A Tunable, 3D Printed "Textile" for Soft or Wearable Robots

Sonia F. Roberts[1], *Jack Forman* [2], *Hiroshi Ishii*[2], *and Kristen L. Dorsey*[*1,2]
[1]Northeastern University, Boston, USA
[2]Massachusetts Institute of Technology, Cambridge, USA

Abstract

3D printed materials are of interest in soft and wearable robotics due to the wide range of printable materials, but success in demonstrating sensors, actuators, and structures typically requires specialized equipment or techniques. We present a 3D printed, textile like material using a commercial fused deposition modeling printer and a common 3D printing filament. By modifying the print settings, we demonstrate tunable mechanical, material, and electrical properties of the resultant textile.

Introduction

Many materials for soft robotics, including textiles. Wearable robots. Robots require sensors, actuators, conductors for electronics. Researchers have expended significant effort to fabricate sensors embedded in cloth or rubbery materials; many of these fabrication processes require fume hoods or specialized equipment. Some notable exceptions to lab-based fabrication processes include printing conductive ink onto clothing [1] and fibercraft with conductive yarn or thread [2]. While these processes empower users to fabricate cloth-embedded sensors at home or in makerspaces, specialized tools may still be required to achieve precise sensor placements and repeatable performance.

3D printing offers an approach to generate both soft structure and conductors for sensors and electronics in a process that is accessible to a wide range of robotics designers. Innovations in 3D printing have spurred interest in printing flexible materials [3], 3D printed textiles [4, 5], and 3D printed sensors [6]. A common fabrication approach for 3D printed flexible sensors is to print the conductive layer(s) on top of or embedded within a flexible substrate such as silicone [7]. While these works are major steps towards sensors that are seamlessly integrate, they require custom fabrication equipment and significant user training or advanced materials for the substrate or conductive layers [8].

This work demonstrates a 3D printing process towards textile-like materials, conductors, and sensors. In contrast to previously demonstrated flexible filament 3D printed sensors, the process uses only commercially available filaments in an unmodified fused deposition modeling (FDM) printer. The resultant material — defeXtiles [9] — is mesh-like, compliant, and its properties are tunable with print settings. To illustrate defeXtile's applications as a smart material for robotics, we characterize its electrical and mechanical responses and demonstrate a strain sensor.

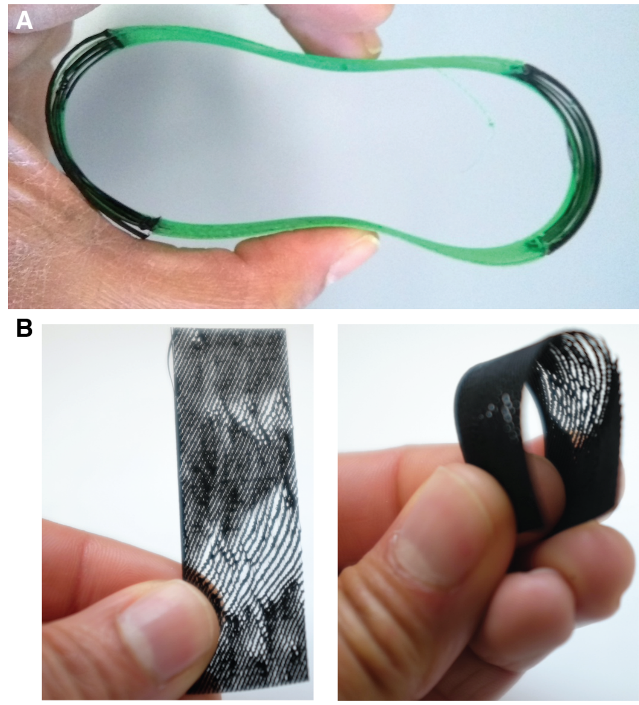

Figure 1: Photographs of defeXtiles samples. (a) A multi-material band with standard PLA (green) and conductive PLA (black). (b) A conductive sample with extrusion multiplier (EM) = 0.4.

DefeXtiles Structure

Defextiles are fabricated by reducing the extrusion multiplier (i.e., the fraction of material extruded by the print head) in the slicer software during 3D printing. The printed material is a network of thin "threads" between "posts" of larger deposited material. The print's flexibility arises from the mechanical compliance of the threads rather than the use of a flexible filament. In contrast to other flexible prints that print a single layer onto the bed, this approach enables more complex, 3D structures. Fig. 1 is a series of photos of defeXtiles samples. Fabrication process details are available in the Materials and Methods section.

