DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion

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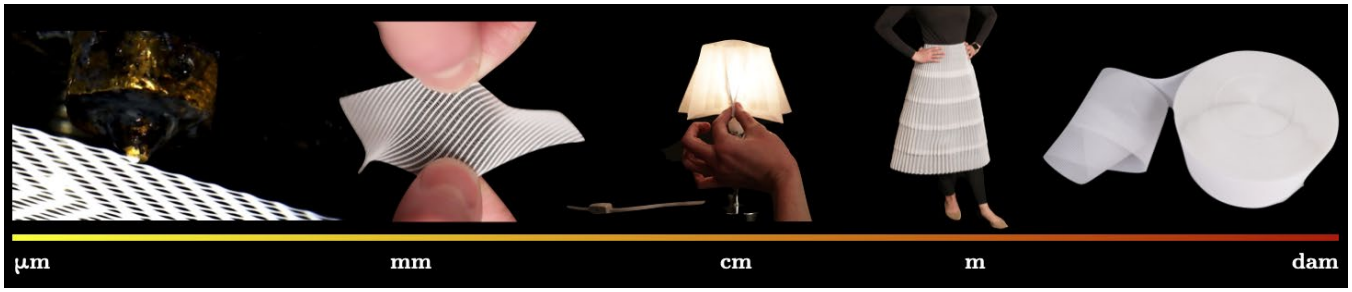


Figure 1: Length scale overview of DefeXtiles from millimeters to decameters. (1) microscope image of a DefeXtile being printed, (2) A DefeXtile being stretched, (3) an interactive lampshade with capacitive sensing, (4) a full-sized skirt, (5) a 70m roll of fabric produced in a single print. All samples were printed on a desktop FDM printer.

ABSTRACT

We present DefeXtiles, a rapid and low-cost technique to produce tulle-like fabrics on unmodified fused deposition modeling (FDM) printers. The under-extrusion of filament is a common cause of print failure, resulting in objects with periodic gap defects. In this paper, we demonstrate that these *defects* can be finely controlled to quickly print thinner, more flexible textiles than previous approaches allow. Our approach allows hierarchical control from micrometer structure to decameter form and is compatible with all common 3D printing materials.

In this paper, we introduce the mechanism of DefeXtiles, establish the design space through a set of primitives with detailed workflows, and characterize the mechanical properties of DefeXtiles printed with multiple materials and parameters. Finally, we demonstrate the interactive features and new use cases of our approach through a variety of applications, such as fashion design prototyping, interactive objects, aesthetic patterning, and single-print actuators.

CCS Concepts

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

Author Keywords

fabrics; textiles; 3D printing; personal fabrication.

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INTRODUCTION

For thousands of years, the manufacturing of textiles into shaped forms has remained largely the same — fiber becomes a fabric which is then constructed into a 3D object. Machine knitting has made a considerable advance in changing this paradigm as the fabric and form can be generated simultaneously. Inverse design pipelines for machine knitting have further shifted the nature of textile construction towards the computational production of fully shaped textiles [16, 18]. Despite these advances, the ability to generate complex 3D forms with textiles outside of industrial manufacturing settings remains elusive. The high-tech approach, machine knitting, currently uses expensive machines with a significant learning curve for programming. The low-tech approach, classic sewing, requires skilled and practiced hands to carry out pain-staking processes such as draping, tracing patterns onto fabric, adding seam allowances, and sewing.

Recently, 3D printing of textiles has become an area of increasing interest in HCI and the fabrication community [3, 17, 30]. However, the properties of these fabrics are not close to what we normally think of when we think of textiles: thin, flexible, and breathable. Other previous approaches have been inaccessible to everyday users as they require either new materials, expensive printers, or custom hardware beyond a standard FDM 3D printer setup [11, 20, 24].

We present a new strategy, called *DefeXtiles*, to 3D print quasi-woven fabrics that are thinner, more flexible, and faster to fabricate compared to other approaches. Since our approach prints the textiles *perpendicular to the print bed*, complex geometries can be produced including pleated and

curved textiles, as well as metamaterial structures. DefeXtiles are *quasi-woven textiles* in that they appear similar to a woven textile due to their flexibility, have an apparent warp/weft, and stretch along their bias, but lack the sewability, the bias in both directions, and the softness of woven textiles. These quasi-woven textiles, henceforth referred to as textiles for simplicity, have a look and feel comparable to tulle. With our approach, a standard 3D printer can print decameters of fabric in a single print. The use of multi-material printers further extends the design space of this technique, allowing users to embed circuit traces into the textile via conductive filament.

Our use of the word *defect* stems from materials science. In this field, defects are imperfections that interrupt the repeating spatial arrangement of atoms in a crystal. However, defects are not inherently bad, in fact, they are commonly used to vary the properties of a material for various applications (e.g., pore defects in contact lenses allow for oxygen transfer).

Under-extrusion is often seen as a defect in fused deposition modeling (FDM) 3D printing, as it can result in a 3D print with gaps. In DefeXtiles, we intentionally exploit this phenomenon to introduce gap defects that afford the prints greater flexibility than a continuous sheet of plastic. By leveraging the periodic deposition and stretching of thermoplastics, we generate textiles in a single nozzle pass.

Altogether, the benefit of this approach is that *flexible*, *thin* textiles of *many materials* can be *quickly printed* into *arbitrary shapes* with *tunable properties* using *unmodified, inexpensive* 3D printers.

DefeXtiles presents the following contributions:

- A fast and accessible approach to 3D print quasi-woven textiles that are much thinner and more flexible than previous methods and can also be structured in complex three-dimensional forms.
- A study of the relevant printing parameters to control the mechanical and aesthetic properties of the textile.
- The development of workflows to enable surface patterning, warp direction control, multi-material printing, and production of ultra-long textiles.
- Demonstration of applications including sensing textiles, actuators, garment design/augmentation.
- A variety of post-processing techniques that can be used on such textiles, such as heat-bonding, sewing, and depleating.

