Hydrogel-Textile Composites: Actuators for Shape-Changing Interfaces

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Abstract
The current work examines interactions that are enabled when depositing a human-safe hydrogel onto textile substrates. These hydrogel-textile composites are water-responsive, supporting reversible actuation. To enable these interactions, we describe a fabrication process using a consumer-grade 3D printer. We show how different combinations of printed hydrogel patterns and textiles create a rich actuator design space. Finally, we show an application of this approach and discuss opportunities for future work.

Author Keywords
textiles; hydrogel; shape-changing interfaces; 3D printing; digital fabrication; composites; actuators

CCS Concepts
•Human-centered computing → Human computer interaction (HCI);

Introduction
Textiles have long been valued for their engineerable properties including flexibility, softness and stretchability. In recent years, there has been growing interest in textiles as an interactive media. The material has been explored as a sensor for human-activity [10,22] and musical performance [25], and as an actuator for interactive experiences [1,6]. Such interactive capabilities have been enabled through traditional

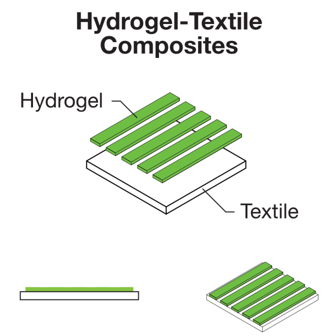

Figure 1: Hydrogel-textile composites are fabricated by 3D printing hydrogel patterns onto textile substrates.

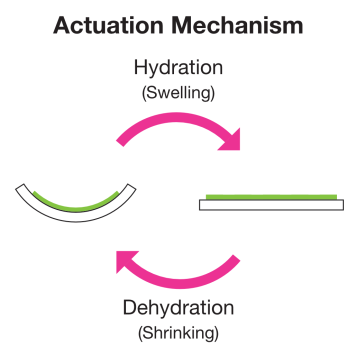

Figure 2: Hydrogel-textile composites actuate in response to water. As they dehydrate, or dry, they reverse their actuation.

textile-working techniques, like sewing [13, 22] and knitting [1], as well as through new manufacturing processes such as 3D printing [8, 16, 17, 21] and electrospinning [20].

The current work builds on this space and explores a new method for creating interactive textiles that can reversibly change shape. This method combines textiles with κ-carrageenan [1] hydrogel (Figure 1), a human-safe material that swells in response to water. Water-based actuation allows these composites to move without the need of a power source unlike similar approaches that rely on joule heating [5, 6, 13] and motor-driven tendons [1, 21] (Figure 2). To this end, we demonstrate a fabrication approach that supports the creation of these hydrogel-textile composites. Furthermore, we explore a range of shape-changes that can be achieved through variations in the hydrogel patterning as well as the textile substrate. With these explorations we hope to inspire the use of hydrogel-textile composites for power-less, but powerful shape-changing interfaces.

Related Work

Our work is tied to areas of research in the Human-Computer Interaction (HCI) and Material Science communities including interactive textiles, fabrication of textiles, and responsive hydrogels.

Interactive Textiles

Textiles have seen a variety of interactive use cases. Recent work has explored the material as a means to sense human gesture input [10, 15, 22, 25] and display information through light [15] and color change [3]. Others have examined actuating textiles in response to external stimuli such as motor-driven tendons [1, 21] and joule heating [5, 6, 13]. The current work demonstrates another technique for fabricating interactive textiles that can actuate. However, actuation is achieved without the use of a power source. Our approach patterns a human-safe hydrogel onto textiles. This composite form enables a textile to change shape when the hydrogel swells in response to water.

[1]Carrageenan: https://en.wikipedia.org/wiki/Carrageenan

Fabrication of Textiles

Researchers in the HCI community have leveraged traditional textile-working techniques and new manufacturing processes to create textiles for soft interactions. Albaugh *et al.* explore the use of machine knitting to enable soft actuation in knitted forms [1]. Project Jacquard [18] demonstrates a large-scale process for producing highly conductive yarns. Others have developed 3D printing processes that fabricate textile forms by adhering layers of fabric together [16], felting yarn [8], and melt electrospinning plastic [20]. Our work builds on efforts that use 3D printing processes with textiles. We rely on a similar technique used in [21] to print directly onto textile substrates. However, rather than depositing rigid plastic, we print a human-safe hydrogel that facilitates water-based actuation.

