-printed textiles are limited compared to traditional textiles in that they are entirely comprised of extruded thermoplastic filaments. Thermoplastic materials have different visual and physical properties compared to fiber-based textiles. For example, creating fully opaque, multi-colored, single-layered textiles with existing methods is challenging. In contrast, fiber-based textile fabrication methods like knitting, weaving, and embroidery can be applied across a wide range of yarn gauges and colors to produce different patterns and textures. We see an opportunity to extend the expressive space of personal textile fabrication by integrating the equally rich but different domains of 3D-printed and fiber-based textiles. We seek to develop methods to combine established forms of manual textile craft with domain-specific methods for additive fabrication to support new forms of personal textile production. We present PunchPrint: a technique for integrating filament and fiber-based textiles by combining the 3D printing of a parametric fabric substrate with punch needle embroidery.

Punch needle is a form of manual embroidery in which the craftsperson uses a needle to push a continuous strand of yarn into a foundation fabric. Punch needle requires less manual skill than other needlecrafts, such as cross-stitch and traditional embroidery, and enables a wide range of textile effects [25]. Punch needle designs vary according to the properties of the foundation fabric which dictates the size of the needle, the gauge of the yarn, and the scale of the design [32]. PunchPrint extends the advantages of digital fabrication to punch needle embroidery while simultaneously providing an approach to create composite fiber-filament textiles. We developed a method to create a parametric 3D-printed fabric comprised of thermoplastic polyurethane (TPU) filament that resembles a woven fabric structure. We use a custom toolpath to produce a grid with continuous extrusion and alternating directionality. By varying the cell size of the grid, we can fabricate robust materials that mimic the ends per inch (EPI) of traditional punch needle substrates with a substantially thinner fabric weight. We evaluate our approach through a characterization that demonstrates the performance of our material for various needle sizes and EPIs. In addition, we present findings on optical imaging of high-stress points and mechanical tests for tensile strength. We make the following contributions:

First, we present a robust method to integrate punch needle embroidery and 3D printing through the production of punch needle compatible 3D-printed TPU foundation fabric that can be printed on an unmodified desktop 3D printer. Our fabrication method produces a substrate for punch needle embroidery with greater material flexibility and support for punch needle sizes and yarn gauges than traditional fabrics. By developing a hybrid of grid and line-3D printing infill methods, we substantially reduce material weak points and defects created by each individual infill method while optimizing the thickness and flexibility of the resulting 3D-printed fabric. Our method displays a substantially reduced risk of material breakage by achieving approximately twice the load capacity at similar displacement and 3X the elongation capacity compared to fabrics created with the grid infill method with the same thickness.

Second, we integrate our fabric method into a novel parametric design tool capable of producing fabric designs with varying EPIs, design guides, and 3D-printed design features to simplify the process of creating punch needle craft artifacts. These features extend traditional punch needle craft by enabling multiple yarn weights in the same piece of fabric and supporting the integration of hollow spaces and solid 3D-printed structures in the fabric.

Third, we demonstrate how the use of computational design and traditional punch needle methods can expand the expressive range of both 3D printing and punch needle embroidery through a series of artifacts produced with our method. These examples show how the integration of punch needle embroidery and 3D-printed textiles can scaffold the construction of three-dimensional soft textile structures and garments while reducing labor when creating small, highly detailed punch needle artifacts. We also provide a preliminary evaluation of the durability of PunchPrint artifacts by fabricating an iPhone case and using it for seven weeks.

2 RELATED WORK

We draw from two areas of research: integrating textile craft and digital fabrication, and 3D-printed textiles.

2.1 Integrating Textiles and Digital Fabrication

The combination of craft, computational design, and digital fabrication can engage digital fabrication newcomers in personally relevant craft practices [15] and create new economic opportunities [2]. Researchers have added to the design space of textile craft through digital fabrication. One approach is to extend existing computer-numerically-controlled (CNC) embroidery machines. Sketch & Stitch enables craftspeople to convert hand-drawn sketches to CNC embroidery patterns. Craftspeople can embroider with conductive thread and integrate circuit elements to create interactive textile artifacts [12]. FabricClick showcases methods to create haptic buttons in fabric through an integrated workflow of embroidery and 3D printing [11]. In the adjacent domain of e-textiles, researchers have explored using punch needle for rapid prototyping [16].

Researchers have also developed novel CNC machines that are compatible with craft materials. Hudson created a 3D printer that uses a modified layered felting process [14] and Peng *et al.* developed a method to laser cut and fuse 2D sections of fabric [26]. Digital textile fabrication is widely used in industrial production; however, industrial computer-controlled looms and knitting machines are prohibitively expensive for individuals. Albaugh *et al.* sought to broaden digital textile fabrication through the creation of a tabletop programmable Jacquard loom [1]. Moyer developed CNC machines for fabricating braided [21] and woven [22] textile bracelets. Similar to our integration of 3D printing and manual punch needle, Albaugh and Moyer's weaving machines deliberately incorporate hand-weaving. Most closely related to our work, He and Adar present a low-cost alternative to industrial punch needle machines by adapting an x-y plotter to support machine-automated punch needle fabrication [13]. We also seek to make digital textile fabrication more widely available. Rather than developing automated textile fabrication machines, we create a method for printing punch needle-compatible substrates for desktop 3D printers.

Our approach builds on prior work that integrates digitally fabricated and manual craft materials. Rivera *et al.* developed a set of techniques to 3D print rigid structures and components directly onto fabric to produce composite rigid objects with embedded flexibility [29]. The ClothTiles technique extends this work by integrating shape memory alloy into 3D-printed fabric composites to create soft actuated structures [23]. Our method takes a reverse approach. Instead of augmenting fiber-based textiles through the addition of 3D-printed components, we create a composite by using a filament-based fabric as the reinforcement.

Other researchers have also used digitally fabricated structures as scaffolds for manual crafting. Hybrid Reassemblage [41] and Hybrid Basketry [40] integrate 3D-printed pieces as a structural foundation in ceramics restoration and basket weaving, respectively. The unique structures possible through 3D printing can facilitate otherwise challenging craft outcomes like novel joinery in carpentry [20]. Digitally fabricated structures can also guide the craft workflow. Torres *et al.* use 3D-printed scaffolds to aid in shaping materials for wire sculpture [37]. For textiles, EscapeLoom uses soluble 3D-printed substrates and custom heddles to guide hand-weaving and 3D-printed scaffolds to aid in creating rigid geometry [7]. EscapeLoom also uses 3D-printed TPU guides to aid in weaving craft objects. This approach is the most closely related to our method. We use punch needle rather than weaving and therefore create structures that tension yarn loops rather than provide warps for woven fibers.

2.2 3D-Printed Textiles

Researchers have explored a range of additive fabrication methods to produce flexible materials with similar properties to fiber-based textiles. Rosenberg and Rosenkrantz developed a system for designing flexible hinged modules that support selective-laser-sintering (SLS) printed construction of flexible garments without manual assembly [30]. Beecroft used SLS to produce a series of textiles with a warp-based structure that exhibits the same properties of traditional knitted textile structures [3].

Researchers have also used FDM printing to produce textiles. FDM printers are often more affordable than other 3D printing technologies and suitable for at-home use [4]. Takahashi and Kim used FDM to print textiles with a warp and weft structure where a single strand of filament is woven around a series of columns. Forman *et al.* under-extruded filament to produce large sheets of flexible semi-transparent fabric. They demonstrated applications in garment prototyping and aesthetic patterning [8]. Li *et al.* created extrusion-based sheet materials with sliding qualities through a toolpath that prints an arc-shaped channel over the crossing strand [18]. Rivera and Hudson modified a desktop printer to support the electrospinning of textile structures in combination with standard polylactic acid (PLA)-based printing [28]. We also seek to support desktop textile fabrication with FDM equipment. We create a 3D-printed textile suitable for fiber-based textile integration. Rather than woven structures or under-extrusion, we use a toolpath that reinforces the joints of a 3D-printed grid structure to produce a fabric that is robust enough for punch needle applications by reinforcing the segments at the filament crossings. Further, we develop a method compatible with TPU filament. This is critical to provide adequate elasticity to support punch needle insertion and yarn tensioning without breakage.

One key advantage of 3D-printed textiles is that they are programmable, meaning they afford a range of material and aesthetic properties depending on their print parameters. Researchers have developed general-purpose tools for designing toolpath behaviors for desktop 3D printers. Pezutti-Dyer and Buechley created a GCode generation programming library based on Turtle geometry that enables the creation of a range of flexible structures including textiles [27]. Subbaraman and Peek extended the p5.js programming library to control the behavior of a 3D printer. Their system enables the creation of bridged structures, compressible materials, and other forms [35]. As systems like these expand the design space of desktop printers, we see opportunities to further grow that space by developing methods to integrate established craft practices with material exploration in 3D printing. Our research contributes a CAM-based design toolset for programmable punch needle embroidery that could further expand general-purpose desktop CAM design tools.

3 TRADITIONAL PUNCH NEEDLE CRAFT

We developed PunchPrint to align with traditional punch needle techniques and workflows. In this section, we describe the punch needle stitch structure and common methods to convert traditional punch needle textiles into functional artifacts. We identify the challenges and limitations of traditional punch needle techniques and then present the design goals of PunchPrint to extend punch needle craft with digital fabrication techniques.