RELATED WORK

In the following section, we first explain how conventional textile manufacturing has become a topic of interest in personal fabrication. We then outline how off-the-shelf 3D printers are being used in this field, and how different printing parameters have been leveraged for various applications in HCI and how it can be used for textile generation.

Digital Fabrication of Textiles and Soft Objects

There has been a lot of interest in design and fabrication of fabrics and soft functional objects in HCI [8, 23, 26]. The works that were able to generate the most realistic textiles often require special hardware. *SHIMA SEIKI* machines [28] have been popular among computational textile generation [1]. For example, *KnitPicking Textures* [10] turns hand-knitting texture patterns into instructions for these machines. *Knitting Skeletons* [12] is an interactive software tool for designing machine-knitted garments. However, these machines are ~200 times more expensive than a basic FDM 3D printer, and remain out of reach to the general public [37].

Researchers have proposed building the hardware themselves or modifying existing personal fabrication machines, such as a 3D printer, as an alternative. Peng et al. engineered a layered fabric printer which cuts and glues textile sheets to form soft interactive objects [20]. *Printing Teddy Bears* [11] demonstrates how a felting needle can be used to print yarn onto foam. *Desktop Electrospinning* [24] adds melt electrospinning to 3D printing for producing electro-spun textiles. Alternatively, existing textiles can be augmented by directly printing onto a fabric surface [25].

3D Printing Fabric on Unmodified Printers

As an accessible medium for producing 3D forms, 3D printing has emerged as an area of inquiry for the personal fabrication of textiles. A number of projects have focused on printing textiles with off-the-shelf printers to avoid the need to modify hardware and add special components or materials.

Kinematics garments by *Nervous System* [27] consist of interlocking components with triangular panels linked by hinges. It uses a folding strategy to compress garments into a smaller form for efficient fabrication. However, as the fabrication requires SLS printing, it is a time-consuming process, 40 hours or more per dress, and is followed by post-processing steps to remove the powder between hinges. Pattinson et. al [19] devised an approach to 3D print flexible mesh materials with digitally tailored mechanical properties, but this horizontal printing approach limited the size and forms possible.

Another strategy for replicating textiles is by directly mimicking their structures. Beecroft et. al [3] does this by 3D printing weft-knit structures, although the granularity is limited. *3D Printed Fabric* [30] approaches this challenge by replicating the weaving *process* with a FDM printer. To do so, thin vertical pillars are printed, then a string of fiber is weaved back and forth between them. The pillars are then extended and the process repeats. With this approach they demonstrate the ability to print thin textiles with curvature on the XY plane, multi-material textiles, control of the weaving pattern/density, and integration of solid and textile components. However, the drawbacks of the approach include slow print speeds (~500 mm/min), limited pillar flexibility due to pillar thickness, limited pillar density, required support material, and an inability to print with some materials

(such as TPU). Additionally, the work only demonstrates textiles curved on the XY plane, and not along their height.

Leveraging 3D Printing Parameters of FDM Printers

Before an object is 3D printed, the 3D model is converted into a G-code file: a machine instruction file of the print path. This path is computed by the slicer software, which allows users to change certain print parameters, such as print speed, nozzle temperature, or infill pattern.

	hardware & fabrication				textile properties			
	off-the-shelf	affordable	rapid	high resolution	thin (<1mm)	curvature DOF	stretchable	long (>10mm)
Machine Knitting	✓	✗	✓	✓	✓	3	✓	✓
Printing Teddy Bears [11]	✗	✓	120mm /min	✗	>2 mm	3	✓	✗
Desktop Electrospin. [24]	✗	✓	10mm /min	✗	<1.2 mm	0	✓	✗
Kinematics [27]	✓	✗	✗	✗	✗	3	✗	✗
Biomech. Meshes [19]	✓	✓	✓	✓	✓	0	✓	✗
3D Printed Fabric [30]	✓	✓	500 mm /min	✓	~0.8 mm	2	✗	✗
DefeXtiles	✓	✓	12,000 mm /min	✓	0.3 mm	3	✓	✓

Table 1: A comparison of features of different textile generation techniques. Exact values are reported when possible and appropriate.

Researchers have manipulated these slicing parameters for various applications in HCI. For instance, *G-ID* [7] changes the parameters that affect the print path to create unique textures on objects that serve as subtle identifiers. *Thermorph* [2] leverages the warping behavior common in 3D printed objects to create self-folding objects. *Furbrication* utilizes the stringing effect of 3D printing filaments to create hair-like structures [13]. *Expressive FDM* [32] generates new forms by varying parameters that affect the height and amount of extruded material, similar to aesthetic filament sculptures [14] and *Making Mistakes* [33]. This can also be used to print tactile sheets [31]. For all of these projects, precise control of printing parameters allows phenomena commonly viewed as defects to be repurposed as a feature.

In DefeXtiles, we leverage the gap defects that arise from the under-extrusion of the print filament to vertically print sheets with woven-like structures in a single nozzle pass. Our single-step approach not only allows us to print much faster, but also allows us to generate thinner columns, thus improving the flexibility of the textiles. While we lose the exact control of the weave pattern capable in *3D Printed Fabric* [30], we are able to print thinner, stronger, higher granularity textiles up to 24 times faster with more complex geometries. Table 1 relates the fabrication and properties of DefeXtiles to other relevant works.

OVERVIEW OF DEFEXTILES

The power of the DefeXtiles approach comes from its compatibility with FDM printing. In this section, we explain how we leverage under-extrusion to print woven-like textiles

Mechanism of Printing DefeXtiles

Fused Deposition Modeling (FDM) is the most common and inexpensive approach for 3D printing. In this technique, a material, most often a thermoplastic filament, is melted and deposited by a heated, moving printer extruder head to build up an object layer by layer. In order to yield successful prints, the speed of the nozzle head, and amount of material extruded must be carefully coordinated to yield uniform layers. The most common parameter used to fine tune this coordination is the extrusion multiplier (EM). For example, setting the EM to 2 will double the amount of material extruded through the nozzle, and setting the EM to 0.5 will halve it. Over-extruding material can cause excess buildup of material on the corners of prints, and under-extruding material can cause gaps to form between layers.