Responsive Hydrogels

Hydrogels[2] are hydrophilic polymer networks that can absorb significant amounts of water. They have been engineered to respond to external stimuli such as pH [26], temperature [9, 14], and light [11]. In the HCI community, poly(N-isopropylacrylamide), or PNIPAM, hydrogel has previously been used to support stiffness- and opacity-changing interfaces [9, 12]. However, PNIPAM hydrogel is not recommended for direct contact with human skin and its synthesis requires the use of hazardous materials (*i.e.* N-isopropylacrylamide[3]). In contrast, the current work relies on κ-carrageenan, a human-safe material that is extracted

[2]Hydrogel: https://wikipedia.com/hydrogel
[3]N-isopropylacrylamide: https://pubchem.ncbi.nlm.nih.gov/compound/16637

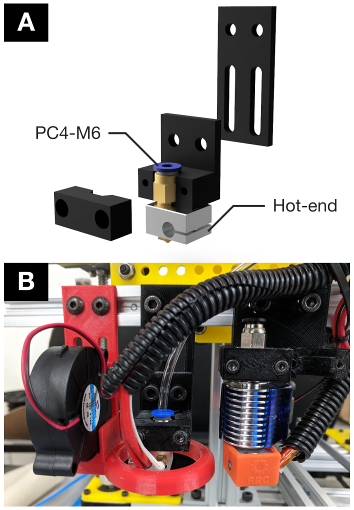

Figure 3: Component view of our hot-end mount design showing the PC4-M6 connector threaded into the hot-end. (A). Our hydrogel hot-end and radial fan mounted onto a 3D printer to the left of a rigid plastic extruder (B).

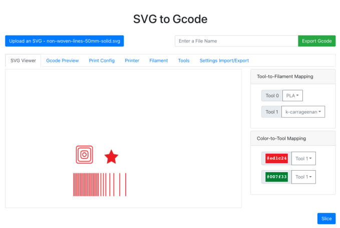

Figure 4: Design tool that converts SVG patterns into 3D printer tool-paths.

from red seaweed. Transformative Appetite [24] explores food made of gelatin-cellulose films that changes shape when cooked in water. However, these films only achieve one-time actuation. Finally, Gallegos *et al.* demonstrated using a 3D printer to extrude κ-carrageenan hydrogel [4]. We employ their material preparation procedure and explore how the hydrogel can be leveraged for interactive purposes. In particular, we use κ-carrageenan hydrogel alongside textiles to create reversible water-responsive actuation.

Fabrication Technique

This section describes how to prepare κ-carrageenan hydrogel for use in a consumer-grade 3D printing process. We provide open-source 3D printer modifications that are necessary to extrude the hydrogel. Additionally, we show a web-based design tool that supports converting Scalable Vector Graphic (SVG) patterns into Gcode instructions for a 3D printer. As a whole, this process enables hydrogel patterns to be designed and fabricated onto textiles.

Hydrogel Preparation

Prior efforts in Food Science literature have shown how to 3D print κ-carrageenan hydrogel with in situ polymerization [4]. We leverage their material preparation procedure in our work. We prepare a 3% solution of κ-carrageenan hydrogel by dispersing 3 grams of κ-carrageenan [4] into 100 grams of cold water. The water is placed into in a beaker along with a magnetic stirring rod. We then slowly add κ-carrageenan, ensuring that the powder does not cake together. The dispersion is left to mix on the magnetic stirrer plate for 30 minutes to create a homogeneous solution. The prepared gel is then transferred to a 60 mm syringe [5].

[4] κ-carrageenan : https://www.sigmaaldrich.com/catalog/product/sigma/22048
[5] 60 mL Syringe: https://www.amazon.com/dp/B01MSWPOO2/

We experimented with different concentrations of the hydrogel and found that 2% and 3% worked best. Higher concentrations ($\geq$ 4%) resulted in a significantly higher viscosity gel that was not able to be homogeneously mixed with our magnetic stirrer plate. Lower concentrations were obtainable, however, we chose a 3% solution to obtain a more robust and tough hydrogel without sacrificing too much swelling capacity for shape-changes.