3.1 Punch Needle Stitch Structure

In punch needle embroidery, the craftsperson uses a pointed needle with a hollow stem and an eye hole to create loops of yarn in a woven foundation fabric. Yarn is threaded through the needle and punched through the foundation fabric, creating loops along the back of the fabric and flat stitches along the top [25]. The side with the flat stitches is more detailed and resembles traditional embroidery, while the side with the loop stitches is textured like a rug. Unlike other types of needlework, punch needle stitches do not require the craftsperson to knot or otherwise secure the stitch ends, and rows of stitches can be removed from the foundation fabric with ease.

Unlike regular embroidery stitches which interweave yarn back and forth between the fibers of the foundation fabric, punch needle structure relies on fabric tension to hold stitches in place. When the needle pierces the fabric, the warp and weft are displaced. As the needle is pulled out, the tension of the woven structure holds the yarn in place and creates a loop [33]. This tension mechanism limits craftspeople to specific foundation fabrics.

The appearance of a punch needle textile is determined by the gauge of embroidery yarn and the structure of the foundation fabric. Loose woven fabrics like primitive linen, monk's cloth, rug warp, and weaver's cloth are the most common [32]. See Figure 3 for examples of foundation fabrics. Woven textiles are measured by the number of warp threads or ends per inch (EPI). To punch needle with a desired yarn gauge, the craftsperson must select a foundation fabric with a suitable EPI. Larger gauge yarns require a lower EPI and finer gauge yarns require a higher EPI. The craftsperson must also select a needle diameter that is compatible with the EPI of the fabric. The lower the EPI, the smaller the needle. Incompatible needles increase the risk of fabric breakage during punching.

The thickness of the yarn is also constrained by the size of the needle. Yarn needs to continuously slide through the needle's handle during embroidery. If the yarn is too thin for the diameter of the needle, the needle will stretch the foundation fabric to a point where the fibers cannot create enough tension to keep the yarn in place [32]. Punch needles are available in a range of sizes to accommodate different yarn gauges and foundation fabrics. Large needles are best suited for thick yarns and low EPI foundation fabric. Small needles are required for delicate yarns and high EPI foundation fabric.

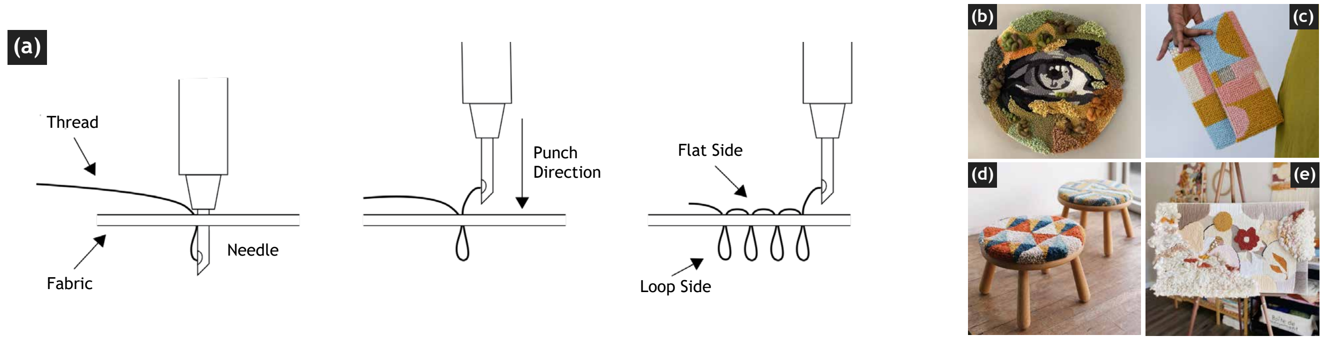

Figure 2: (a) To create a punch needle stitch, a craftsperson perforates the foundation fabric with a specialized needle and then glides a small distance to insert the needle into the next location, creating a loop and a flat stitch simultaneously. (Diagram adapted from Zweigart [39].) Craftspeople commonly use punch needle textiles to produce craft artifacts ranging from decorative pieces to accessories, to garments. Examples include (b) *The Wise*– a visual artwork by Sara Luna [19], (c) *Embellished Clutch*– a handbag by Micah Clasper-Torch [5], (d) *Stool Top*– upholstery by Arounna Khounnoraj [17], (e) *Untitled*– tapestry by Adeline Wang [38].

3.2 Traditional Punch Needle Workflow

Craftspeople use punch needle textiles to create garments, accessories, and decor. While approaches vary, the crafting workflow generally includes the following steps:

(1) *Transferring the design template:* The craftsperson draws, traces, or irons on a reference pattern to the foundation fabric to guide their stitch pattern [34].
(2) *Securing the foundation fabric:* The craftsperson mounts the foundation fabric in a hoop to create a taut surface to allow punching with ease and efficiency.
(3) *Punching the design:* The craftsperson threads the needle and, using a pen-like grip, punches rows of stitches. Craftspeople can vary the length of the flat stitch to create different aesthetics.
(4) *Post processing:* Craftspeople commonly incorporate punch needle textiles into decorative pieces, accessories, and garments (Figure 2b). To create a finished artifact with a punch needle textile, it is crucial to secure the edges of the foundation fabric to prevent them from unraveling. Craftspeople sew or glue the edges to avoid fraying. Craftspeople often select a method for securing edges based on their project. For example, when making pillows or bags, craftspeople usually sew the edges and add additional functional components like zippers, clips, and other fabric. For wall decorations, craftspeople often glue the punch needle textile to the embroidery hoop as a frame.

3.3 Traditional Punch Needle Limitations

Traditional punch needle is versatile but presents several key limitations. Craftspeople are limited to using specific foundation textiles with proper EPI and durability. Foundation textiles are usually thick and stiff to maintain adequate yarn tension and withstand the punching process. This decreases the flexibility of punch needle pieces and constrains the scales and forms that are possible [31, 32]. Small delicate pieces are particularly difficult to create and stiff textiles can limit the production of flexible garments. Thin, lightweight fabrics can easily and irreversibly break, fail to adequately tension the loops, and create loops with inconsistent height [31]. Woven foundation textiles fray easily if unsecured. Much of the labor in punch needle involves post-processing steps to secure the edges. The more complex the outer perimeter of a design, the greater manual skill is required to secure the edges without altering the initial outline. Since the fabric frays when cut, designs with holes or hollow spaces on the interior of the structure are extremely difficult to achieve without a high degree of manual skill and labor.

3.4 PunchPrint Design Goals

We analyzed the workflow and constraints of traditional punch needle practice to identify the following design goals for a method to integrate 3d-printed textiles and punch needle craft.

- **Programmable structure:** We seek to develop a 3D-printed textile that can vary in flexibility, thickness, and density while maintaining a structure that is robust enough to support manual punch needle stitches.
- **Novel textile properties through composite materials:** We aim to extend the design space of punch needle embroidery by incorporating affordances of filament-based textiles while also broadening the aesthetic and textural qualities of 3d-printed materials.
- **Support for new workflows in punch needle craft assembly:** We seek to integrate construction methods from both 3D printing and traditional textile craft to create new opportunities for punch needle craft.

4 3D PRINTING A FOUNDATION FOR PUNCH NEEDLE EMBROIDERY

The initial component of our technique is a 3D-printed foundation fabric. We mimic the woven structure of fiber-based punch needle foundation fabric by printing a TPU-based grid structure that reproduces the behavior of textile fibers while providing visible holes for needle insertion. Our approach supports a wide spectrum of fabric

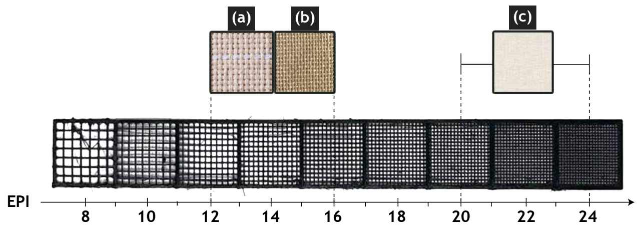

Figure 3: In comparison to traditional punch needle foundation textiles, our method supports a range of fabric densities with significantly reduced thickness and increased flexibility. We can create fabrics with varying ends per inch (EPI) and combine them in a single piece of fabric. The bottom strip shows nine ~2.5 cm squares with increasing EPIs, and the top images compare three commonly used fabrics for punch needle embroidery: (a) Monk's cloth (12-16 EPI), (b) primitive linen (12-16 EPI), and (c) weavers cloth (20-24 EPI).

densities with significantly reduced thickness and increased flexibility compared to traditional foundation textiles. In this section, we describe the design and development process of the PunchPrint foundation fabric and detail our fabrication technique. We also present the results of two studies to evaluate the tensile strength and range of needle compatibility of our 3D-printed textile.

4.1 PunchPrint Fabric Development Process

Traditional woven punch needle foundation fabrics are comprised of vertical warp and horizontal weft fibers woven tightly together. When a needle with yarn goes through a hole in the fabric, its fibers move outwards. When the needle is retracted, neighboring fibers contract and force the yarn to stay in place (Figure 4a).

We designed PunchPrint fabric geometry to resemble this construction using intersecting filament extrusions. FDM manufacturing uses a hot end to melt and fuse filament strands. We use this property to avoid weaving warp and weft structures. Instead, we print horizontal and vertical filaments in two fused layers, creating a two-dimensional grid structure. Figure 4b demonstrates how PunchPrint fabric performs similarly to fabric fibers: The filaments stretch outwards as the needle goes through and compresses as the needle is withdrawn, keeping the yarn in place.

