Defextiles:

3D Printing Quasi Woven Textiles Via Underextrusion

by Jack Forman

B.S., Carnegie Mellon University (2019)

Submitted to the Department of Media Arts & Sciences
in partial fulfillment of the requirements for the degree of

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Abstract

I 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.

In this thesis, I 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. Additionally, I demonstrate the interactive features and new use cases of our approach through a variety of applications, such as fashion design prototyping, interactive object, aesthetic lace patterning, and single-print actuators. Finally, I discuss the number of external technique reproductions and expansions, and reflect on methodology strategies to support such phenomena.

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0.1 Acknowledgements

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0.2 Preface

Before transiting to the formal presentation of the work, I wanted to provide a brief insight into the backstory behind the project, and the conditions of its engenderment. It starts in 2019 when I was finishing my undergraduate Materials Science & Biomedical Engineering B.S. from Carnegie Mellon. A friend and lab mate, Jenny Hu, showed me the beautiful work of Mary Tsai on under-extruding to create beautiful vases [33]. I noticed the woven-like structure, and wondered if some parameter refinement could result in 3D printed textiles. This potential was of great relevance to me at the time, as I (and my collaborators Mohan Yeh, Alan Guo, and Prof. Lining Yao) had just finished a fashion collection on a shape-changing fiber we invented [8]. During this process, I learned, due to a hand tremor that runs in the family, I am eminently unskilled in the art of delicate handwork. Producing the garments was a frustrating and tedious process, and I thank my fantastic collaborator Mohan for saving me. This experience nurtured a profound bedevilment, as I loved the idea of making with textiles, but loathed the execution. The idea of being able to directly print 3D textiles, while exciting at the time, was forgotten as graduation, grad school applications, and other projects built up.

As I started my masters at the MIT Media Lab in the Tangible Media Group with Prof. Hiroshi Ishii, I was determined to take the course “How To Make (almost) Anything”. While my previous collaborations with makers were exciting and fulfilling, I yearned to *become* the maker. Thankfully, Prof. Neil Gershenfeld accepted me, and in the third week I learned to 3D print for the first time. While I was new to printing myself, I had been surrounded by literature on interesting 3D printing methods based modifying the printers behavior. I originally intended to replicate the wonderful loopy printing work by Takahashi et al. [32] but gave up when I found it required a custom slicer to work, which was open source but not compatible with my printer. I simply did not have the time availability, or strong justification, to modify it to work on the CBA printers. As I thought about what could be printed that was interesting and fast to implement, I remembered Mary Tsai's work shown to me at CMU. After patiently modifying the printer settings and parameters, I had produced a cylinder of under extruded material. In retrospect, a humorous detail is that I was actually annoyed by how homogenous the defect structure was. At the time I was going for the aesthetic of chaotic beauty. However, as I touched and played with the material I re-realized the idea of printing textile this way - the power of tangible interaction!

https://fab.cba.mit.edu/classes/863.19/CBA/people/jack/week-4.html

That week I went down a rabbit hole of textile printing (a rabbit hole I would stay in for the next few months). While the first print had some flexibility, later prints with optimized parameters produced something that really felt and moved like real fabric. During the 3D printing show and tell, Neil's interest piqued when he got to my sample as he asked how it was made. I explained I was under extrusing to create periodic gaps, and that by printing a ribbon as a cylinder I created a textile that - once opened - was larger than the printer volume. Neil's reaction was a duality of confusion and excitement. Neil's confusion led me to think this technique was particularly novel, his excitement led me to think this technique was particularly useful, and his questions days later led me to think this technique was particularly fascinating. I began to entertain the idea of a master's thesis focused around this idea.

Then, about two weeks later a 3D printing fabric paper was published in a top HCI conference. Realizing my technique was liberated from many of the limitations that work faced - the notion of publishing came to a head. I then presented the work to Hiroshi in the format of the CHI paper. Hiroshi posed many challenging questions to simulate the critiques of the reviewers - one of Hiroshi's best abilities. After leaving Hiroshi sufficiently satisfied, this paper became the main event of my time at MIT.

Well, at least I believed it would be at MIT. On March 14th America was jolted awake by the COVID-19 pandemic. I hastily packed up my printers, tools, and camera equipment and drove to my parents cabin in upstate New York. It was there, in the basement, that I set up a fablab and produced the paper contents (characterizations, photos, video, etc.). "Good morning!" I would tell my dad, as I walked upstairs at 5 AM for a late night snack as he was starting his day. I cherished the opportunity to show my parents what research was, and why I loved it so dearly. This was my thin silver lining to a year that was difficult for everyone.

In reflection, I am so proud of what we managed to accomplish thanks to the dedication of my fab-ulous collaborators.

Figure 0: My basement #homelab March 15th, 2020

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Chapter 1: Introduction

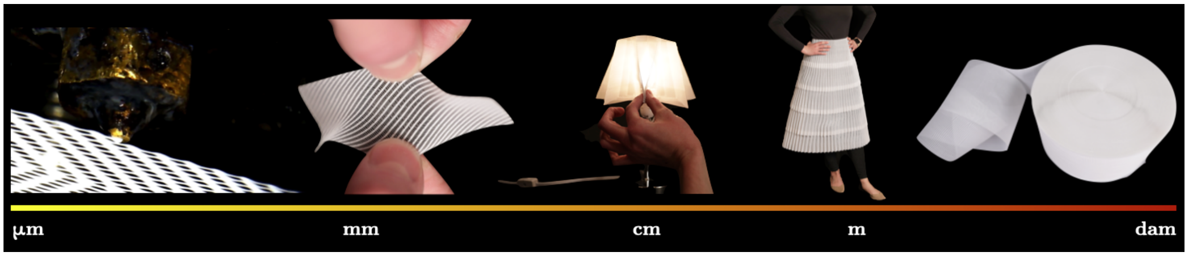


Figure 1: Length scale overview of DefeXtiles from millimeters to decameters. (1) microscope image of a DefeXtile being printed, (2) A DefeXtile being stretched, (3) an interactive lampshade with capacitive sensing, (4) a full-sized skirt, (5) a 70m roll of fabric produced in a single print. All samples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

For thousands of years, the manufacturing of textiles into shaped forms has remained largely the same — discrete steps where 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 de-pleating.

Chapter 2: 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.

2.1 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].

2.2 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.

2.3 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 patte

	hardware & fabrication				textile properties			
	Off the shelf	affordable	rapid	high resolution	thin (<1 mm)	curvature DOF	stretchable	long
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.

Chapter 3: 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

3.1 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.

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.

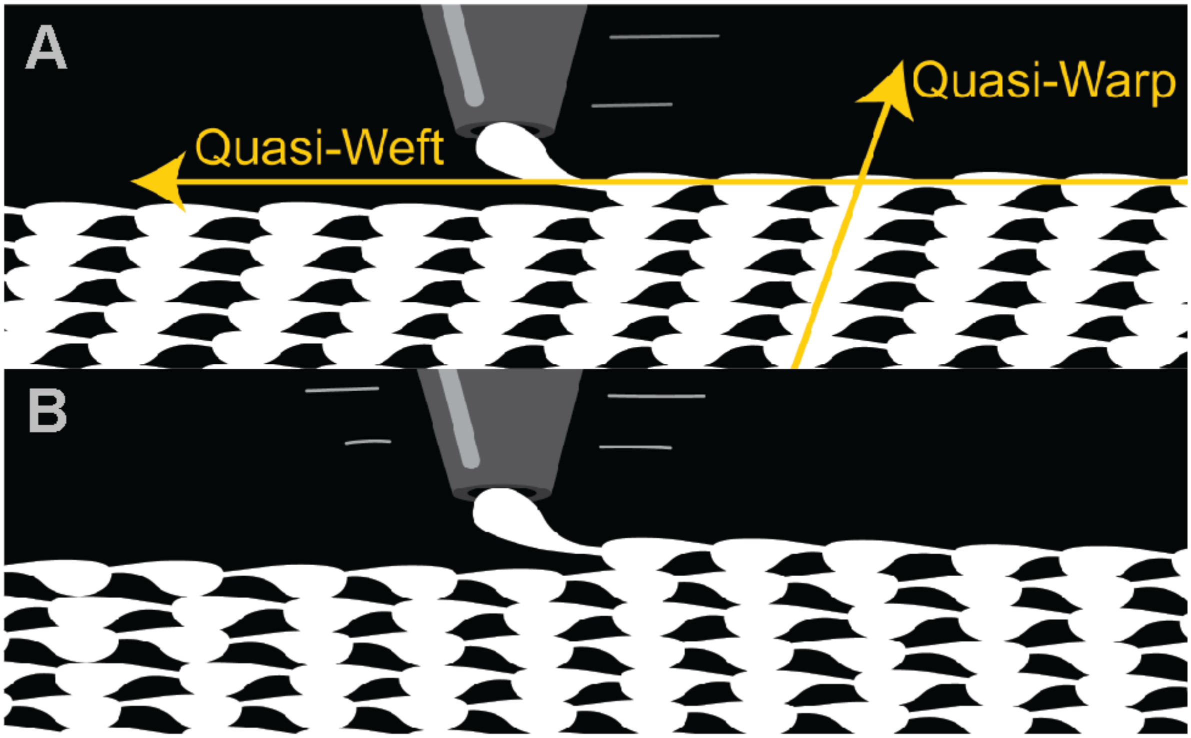


Figure 2: DefeXtiles' working principle leverages under-extrusion of 3D printing filament to create breathable textile structures. Note that the extrusion rate is constant; the structure is formed as small globs are simply stretched along the print direction. A) shows this gap-stretch behavior which 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.