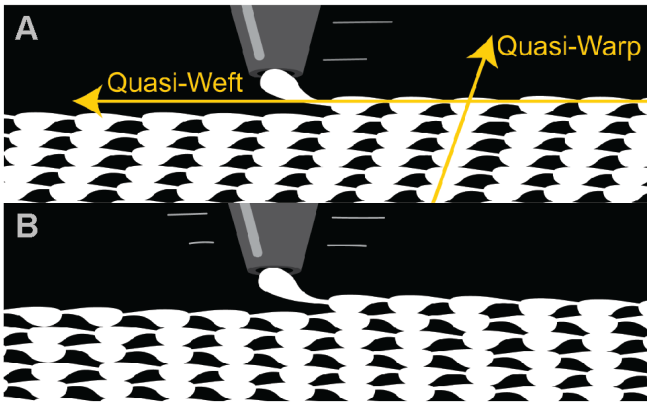


Figure 2: DefeXtiles' working principle leverages under-extrusion of 3D printing filament to create breathable textile structures. Note that the extrusion rate is constant; the structure is formed as small globs are simply stretched along the print direction. A) shows this gap-stretch behavior which generates a "quasi-warp" and "quasi-weft". For A) the nozzle prints from right to left causing the pillars to lean right. For B) the quasi-warp is straight as the nozzle alternates direction each layer.

In this paper, we demonstrate that under-extrusion can be leveraged to quickly print thin, flexible, textiles. Specifically, as the extrusion multiplier decreases, there exists an

ideal regime where globs form with fine strands connecting them as demonstrated in Figure 2.

As the printing continues, the globs continue to stack on top of each other forming a *quasi-warp*. In between these globs are fines strands of filament that form the quasi-weft. Henceforth, we will refer to this process as *glob-stretch printing*, and the quasi-warp/quasi-weft will be referred to as *warp*/*weft*. It is important to note that the extrusion rate is not dynamic: it does not extrude slightly more to form each pillar as it passes. Instead, the globing and stretching simply occurs when too little material is extruded to form a solid wall but enough where there is some periodic interlayer adhesion.

The print warp has a tendency to lean opposite the nozzle direction. If the nozzle prints a sheet from left to right, the pillars will drift to the left. Pillars that drift to the right can be achieved by printing from right to left. Finally, straight columns can be produced by alternating the print direction. Glob-stretch printing does not just yield textile-like aesthetics and breathability, but also textile-like properties such as flexibility and stretchability even with classically rigid materials such as polylactic acid (PLA). The flexibility is due to the many gaps lowering the moment area of inertia during bending (i.e., less material is being bent) compared to a perfect sheet of the same thickness. The stretchability of DefeXtiles is mostly due to the extremely thin weft which can move freely. Acting as hinges connecting the warp pillars, the weft bends in-plane to accommodate stretching. This behavior is similar to the approach used in kirigami to engineer elasticity into a material by cutting a sheet into units with thin "hinges" connecting them to each other [5, 35].

A key advantage of our approach is it requires no preparatory steps, no mandatory post-processing, no extra nozzle movements, and no specialized printing hardware. Because of this, our approach allows us to combine the affordances of textiles with nearly all the benefits of well-developed 3D printing workflows. That is, support of a diverse range of materials and forms, hands-free fabrication, rapid production and iteration, full use of the print volume, and computer-aided design.

DESIGN SPACE OF DEFEXTILES

The general characteristics of DefeXtiles is that they are thin (0.286 mm), flexible, and translucent. In this section, we detail the design space involving the material choices, supported geometries, surface pattern variations, and post-processing options.

Material Choices

The glob-stretch phenomena that occurs in DefeXtiles is not exclusive to PLA. Indeed, we show that we are able to print with many common 3D printing materials, including Nylon/Polyamide (PA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU), glycol modified polyethylene terephthalate (PETG), and PLA. Additionally, we can print with conductive PLA to generate conductive textiles for resistive and capacitive sensing. Details on printing with these materials and their resulting properties are described in the characterization section.

Supported Geometries

DefeXtiles supports three levels of geometric complexity as explained below. Figure 3 shows a sample print of each.

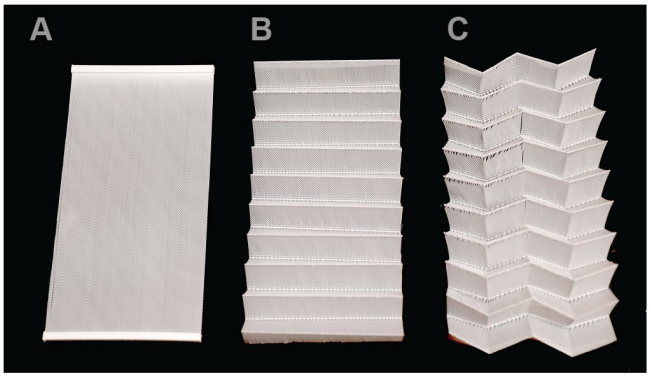


Figure 3: DefeXtiles of increasing complexity. A) A flat sheet printed with support pillars, B) a pleated sheet, and C) a metamaterial sheet

1D (flat sheets): A flat sheet is the most basic DefeXtile that can be printed. To do this, there are two approaches. The first is to print a perfectly flat upright rectangular sheet as shown in Figure 3A; however, this technique requires two support pillars to hold the sheet straight during printing, so it does not lean. We found 5mm x 5mm square pillars to be suitable for our prints. The DefeXtiles portion is set to have the same thickness as the extrusion width: 0.45 mm. Using *Simplify3D* slicer software [29], we divided the print into two processes: one for the DefeXtile and one for the pillar. For PLA, we set the EM for the DefeXtile process to 0.3, and the EM for the pillar process to 1.