4.1.1 Limitations of Existing Printing Methods. Commercial slicer software tools like Ultimaker Cura[1] support grid (Figure 5a) and line (Figure 5b) infill methods that can produce a visually similar grid structure to the PunchPrint fabric. These methods create robust structures for rigid volumetric prints but introduce weak points for flexible sheets with a small number of vertical layers. We conducted exploratory tests by printing two to four-layer grids using Cura grid and line infill methods and punching into the resulting fabric. We discovered these initial fabrics frequently broke as the needle was inserted during punching. We observed that grid infill produces weak points in the material at the point of intersection when freshly extruded material passes over a previously printed filament (Figure 6i,a-c). At the intersection, the melted filament collides with the solidified filament. Following the collision, the filament will under-extrude for several steps (Figure 5a).

The line infill avoids collisions by printing perpendicular lines at different layer heights (using a 100% offset) and allowing gravity to deposit the extruded filament on the layer below. This introduces weak points as the material stretches in the air as the nozzle moves away from the intersection (Figure 6ii,a-c). The increased layer height of line infill also results in poor layer adhesion (Figure 6ii,d-e) and creates thicker structures because it requires twice the layer height as the grid method for the same number of layers. The lack of adhesion in the line infill method can be reduced by increasing the infill extrusion rate to 150% (Figure 6iii,d-e).

We tested the infill methods using the support blocker feature in Cura which allows the printing of regions with exposed infill in combination with solid structures. However, using support blockers with non-cubic geometry is challenging since the feature only supports rectangular shapes. The combination of the structural weaknesses of standard infill methods and the absence of expressive design tools for grid toolpaths led us to develop a custom toolpath method that combines the benefits of grid and line infill methods to make a robust fabric for punch needle embroidery.

4.1.2 PunchPrint Iterative Development. To create a robust 3D-printed punch needle foundation fabric, we developed a custom GCode generator that allowed us to have granular control over toolpath generation. We implemented both grid and line infill in our generator and reduced the print speed and deposited extra material, but the process still produced weak points at the intersections. We then attempted to reinforce the line infill method by experimenting with increasing the height of the second layer by increments of 25%. We found that a height increase of 50% or lower produced notable weak points due to a considerable material collision between filaments, whereas 100% created poor layer adhesion.

To produce an even continuous filament with strong intersection adhesion, we printed the second filament layer that crosses the

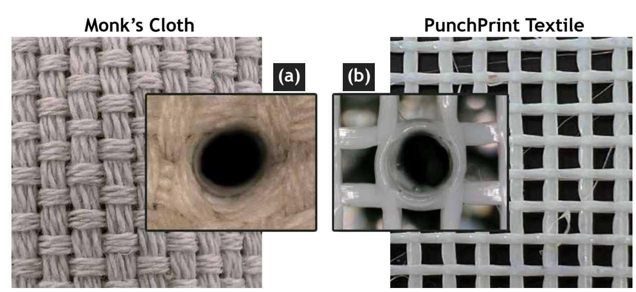

Figure 4: PunchPrint mimics the warp/weft construction of traditional woven fiber-based textiles using a grid structure. Here we show 12 EPI Monk's cloth– a popular punch needle foundation fabric. (a) By magnifying (50x) and piercing Monk's cloth with a 2.5 mm punch needle, we can observe how the threads in the fabric are displaced. (b) As a 2.5 mm needle perforates our material, we can observe a similar deformation in the cell, analogous to the displacement of threads in traditional fiber textiles.

[1]https://ultimaker.com/software/ultimaker-cura

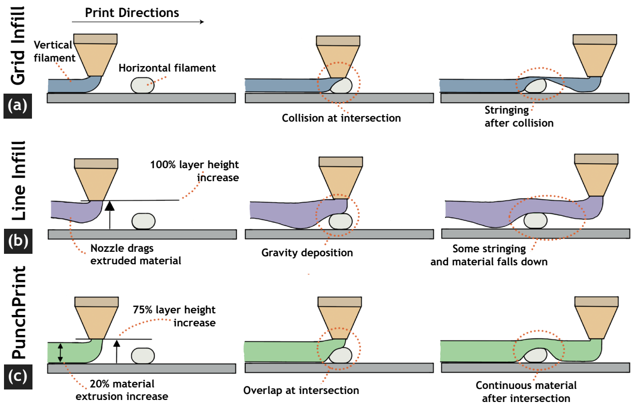

Figure 5: Commercial slicers can be used to produce thin grid-based structures using the grid and line infill patterns. The resulting prints are similar in appearance to our textile; however, both infill methods create structural limitations for punch needle embroidery. This figure illustrates the difference between the PunchPrint toolpath and the two infill methods in Cura slicer. The grid infill method (a) extrudes fresh material at the same layer height as the previous filament and creates a weak point at the intersection. The line infill method (b) extrudes fresh material at 200% of the initial layer height (next layer), resulting in poor layer adhesion between the previous and current extrusion. Our method (c) extrudes fresh material at 175% of the layer height and a 20% flow rate increase, resulting in continuous material flow and strong layer adhesion at the intersection points.

first layer at 175% of the layer height. This overlap of 25% of the layer height produced adequate adhesion at intersections without disturbing the material flow (Figure 5c). This small overlap at intersecting filaments still causes minor weak points. We addressed this by reversing the print direction and order of horizontal and vertical filaments in successive layers. This ensures that the minor weak points do not concentrate on a single spot (Figure 6iv,a-c). We found that alternating the order of horizontal/vertical filaments and increasing the material flow rate of the second filament by 20% ensures stronger layer adhesion (Figure 6iv,d-e). This combination of techniques produced a sturdy fabric that did not display visual weak points when stretched and held up when punched.

4.2 Characterization of PunchPrint

In this section, we provide comprehensive print parameters and present the results of a needle compatibility test with various needle diameters and fabric densities. We compare the tensile strength of our fabric to the grid infill method, which produces fabric of a similar thickness.

4.2.1 Characterization Metrics and Properties. In characterizing our foundation fabric, we adopt EPI as the primary metric for the fabric *density*. In Figure 3 we compare commonly used fiber fabrics and our filament-based solution. While smaller EPIs support thicker needles and yarn, higher EPIs provide a foundation for intricate designs with thinner needles (Figure 7). In addition to the density, we can control the *stiffness* of the fabric by controlling the number of vertical layers. As the number of layers increases, the fabric becomes stiffer and harder to stretch.

4.2.2 Printers and Print Parameters. We printed our foundation fabric using elastic TPU95 filament with a 0.4 mm nozzle diameter and 0.2 mm layer height. We used a nozzle temperature of $220°C$ and a bed temperature ranging from $50°C - 60°C$. We tested our method on two different printers– the Creality Ender S1 Pro, which currently retails for $479 USD[2] and the Ultimaker S5, which currently retails for $6,950 USD[3]. Ultimaker and Ender use filament diameters of 2.85 mm and 1.75 mm, respectively. We observed no significant difference in printing qualities across either the Ender or the Ultimaker. We used 10 mm/s as the retract speed, 20 mm/s as the fabric printing speed, and 30 mm/s for other geometry. Since TPU is an elastic material and buckles if the filament retracts too far, we used a 1.5 mm retract distance. We use extrusion multipliers of 1.5 on the first layer (the direction that corresponds to the warp in woven fabrics) and an extrusion multiplier of 1.8 for the second layer (the direction that corresponds to the weft). As we describe in section 5, our method is compatible with printing solid elements including walls, borders, tabs, and loops. We do not modify the extrusion rate for these elements.

4.2.3 Punching Testing. The programmable nature of PunchPrint enables us to vary the EPI of the fabric to support different yarn types. Even though our substrate is flexible, it will break when stretched by a needle of an incompatible diameter. We, therefore, sought to understand the behavior of different PunchPrint EPIs with different punch needles. We characterized needle compatibility by printing two sets of nine test fabrics with varying EPIs for one-layer and two-layer stiffness values. We then punched each fabric with a gradually increasing needle size. To evaluate representative methods in punch needle craft practice, we selected a range of popular needle sizes that comes in most punch needle kits instead of sampling needle diameters from a uniform distribution. We report our findings in Figure 7. We present a single value for both the one-layer and two-layer conditions for each EPI setting because we found that layer count did not affect needle compatibility. We performed each punch test three times. We present the outcome of the majority voting. Our results demonstrate that our method successfully fabricates materials that are compatible with standard punch needle diameters. For each needle we tested, we fabricated at least two compatible fabric EPIs. Our results also show that our method creates individual EPIs that can accommodate a wide range of different needle diameters. In the majority of cases, a single EPI supported five or more different needle diameters without permanent visual deformation or breakage. This suggests that a single PunchPrint fabric can support a range of different yarn gauges.

