There exist many methods for processing of materials: extrusion, injection molding, fibers spinning, 3D printing, to name a few. In most cases, materials with a static, fixed shape are produced. However, numerous advanced applications require customized elements with reconfigurable shape. The few available techniques capable of overcoming this problem are expensive and/or time-consuming. Here, the use of one of the most ancient technologies for structuring, embroidering, is proposed to generate sophisticated patterns of active materials, and, in this way, to achieve complex actuation. By combining experiments and computational modeling, the fundamental rules that can predict the folding behavior of sheets with a variety of stitch-patterns are elucidated. It is demonstrated that theoretical mechanics analysis is only suitable to predict the behavior of the simplest experimental setups, whereas computer modeling gives better predictions for more complex cases. Finally, the applicability of the rules by designing basic origami structures and wrinkling substrates with controlled thermal insulation properties is shown.

1. Introduction

The rapid rise of many advanced technologies is closely related to, and heavily dependent on, the fabrication of complex 3D structures. Another vital requirement for 3D fabrication technologies is the possibility to quickly and accurately create custom-designed objects on-demand. There exist many methods for processing of materials: extrusion, injection molding, rotor molding, fiber spinning, weaving, 3D printing, etc. However, in most cases, materials with static, fixed shape are fabricated.

One highly attractive approach capable of overcoming this problem is the origami-inspired self-folding, which enables the morphing of 2D objects (films and sheets) into 3D ones,[1–4] a trait highly demanded in areas such as robotics,[5,6] sensors,[7] smart textiles,[8] batteries,[9] metamaterials,[10,11] etc. Until now, the research focus has been on the fabrication of self-folding patterned polymer sheets[12] either from stimuli-responsive hydrogels,[13–15] or from liquid crystalline elastomers,[7,16] and on the investigation of their folding behavior.[17] The actuation behavior of such sheets is determined by their patterns.[18] Complex actuation requires a highly complicated multilayer patterning, which is commonly done by multistep photolithography or by photolithography combined with electrosprinning.[19] Even manual assembly of multilayer systems proves challenging.[5]

Another promising approach is 3D printing; however, not every material can be 3D printed and complex shapes are still difficult to manufacture.[20–22] In this paper, we apply one of the most ancient structuring technologies, embroidering, to a new set of materials to generate complex patterns of active materials and in this way to achieve complex actuation. According to this concept, pattern is generated by an incorporation of an active fiber in a passive matrix. A change in the length of the fibers will induce a change in the shape of the fabric and the folding behavior will be determined by the embroidery pattern. Thus, using actively moving fibers with very simple contraction/elongation actuation will allow for the controlled transformation from 1D and 2D to 3D.

In order to achieve a change of the shape of the sheets, we use temperature-responsive shape-memory fibers. The use of shape-memory polymeric fibers has a number of advantages: (i) the degree of actuation can be controlled by the degree of stretching; (ii) the direction of actuation is controlled by the orientation of the stitches; (iii) the force generated by the fiber depends on the thickness of the fiber; and (iv) the actuation temperature can be finely tuned by the polymer composition, allowing actuation in the ambient temperature range. By combining experiments and computational modeling, we elucidate fundamental rules that allow predictions of the folding behavior of sheets with any stitch-pattern.

2. Results and Discussion

In this work, we used shape-memory polyurethane (SMPU) fibers to perform both experiments and modeling. SMPU is a rubber material with Young’s modulus of about 3.5 GPa at 20 °C and 0.045 GPa at 60 °C. These fibers demonstrate clear shape-memory behavior—they can be stretched at 60 °C and then cooled down to freeze the temporary shape. They slowly relax when heated to around 20 °C (Figure S1, Supporting Information) and typical shape-recovery times at this temperature are...
in the order of tens of minutes. The shape recovery proceeds much faster at 60 °C, with typical recovery times in the order of seconds. The completeness of recovery of shape after heating depends on the strain. Full recovery was observed when the fiber was stretched up to 200%. Samples stretched to more than 200% experience residual strain after recovery is completed. Based on these results, we chose 200% strain as an optimal for further experiments.

First, we tested the deformation of single stitches. Strips of different dimensions were cut from the model materials (rubber or fabric). Prestretched SMPU fibers with a diameter of 1.4 mm and of corresponding length, fixed at 200% strain at 20 °C temperature, were attached at the opposing sides of the strips. The temperature was then quickly increased to 60 °C that induced shape-transition of the fiber. The contraction of the fiber led to bending of the rubber and the fabric in a way that arc-like shapes were formed (Figure 1a,b; Movie S1 and S2, Supporting Information). The diameter of the SMPU fiber was chosen so it assures actuation for both substrates: rubber and fabric (see Supporting Information for details). Finite element (FE) simulations of the fiber-substrate structure in Figure 1b also predict the same folding pattern as experimental results show.