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.

Chapter 4: 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.

4.1 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.

4.2 Supported Geometries

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

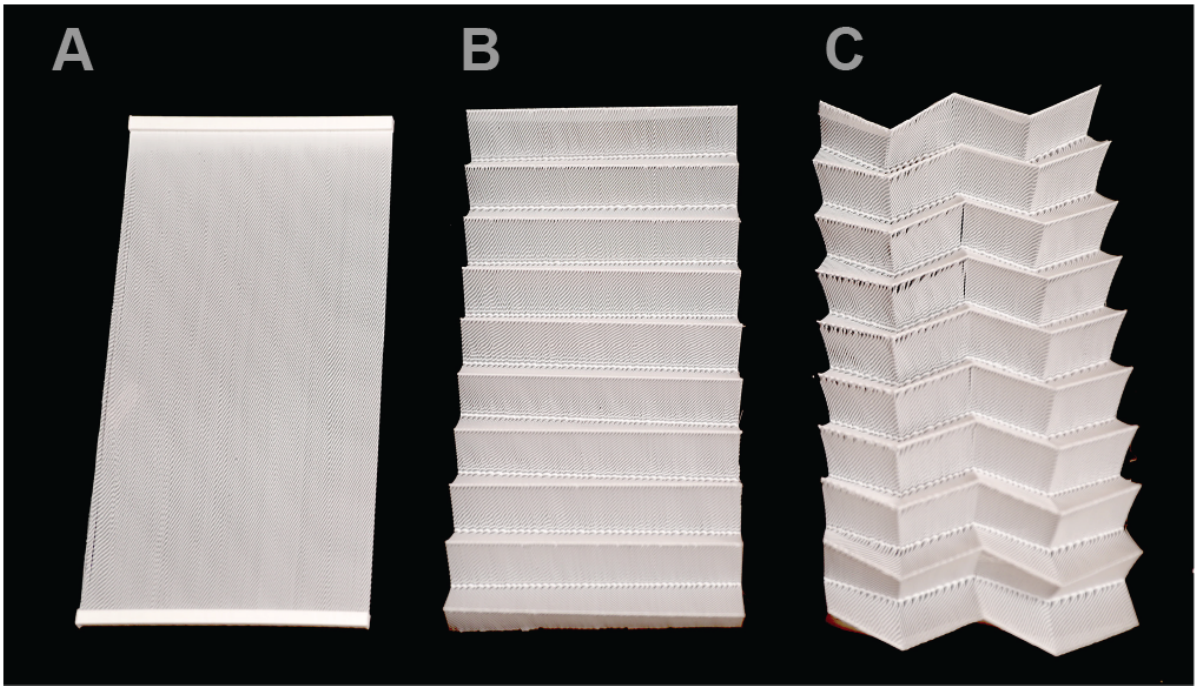


Figure 3: DefeXtiles of increasing complexity. A) A flat sheet printed with support pillars, B) a pleated sheet, and C) a meta-material sheet

4.1.1 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.

4.1.2 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.

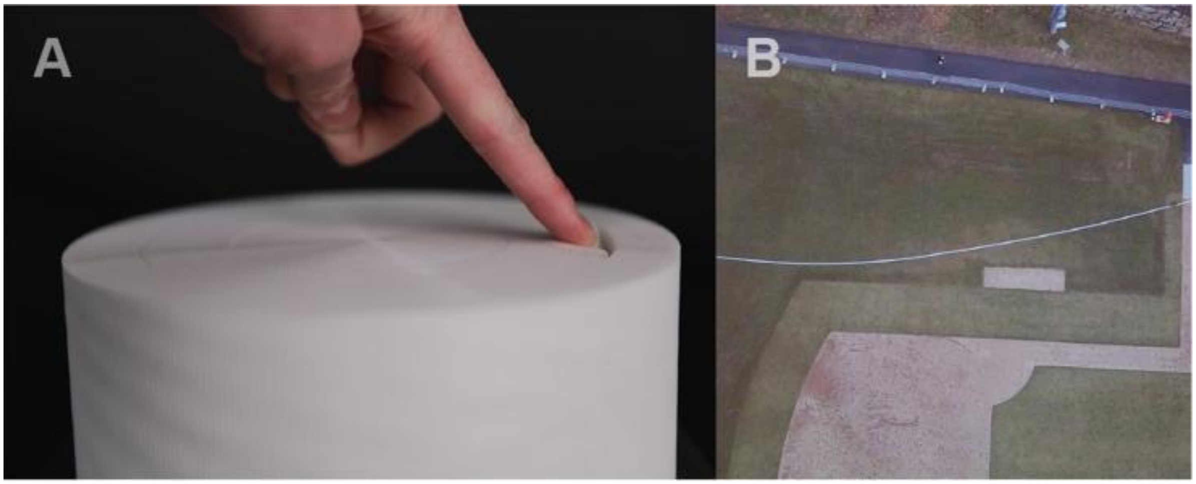


Figure 4: DefeXtiles up to 70m in length can be printed on a standard 3D printer in a single print. B) is the unrolled print on a baseball field, seen as a white line.

4.1.3 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.

4.2 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:

4.2.1 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.

4.2.2 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.

4.2.3 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.

4.2.4 Gaps (overhangs):

Finally, gaps or cutouts in the textile can be printed without support materials.

4.3 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.

4.3.1 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.

4.3.2 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.

4.3.3 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.

Chapter 5: Applications

In this section, we demonstrate use cases of DefeXtiles leveraging the design space described in the previous section.

5.1 Lamp Shade (Multimaterial, 3D geometry, Soldering)

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.