4.2.4 Mechanical Stretch Testing. PunchPrint provides a flexible substrate for foundation fabric that can be stretched as a craftsperson works with it. We performed a tensile stress test to demonstrate the stretch limit of our fabric and estimate the load capacity compared to the Cura grid infill method. All PunchPrint artifacts, with

[2] https://store.creality.com/products/ender-3-s1-pro-3d-printer
[3] https://www.matterhackers.com/store/l/ultimaker-s5

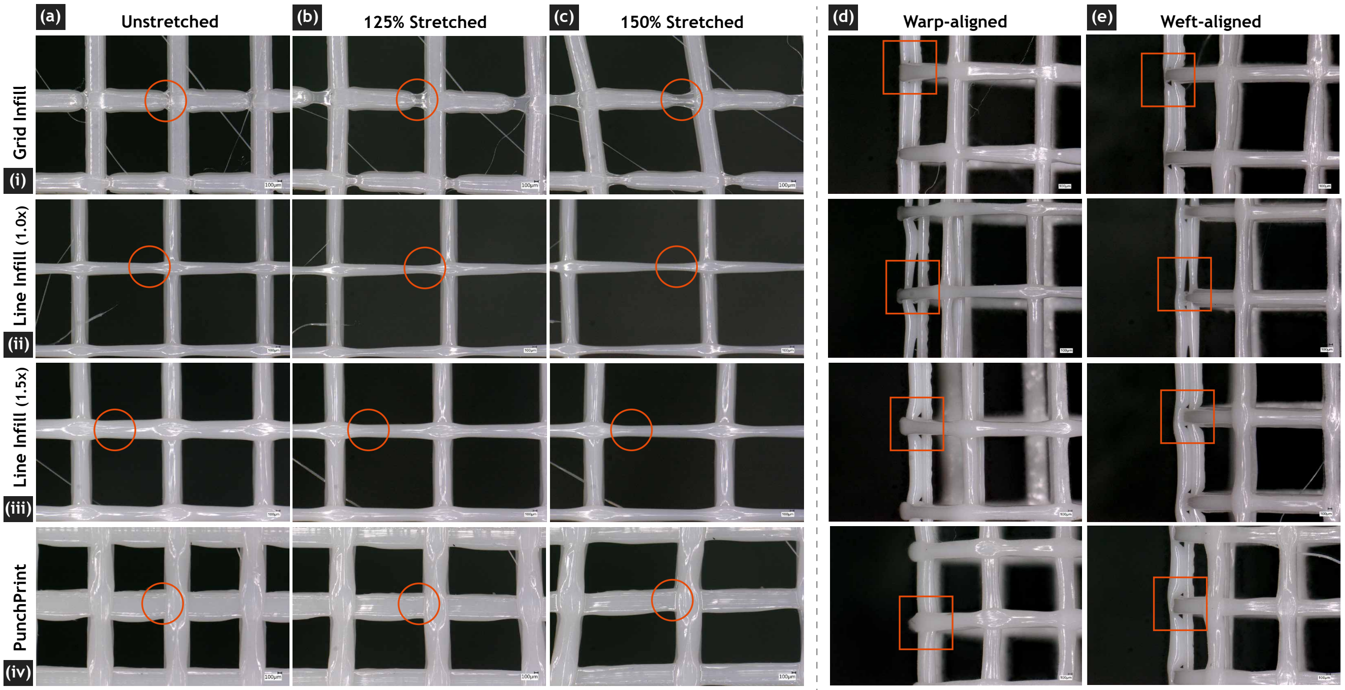

Figure 6: We fabricated two-layer textiles and compared the intersections of the grid infill method (i), line infill method with 100% flow rate (ii), line infill method with 150% flow rate (iii), and PunchPrint (iv) at 50x optical magnification. (a-c) shows the top view of the fabric when stretched laterally: (a) shows unstretched fabric, (b) and (c) show the fabrics stretched in one direction at 125% and 150% of their original size (corresponding to 6.35 mm and 12.7 mm displacements), respectively. (d-e) showcases the side profile of fabric walls: Warp-aligned view (d) displays the side profile of the first printed filament, and weft-aligned view (e) shows the side profile of the other direction of the fabric grid. Red circles identify the weak points' position and red boxes identify the under-extruded regions at the intersections.

the exception of one, use a two-layer fabric (see section 6). We found that two layers create a flexible and lightweight material suitable for wearable and deformable products. We compared our two-layer fabric to Cura grid infill because grid infill produces a fabric of comparable weight. Printing a two-layer line infill fabric produced a result that was substantially thicker than our fabric. We also compared three-layer PunchPrint and grid infill fabrics to examine if three layers increased tensile strength.

We designed a fabric test geometry based on the commonly used dog bone design for tensile tests. We created the test specimens with TPU95A with solid flaps in the fixture points and a 76.2 mm x 25.4 mm (3 in x 1 in) fabric with an external wall in the middle section. We recorded displacement and load during each test. Figure 8a and 8b present load vs. displacement for each two-layer and three-layer test specimen. In both graphs, the behaviors are consistent for the grid infill and our method. Across both layer counts, the grid infill method showed signs of rupture at different intersection points along the fabric. Our method shows a consistent increase in the load and displacement. The only rupture points that were consistent in both pieces occurred at the outer walls, which were printed using a toolpath without modifying layer height when crossing already extruded filament. We found our method could stretch three times its original size with no break points in the fabric. [4] In contrast, the grid infill method began breaking at 15 mm of displacement for two-layer 12 EPI fabrics and 20 mm of displacement for three-layer 16 EPI fabrics, respectively. These results validate our printing approach; by changing the toolpath to optimize for material extrusion, we can create a grid-like fabric with stronger mechanical properties using the same material and desktop 3D printing equipment.

5 PUNCHPRINT DESIGN WORKFLOW

We integrated our fabric toolpath process into a parametric design tool for craftspeople to control fabric properties and integrate other design elements into the print. Our approach supports a new punch needle fabrication workflow that can expedite the punching process and help integrate complex patterns and shapes without having to punch them. Our tool also allows the incorporation of 3D-printed structural elements into the foundation fabric which can reduce labor and support new assembly methods.

5.1 Preparing the PunchPrint Geometry

We developed a Rhino and Grasshopper-based parametric system [6] that enables craftspeople to create punch needle foundation

[4]It is unlikely any fabric would need to withstand 115 mm of displacement for punch needle artifacts. We report results at this stage for completeness.

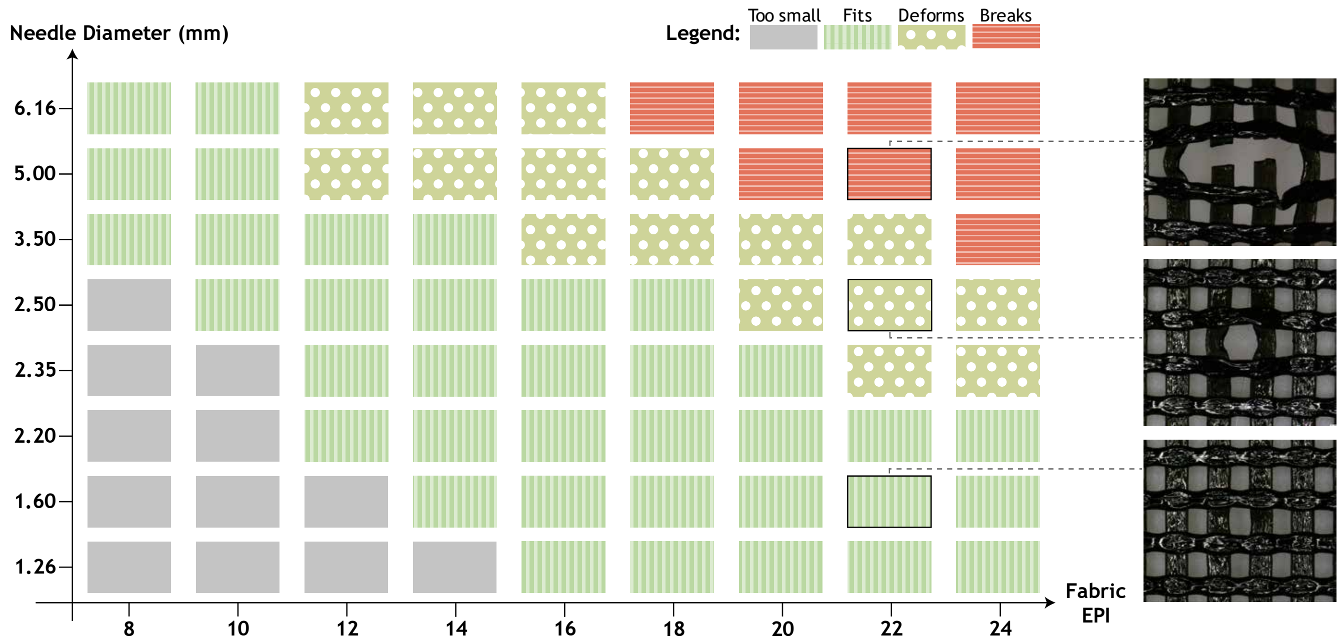

Figure 7: Using PunchPrint's parametric design interface, craftspeople can design foundation fabrics for desired needle sizes and yarn gauges. (Left) This chart shows the compatibility of different needle sizes with various foundation fabric densities. The color codes are as follows: *Gray* with flat background signifies that the needle is smaller than the hole; *green* with the vertical stripe pattern signifies the needle is compatible with the fabric hole; *green-yellow* with the circular pattern signifies the needle deforms the fabric hole, yet still is compatible for punch needle; *red* with the horizontal stripe pattern signifies the fabric breaks). (Right) 50x magnified optical results of punching a 22 EPI foundation fabric with 1.6, 2.5, and 5 mm needles.

fabric by designing a form comprised of simple curves to be filled with foundation fabric. We implemented a PunchPrint Grasshopper component with two parameters for controlling fabric structure: *EPI*, which controls the fabric density, and *stiffness*, which is the number of vertical layers of the fabric. The PunchPrint component has a third parameter that accepts any closed planar curve as input. Our tool will constrain the dimensions of the fabric within the boundaries of the input curve. By adjusting sliders for the EPI and stiffness and altering the input curve, the craftspeople can produce a range of fabric geometries with different structural properties.