We found our prints were more even when we ordered the processes so that the DefeXtile portion was printed first, and then the pillar. Before printing, we lower the nozzle ~0.1 mm, so that the first layer is even and well-adhered, after which the gap-stretch behavior begins. We found that lowering the nozzle this much did not noticeably affect the quality of solid normal prints. Additionally, we recommend a thin layer of glue on the print bed to help adhesion. Once printed, the best strategy for optimal print bed removal is a swift strike with a scraper at the base of the print. After printing, the pillars can be cut away. In cases where perfectly flat sheets are not needed, use the procedure described in the next section.

2D (curved sheet): Nearly flat sheets can be produced without pillars by printing a hollow cylinder instead. Once printed the cylinder can be cut and laid flat. We prefer this approach as it reduced print time and was easy to set up. In general, shapes with curvature in the XY plane, such as the one shown in Figure 3B, are simple to print. Sharp corners may cause occasional printer failures, if this happens one can

round the corners of the digital model, or slightly increase the extrusion multiplier. Curved sheet printing also enables rolls of fabric to be printed, and the thin nature of the textile means they can be densely packed. As a stress test, we successfully printed a 70m x 10 cm roll of fabric produced in a single 10-day print on an unenclosed *Prusa i3 MK3s* [21] in a heavily accessed makerspace.

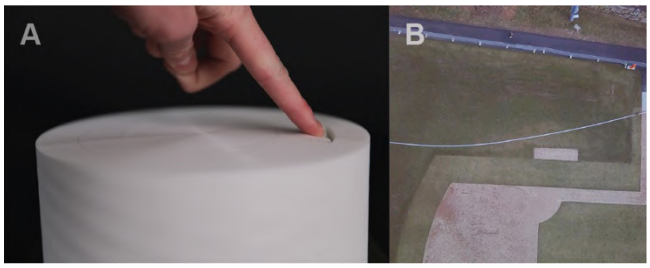


Figure 4: DefeXtiles up to 70m in length can be printed on a standard 3D printer in a single print. B) is the unrolled print on a baseball field, seen as a white line.

3D Shapes: A distinct benefit of our approach is that shapes with curvature along the z-axis are straightforward to print. One can take a 3D form, shell it to have a wall thickness of 0.45 mm, and print. Prints with sharp overhangs may require a slight increase in the extrusion multiplier. We used this process to generate a metamaterial DefeXtile with a *Miura-Ori* fold shown in Figure 3C. Empirically, we found any overhang beyond 45° to be unprintable, which is similar to the limitation of normal 3D prints.

Surface Patterning

In our explorations, we developed multiple ways to pattern the surface of a DefeXtiles. Specifically, images can be encoded by the following approaches:

Variable Opacity: In order to achieve this effect, we designed the pattern in a CAD software as we would with a multi-material print. By splitting the print into two processes, we were able to tell the printer to print part of a pattern with a higher extrusion multiplier that yields a denser mesh, and the other portion of the pattern with a lower extrusion multiplier that yields a sparser mesh.

Varying Column Direction: By splitting the print into two processes, we could control the direction of the pillars for each of the two components. This was done by setting the "start layer nearest (x, y)" to opposing sides of the print.

Multi-Material: Using a multi-material printer we are able to print textiles with varying color and properties. By using conductive PLA filament, we can integrate conductive traces into our textiles for capacitive sensing. This allows the traces to be precisely integrated into the textile. Additionally, since no material needs to be cut away, waste material is minimized.

Gaps (overhangs): Finally, gaps or cutouts in the textile can be printed without support materials.

Post-Processing

DefeXtiles require little to no post-processing. However, we detail optional processes to further extend the design space of DefeXtiles. These techniques are explained below.

Heat bonding: Much like iron-on patches, DefeXtiles can be ironed onto fabric and textiles, or another DefeXtile. This is possible as the textile melts under heat, allowing it to fuse with the fabric before cooling and hardening. Robust adhesion is owed to the mesh-like nature of DefeXtiles allowing better integration with textile fibers. When bonding, a Teflon sheet or iron transfer paper should be used to prevent the DefeXtile from sticking to iron.

De-pleating: Pleated DefeXtiles exhibit elastic-like behavior, where they return to their original geometry even after stretching; However, in some scenarios, such as Figure 7, it may be useful to remove or soften these pleats. A simple way to do this is to hold the DefeXtile flat and quickly heat the surface with a blow-dryer. The heat will soften and set the new shape.

Soldering: For textiles printed with conductive filament, wires can be easily "soldered" using a 3D printing pen loaded with conductive filament. Stranded wires are recommended as they are better held by the conductive filament.

Cutting: Due to the very thin nature of our textiles, they can be easily cut with scissors. In our work, we found sharp fabric scissors gave us the cleanest edges.

Annealing: As we described later in the characterization section, annealed PLA DefeXtiles have a dramatic improvement in tensile strength but a slight decrease in flexibility. Annealing PLA is done by sealing the sample in a bag, then submerging it in a 70°C water bath for 30 minutes, then removing the heat source and allowing the water to come to room temperature before removing the samples. This is only recommended for flat DefeXtiles, as the heat softens the PLA.

APPLICATIONS

In this section, we demonstrate the main benefits of DefeXtiles and the range of its design space.

Lamp Shade

In this application, we demonstrate how multi-material printing allows us to, in a single print, produce a deformable DefeXtile lamp shade, similar to [35, 36], with solid conductive pads, which we use for two wire transmit-receive capacitive sensing [9]. The user can turn the lampshade by pinching the pleats together (Figure 5). The light can be made brighter by pulling the pleats further apart, or dimmer by pushing them together. The lampshade, the solid supports that suspend the lampshade around the bulb, and the conductive pads were all printed as one piece.