We measured the residual strain (RS) (Equation (1)) in the SMPU fibers after its contraction (Figure 1c) depending on the size of the stitch, which is defined as:

\[
RS = \left( \frac{L_{\text{stretched}} - L_{\text{initial}}}{L_{\text{stretched}} - L_{\text{relaxed}}} \right) \times 100\% \quad (1)
\]

where \(L_{\text{stretched}}\) is the length of the fiber between the stitch points prior to heating, \(L_{\text{relaxed}}\) is the length of the fiber between the stitch points after heating (i.e., after shape recovery), and \(L_{\text{initial}}\) is the length of the fiber between the stitch points with 100% recovery. RS = 100% means that the fiber does not contract at all, 0% means that the fiber fully contracts to its initial length. In the case of the nonelastic fabric substrate, no residual strain was observed (RS = 0%) This is in agreement with the mechanical properties of the material—it is very soft toward out-of-plane deformations and, due to its fibrous and porous structure, provides less resistance to bending than the rubber substrate. However, a different behavior was observed for the elastic rubber substrate. At large stitch-to-stitch distances (8 and 12 cm), the residual strain was close to 5%, i.e., the substrate exerts a negligible resistance during actuation. Residual strain increases when the stitches become shorter. It was found experimentally that the RS can be best approximated as \(RS = \frac{1}{L_{\text{stretched}}}\). Finite element simulations provided similar prediction for the residual strain of the shrinking fiber (Figure 1c). Simulation results were in good agreement with the experimental results. The small discrepancy could possibly be attributed to the material model of the fiber. In finite element models, a purely elastic material model was used for the fiber, while in the experiments it shows a complex material behavior other than just elastic behaviors.

Here, we also modeled the deformation of fabric/rubber-fiber system theoretically (see Supporting Information for details). First, we applied a simple mechanical model where the equilibrium shape was determined by the balance between the force generated by the fiber during contraction and the force needed to deform the substrate. The residual strain can be expressed as:

\[
RS = \left[ \frac{1}{1 + \left( \frac{3\pi^2 E_f t}{w^2 E_s} \right) R^2} \right] \times 100\% \quad (2)
\]

where \(w\) and \(t\) are the width and thickness of the substrate cross-section, \(d_f\) is the fiber diameter, \(E_f\) and \(E_s\) are the elastic moduli of the fiber and the substrate, respectively, \(R\) is the radius of the folded substrate. Since the length of stitches \((L_{\text{stretched}})\) is proportional to the radius of the folded substrate, the dependence of residual strain on the length of the stitches can be expressed as \(RS = \frac{1}{L_{\text{stretched}}}\) that correlates well with the experimental observations. According to Equation (2), the residual strain decreases with the increase in fiber diameter and substrate thickness. The ratio between the elastic moduli

![Figure 1](image-url). Schematic plots of the fold of rectangular substrates with different lengths due to the contraction of SMPU fibers a); folded 12 cm substrates b); dependence of the residual strain in the SMPU fiber on the length of the stitch length c).
of the fiber and the substrate also plays a significant role in the residual strain: the higher the ratio is the smaller the residual strain is. This role was observed experimentally. For example, the fiber/fabric system with $E_f/E_s = 0.045 \text{ GPa}/3 \text{ MPa} = 15$ had almost no residual strain ($RS = 0\%$), while the one with $E_f/E_s = 0.045 \text{ GPa}/12 \text{ MPa} = 3.75$ did. Besides residual strain, another highly relevant parameter is the folding curvature. However, due to the fact that the stitch length is fixed and the initial strain of the fibers is known, one can easily calculate the bending radius from the residual strain by simple geometric considerations (see Supporting Information).

Next, we tested if the folding of multiple sequential stitches is different from that of the singular ones. With this purpose in mind, long and narrow strips were prepared and the SMPU fiber was stitched onto them with a running stitch, which was made by passing the needle in and out of the fabric. The length of the stitches was varied: 1, 2, and 4 cm. We tested two scenarios: in the first one, the length of all stitches along one fiber was the same (Figure 2a; Movie S3 and S4, Supporting Information); in the second one, the stitches along one fiber had different length. Similar to the experiments with a single stitch, fiber contraction resulted in wrinkles of both substrates: rubber and fabric. However, the characteristics of wrinkles depend on the type of substrates: the wrinkles were regular when rubber was used as substrate and less regular when fabric was used. We explain the irregularity of the fabric wrinkles by the presence of limited slip between the fiber and the substrate. At the beginning of the process, when the fiber is under full stretch, the diameter of the holes in the fabric is larger than the cross-section of the fiber, which is a result of the sewing and the nonelastic behavior of the fabric. This size difference implies that at the initial stages of the folding the fiber can freely slip through the stitch holes, thereby leading to irregular folding of the fabric. Later on, this slip is hampered due to the increasing diameter of the fiber during folding, fixating, and augmenting any irregularities from the first stages.