The mechanical properties of the material and thread size are tunable through the extrusion multiplier (EM) and the print head speed settings [4]. Micrographs of conductive (Fig. 2) and standard (Fig. 3) PLA illustrate that the filament selection influences the thread size and morphology, as standard PLA threads (10 µ) are thinner for the same speed and EM than conductive PLA (100 µ). In the standard PLA, a network of posts and threads is visible in all samples, while in the conductive PLA, the 0.5 EM sample is almost entirely opaque. The thread diameters are approximately 35 µm and 100 µm for the 0.3 and 0.4 EM settings, respectively. The samples with EM of 0.5 have a high enough material extrusion that individual threads are not visible, and the structure similar to a solid print. The thickness of the sample at the posts is approximately 400 µm, which is determined by the nozzle size of the printer.

Using a multi-material 3D printer, both standard and conductive PLA may be deposited to form sensing and structural regions of a print. Due to the brittle nature of the conductive PLA, the extrusion multiplier typically needs to be higher (e.g., EM > 0.3) than for standard PLA (e.g., EM > 0.2) for the print to be successful. Fig. 1a is a photograph of a two-material band of defeXtiles, with standard PLA in green and conductive PLA in black.

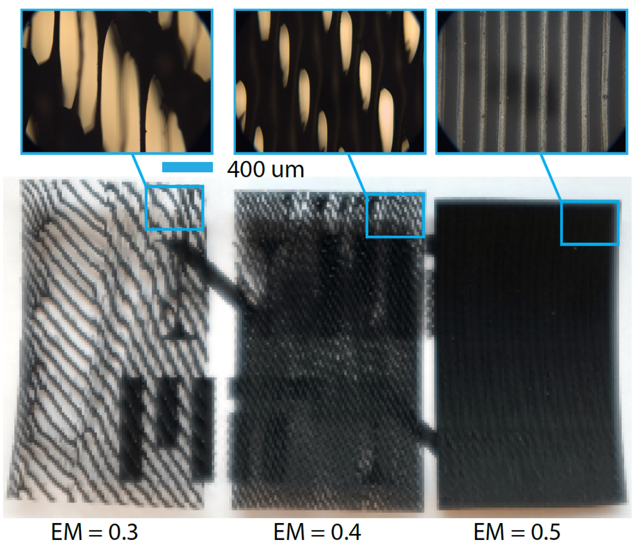

Figure 2: Photographs of conductive PLA defeXtiles samples with varying EM. Insets: Optical micrographs of conductive defeXtiles samples.

Tunable Material Properties

The structure of defeXtiles determines both its mechanical and electrical properties. Samples with longer, thinner threads are more compliant and less mechanically robust, while samples with thicker threads are more mechanically robust. Fig 4 is a series of photographs that show the shape of standard PLA samples under a mass. As EM increases, the textile becomes less compliant in bending.

Fig. 5 illustrates the response of each EM to tension. The 0.5 EM sample had the largest stiffness and was able to tolerate forces of 50 N, at which point the test was stopped. The 0.3 EM sample is most compliant and has the lowest initial sensitivity. Above strains of 1%, the resistance of each sample increases by a percentage of greater than 50 before the samples begin to tear. The force-tension curve illustrates these partial tears (e.g., EM of 0.4 at 2-4% strain), and the samples after the test are shown with the inset photographs. The average and standard deviation