Printer Construction

We modified an existing Fused Filament Fabrication (FFF/FDM) 3D printer similar in design to the Prusa I3[6] to support printing the κ-carrageenan hydrogel. Extrusion of the κ-carrageenan hydrogel is done using an open-source, large volume syringe pump design [19]. Initially, we connected the syringe pump to a bowden hot-end set-up[7] that is typically used for rigid plastic printing. A similar approach was used by prior work [4]. However, we found that hydrogel would frequently dry in the cold region of the extruder (*i.e.* heat sink) during a print, blocking further extrusion.

Because the extrusion temperature of the hydrogel (50-80℃) is relatively low compared to printing rigid plastic filaments, the heat sink is not required and can be removed to reduce blockages. We replaced the heat sink with a PC4-M6[8] fitting and directly connected the bowden tube from the syringe pump (Figure 3).

As a note, the threads of the PC4-M6 fitting and the hot-end nozzle (0.4 mm) must be wrapped in PTFE thread seal tape[9] to ensure the connections are water-tight. Lastly, we designed a mount to hold the hot-end as seen in Figure 3A.

[6] Prusa I3: https://reprap.org/wiki/Prusa_i3
[7] Bowden Hot-end: https://www.amazon.com/dp/B07B4FHN72
[8] PC4-M6 Fitting: https://www.amazon.com/dp/B01NANKRTD/
[9] PTFE Thread Seal Tape: https://www.amazon.com/dp/B079T52ZYJ/

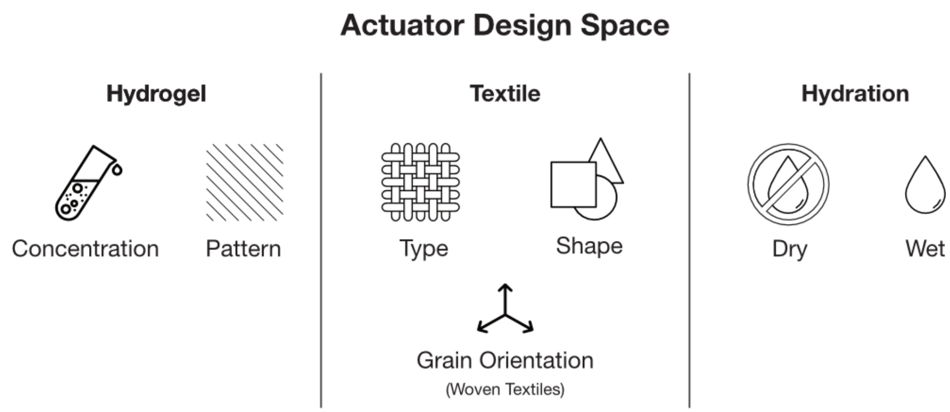

Figure 5: Hydrogel-Textile composite actuator design space.

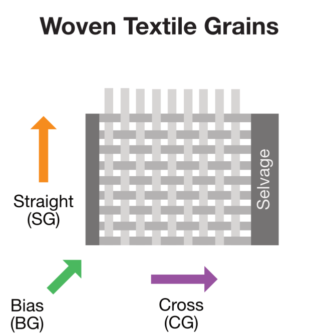

Figure 6: The structure of woven textiles gives rise to anisotropic behavior when the textile is stretched. The straight grain has the strongest resistance to deformation followed by the cross grain, and then the bias.

We also designed an adjustable radial fan mount to dry the hydrogel as it is extruded onto a textile. We have open-sourced both 3D printable mount designs here: https://github.com/mriveralee/hydrogel-textile-composite-parts.

Hydrogel Printing Parameters
We print the κ-carrageenan hydrogel at 70℃ with a print speed (*i.e.* feed rate) of 1200 mm/min. Our hot-end uses a nozzle with a 0.4 mm diameter. In our early investigations, we found that the hydrogel has a lower viscosity than rigid plastic filaments like PLA. Thus, as it is extruded, the hydrogel spreads, forming a wider extrusion width than expected. For a 0.4 mm extrusion width, we found the hydrogel's actual extrusion width to be roughly 2 mm. We calibrated the printing parameters to reflect this new extrusion width and ensure our designed patterns are printed correctly. In our design tool software, we set the extrusion width to be 2 mm and the extrusion flow to 0.36 (matching the material volume output for an 0.4 mm extrusion width for rigid plastic).