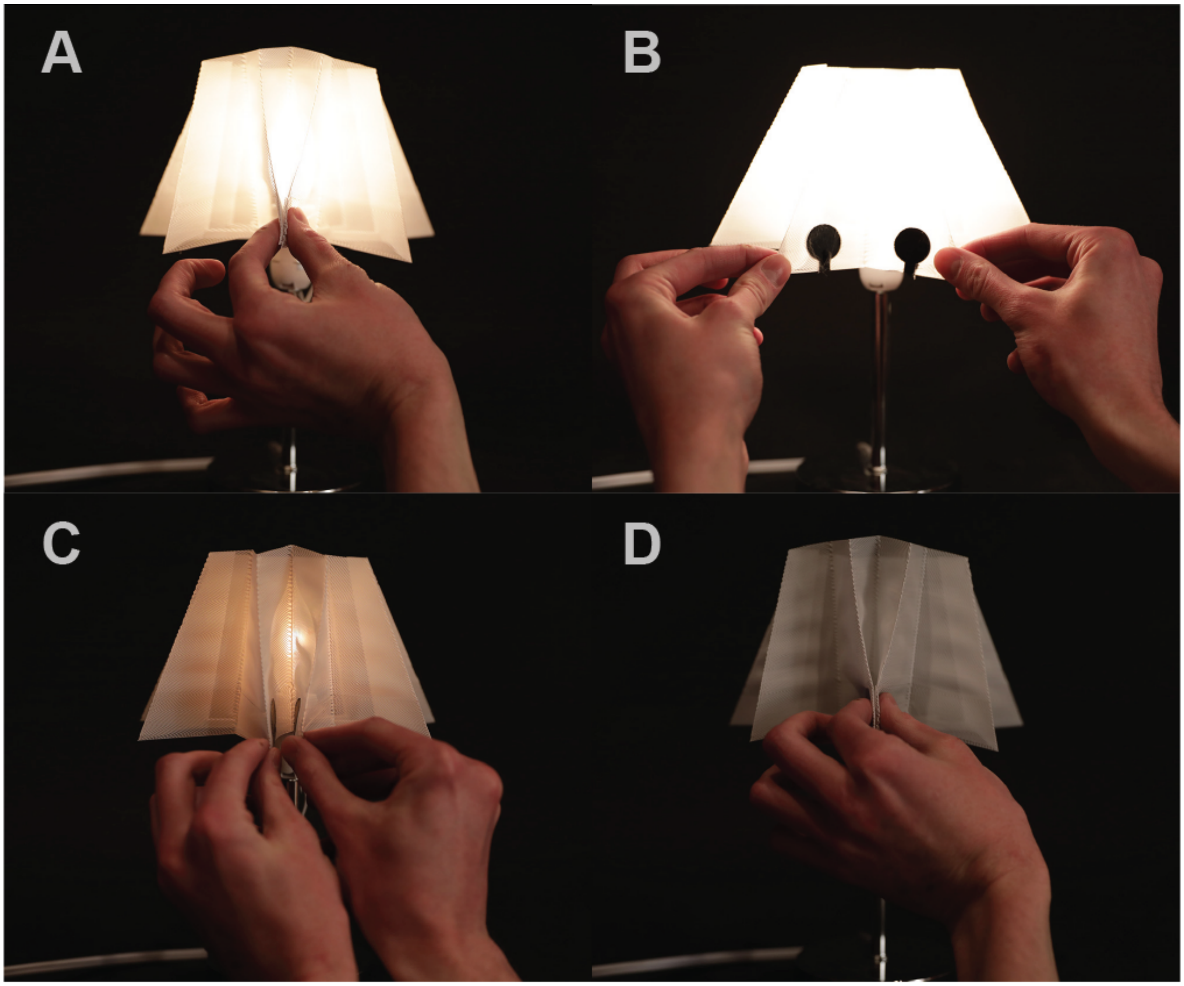


Figure 5: A diagram that shows the interaction/pinching and pulling of the lamp. A) demonstrates pinching the pleats together turning the lamp on. B) demonstrates pulling the pleats apart brightening the light. C) demonstrates pushing the pleats together, without touching, to dim the lamp. Finally, D)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

5.2 Tangible Online Shopping (3D geometry)

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.

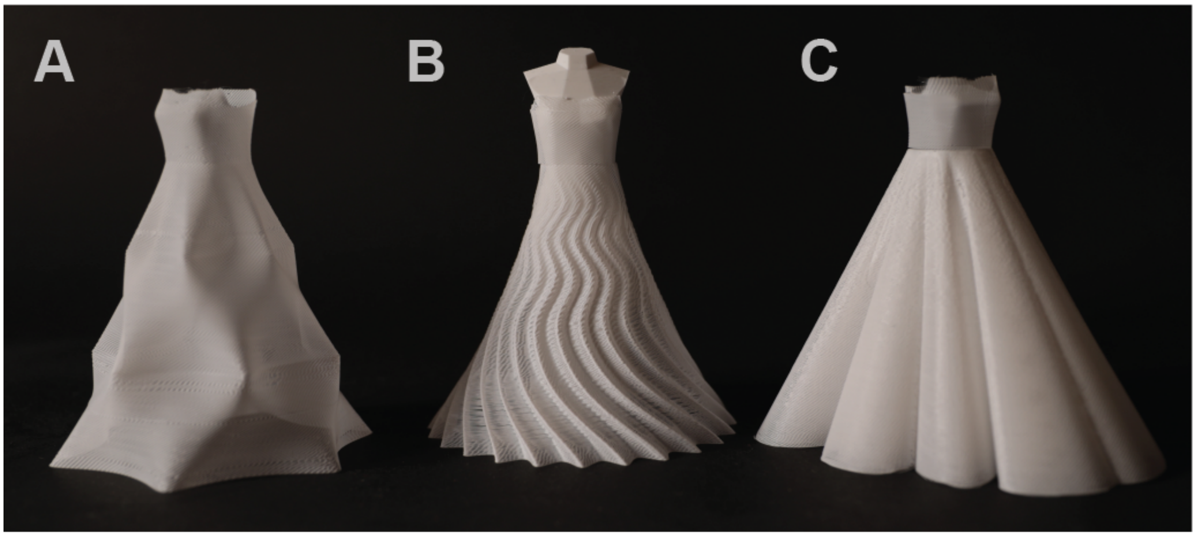


Figure 6: Three miniature dresses printed with PLA all 140cm in height. A) is a dress with a complex non-developable garment. In B) the dress and the dress form are printed simultaneously. C) shows a wedding gown with 3 layers of fabric affording opacity.

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.

5.3 4D Printing for Clothing Try-On (3D geometry, de-pleating, heat bonding)

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.

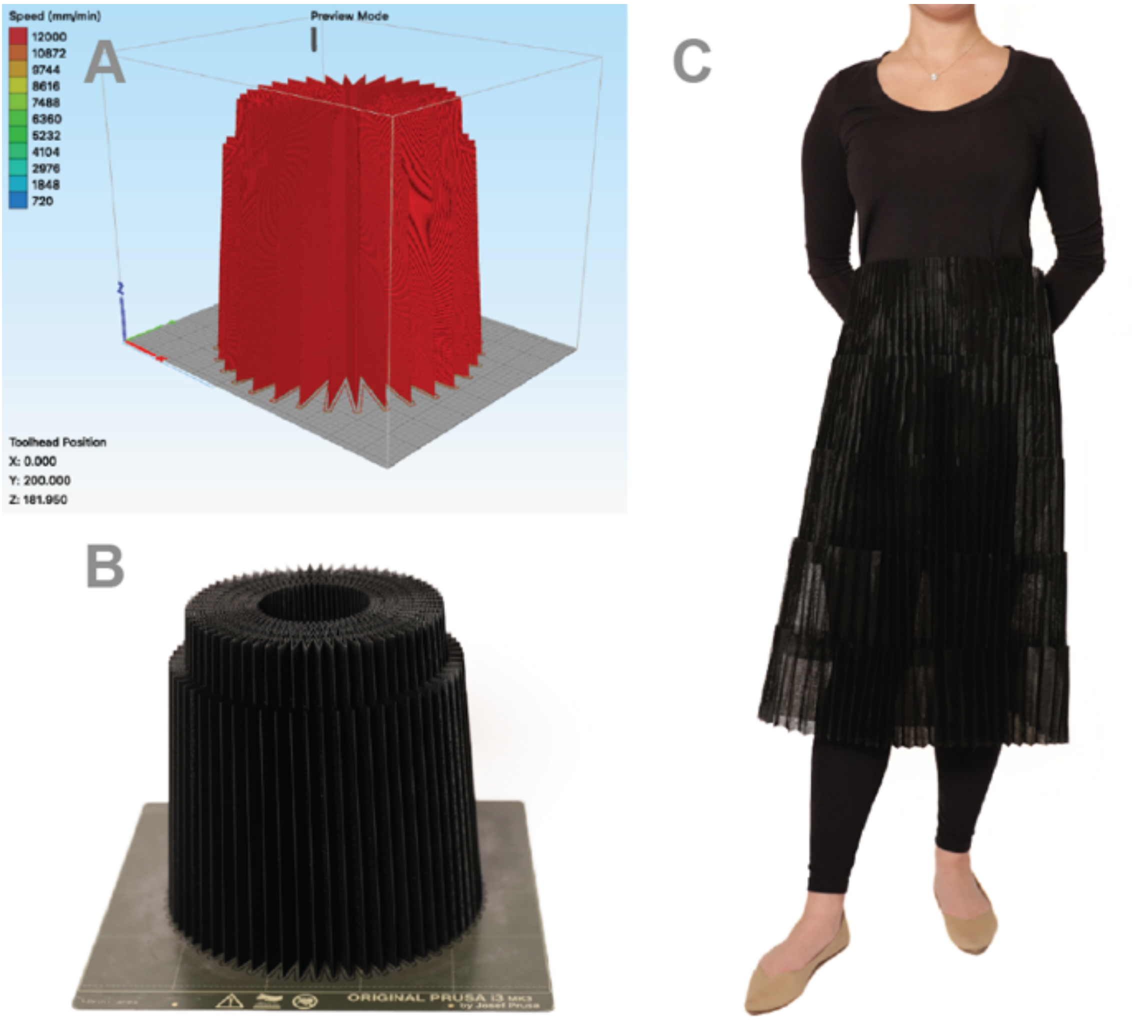


Figure 7: A) The digital version of the pleated skirt design. B) The 3D printed version. C) The unpacked version worn.