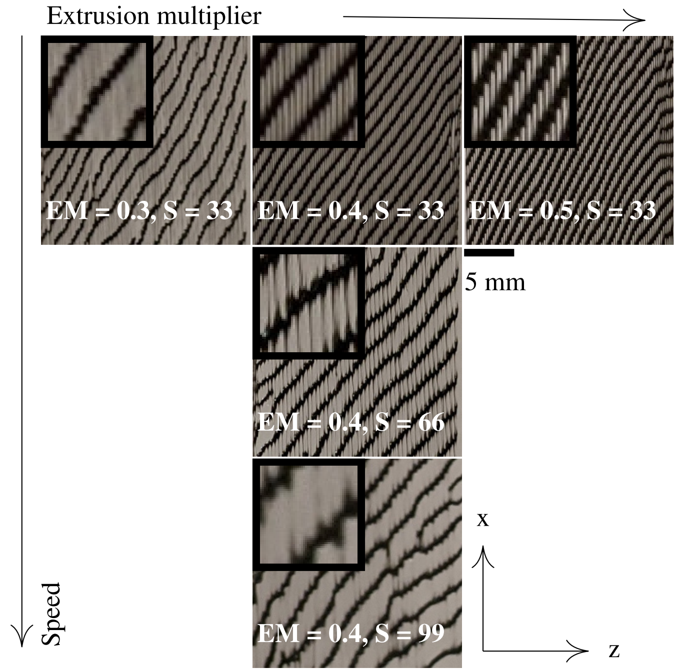

Figure 3: Photographs of standard defeXtiles samples with different print parameters. Insets: A close-up (6 ×) view of each sample, showing the mesh structure. Increasing speed creates a thinner thread, while increasing extrusion multiplier creates a thicker and shorter thread. The uniformity of thread orientation with respect to the print direction also decreases with print speed.

in maximum force and tensile gauge factor (GF) (i.e., the ratio of the resistance change to the applied strain) at a tensile strain ε of 1% is presented in Table 1 (N = 5).

To detect contact with the environment and serve as proprioception for actuators, resistive sensing, rather than inductive or capacitive, are best suited to defeXtiles because the material has a sheet resistance in the 1 kΩ/sq range. In defeXtiles, similar to many textiles, the material is flexible out of plane but stiff in plane as planar deformation exerts an axial force on the threads. As such, the conductivity of the material under deformation can change in a few ways: the deformation can change the thread geometry, the deformation can cause delamination between printed layers of the material, and the deformation can modify conductivity within the PLA.

The average and standard deviation of sheet resistances for five samples of each EM are displayed in Table 1. The unstressed resistance of a sample ranges with EM. Samples with an EM of 0.3 have the largest sheet resistance, while samples with an EM of 0.5 have the smallest.

Table 1: Mechanical and electrical properties with EM (average ± one standard deviation).

Property	0.3	0.4	0.5
Resistance (kΩ/sq)	5±0.34	0.74±0.06	0.44±0.06
Max Tension (N)	3.0±1.0	33.8±6.9	> 50

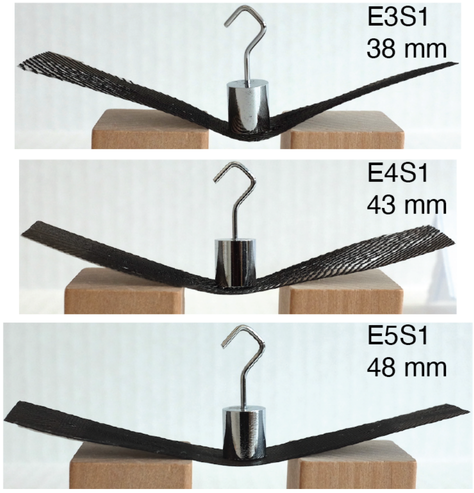

Figure 4: Photographs of standard defeXtiles samples deforming under a 10 g mass. The shape of the sample illustrates how compliant or stiff it is to bending, most akin to the textile property of "drape."

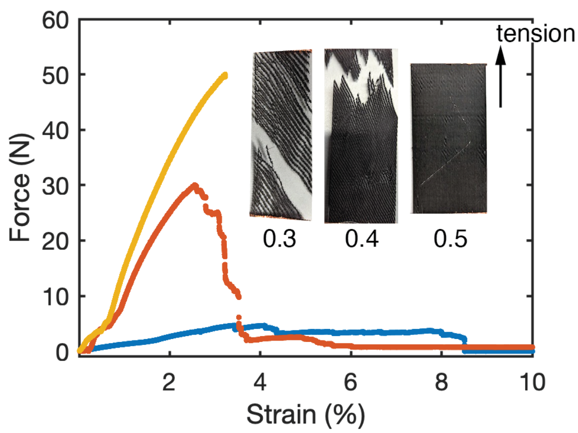

Figure 5: Force response of conductive samples to tension during one cycle of loading to failure. A representative sample of each EM is included.

Conclusions and Future Work

This paper introduced a 3D-printed conductive textile material and demonstrated the material's applications to conductive wearable sensors. This process makes it possible to fabricate mechanically and electrically tunable materials and multi-material structures using hobbyist materials and equipment, making it a promising approach for "democratizing" access to wearable robots and sensors. Additional effort is required to understand sources of electrical and mechanical variation and develop strategies for increasing mechanical robustness while maintaining flexibility.