Design Tool
We developed a web-based design tool to support quickly generating hydrogel tool-paths from SVG patterns. As seen in Figure 4, the user uploads a colored pattern and matches the color to the appropriate material and tool. Once selected, the user can change various parameters such as print speed, infill percentage, extrusion flow, and extrusion width. The design's tool-path can then be exported as a Gcode file for use with a 3D printer.

Exploration of Hydrogel-Textile Composites

The hydrogel-textile composites presented in this work operate under the principle of a bilayer actuator (Figure 2). Prior work has shown that through manipulation of the bilayer's material composition and/or the placement of another material, different interactions such controlled bending can be obtained [2, 7, 23]. These interactions are enabled when one material changes its underlying properties or organization based on some energy source. For example, polylactic acid

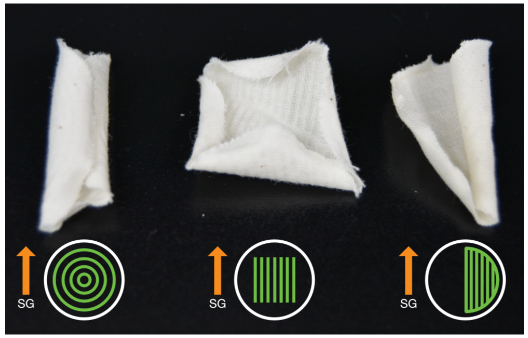

Figure 7: Test showing variations in hydrogel patterning produce different actuation states.

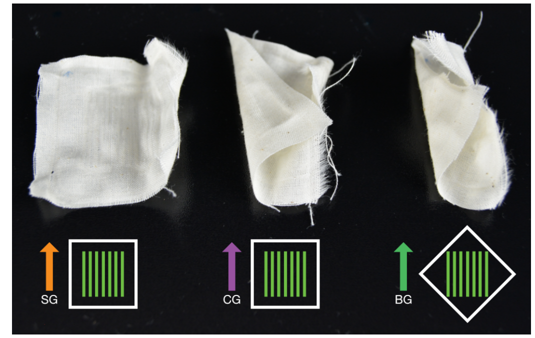

Figure 10: Resistance to shape-change with hydrogel printed across the different grains of a woven cotton textile.

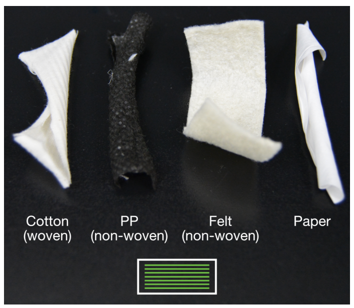

Figure 8: Test showing different actuation is produced based on the type of textile substrate.

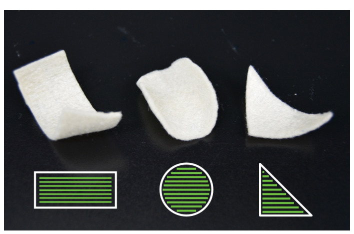

Figure 9: Test showing variations in the shape of a felt textile produce different actuation states.

(PLA) when 3D printed has stored internal stresses that can be released when the material is heated to its glass transition temperature, creating a controlled shape-change [2].

The bilayer mechanism in the current work is achieved through interactions between the κ-carrageenan hydrogel and a textile substrate as the hydrogel swells in response to water (Figure 2). In our explorations, we found that as the κ-carrageenan hydrogel dehydrates, it shrinks and pulls along the XY plane of a textile substrate. Decreasing the concentration of the hydrogel solution creates polymer networks that are less dense and increases the amount of shrinkage. Additionally, controlled placement (*i.e.* patterning) of the hydrogel onto a textile substrate can be used to obtain different shape changes (Figure 7).

The textile's composition (*i.e.* how it was manufactured), its grain orientation during hydrogel printing, and its shape (once cut to size) also serve as parameters to control the interaction in the bilayer mechanism. Our explorations demonstrate that non-woven textiles, *e.g.,* felt and polypropelene (PP), primarily respond to the hydrogel dehydration's along a single axis (either X or Y) causing bending of a textile substrate (Figure 8). While woven textiles, such as muslin cotton, tend to have interactions along both axes, resulting in twisting actuation. Non-woven textiles are thus manipulated through the substrate's shape and the hydrogel itself (Figure 9).