5.4 Badminton Shuttlecock (Elastic material)

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.

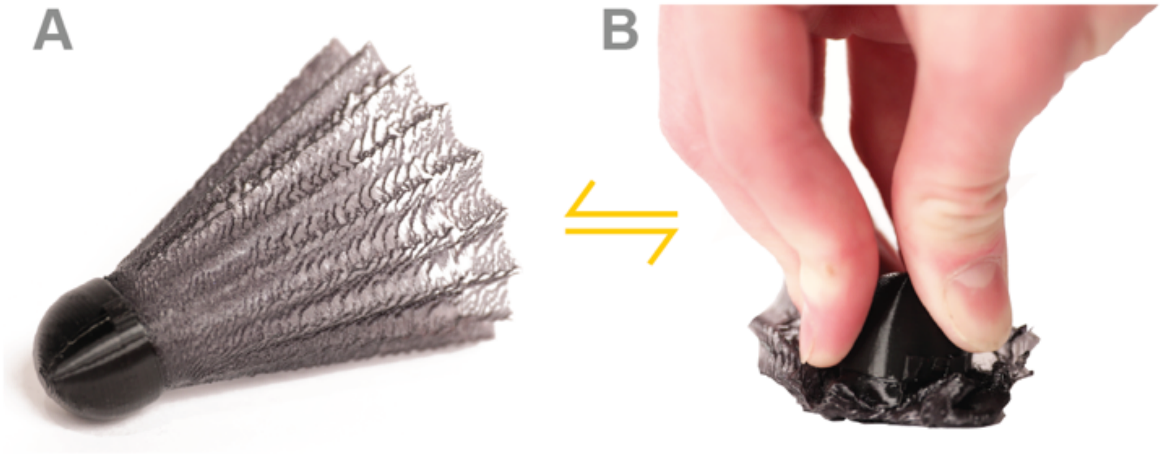


Figure 8: A) The printed shuttlecock is elastic and can be crushed as shown in B). Once lifted it will return to its original shape.

5.5 Iron-On Pocket (Heat Bonding, 3D geometry)

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.

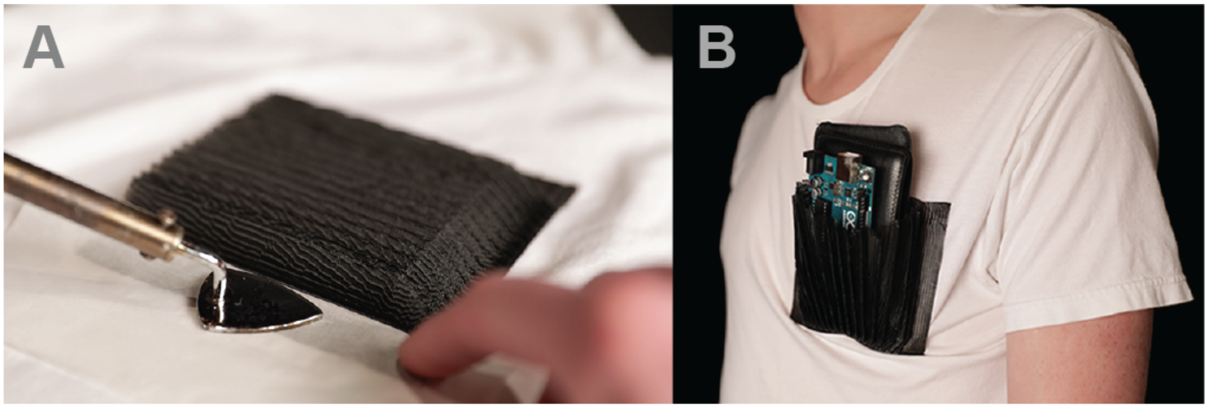


Figure 9: A) The pleated DefeXtile pocket is bonded to the shirt with an iron. B) The pocket supporting the weight of a phone, wallet, and Arduino board.

5.6 Variations of Lace (Surface patterning)

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

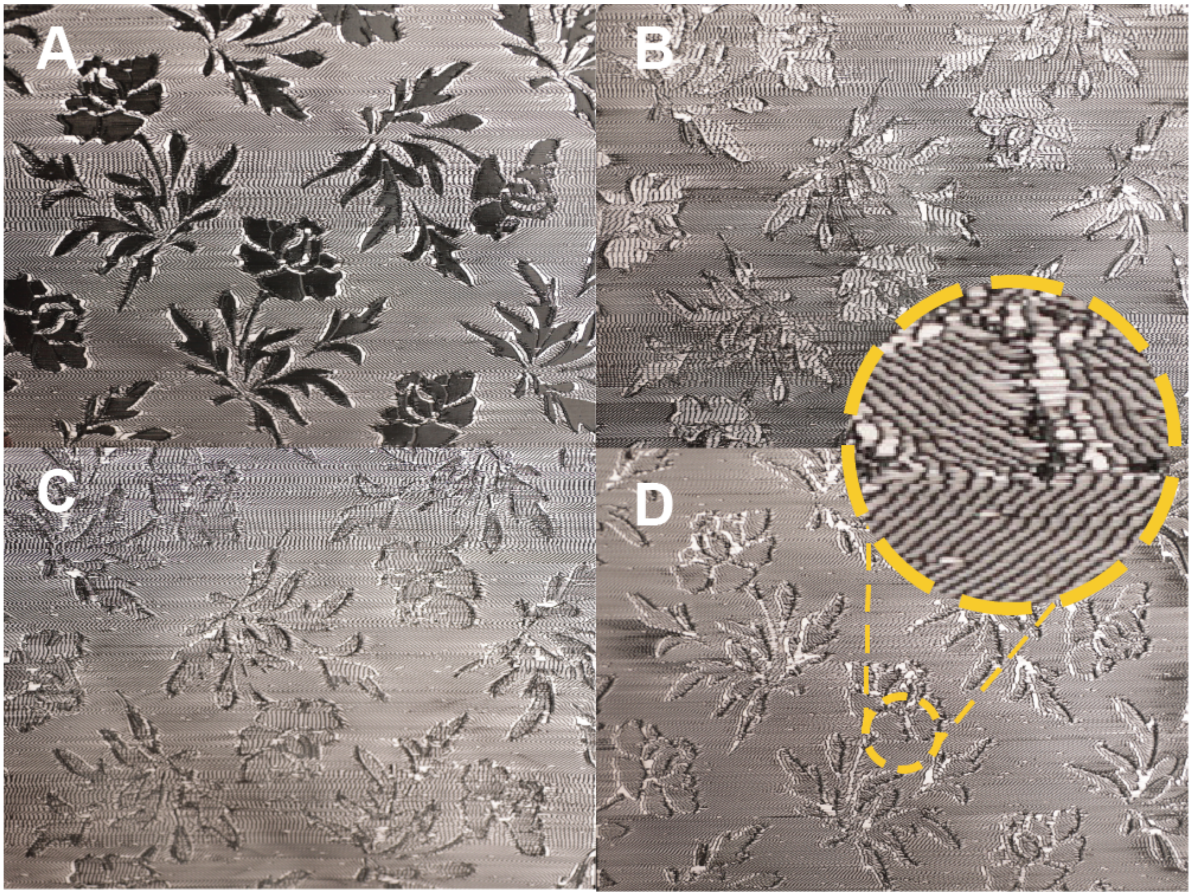


Figure 10: Four different styles of lace-like DefeXtiles. A) Solid flowers on mesh background, B) sparse mesh flowers on mesh background, C) mesh flowers on mesh background D) mesh flowers on mesh background with contrasting quasi-warp direction.

5.7 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.