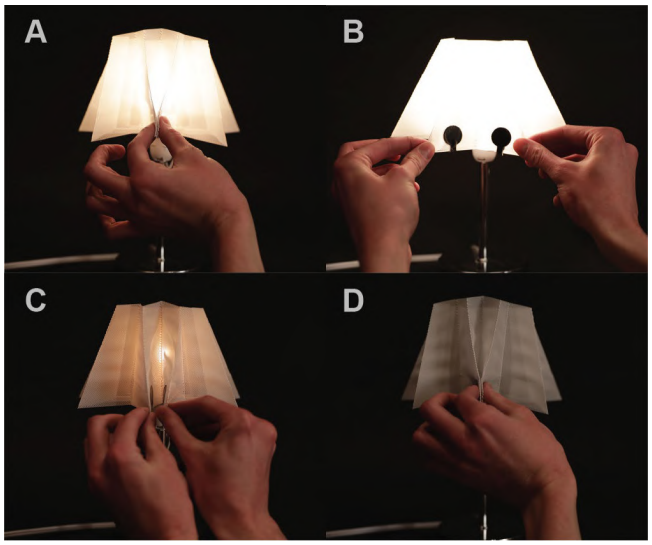


Figure 5: A diagram that shows the interaction/pinching and pulling of the lamp. A) demonstrates pinching the pleats together turning the lamp on. B) demonstrates pulling the pleats apart brightening the light. C) demonstrates pushing the pleats together, without touching, to dim the lamp. Finally, D) indicates the pinching of the pleats turns off the lamp.

Tangible Online Shopping

An unnecessary cause of waste in the fashion industry is clothing ordered online that is returned due to poor fit or misrepresentation on websites [4]. A recent study showed nearly 20-60% of clothing bought online is returned [6]. While virtual dressing rooms are helping address this issue, the user is still unable to physically try-on and interact with the garment before shipping. We envision two approaches that DefeXtiles can be used to minimize these unnecessary returns.

The first is to print out miniature versions of garments that look and feel like fabric so the user can get a better sense of the form than that afforded by a rigid print. Additionally, the dresses can be printed around a dress form based on a scan of the customer, allowing for them to physically check for proper fit. The dresses, without the dress-form, took 1-3 hours to print.

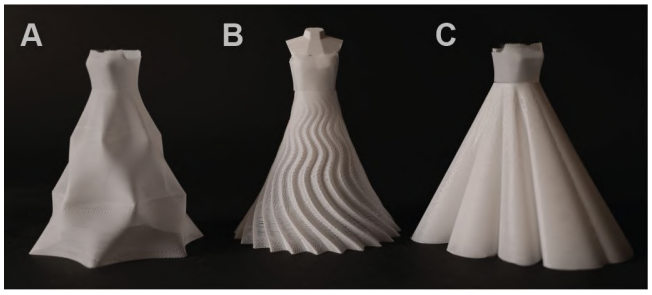


Figure 6: Three miniature dresses printed with PLA all 140cm in height. A) is a dress with a complex non-developable garment. In B) the dress and the dress form are printed simultaneously. C) shows a wedding gown with 3 layers of fabric affording opacity.

We also believe this could be useful for costume/fashion designers who render their design digitally. This would enable them to physically inspect and convey their ideas before moving on to physical fabrication.

4D Printing for Clothing Try-On

In the second approach, full-sized *pre-forms* of the garments can be tried on. In this scenario, a full-sized skirt is produced in a single print. Inspired by the 4D printing approach taken by *Nervous System* [27], this was achieved by pleating then compressing the textile to fit within the XY area of the printer. The skirt was then vertically segmented and nested to fit within the height limitations of the printer (Figure 7).

The skirt was designed similar to a telescope, with the bottom of one segment being wider than the top of the next. Once extended to a size much taller than that of the printer, the 2-inch overlap between the layers of the skirt were joined together by heat-bonding with a mini-iron, and the entire skirt was de-pleated with a blow dryer to horizontally expand the shape. The skirt was printed at the maximum speed of 12,000 mm/min, allowing it to be printed in <30 hours.

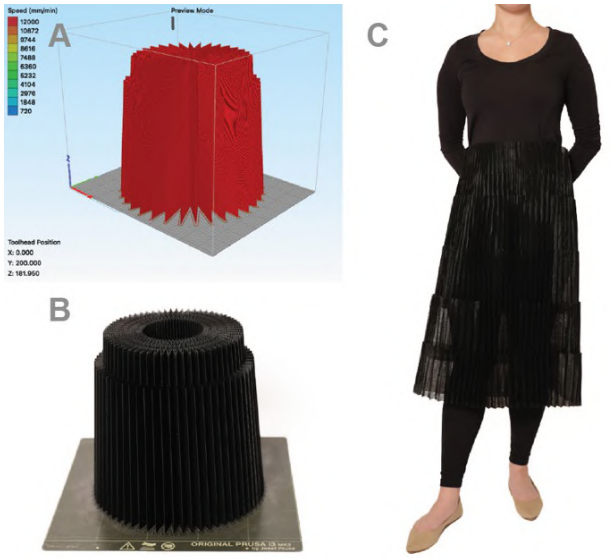


Figure 7: A) The digital version of the pleated skirt design. B) The 3D printed version. C) The unpacked version worn.

Badminton Shuttlecock

For synthetic shuttlecocks, the presence of gaps in the net are critical to obtain proper aerodynamic properties, particularly the drag coefficient, that mirror those of feathered shuttlecocks [34]. As printing with TPU produces highly durable textiles, we were able to print tough shuttlecocks. The tail of the shuttlecock is printed as a DefeXtile to mimic feathers, and the head as a solid to mimic the rubber head.

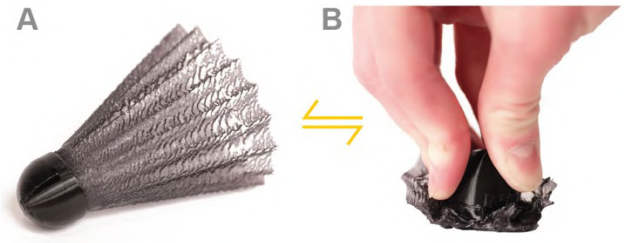


Figure 8: A) The printed shuttlecock is elastic and can be crushed as shown in B). Once lifted it will return to its original shape.

Iron-On Pocket

The ability to heat-bond DefeXtiles allows users to augment existing garments. Here, we added a PLA pocket printed with a pleated structure so it can expand to accommodate more objects, and automatically retracts when those items are removed. This allows textile augmentation similar to [25], but removes the chances of print failure due to the textile wrinkling or stretching. Additionally, this heat-bonding approach allows textiles of any size to be easily augmented.