Woven textiles have different bilayer interactions based on the anisotrophy of their underlying grain structure (Figure 6). The straight grain of textile (parallel to the selvage) has the strongest resistance to deformation, followed by the cross grain, and then the bias (along the diagonal of the textile). In general, shrinking and swelling of a printed hydrogel is most likely to act on the bias as this direction has the most flexibility to respond to shrinkage. As seen in Figure 10, printing along the bias creates a twist and curling actuation. While printing along the straight grain introduces very little shape-change. Choosing the grain orientation of a woven textile during the printing process is thus important to ensure the desired actuated form is achieved. We have

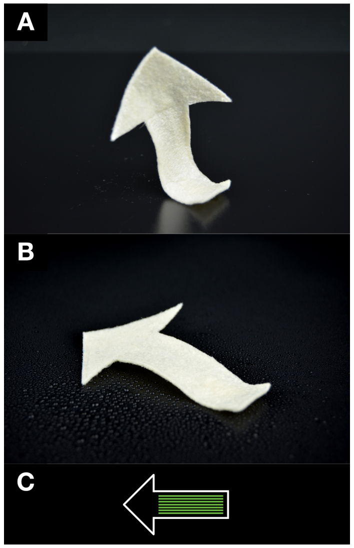

Figure 11: Weather-responsive direction indicator. When the weather is dry, the arrow points upwards (A). When it begins to rain, the arrow transforms 90-degrees to the left (B). The printed hydrogel pattern and textile shape (C).

summarized the design space for hydrogel-textile composite actuators in Figure 5.

Properties of Shape-Change
Hydrogel-textile composites change shape based on the amount of water present in the hydrogel. As the hydrogel dehydrates, it shrinks and pulls the substrate along its path of least resistance. Rehydration of the hydrogel causes the composite form to revert to its flat, neutral state. This change can occur in seconds depending on the mechanism in which the water is applied. We found using a spray bottle to hydrate the composite form achieved the fastest and most uniform actuation response when compared with an eye dropper . The rate at which the textile substrate dehydrates can vary based on the amount of water present and the thickness of the textile substrate. Very thin textiles (*e.g.,* muslin cotton, 0.3 mm in thickness) can dehydrate in a matter of minutes, while felt (1.3 mm in thickness) can take up to an hour. We are currently exploring strategies to speed up dehydration and enable faster response times such as using hot air or joule heating with conductive textiles.

Weather-Responsive Direction Indicator
As a demonstration of an interaction enabled using this technique, we created a passive, weather-responsive direction indicator (Figure 11). Many events, such as music concerts, have venues that change their location (*i.e.* from outdoor to indoor) based on the weather at the time of the event. By printing a rectilinear pattern onto an arrow-shaped piece of felt (Figure 11C), we created a direction indicator that points 90-degrees in one direction when the weather is dry (Figure 11A). When it rains, the arrow changes to a flattened state to point in another direction (Figure 11B).

Future Work
This effort is the beginning of a larger exploration in integrating hydrogels and textiles into 3D printing processes. The combination of textiles with this material creates interesting opportunities for objects that change shape and/or functionality in response to water. We plan to explore how the swelling of the hydrogel on a textile can be used to sense different environmental based-interactions (*i.e.* relative humidity in a room) and trigger actuation responses. For example, a textile-based lampshade could actuate to cover a light as steam from a user's shower increases in the bathroom. The change in lighting can serve as a passive reminder of how much water an individual is consuming while showering.

While we were able to demonstrate a variety of different actuators, we aim to fully understand the mechanism underpinning how the patterning is influenced by the type of textile substrate to which it is applied. A physical understanding of this mechanism can be used to enable simulation of the hydrogel-textile composite's actuation prior to fabrication. We also believe this could support an inverse design tool that determines the optimal textile substrate and hydrogel patterning for a user-specified shape-change.

Conclusion
We have demonstrated an approach to fabricating interactive hydrogel-textile composites. We believe the interactions between these two materials can support new dimensions of experience such as selectively activated texturing, moisture-responsive clothing, and power-less environmentally-responsive applications such as rain-driven seed deposition. As a whole, hydrogel-textile composites provide a new tool for HCI researchers and practitioners to create shape-changing interfaces.

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