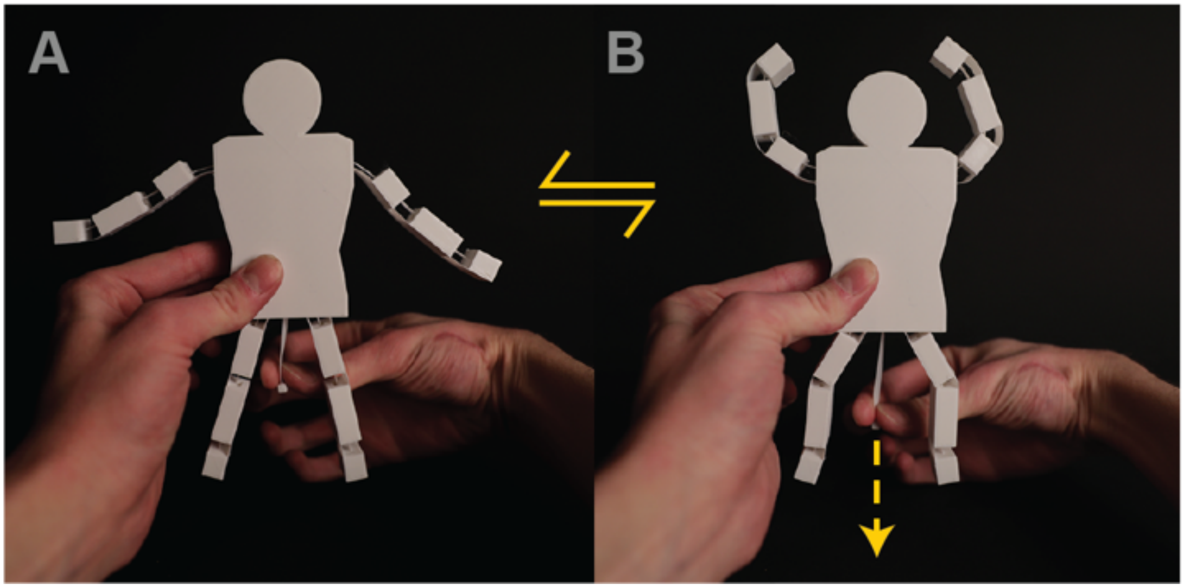


Figure 11: Dancing person toy. A) The rest state and B) the actuated state.

Chapter 6: 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.

6.1 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 characterize 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

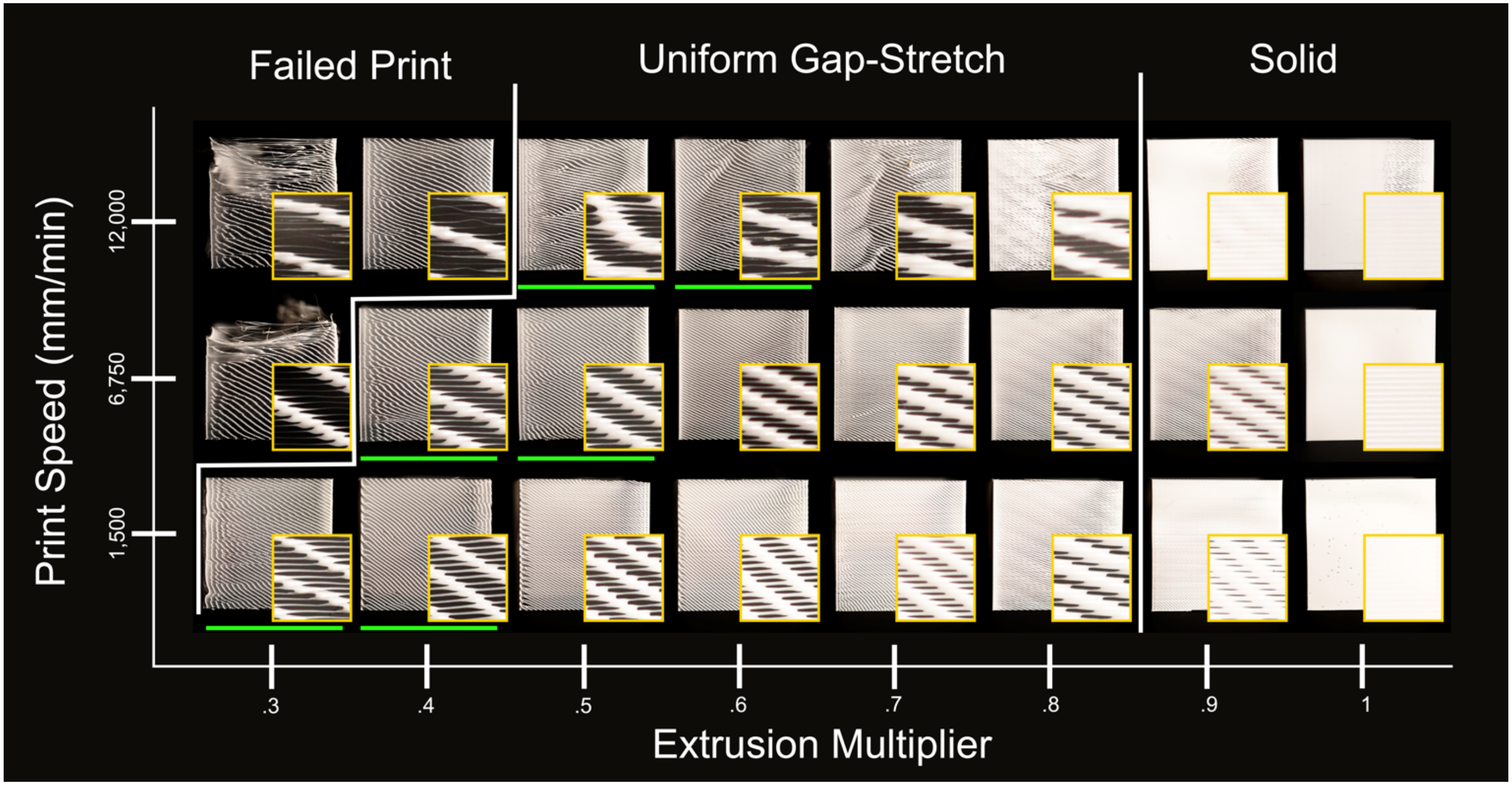


Figure 12: Resulting structure of PLA prints with different extrusion multipliers and print speed. The underlined green samples are our recommended values.

6.1.1 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.

6.1.2 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.

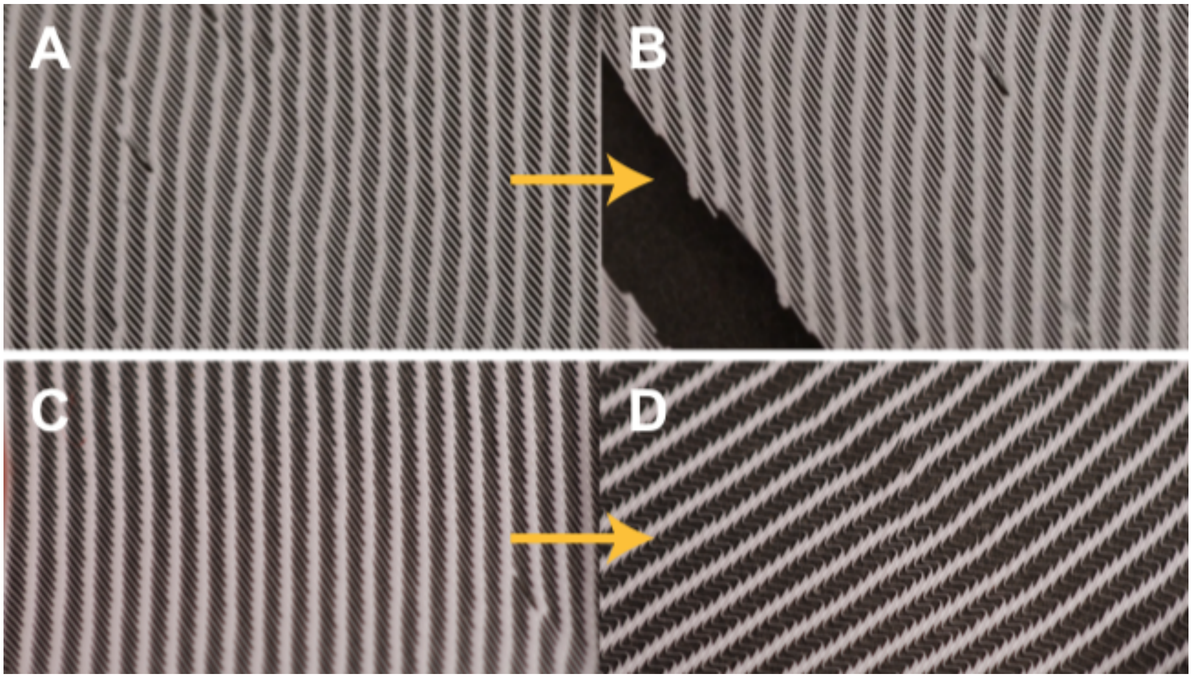


Figure 13: Importance of the print speed for flexibility. A) Unstretched PLA printed at 1,500 mm/min and .3 EM. B) The same sample but broken under little tension. C) Unstretched PLA printed at 6,750 mm/min D) The same sample, able to withstand large displacement.