Our tool also allows craftspeople to create *design guides* and *holes* on the fabric geometry using simple curves. Design guides evoke the guides craftspeople manually transfer onto fabric in traditional punch needle practice. The design guides in PunchPrint consist of continuous filaments printed over the foundation fabric. We can adjust the thickness of the guides to either produce thin structures hidden by the yarn or thick structures that act as design elements in the final piece. Design guides can be specified as an additional curve input to the PunchPrint Grasshopper component. The same process can be used to create arbitrarily shaped holes in the fabric geometry. The PunchPrint component contains a "hole" parameter that accepts curves as input and produces a gap in the printed fabric that conforms to the hole curve geometry. The PunchPrint component has different settings for internal and external walls. The curves that designate the fabric and hole boundaries can also act as additional structural geometry by forming internal walls or external frames. The dimensions of these features can be specified by the *width* and the *height* parameters of the walls.

We also developed a workflow that allows pre-sliced 3D geometry to be incorporated into our fabric to leverage commercially available slicers to generate highly optimized toolpaths for complex 3D parts. In this workflow, we design a 3D form in any CAD software and export a 2D-profile curve that corresponds to the base of the 3D form. We then use this curve as input to the PunchPrint Grasshopper component to generate the toolpaths for fabric that fits their part. We export the toolpaths for the fabric and create an STL file for the 3D geometry. We slice the STL in a commercial slicer with print parameters that correspond to our fabric. This results in two GCode files– one for fabric and one for the 3D geometry. We append each layer of the fabric GCode to the start of the corresponding layer of the sliced geometry GCode. We insert the correct extrusion position (G92 E#) before and after the fabric code to overcome the discrepancy between the two toolpath creation methods. We use this approach to create both the butterfly jewelry (Section 6.1) and 3D chess pieces (Section 6.2) in our applications section.

5.2 Embroidering PunchPrint Fabric

Creating punch needle stitches in PunchPrint fabric is nearly identical to the traditional punch needle technique, with the notable exception that fabric structures do not need to be secured in a frame

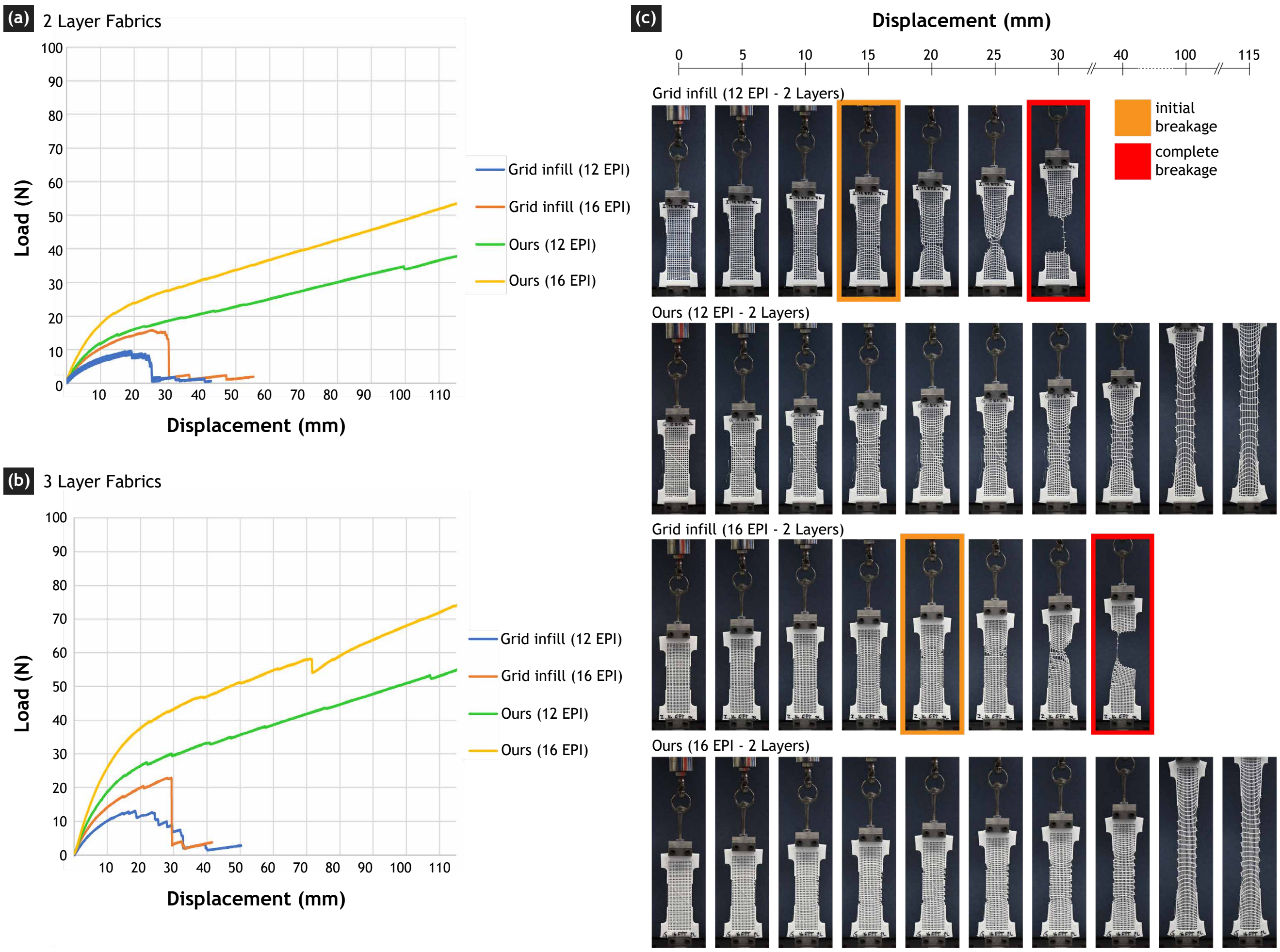

Figure 8: Tensile test analysis showing the mechanical superiority of our fabric method to the grid infill method by comparing load and stretching capacity. Load vs. displacement graph for test specimens with 12 and 16 EPI for infill and our method with (a) 2 layers and (b) 3 layers. (c) Tensile specimen deformations based on displacement for 12 and 16 EPI for the 2 layered pieces. Our method substantially outperforms infill in all performed tests. The sudden load drop for the sample using our method at 16 EPI with 3 layers was due to slight displacement of the specimen at the grips.

or hoop. This is because, unlike fiber-based fabric, PunchPrint fabric does not require considerable force to pierce the fabric. The grid structure also facilitates consistent stitch spacing and length, and design guides can aid in following the contours of the pattern.

5.3 Post-processing and Assembly

Unlike woven fabric, PunchPrint does not require post-processing to secure the fabric edges. We, therefore, eliminate one labor-intensive step in the traditional punch needle workflow, particularly when creating small, detailed, and irregularly-shaped pieces.

PunchPrint also supports a range of assembly methods to create artifacts that are not possible to print as a single piece. PunchPrint pieces can be sewn together using methods that are nearly identical to those for fiber-based textiles. Because PunchPrint fabric does not need to be secured along the edges, pieces can be sewn together along the fabric frame using the exterior holes in the grid. Like traditional sewing, stitches can be easily removed and pieces can be disassembled. Sewing, while more laborious than other forms of assembly, was well suited for connecting multiple curving pieces while maintaining flexibility.

Like traditional punch needle craft, PunchPrint pieces can also be assembled or finished with craft connectors like hooks, loops, and buttons. Rather than manually attach connection points for these pieces, we directly print the connection features as part of the PunchPrint material.

Lastly, PunchPrint pieces can also be assembled through common methods in digital fabrication including press fit joints and mechanical assembly. By changing the shape and size of the fabric frame, we can generate sturdy insertion points and tabs for snap and press fit features.