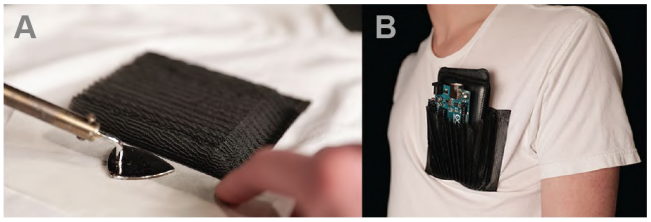


Figure 9: A) The pleated DefeXtile pocket is bonded to the shirt with an iron. B) The pocket supporting the weight of a phone, wallet, and Arduino board.

Variations of Lace

Lace is a decorative fabric knit into complex web-like patterns.

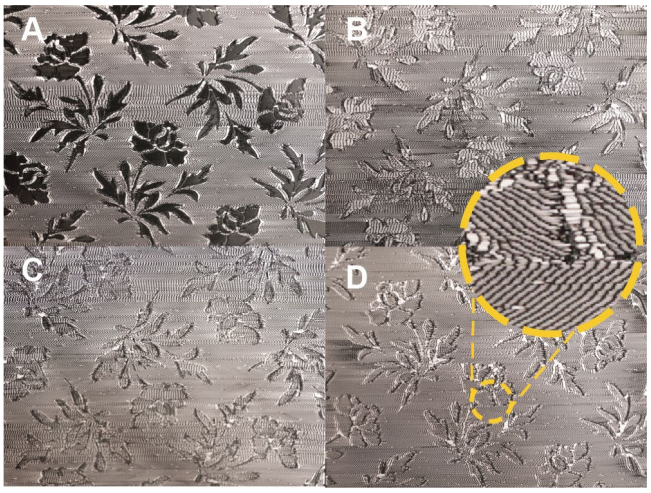


Figure 10: Four different styles of lace-like DefeXtiles. A) Solid flowers on mesh background, B) sparse mesh flowers on mesh background, C) mesh flowers on mesh background D) mesh flowers on mesh background with contrasting quasi-warp direction.

In this application, we show how our approach expands the aesthetic capabilities of 3D printers to produce intricate lace-like fabrics. We use different surface patterning primitives to generate lace with subtle nuances in how the pattern is encoded.

Specifically, Figure 10 shows four different styles of 3D printed lace. In A) the pattern is encoded by printing the flowers as solid (EM=1) and the background as a mesh (EM=.32). In B) the flowers are a less dense DefeXtile (EM=.28) than the background (EM=.32). In C) the mesh and the background are the same density (EM=.32) with only a subtle interface between the two denoting the pattern. D) is similar to C) but here the warp of the flower petals is programmed to tilt to the left, and the warp of the background is programmed to point to the right.

Tendon Actuator Toy

In this application, we develop a dancing person toy that can be printed in one piece with no post-processing (Figure 11). Both the tendons and joints are printed as DefeXtiles affording greater flexibility. This example is similar to the approach taken by [25], where rigid plastic was printed onto a textile substrate to selectively stiffen it, and a thread was added after printing to make a tendon bending actuator. However, in our approach the rigid stiffeners, the textile flexures, and the embedded tendon are all printed at once without post-processing. We leverage the well-known mid-air bridging capabilities of PLA to print a DefeXtiles fabric-like tendon which has necessary flexibility to curve around corners during actuation and can be printed without supports allowing it to be encased within the print.

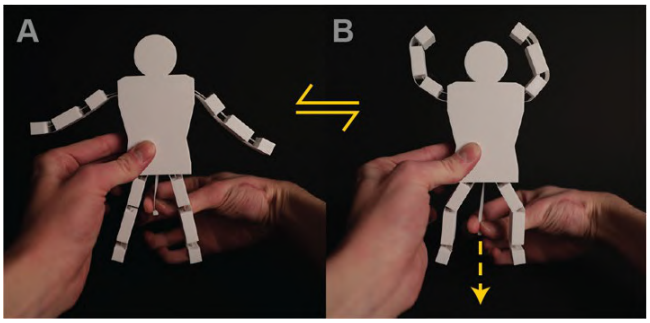


Figure 11: Dancing person toy. A) The rest state and B) the actuated state.

CHARACTERIZATION OF DEFEXTILES

In this section we show the results from a series of tests that illustrate how the printing parameters and materials selection affect the resulting properties of DefeXtiles.

Printing Parameters

As mentioned earlier, proper setting of the printing parameters is crucial for gap-stretch printing and for the resulting mechanical properties of the DefeXtile. In early experimentation, we found extrusion multiplier and print speed to most prominently affect the resulting DefeXtiles. In order to char-