6.1.3 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.

6.2 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.

6.2.1 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.

6.2.2 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.

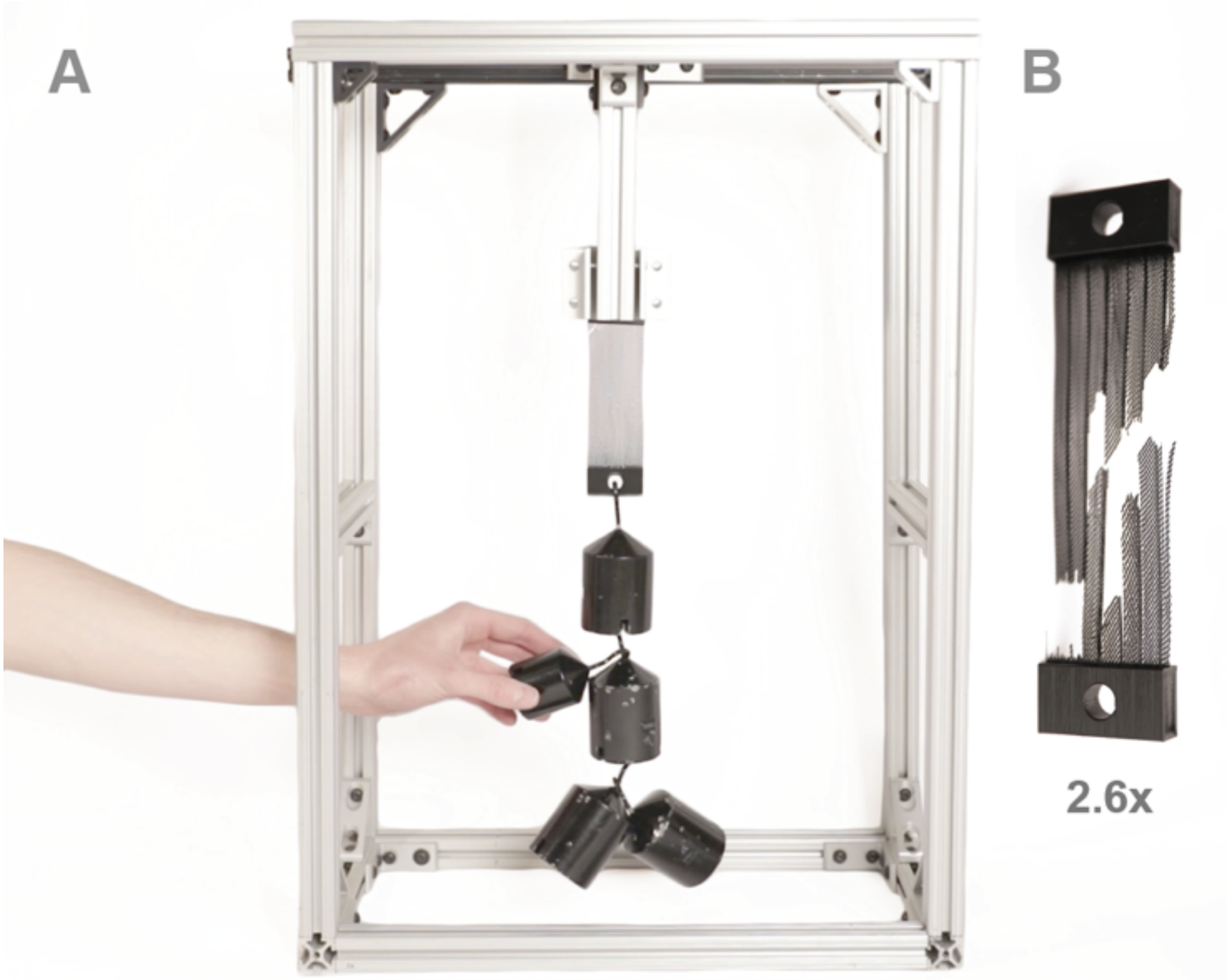


Figure 15: A) Tensile testing of a PLA DefeXtile. B) A broken Nylon DefeXtile after testing at 2.6X scale compared to A).

6.2.3 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.

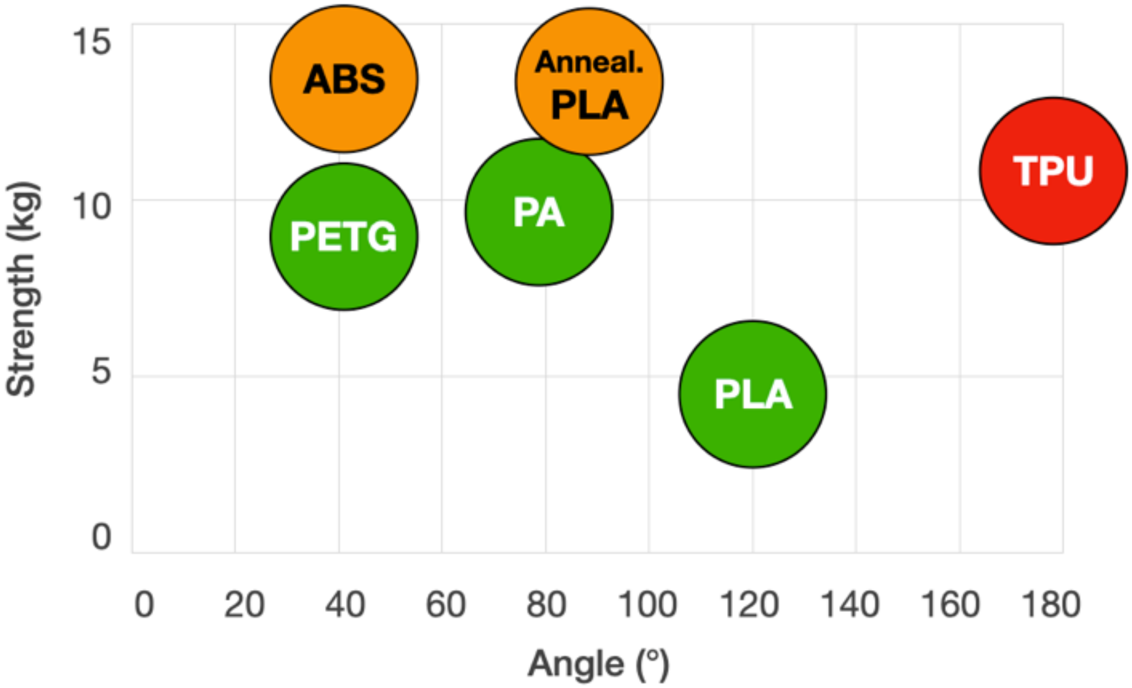


Figure 16: Measured properties of each material. Red, orange, and green indicate high, moderate, and low difficulty of printing, respectively.

	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.

Chapter 7: Limitations and Future Work

7.1 Quantitative Examination of Printing Phenomena

While the current work showcases the phenomena of glob-stretch printing, future work should develop a rigorous understanding of the underlying rheology and polymer physics of the process. There is a need for a quantitative analysis and model to capture the periodic deposition and shearing of extruded thermoplastic to correlate material properties, printing parameters, and resultant mechanical performance. Such a model enables a host of applications including gradated foams for bulk acoustic absorption, high precision print of low-viscosity high-elasticity thermoplastics, and conformable sensors for biometric signal acquisition. The current implementation of DefeXtiles relies on software workarounds that don't allow renderings and prediction of the resulting prints. A quantitative model would inform the creation of a dedicated design tool that takes a user input (grayscale image, stl, etc.) and generates the g-code for surface patterning effects or varied mechanical properties.

7.2 3D Printed Foams

As this paper is about 0w3D 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.

7.3 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.

7.4 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.

7.5 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.