In multistitch experiments, the residual strain of fibers depends on the length of the stitches, similarly to the trend we observed in the single-stitch experiments. The total shape-recovery of the SMPU fiber approached 100% (corresponding to $RS = 0\%$) for the fabric substrate, regardless of the initial stitch-to-stitch distance, a result fully in line with our previous observations (Figure 2f). In the case of rubber substrates, the residual strain in the consecutive stitches matched that observed in the single-stitch experiments (Figure 2f compare with Figure 1c). Therefore, every single stitch can be considered separately and independently from each other. FE models also verify experimental results (Figure 2c,e). Similar to the experimental observation, the substrate starts to fold between stitch points. The number of folds is always one less than the number of stitch points.

Next, we investigated the folding of rubber with multiple stitches of different lengths in different directions. In particular, we compared the folding of rubber with several parallel stitches, made by individual fibers and a Π-shape stitch. The Π-shape stitch pattern results in actuation forces directed at an angle of 90° to each other. All fiber segments are parallel to each other on the front side and they act like multiple parallel basting stitches. This results in a folding force, which is the sum of the forces, exerted by each individual fiber segment on front side. On the back side of the rubber, the fiber segments are allocated apart from each other in two parallel lines of evenly spaced segments. Here, we focused on the changes of rubber substrates because, first, they are elastic and actively influence the folding behavior and second, the stitches can be assumed to separate from each other. The combination of both

![Figure 2. Folding behavior of 12 cm strips, basting stitch; stitches of equal lengths for a) fabric and b) rubber substrates with c) corresponding computer simulation; d) combination of stitches of different lengths on a rubber substrate and e) computer models of them; f) average residual strain as measured between the stitch points for rubber (black) and fabric (red), the lines are just to guide the eye. Scale bars are 1 cm.](image-url)
properties allows us to describe the folding without accounting for other unknown factors due to influences from neighboring stitches. Individual stitches result in the simple bending of the rubber substrate and the bending angle is proportional to the density of stitches.

Folding of multiple parallel single stitches proceeds qualitatively similar to the folding in the case of one single stitch. The amplitude of substrate fold with multiple parallel single stitches depends on the density of stitches—the number of fibers per centimeter width of the substrate. It was observed that the folding of the substrate, measured by the angle between its folded parts (Figure 3a1–a3), becomes more pronounced with the increase in the number of stitches. Different folding patterns were observed for the case of the Π-shape stitch. A larger number of stitches still resulted in stronger folding in the x-direction while the substrate still bent in the y-direction due to the contraction of the perpendicularly positioned stitches. This bending brought the halves of the sample even closer and enhanced the folding amplitude. The folding behavior of the rubber band with multiple single stitches and Π-shape stitch predicted by computer modeling correlates with the experimentally observed one.

Next, we designed the two curve-creased elements[23] that are the base of many origami structures:[24,25] the waterbomb base (Figure 4a; Movie S5, Supporting Information) and the Miura-ori pattern (Figure 4b). The waterbomb structure was achieved by applying a running stitch in an octagon pattern. The Miura-ori pattern was achieved by a simple Π-stitch; one additional stitch was added to enhance the folding in the Y-direction. Square substrates were used for both the waterbomb and the Miura-ori patterns. As another demonstration of the capabilities of the embroidery-based origami approach, we designed a self-folding “chair” (Figure 4c). For the purpose, a circle with four rectangular appendages was cut out of fabric. Then, running stitches of different lengths were applied to the rectangles. After contraction of the fibers, the circular center remained undeformed, while the rectangles bent to form the legs of the stool. Thus, the use of active fibers allows the fabrication of basic origami elements and other structures that opens perspectives for the design of highly complex origami shapes. Here, we should point out that the stitch pattern used to achieve the desired forms was derived from the folding pattern of the origami structures. Where a negative crease (facing “down”) is necessary, the stitch was placed in a way that the actuating fiber is on top of the structure. In this way, contraction would lead to the desired result. The same logic was used for the positive (facing “up”) creases, where the stitch was placed on the lower side of the substrate. In our case, in the Miura-Ori pattern, an additional stitch was necessary for the folding to occur. We attribute this to the increased resistance of the material to bending due to earlier onset of folding in the perpendicular direction. The present approach provides a general rule for the design of simple origami structures. However, larger and more complex constructs, especially ones that require multistep folding process, would be difficult to design based on this simple idea. More studies in the mechanics of interaction between the creased surfaces and the actuating fibers are necessary to allow for accurate prediction and design of such structures and would be the goal of our further research activities.