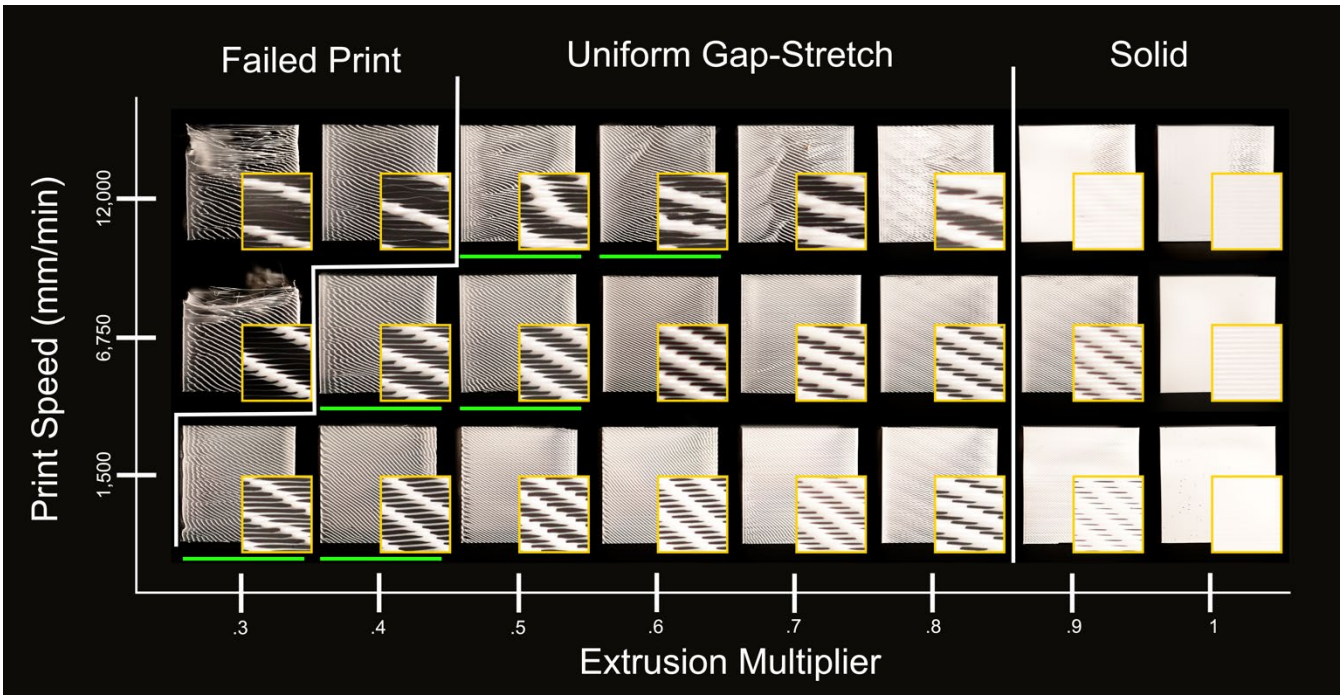


Figure 12: Resulting structure of PLA prints with different extrusion multipliers and print speed. The underlined green samples are our recommended values.

acterize the effects of changing these parameters, and the interplay between them, we report the results of tests performed to determine the optimal printing parameters for DefeXtiles printing (Figure 12).All tests were performed by printing a 5cm x 5cm square swatch of PLA at a print temperature of 210°C, a 0.20 mm layer height, a .4 mm nozzle, and a .45 mm extrusion width.

Extrusion multiplier (EM): For all print speeds, an extrusion multiplier of 0.8 initiates a regime of uniform gap-stretch printing. As the EM continues to decrease so does the density of the weft columns. Additionally, the length of the thin strands horizontally connecting the columns, the warp, get longer and thinner. At an EM of ~0.3, periodic layer adhesion no longer occurs, and print failure occurs. Additionally, we observed that DefeXtiles become more flexible when printed with a lower EM.

Print Speed (PS): Here we demonstrate that DefeXtiles can be printed at a range of speeds from 1,500 mm/min to 12,0000 mm/min (the maximum speed of our printer) for the *Prusa i3 MK3s* [21] printer. However, like all 3D printing, there is a trade-off between speed and quality. At slow speeds, the density and opacity are uniform across the surface and the weft between pillars is consistent. As the speed increases, the density becomes more heterogeneous across the surface. While the warp does successfully connect the weft to create a DefeXtile, it is thinner and more sporadic. While the samples printed at low speeds look more ideal, we found that the extra thinning of the warp dramatically improved the elasticity of our textiles, as shown Figure 13.

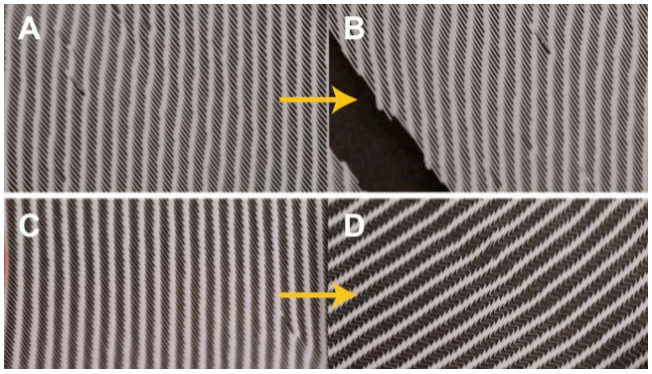


Figure 13: Importance of the print speed for flexibility. A) Unstretched PLA printed at 1,500 mm/min and .3 EM. B) The same sample but broken under little tension. C) Unstretched PLA printed at 6,750 mm/min D) The same sample, able to withstand large displacement.

Recommendations: Highlighted in green on Figure 12 we report our recommended parameters for printing DefeXtiles at different speeds; however, the exact values may have to be tuned based on different printers and filament brands. These values result in the most flexible DefeXtiles while still maintaining the intended geometry. For prints with complex geometries, we recommend using a higher extrusion multiplier or slower print speed.

Mechanical Material Characterization

Since DefeXtiles can be printed with many materials, there is a variety of resulting properties that can be achieved for various use cases. While the tensile strength of different printer filaments is already well characterized, these measurements are generally for prints of the same thickness and

amount of material. For DefeXtiles, since each filament requires a different extrusion multiplier, each sample has a different amount of material. This means the proportionality of tensile strengths between materials for DefeXtiles is likely to differ. This is also true for flexibility.

For both z-axis bend testing and weft tensile testing, 10cm (horizontal) x 4cm (vertical) swatches of each material were printed using the optimized parameters detailed in Table 2. For z-axis tensile testing a 4 cm (horizontal) by 10 cm (vertical) swatch was printed with PLA.

Bend testing methods: For all DefeXtiles, the warp is the area most prone to breaking as there is weaker adhesion between layers. To determine the most flexible material, samples were loaded into the rig shown in Figure 14. As the samples were slowly bent, cracks were watched and listened for. Once a crack was detected, the angle of bending was recorded.



Figure 14: Bend Testing of PLA DefeXtiles. A microscope was used to help monitor crack initiation.

Tensile testing methods: Ultimate tensile strength is the maximum amount of force a sample can withstand before failure. In order to characterize this for the weft direction, the samples were hung from a rig, and the weight was increased in 250g increments every 30 seconds until failure. If cracking was heard or observed, the addition of weights was paused until 30 seconds after stopping. The reported weight is the final weight minus 250g. For the z-axis testing of PLA, the same procedure was followed but with 100g increments.