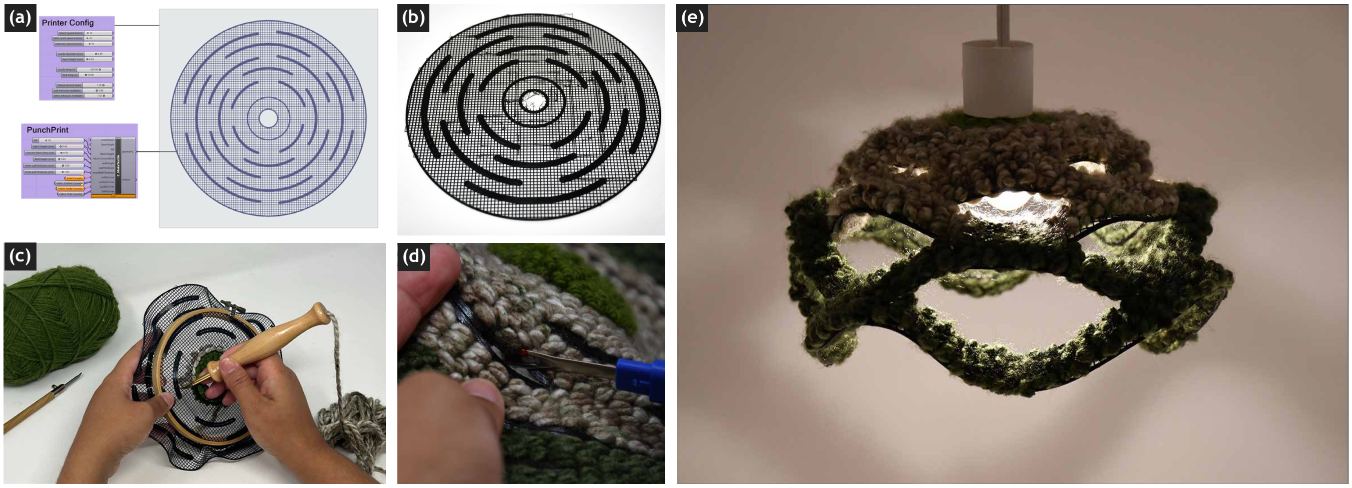

Figure 9: PunchPrint design workflow for punch needle kirigami lampshade: (a) Grasshopper parametric design tool that generates a toolpath for 3D-printing of a textile substrate; (b) fabricated 2D fabric with unopened holes; (c) attaching an embroidery hoop to punch needle the fabric with yarn; (d) cutting the stringing material inside holes with a seam ripper; (e) final artifact assembled with a light bulb.

5.4 Limitations

PunchPrint relies on TPU which is notoriously prone to stringing in comparison to other thermoplastic filaments [8]. Although our printing method limits stringing, when it occurs, it can cause the layer to de-adhere or break at the intersections. We address this by printing fabric structures of two or more layers which can compensate for missing portions in the previous layer. Another issue with stringing is that it can interfere with the embroidery process. It is necessary to remove excessive stringing manually using a scissor or utility knife. We found in practice this took 1-5 minutes depending on the scale of the piece.

The PunchPrint slicer insertion workflow requires accurate specification of a few key parameters to function correctly. Namely, it is important to overlap the sliced geometry and fabric to have proper form, but aligning these two separate processes can be challenging. Developing a script to automate the GCode insertion process would address this issue and could be implemented in a future PunchPrint system.

PunchPrint fabric has a flexible quality not found in traditional foundation fabrics. If the holes are stretched too far, fibers that are punched with the needle may not be properly tensioned. This issue is less likely when needle size and yarn thickness match well with the fabric EPI, as demonstrated in Figure 7. To avoid the fibers slipping through the fabric, some craftspeople prefer placing glue on the flat stitches. However, glue does not couple the fiber into the TPU-based fabric as effectively in comparison to fiber-based foundation fabrics.

6 APPLICATIONS

By integrating punch needle methods with 3D-printed textiles, we can expand the applications of both domains. Here we demonstrate the expressive potential PunchPrint to fabricate composite garments with 3D-printed and fiber-based textile structures and enable the production of small intricate jewelry pieces. We further demonstrate how we can build on standard assembly methods in 3D printing to re-envision common hobbyist 3D printing projects in punch needle form.

6.1 Crafting Multi-material Reversible Garments

Both traditional textile craft and 3D printing provide opportunities for personalizing and fabricating garments. To demonstrate how PunchPrint supports the construction of punch needle garments that can be shaped or bent to fit the body comfortably, we fabricated and assembled a reversible bucket hat (Figure 10). This piece exemplifies how PunchPrint enables the creation of highly bendable 3D-printed textiles by augmenting the methods of textile garment sewing to create reversible garments.

To create the hat, we converted an existing 9-piece traditional sewing cut pattern (crown, four sides, four brims) into a series of Rhino curves. We manually drew additional curves within each cut pattern to serve as design guides for different yarn colors. We set the design guides to a width of 2 mm so they would be entirely hidden by the punch needle loops but visible on the reverse flat-stitched side. We used the cut patterns and design guide curves as input to PunchPrint Grasshopper tool to generate a set of fabric toolpaths with 12 EPI. We printed each piece in white TPU on a Creality Ender S1 Pro (Figure 10a). The total print time was approximately 6 hours. We punched the hat with a 3 mm needle and 4-medium gauge worsted cotton yarns in various colors to correspond with the design guides. We deliberately left some portions un-punched to create stylized ventilation patterns in the design (Figure 10b). After punching, we used a standard embroidery needle and white thread to sew each piece together by looping thread through the holes in the PunchPrint textile (Figure 10c). The completed hat is reversible with a plush appearance on the looped side (Figure 10d)

Figure 10: PunchPrint design workflow for punching a reversible bucket hat that consists of four brim pieces, four side pieces, and one crown piece: (a) One crown, side, and brim piece fabricated using PunchPrint’s parametric workflow; (b) the same pieces punched with yarn; (c) assembling the hat using an embroidery needle and white sewing thread; (d) the looped side and (e) the flat side of the final artifact. Reversing the hat also demonstrates the bendability of embroidered PunchPrint fabric.

and a fabric-like appearance on the reverse with visible white plastic design guides (Figure 10e).

6.2 Reducing Labor and Ensuring Consistency in Small, Intricate Designs

Crafting small-scale punch needle pieces like jewelry can be difficult. It requires a high degree of manual skill to produce consistently tight stitches and the post-processing of small-scale items is challenging. For example, most punch needle earrings are limited to simple geometric profiles due to the complexity of post-processing a small fabric artifact [10, 24]. We developed two Monarch butterfly-themed earrings to demonstrate how PunchPrint facilitates small-scale punch needle embroidery artifacts (Figure 1). We imported a 2D butterfly SVG design into Rhino and extruded it into a 3.5 mm-high 3D solid with holes corresponding to the veins of the butterfly’s wings. We modeled loop anchor points and merged them with the extruded butterfly pattern. We used the original 2D butterfly outline as input to the PunchPrint Grasshopper component (Figure 1a) and generated a fabric toolpath with 18 EPI. We exported the 3D butterfly form as an STL, sliced it in Cura, and appended the fabric GCode into the sliced GCode. We printed the resulting code twice on the Ultimaker S5 using black TPU. Each earring took approximately 25 minutes to print. The smaller scale resulted in a significant amount of stringing, which we removed by hand. To maintain the details of the design, we matched a 1.6 mm needle with three strands of embroidery floss. We punched with a loop height that corresponded with the height of the 3D butterfly geometry (Figure 1b). We assembled the butterfly pieces into earrings by placing jump hoops and beads in the anchor points (Figure 1c), enabling the earring to dangle and move freely without any risk of damaging the fabric. The completed piece showcases how our PunchPrint enables the creation of small-scale punch needle designs with minimal finishing effort and fine-grained details in both the loop and flat side.

6.3 Extending Common 3D Printing Techniques and Projects with Punch Needle Aesthetics

PunchPrint also provides opportunities to use common desktop 3D printing techniques to construct composite 3D-printed textile artifacts. 3D printing and other forms of digital fabrication allow for the design and fabrication of precise joints and fixtures for modular assembly. Inspired by the common desktop 3D printing chess set project[5], we created a press fit knight piece (Figure 11i-j).

We extruded a 2D knight outline with a tab in the middle into a 3.5 mm-high border and sliced it in Cura (Figure 11a). For the base, we created a 5 mm-high extruded exterior hexagonal border and the interior border with a hole supported by four narrow cross-sections. We also sliced these forms in Cura. We appended the knight and base GCode from Cura to corresponding fabric toolpaths generated in Grasshopper with 16 EPI (Figure 11c-d). We printed the parts with white TPU on the Creality Ender S1 Pro in approximately 30 minutes each (Figure 11e-f). We punched each piece using a 2.20 mm needle and embroidery floss. We used a small loop height on the knight body to preserve the 3D-printed eye and nose details and a large loop height on the mane and base to mimic the appearance of hair and grass (Figure 11g-h). Once the punching process was complete, we press-fit two pieces together without using adhesives. This approach allows for a seamless intersection of two perpendicular fabric surfaces which is difficult to reproduce with traditional fabric alone. The completed piece exhibits a 3D rigid structure and includes fine-grained details produced through both TPU and varying punch needle stitch structures.

PunchPrint also allowed us to extend other common desktop 3D printing projects. Lampshades are popular among personal 3D printing projects because the build volume of desktop 3D printers can accommodate the dimensions of a lampshade [4]. 3D-printed lampshades often include perforations to allow light to pass through– a design feature previously not possible in punch needle lampshades. We used PunchPrint to create a kirigami-based lampshade with gaps to allow the light to shine through (Figure 9e). We imported an existing kirigami cut pattern into Rhino and used the PunchPrint Grasshopper component to specify interior curves that would serve as holes, an exterior border, and a fabric fill with 10 EPI (Figure 9a). We deliberately printed the cut pattern as semi-fused borders to mimic the kirigami process and retain a cohesive material for punch needle embroidery. We printed the shade on the Ultimaker S5 using black TPU (Figure 9b) in 1 hour and 20 minutes. We punched the resulting pattern with two different yarn gauges and corresponding needles (Figure 9c). We used a 3 mm needle for the green yarn and a 5 mm needle for the multi-color (green and beige) yarn. Because the lampshade print was round and had no extruded borders, we

[5]https://all3dp.com/2/3d-printed-chess-set-pieces/

Figure 11: PunchPrint design workflow enables integration of our fabric method and complex geometry sliced with commercial slicers in the same print. It also creates an opportunity in assembling punched pieces together using press fit methods: (a) Surrounding geometry sliced with Cura; (b) our fabric generated in Grasshopper; (c) inserting the fabric GCode into sliced GCode results in a unified form; (d) the same procedure as in (a)-(b) repeated for the base of knight; (e) fabricated and (g) punched knight piece; (f) fabricated and (h) punched base piece; (i) the looped and (j) flat sides of the final artifact (6.5 cm).

secured it with an embroidery hoop to speed up the punching process. We used a seam ripper to open the kirigami holes in the shade (Figure 9d) and attached a light fixture. The completed lamp shows how our method incorporates hollow regions in a punch needle design with minimal post-processing.