Materials and Methods

A Flash Forge Creator Pro 2 with dual nozzles was used for all prints. Parts were sliced using Simplify3D and printed at a speed of 3600 mm/min as a ring with 20 mm height and 8 cm diameter. Before printing, the global height between nozzle and bed was decreased by 150 µm from the leveling step to allow the material to adhere to the bed. Conductive structures were printed with using ProtoPasta conductive PLA (T = 220 °C, EM = 0.7) and standard PLA structures were printed using Hatchbox PLA (T = 220 °C, EM = 0.4), with a bed temperature set to 40 °C. After printing, the defeXtiles rings were cut into 60 mm × 20 mm strips and annealed by placing into an oven heated to 60 °C which was allowed to cool to room temperature over 3 h. After annealing, the end of each sample was wrapped with copper tape, which served as electrodes. The copper tape was coated with a thin later of hot melt adhesive to provide additional adhesion during mechanical testing and to electrically isolate the samples from the materials testing system.

Resistance during mechanical testing was measured using an NI-6002 USB data acquisition board and voltage divider, and sheet resistance was measured with a benchtop digital multimeter (BK Precision 5492B). Samples were loaded into a materials tester (i-Test 2.5, Mecmesin), gripped with a set of pneumatic grips, and strained at a rate of 2 mm/min for the tension tests and -2 mm/min for the compression tests. Tension tests were terminated when the load reached 50 N or the extension reached 10 mm, while compression tests displaced to -10 mm and returned to 0 mm.

Acknowledgements

The authors would like to thank Dr. H. Hochsztein for guidance with mechanical test equipment.

References

[1] C. Honnet, H. Perner-Wilson, M. Teyssier, B. Fruchard, J. Steimle, A. C. Baptista, and P. Strohmeier, "PolySense: Augmenting Textiles with Electrical Functionality using In-Situ Polymerization," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, Apr. 2020, pp. 1–13. [Online]. Available: https://doi.org/10.1145/3313831.3376841

[2] Y. Li, X. Miao, L. Niu, G. Jiang, and P. Ma, "Human Motion Recognition of Knitted Flexible Sensor in Walking Cycle," *Sensors*, vol. 20, no. 1, p. 35, Jan. 2020, number: 1 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/1424-8220/20/1/35

[3] R. Uysal and J. B. Stubbs, "A New Method of Printing Multi-Material Textiles by Fused Deposition Modelling (FDM)," *TEKSTILEC*, vol. 62, no. 4, pp. 248–257, Nov. 2019. [Online]. Available: http://www.tekstilec.si/wp-content/uploads/2019/11/10.14502Tekstilec2019.62.248-257.pdf

[4] K. L. Dorsey, S. F. Roberts, J. Forman, and H. Ishii, "Analysis of DefeXtiles: a 3D printed textile towards

garments and accessories," *Journal of Micromechanics and Microengineering*, vol. 32, no. 3, p. 034005, Feb. 2022, publisher: IOP Publishing. [Online]. Available: https://doi.org/10.1088/1361-6439/ac4fad

[5] J. Forman, M. Dogan, H. Forsythe, and H. Ishii, "DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion," in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 2020. [Online]. Available: https://dl.acm.org/doi/abs/10.1145/3379337.3415876

[6] H. Liu, H. Zhang, W. Han, H. Lin, R. Li, J. Zhu, and W. Huang, "3D Printed Flexible Strain Sensors: From Printing to Devices and Signals," *Advanced Materials*, vol. 33, no. 8, p. 2004782, 2021. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202004782

[7] M. R. Khosravani and T. Reinicke, "3D-printed sensors: Current progress and future challenges," *Sensors and Actuators A: Physical*, vol. 305, p. 111916, Apr. 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924424720300868

[8] T. Xiao, C. Qian, R. Yin, K. Wang, Y. Gao, and F. Xuan, "3D Printing of Flexible Strain Sensor Array Based on UV-Curable Multiwalled Carbon Nanotube/Elastomer Composite," *Advanced Materials Technologies*, vol. 6, no. 1, p. 2000745, 2021. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.202000745

[9] J. Forman, M. D. Dogan, H. Forsythe, and H. Ishii, "Defextiles: 3d printing quasi-woven fabric via under-extrusion," in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 2020, pp. 1222–1233.

Correspondence

*K.L. Dorsey, +1-617-373-2071, k.dorsey@northeastern.edu