Finally, we demonstrated the application of fiber induced textile folding to change its thermo-insulation properties (Figure 5). A folding textile was fabricated by applying several parallel running stitches. An increase of temperature to
50 °C results in the contraction of the fiber and the formation of multiple wrinkles on the textile along the direction of fiber contraction. The wavelength of these wrinkles corresponds to the length of the stitches after fiber contraction. Technically, we place flat and wrinkled textiles on a heating plate and put thermal sensor on the top. As a control, the temperature sensor was placed directly on the surface of the hot plate in order to record its response. We observed that the rate of temperature increase and the final (equilibrium) temperature depend on the geometry of fabric. The fastest temperature increase was observed when there was no textile between the heating plate and thermal sensor. The equilibrium temperature was ≈ 50 °C. Flat textile provides slower temperature increase and lower equilibrium temperature \( T = 42 \) °C. Wrinkled textile grants even slower temperature increase and low equilibrium temperature \( T = 32 \) °C because of an increased distance between the heating plate and the thermal sensor. Thus, we have shown that the thermo-insulation properties of the fabric can effectively be modified by temperature-induced wrinkling.

### 3. Conclusion

In this work, we have employed the ancient technology of embroidery for the design of self-folding origami, based on elastic and nonelastic quasi-2D substrates tailored with actuating shape-memory fibers. By analyzing the folding of simple rectangular structures, we were able to analytically model their actuating behavior. Advanced computer models of the system were developed, enabling us to simulate and predict the folding of such systems with even greater accuracy. We also found out that stitches, connected in more complex patterns, actuate independently from each other. Their combined actuation, however, can result in complicated bending behavior, where the folding of oriented fibers is influenced by the actuation of adjacent stitches. We have shown the applicability of the approach in creating two of the basic origami structures—the waterbomb base and the Miura-ori pattern, as well as for self-wrinkling fabrics for smart thermal insulation. Our approach provides with unprecedented versatility in terms of pattern creation, and is also cheap and technologically simple.

### 4. Experimental Section

**Synthesis of SMPU**: SMPU was prepared as described elsewhere \([26-29]\).

In a typical procedure, 50.65 g poly(caprolactone diol) (\( M_\text{w} 2000 \)) and 56.76 g methylene diphenyl diisocyanate were melted together in a glass beaker at 150 °C. Then, 0.2 g dibutyltin dilaureate were added dropwise to the melt. The mixture was stirred at 150 °C for 15 min and then 17.2 g of 1,4-butanediol were quickly added. The temperature was then increased to 200 °C. After the polymer melted, it was poured on an aluminum plate to cool down and solidify.

**Preparation of SMPU Fibers**: Polyurethane was extruded into continuous fiber with an average diameter of 1.4 mm on a Noztek Pro extruder (Noztek) at 95 °C. The extrusion rate was ≈1 cm s\(^{-1}\).

**Dynamic Mechanical Analysis**: Dynamic Mechanical Analysis (DMA) analysis of the polymers was conducted on a Perkin Elmer DMA 8000. The samples were cycled 3 times between −20 and 100 °C at 10 °C min\(^{-1}\).

**Sample Preparation**: All substrates were manually cut with scissors. Two materials were used: 0.4 mm thick ethylene propylene diene monomer (EPDM) rubber (elastic substrate) and Kimtech Scottpure fabric, Kimberley-Clark (nonelastic substrate). The SMPU fibers were manually sewn to the substrate with a needle.
Computational Model: Nonlinear finite element models were carried out in order to simulate and predict the folding patterns of the SMPU fiber/substrate system during fiber contraction. The contraction of the fiber was simulated by adjusting a negative thermal expansion coefficient of the fiber. Hence, when temperature increased the fiber started to contract as expected in experimental observation. The ABAQUS finite element package was implemented to perform the pattern changes in the fiber-substrate structures. For the 2D models, beam elements were used to mesh both the fiber and the substrate and the connection between the fiber and the substrate in both stitch points was modeled by a pin connection, which allowed the substrate to freely rotate in both stitch points. For the 3D models, the substrate was made of solid 3D elements, while the fiber was meshed by beam elements. Contact was allowed to mimic the experimental situation between the fiber and the substrate. The elastic modulus of the fiber used in the simulation was deemed temperature dependent and the elastic modulus of the substrate was considered same as experimental data.[6]

Conflict of Interest
The authors declare no conflict of interest.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Keywords
4D origami, self-folding, shape-memory polymers

Received: April 5, 2017
Revised: June 21, 2017
Published online: July 31, 2017