7 DISCUSSION

Drawing from our experience developing and crafting with PunchPrint, we argue that toolpath-based design is critical for expanding the opportunities of desktop 3D printing. Our research demonstrates how integrating textiles and 3D-printed materials creates novel aesthetic opportunities. We discuss how this intersection may extend the use and care of 3D-printed goods. We also examine how PunchPrint material and software may align or conflict with established textile craft workflows.

7.1 Toolpath-level Control Enables Domain-specific Material Development

Developing a 3D-printed punch needle textile required systematic experimentation with low-level additive fabrication parameters. Despite our initial expectations, we found that established slicer methods like grid and line infill were inadequate for fabricating a sufficiently durable fabric. Our method required integrating aspects of both methods and adding discrete adjustments in the toolpath that corresponded to specific aspects of machine behavior. Our analysis shows that we could not have produced a viable fabric by working through existing slicer parameters alone. Our general approach of developing novel FDM toolpaths and iteratively adjusting toolpath behavior correspond with approaches from desktop FDM textile research [8, 27, 35, 36]. Collectively this domain demonstrates the opportunities of designing at the level of 3D printing toolpaths to expand the expressive range of desktop 3D printing. We do not necessarily consider FDM toolpath programming to be desirable for all desktop 3D printer practitioners and there are many benefits to slicers. Our research provides further evidence on how 3D printers can be used for applications and processes that do not directly align with the CAD-slicing workflow. Additional research into FDM toolpath programming toolkits could lead to further expansion of domain-specific desktop 3D printing techniques.

7.2 Extending 3D Printing with Traditional Textile Methods

Unlike prior FDM textile research, which focused on producing entirely thermoplastic-based textiles through a largely automated process, we sought to integrate 3D printing with existing textile practices. This approach had two clear advantages over solely thermoplastic textiles: 1) it produced a durable material with the tactile properties of fiber-based textiles, and 2) it substantially expanded the aesthetic space of 3D-printed textiles through manual selection of different yarn colors and variation in texture through different punch needle stitch structure.

These opportunities come with trade-offs. Unlike the largely automated fabrication of thermoplastic textiles, PunchPrint textiles require manual fabrication. Furthermore, our approach relies on the fabrication of non-biodegradable plastic. While we are excited by the potential growth of desktop-FDM printing, we also recognize that expanding the use of petrochemicals is at odds with efforts to mitigate our global environmental crisis. As we continue our research in this domain, we believe it is important to foreground evaluating long-term use and durability when considering novel 3D printing methods.

We believe the manual fabrication aspects of PunchPrint offer one critical advantage in this respect because craft artifacts that require extended manual effort are potentially less likely to be viewed as discardable. We were limited in our ability to evaluate the durability of PunchPrint longitudinally for this paper. As a starting point, Ashley performed an initial durability assessment by fabricating a PunchPrint iPhone case and using it for 55 days. Figure 12 shows the case before and after a month of regular use. These initial results are encouraging. Aside from minor fiber compression and visible

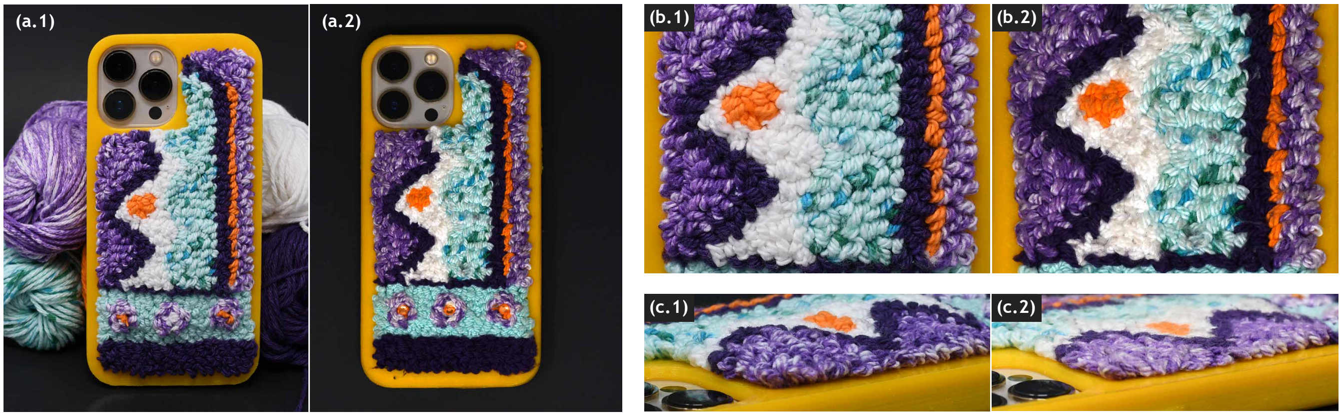

Figure 12: We explored the longer-term use of PunchPrint artifacts with an iPhone case that Ashley used for 55 days. We found no major issues with usability or durability during this period. (a.1) shows the full case immediately after fabrication, and (b.1) and (c.2) show close-up front and side views. (a.2) shows the state of the case following 24 days of use. (b.2) shows a close-up of the minor discoloration on the lighter yarn segments from perspiration and placement on different surfaces. (c.2) shows the compression of the yarn fibers, similar to how a rug pile is compressed over time.

wear on lighter yarns, the case has held up and all yarns remain in place. Ashley plans to continue using the case. For future work, we have begun preparing activities where external participants fabricate PunchPrint artifacts.

7.3 Implications of Introducing 3D Printing and CAD into Punch Needle Workflows

In our original design objectives, we stressed that, for PunchPrint to be effective as a technique, it must offer new design opportunities for punch needle embroidery, while also remaining compatible with the established workflows of punch needle practitioners. Our example applications demonstrate the specific design opportunities that our approach supports in contrast to traditional punch needle materials, including supporting the use of design guides that double as aesthetic elements, the elimination of manual finishing steps for intricate designs, the incorporation of holes and multiple yarn gauges in the same textile, and the addition of 3D structures and rigid forms through the established digital fabrication assembly methods.

Our research also suggests that working with PunchPrint textile aligns with many of the established approaches in traditional punch needle manufacture. We used standard punch needles and yarn in all example applications and found that we could manually cut and adjust the TPU structure similar to fiber-based fabrics. We also demonstrated that it is possible to use an embroidery hoop for support for larger textile structures (Figure 9c). For irregular and less flexible PunchPrint textiles, we could extend our design software to enable the 3D printing of a rigid frame similar to an embroidery hoop, which could be cut away upon completion. We chose to avoid this strategy to reduce material waste. We found in practice that punching without a hoop was highly effective. It is also possible to manually mend the PunchPrint fabric. We found we could re-fuse broken strands together with a 3D-printing pen and then punch into them. The fused strands maintained adequate tension to hold the stitches. Figure 13 shows a detailed workflow of this process.

Unlike traditional punch needle fabric, PunchPrint design guides can obstruct some holes in the fabric, making it challenging to pass the needle through these components. We found that we could still pierce these partially obstructed holes thanks to the material's flexibility. We also found that for larger gauge yarns or designs with higher loops, we could skip the obstructed cells without impacting the appearance of the design. An alternative future approach to explore would be to create design guides by varying the EPI of the fabric to indicate portions where different materials should be used.

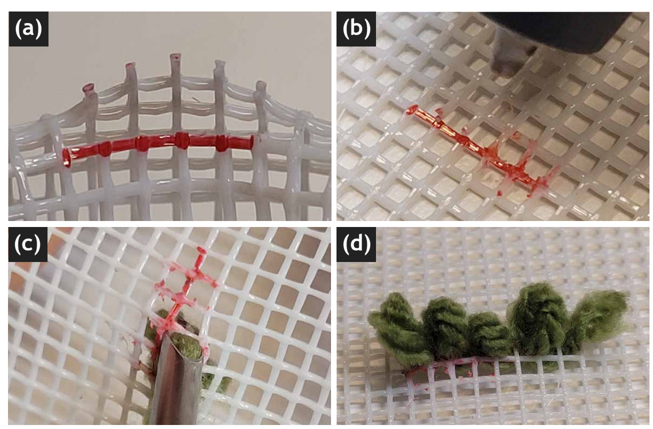

Figure 13: We can repair the PunchPrint fabric with a 3D pen in case small portions get damaged. (a) We cut the fabric for demonstration purposes and marked it red. (b) Applying heat using a 3D pen to mend cut pieces. (c) Using a 3 mm needle to punch the mended portion and (e) yarn stays in the fabric.