Chapter 8: External Reproduction & Reception

8.1 External Reproduction

Since the beginning of this project, I prioritized the reproducibility of this technique so as to empower an external audience with the ability to create formed textiles. At the start, I anticipated I would need to develop a custom slicer/design tool in order to produce the different design space primitives - such as variable opacity and multimaterial printing. However, as I became more familiar with commercially available software, I was surprised to find it offered all the controls I needed to showcase the design space. For example, the quasi-warp direction was controlled by leveraging the “start layer nearest (x,y)” setting to only print from one direction.

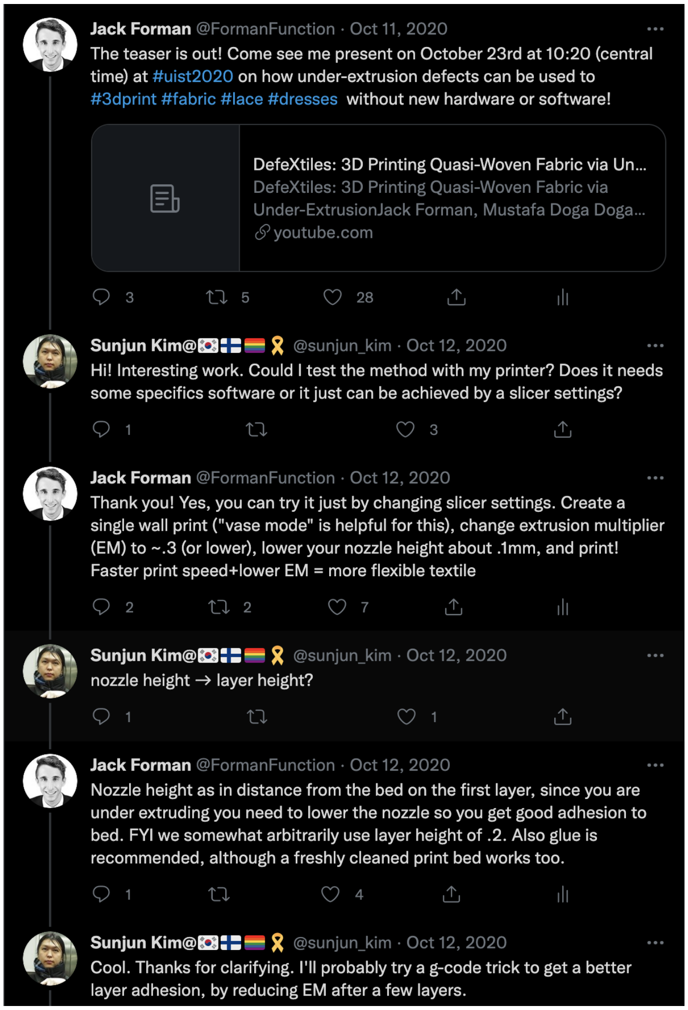
While these tricks and know-how can be perceived as an inhibitory element for reproduction, that is only the case if such know-how is not clearly discussed in the methods. While a design tool that automates the process could seem a solution to aiding reproduction through elimination of process nuances, the production of a design tool which is compatible with all printers and computer software is a time-intensive and demanding task. More often than not, the design tool only works for specific printers on specific operating systems, repressing external reproduction. In fact, I experienced this myself when attempting to replicate the results of two other 3D printing technique papers, only to move on when I found the software was not compatible with my printer. Later, after talking with one of the researchers about this issue, they explained that there was a “quick and dirty” approach that allowed me to generate all of the primitives in 1 hour. If only this was shared in the paper!

The justification for a design tool for an experimental and novel fabrication platform is speculative without demonstrated external interest and reproduction. Researchers risk investing precious time and effort into creating a tool for a method few employ - time that otherwise could be spent expanding the design the space the technique affords. However, there are absolutely cases where an early design tool is justified. Some example scenarios are: 1) the method requires a design tool to work - there is no “quick and dirty” approach, 2) a tool is needed to fully implement the potential design space - the “quick and dirty” approach only goes so far, 3) the method is established and employed by a variety of makers, and a design tool would support this audience by streamlining the process and enable inverse-design of fabricated objects.

For an experimental and novel technique, the strategy of exploiting “what’s there” is beneficial to both the work and the researcher. The researcher has more time on creating compelling demonstrations of the platform’s potential. This, in turn, engenders excitement and external assistance in the design tool creation.

This notion of using “what’s there” was maintained throughout the preparation of this paper. After its publication, I was pleased to see people quickly picking up and reproducing the technique for their own projects - demonstrating the success (albeit anecdotal) of this minimalist implementation approach. I will outline some highlights here:

Before the full paper was even published, Professor Sunjun Kim saw the 30s preview of the work and reached out to me on twitter as they were interested in reproducing the work. In two tweets I was able to communicate the “quick and dirty” approach, and the next day they shared a video of their DefeXtile sample [42]:



Jack Forman @FormanFunction · Oct 11, 2020

The teaser is out! Come see me present on October 23rd at 10:20 (central time) at #uist2020 on how under-extrusion defects can be used to #3dprint #fabric #lace #dresses without new hardware or software!

DefeXtiles: 3D Printing Quasi-Woven Fabric via Un...
DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-ExtrusionJack Forman, Mustafa Doga Doga...
youtube.com

Sunjun Kim@🇰🇷🇫🇮🏳️‍🌈🎗 @sunjun_kim · Oct 12, 2020

Hi! Interesting work. Could I test the method with my printer? Does it needs some specifics software or it just can be achieved by a slicer settings?

Jack Forman @FormanFunction · Oct 12, 2020

Thank you! Yes, you can try it just by changing slicer settings. Create a single wall print ("vase mode" is helpful for this), change extrusion multiplier (EM) to ~.3 (or lower), lower your nozzle height about .1mm, and print! Faster print speed+lower EM = more flexible textile

Sunjun Kim@🇰🇷🇫🇮🏳️‍🌈🎗 @sunjun_kim · Oct 12, 2020

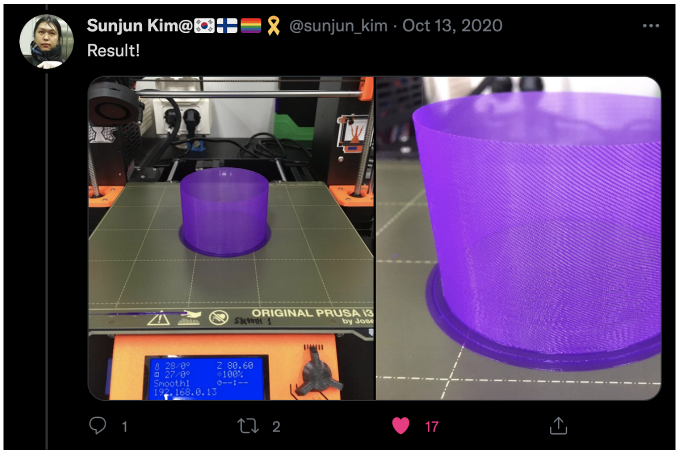
nozzle height → layer height?

Jack Forman @FormanFunction · Oct 12, 2020

Nozzle height as in distance from the bed on the first layer, since you are under extruding you need to lower the nozzle so you get good adhesion to bed. FYI we somewhat arbitrarily use layer height of .2. Also glue is recommended, although a freshly cleaned print bed works too.

Sunjun Kim@🇰🇷🇫🇮🏳️‍🌈🎗 @sunjun_kim · Oct 12, 2020

Cool. Thanks for clarifying. I'll probably try a g-code trick to get a better layer adhesion, by reducing EM after a few layers.



Sunjun Kim@🇰🇷🇫🇮🏳️‍🌈🎗 @sunjun_kim · Oct 13, 2020

Result!