Results: Our preliminary characterization shows that TPU had the best combination of strength and flexibility and is well-suited for applications where durability is needed. However, outside of these applications we do not recommend using TPU as it is a tricky material to print with, requiring exact calibration of first layer height and extrusion multiplier. We also determined a PLA DefeXtile could withstand a 900g load along the z-axis before failure. While this is less than the 4.5 kg load held along the weft, it was not a significant problem for our application development.

Both PA and PLA are easy to print alternatives with a balanced combination of traits. Annealing PLA resulted in a notable improvement in weft tensile strength but became less flexible. This is likely due to the thermal shrinkage of the PLA causing the sample to thicken. Another note is that the process of annealing can cause sample deformation, so it is probably not suitable for 3D shaped textiles. Finally, we do not recommend using PETG or ABS, as they produce brittle DefeXtiles.

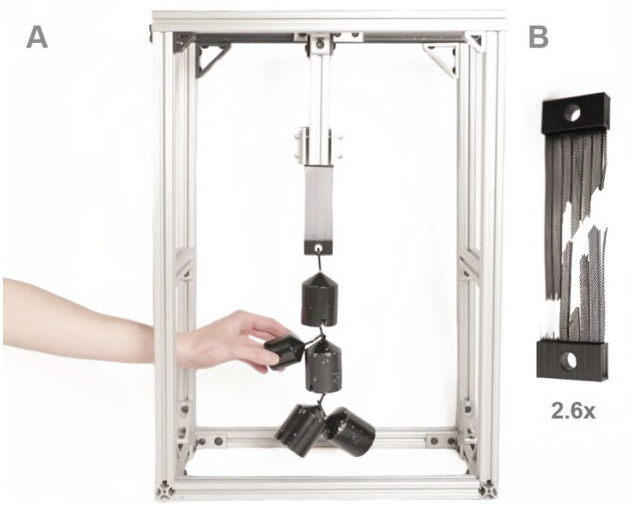


Figure 15: A) Tensile testing of a PLA DefeXtile. B) A broken Nylon DefeXtile after testing at 2.6X scale compared to A).

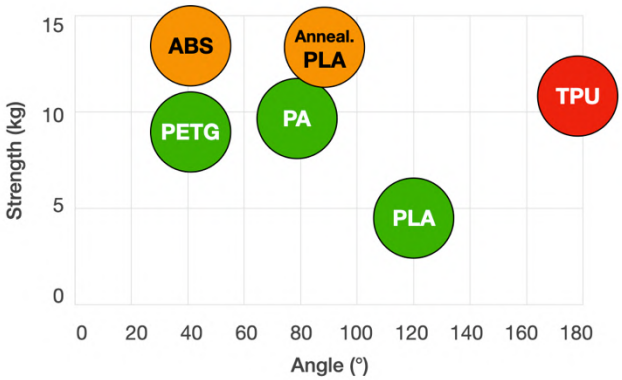


Figure 16: Measured properties of each material. Red, orange, and green indicate high, moderate, and low difficulty of printing, respectively.

	Extrusion multiplier	Nozzle temperature	Bed temperature
PLA	0.25	215 °C	50 °C
PETG	0.35	240 °C	90 °C
TPU	0.30	220 °C	50 °C
ABS	0.35	255 °C	100 °C
PA	0.40	250 °C	75 °C
C-PLA	0.85	215 °C	50 °C

Table 2: A table that shows the appropriate values for extrusion multiplier, nozzle temperature, and bed temperature for various filament types. The nozzle size was 0.4mm for all except for conductive PLA (0.6mm). Print speed was 1,250 mm/min for all.

LIMITATIONS AND FUTURE WORK

3D Printed Foams

As this paper is about 3D printing textiles, we focused on sheet and shell type geometries. An exciting direction of future work is to leverage "gap-stretch" printing to generate porous and flexible foam-like materials. By changing the extrusion multiplier in certain areas, foams with varying stiffness could be produced. These could be used for low-cost prototyping of haptic experiences, similar to [5], or for creating better prosthetic linings that are customized for specific users.

Complex "Pleat and Pack" Design Pipeline

As we demonstrated in the skirt try-on applications, large textile objects can be printed by compressing and segmenting the form, unfolding it after printing, and heat bonding together the segments. We envision an inverse design pipeline that could take arbitrary forms, and pleat and compress it to fit within the print volume.

Support Material

While our approach can print a variety of complex objects, the geometric design rules still adhere to the general limitations of 3D prints (limited bridging distances, limited overhang angles). The use of dissolvable support material, or 3D printing in gel suspensions, could be potential strategies for overcoming these geometric limitations.

Biomedical Devices

Outside of HCI, an ambitious but possible future direction could be in leveraging DefeXtiles to produce low-cost and effective customized surgical meshes that better reinforce organs and tissue after surgery. 3D printed PLA surgical implants have already been shown to be effective [15]. Additionally, if loaded with antibiotics, such as ciprofloxacin HCl, the degradation would slowly release the antibiotic preventing infection [22]. Additionally, the mechanical properties of the mesh could be tuned to match that of the tissue being supported.

CONCLUSION

This paper has introduced a new approach to quickly print thin, flexible textiles composed of common 3D printing materials with an unmodified 3D printer. Our approach combines the flexible, thin, and breathable properties of textiles with the affordances of 3D printing: rapid iteration, hands-free fabrication, and computer aided design. Through characterization, we demonstrate how our approach enables tuning of the mechanical and aesthetic properties through material and parameter selection. Through a series of applications, we demonstrated the potential applicability of our approach for smart textiles, tangible online shopping, toys, fabric design, and everyday life.

Due to the widespread use and accessibility of FDM printers, we envision this approach can immediately empower a wide audience with the ability to fabricate fabric into finished forms. We hope DefeXtiles can enrich HCI's maker toolbox and lower the barrier of entry to computational textile design.

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