These examples demonstrate how our material is well aligned with the existing punch needle workflow. Additional research is required to assess the compatibility of our software design tool with different practitioners. By adopting a parametric approach in which key design parameters are constrained within a range controlled by a slider, the PunchPrint design tool mirrors existing standards in entry-level digital fabrication design technologies. We believe that, with additional interface refinement, this approach would be promising for engaging digital fabrication newcomers in customizing PunchPrint fabrics. It is less clear how PunchPrint software, or CAD software at all, aligns the desired design practices of punch needle craftspeople. While textile CAD software tools are used by some craftspeople, many aspects of traditional punch needle design occur when the designer is working with physical materials. We see an alternative strategy in which, instead of using software, designers would work with physically reconfigurable PunchPrint textiles and connection components in a manner similar to traditional tailoring. While this would reduce the benefits of parametric design, it could increase the ability of experienced textile craftspeople to engage in established design practices with our material. Going forward, we plan to conduct research with experienced punch needle craftspeople to explore the development of such design strategies.

8 CONCLUSION

We present PunchPrint: a combination of a 3D printing technique, design tool, and crafting workflow for producing flexible, functional, and beautiful fiber-filament artifacts. Our technique is relatively fast in comparison to volumetric 3D printing and compatible with desktop 3D printers. Through mechanical testing, we demonstrate the robustness of the PunchPrint textile in comparison to existing infill methods and characterize its performance for different punch needle tools and materials. We showcase the capabilities of the PunchPrint Grasshopper design tool and craft workflow by using it to produce garments, accessories, and decor. We are excited about the potential of PunchPrint to broaden the expressive space of both additive fabrication and manual textile crafting. In the future, we see opportunities to further explore the design opportunities of 3D printing and punch needle by evaluating our method with fellow punch needle craft practitioners.

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REFERENCES

[1] Lea Albaugh, James McCann, Lining Yao, and Scott E. Hudson. 2021. Enabling Personal Computational Handweaving with a Low-Cost Jacquard Loom. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 497, 10 pages. https://doi.org/10.1145/3411764.3445750
[2] Michelle Annett. 2020. Understanding the Homepreneurship Opportunities Afforded by Social Networking and Personal Fabrication Technologies. *Proc. ACM Hum.-Comput. Interact.* 4, CSCW2, Article 99 (oct 2020), 48 pages. https://doi.org/10.1145/3415170
[3] M Beecroft. 2016. 3D printing of weft knitted textile based structures by selective laser sintering of nylon powder. *IOP Conference Series: Materials Science and Engineering* 137 (jul 2016), 012017. https://doi.org/10.1088/1757-899x/137/1/012017
[4] Gabrielle Benabdallah, Samuelle Bourgault, Nadya Peek, and Jennifer Jacobs. 2021. Remote Learners, Home Makers: How Digital Fabrication Was Taught Online During a Pandemic. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, 14 pages. https://doi.org/10.1145/3411764.344545
[5] Micah Clasper-Torch. 2020. Embellished Clutch. https://www.micahclasper-torch.com/
[6] Scott Davidson. 2007. Grasshopper. http://www.grasshopper3d.com.
[7] Himani Deshpande, Haruki Takahashi, and Jeeeun Kim. 2021. EscapeLoom: Fabricating New Affordances for Hand Weaving. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 630, 13 pages. https://doi.org/10.1145/3411764.3445600
[8] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 1222–1233. https://doi.org/10.1145/3379337.3415876
[9] N.A. Gershenfeld. 2005. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication*. Basic Books. https://books.google.com/books?id=Oil3bH6fKBkC
[10] Leah Gordon. 2021. Embroidery Earrings – Punch Needle Embroidery. https://blog.clover-usa.com/2021/01/28/embroidery-earrings-embroidery-stitching-tool-project/
[11] Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen, and Rong-Hao Liang. 2020. FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 379–393. https://doi.org/10.1145/3357236.3395569
[12] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch & Stitch: Interactive Embroidery for E-Textiles. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173656
[13] Shiqing He and Eytan Adar. 2020. Plotting with Thread: Fabricating Delicate Punch Needle Embroidery with X-Y Plotters. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1047–1057. https://doi.org/10.1145/3357236.3395540
[14] Scott E. Hudson. 2014. Printing Teddy Bears: A Technique for 3D Printing of Soft Interactive Objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 459–468. https://doi.org/10.1145/2556288.2557338
[15] Jennifer Jacobs and Leah Buechley. 2013. Codeable Objects: Computational Design and Digital Fabrication for Novice Programmers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1589–1598. https://doi.org/10.1145/2470654.2466211
[16] Lee Jones, Miriam Sturdee, Sara Nabil, and Audrey Girouard. 2021. Punch-Sketching E-Textiles: Exploring Punch Needle as a Technique for Sustainable, Accessible, and Iterative Physical Prototyping with E-Textiles. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 21, 12 pages. https://doi.org/10.1145/3430524.3440640
[17] Arounna Khounnoraj. 2022. Stool Top. https://www.instagram.com/p/CfOxfUorq-T/
[18] Yue Li, Juan Montes, Bernhard Thomaszewski, and Stelian Coros. 2022. Programmable Digital Weaves. *IEEE Robotics and Automation Letters* 7, 2 (2022), 2891–2896. https://doi.org/10.1109/LRA.2022.3145948
[19] Sarah Luna. 2021. The Wise. https://www.kaleido.art/saralunart
[20] Shiran Magrisso, Moran Mizrahi, and Amit Zoran. 2018. Digital Joinery For Hybrid Carpentry. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3173741
[21] Ilan Moyer. 2011. Interweave: CNC Braiding Machine. https://web.mit.edu/imoyer/www/portfolio/interweave/index.html

[22] Ilan Moyer. 2014. 24-Bit Friendship Loom. https://web.mit.edu/imoyer/www/portfolio/jacquard/index.html

[23] Sachith Muthukumarana, Moritz Alexander Messerschmidt, Denys J.C. Matthies, Jürgen Steimle, Philipp M. Scholl, and Suranga Nanayakkara. 2021. ClothTiles: A Prototyping Platform to Fabricate Customized Actuators on Clothing Using 3D Printing and Shape-Memory Alloys. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 510, 12 pages. https://doi.org/10.1145/3411764.3445613

[24] Marching North. 2019. Adorable DIY Punch Needle Earrings. https://www.marchingnorth.com/punch-needle-earrings/

[25] R. Pearlman. 2019. *Modern Rug Hooking: 22 Punch Needle Projects for Crafting a Beautiful Home*. Shambhala. https://books.google.com/books?id=Jj28DwAAQBAJ

[26] Huaishu Peng, Jennifer Mankoff, Scott E. Hudson, and James McCann. 2015. A Layered Fabric 3D Printer for Soft Interactive Objects. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1789–1798. https://doi.org/10.1145/2702123.2702327

[27] Franklin Pezutti-Dyer and Leah Buechley. 2022. Extruder-Turtle: A Library for 3D Printing Delicate, Textured, and Flexible Objects. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 6, 9 pages. https://doi.org/10.1145/3490149.3501312

[28] Michael L. Rivera and Scott E. Hudson. 2019. Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300434

[29] Michael L. Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E. Hudson. 2017. Stretching the Bounds of 3D Printing with Embedded Textiles. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 497–508. https://doi.org/10.1145/3025453.3025460

[30] Jessica Rosenkrantz and Jesse Louis-Rosenberg. 2014. *MoMA Acquires First Kinematics Dress*. https://n-e-r-v-o-u-s.com/blog/?p=6280

[31] Shawna. 2019. Foundation Fabrics - The Good, The Bad, The Pretty. https://www.citationmachine.net/bibtex/cite-a-blog/custom

[32] A. Solar. 2020. *Pretty Punch Needle: Modern Projects, Creative Techniques, and Easy Instructions for Getting Started*. C and T Publishing. https://books.google.com/books?id=k6kGEAAAQBAJ

[33] M. Stewart. 2009. *Punchneedle The Complete Guide*. Krause Publications. https://books.google.com/books?id=0PnFmAEACAAJ

[34] M. Stewart. 2013. *Easy, Elegant Punchneedle: Stunning Accessories and Three-Dimensional Miniatures*. Stackpole Books. https://books.google.com/books?id=YeeEAQAAQBAJ

[35] Blair Subbaraman and Nadya Peek. 2022. P5.Fab: Direct Control of Digital Fabrication Machines from a Creative Coding Environment. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1148–1161. https://doi.org/10.1145/3532106.3533496

[36] Haruki Takahashi and Jeeeun Kim. 2019. 3D Printed Fabric: Techniques for Design and 3D Weaving Programmable Textiles. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 43–51. https://doi.org/10.1145/3332165.3347896

[37] Cesar Torres, Wilmot Li, and Eric Paulos. 2016. ProxyPrint: Supporting Crafting Practice through Physical Computational Proxies. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 158–169. https://doi.org/10.1145/2901790.2901828

[38] Adeline Wang. n.d.. Untitled. https://www.byadelinewang.com/portfolio

[39] Zweigart Weaving. 2022. Needlework Fabrics: Punch Needle. https://www.zweigart.de/featured_item/punch-needle/?lang=en

[40] Amit Zoran. 2013. Hybrid Basketry: Interweaving Digital Practice within Contemporary Craft. In *ACM SIGGRAPH 2013 Art Gallery* (Anaheim, California) *(SIGGRAPH '13)*. Association for Computing Machinery, New York, NY, USA, 324–331. https://doi.org/10.1145/2503649.2503651

[41] Amit Zoran and Leah Buechley. 2013. Hybrid Reassemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness. *Leonardo* 46 (02 2013), 4–10. https://doi.org/10.2307/23468110