Figure 17: DefeXtile printing procedure communicated and replicated over twitter

Another student, without contacting me at all, reproduced a 60ft defextile roll [43]:

Vienhackar
@GNAR_League

60ft spool of DefeXtiles, 42hr print @FormanFunction @scclab115

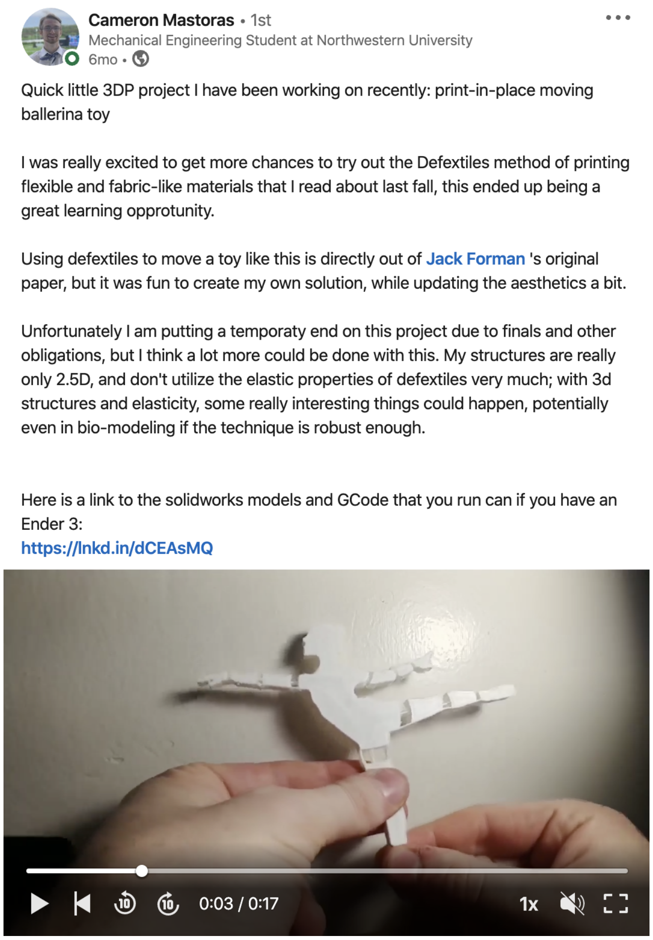
2:57 PM · Jan 27, 2021 · Twitter for Android

Figure 18: DefeXtile external roll reproduction

Weijing Xiao, a Parsons student based a speculative collection off of the technique [41]:

Figure 19: DefeXtile-inspired fashion collection by weijing Xiao

A Cameron Mastoras, a Northwestern mechanical engineering graduate student, created a Ballerina actuator:



Cameron Mastoras • 1st
Mechanical Engineering Student at Northwestern University
6mo •

Quick little 3DP project I have been working on recently: print-in-place moving ballerina toy

I was really excited to get more chances to try out the Defextiles method of printing flexible and fabric-like materials that I read about last fall, this ended up being a great learning opprotunity.

Using defextiles to move a toy like this is directly out of **Jack Forman** 's original paper, but it was fun to create my own solution, while updating the aesthetics a bit.

Unfortunately I am putting a temporaty end on this project due to finals and other obligations, but I think a lot more could be done with this. My structures are really only 2.5D, and don't utilize the elastic properties of defextiles very much; with 3d structures and elasticity, some really interesting things could happen, potentially even in bio-modeling if the technique is robust enough.

Here is a link to the solidworks models and GCode that you run can if you have an Ender 3:
https://lnkd.in/dCEAsMQ

Figure 20: DefeXtile Ballerina Tendon actuator

8.2 External Reception

Another discussion I was eagerly anticipating post-publication was debate onto whether or not DefeXtiles was a textile. As background, let's first define what a textile is. While it is agreed that "Textiles'' share a definition with "fabric", the definition has significant variation across sources. Merriam Webster defines fabrics as "a material that resembles cloth". [40]

I find this definition cautious to a fault, as it establishes little and relies upon the readers' previous experiences. Encyclopedia Britannica and Wikipedia have more discrete definitions that closely overlap. My synthesis of these two - which I find most comprehensive - is “A flexible material made from a network of yarns of threads, which are produced from fibers by weaving, knitting, crocheting, knotting, tatting, braiding, bonding, felting, or tufting.” [38, 39]

In this section, I argue that DefeXtiles are textiles. Someone who objects to this may point out that “3D Printing” is not included in this list of processes. While true, the etymology of textile shows it comes from the french word *texere*, or “to weave” [38]. However, we now use the word to describe fabric that comes from a range of processes. This demonstrates that the definition of textile is descriptively derived, not prescriptively.

Over the course of this thesis, I talked with many textile researchers and professors about whether they thought DefeXtiles is a fabric. Many agreed with categorization, and those that hesitated were swayed when they were able to actually touch the material.

It could be argued that the definition of “textile” is outdated as a result of this work, as none of the mentioned processes quite capture this undextrusion layer-by-layer technique. “Bonding” is the closest, as it includes a thermal processing step where a network of fibers are briefly melted and resolidified to create a non-woven fabric. However, this thermal treatment is a bulk process and yields flat textiles. To spare updating the definition of “textile”, the definition of “bonding” would need to be adjusted. Only time will tell if DefeXtiles becomes widely implemented and notable enough to justify this update. It is fun to imagine.

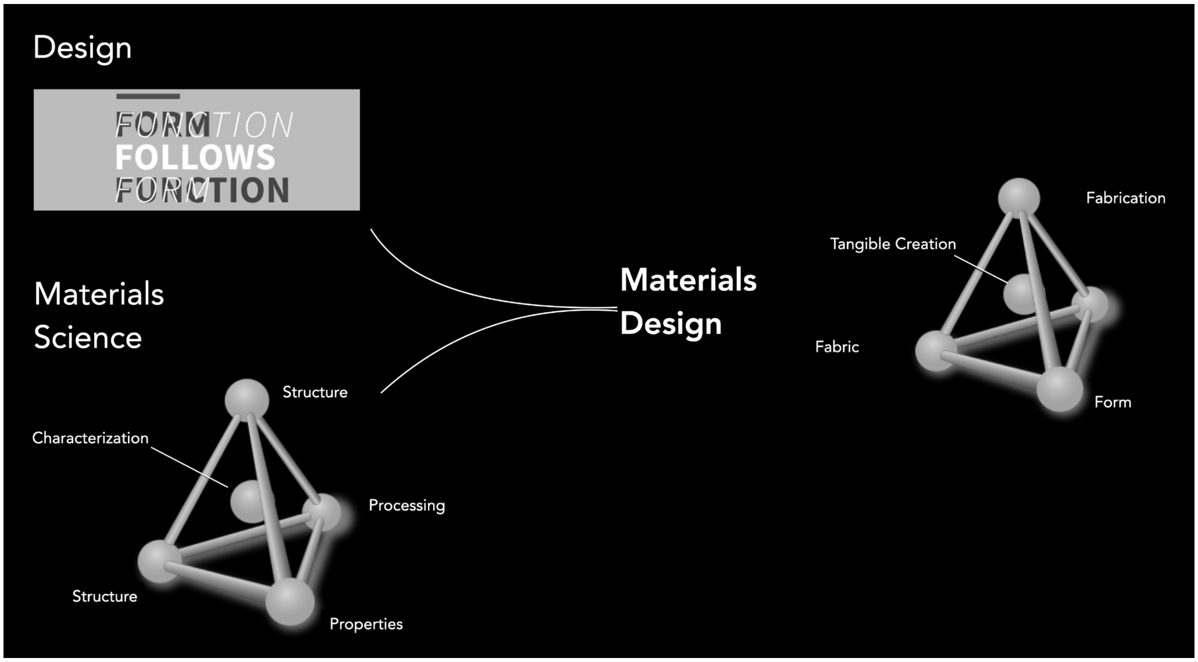
As a philosophical aside, due to the subjective definition and characterization methodology of “textileness”, it would seem impossible to *prove* whether or not DefeXtiles are or are not textiles. This is frustrating to me as a scientist who seeks to produce falsifiable theories. It would be an intellectual sedative to simply say that this property exists in a realm of emotion and consciousness that is untethered to the laws of physics and therefore cannot be predicted or modeled. In my future work, I aim to postulate a *Physics of Materials Experience* that aims to predict the sensory interaction with materials beyond case-dependent observation and frameworks.

Chapter 9: 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.

This work showcases the potential of integrated fabrication; the simultaneous advancement of form, function, fabric, and fabrication. Industrial design, in contrast, focuses on the form to suit a specific function. The question of which manufacturing method to use only comes after the product is designed. The material and fabrication are viewed as black boxes, eliminating chances of serendipitous discovery through manipulation of material and machine quirks. Materials science, on the other hand, looks very specifically at a material, how to make it, and how to fabricate it. However, as the goal is to create platform technologies, the specific forms and functions are intentionally left undetermined. While useful in many cases, this prevents the development of a material and manufacturing process that fulfills design goals in an end-to-end manner. I describe “Materials Design” as the integration of these two. In this approach, there are no black boxes. Each aspect of Tangible Creation is an open variable, adapted around the goal of creation. This creates a symbiotic relationship, as the unexpected ways designers use materials can inspire materials scientists, and designers can benefit from having their needs and wants kept in mind by materials scientists as they develop new materials.



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