Woven Behavior and Ornamentation

Simulation-Assisted Design and Application of Self-Shaping Woven Textiles

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The class of self-shaping woven textiles are those that undergo a transformation in shape exhibiting three-dimensional behaviors due to the interplay between weave structure and active yarns that shrink, twist or otherwise move during finishing processes such as steaming. When weaving with active yarns to produce dimensional fabrics the unpredictability of the complex interactions involved typically necessitates arduous physical sampling for intentional design and use. Current weaving software, overwhelmingly reliant on 2D graphic depiction of woven fabric, is wholly unable to provide the predictive dimensional appearance of such fabrics that might lead to practical decision making and innovative design solutions. This paper describes an iterative workflow to design self-shaping woven fabrics, from simulation-assisted drafting to the creation of a library of woven behaviors categorized by attributes for seating design. This workflow is then used to inform the design of a new yarn-based simulator as well as to design and fabricate a textile-centric furniture piece in which these woven fabric behaviors and ornamentation are intentionally zoned to the form according to structural, ergonomic and aesthetic considerations.

CCS Concepts: • **Computing methodologies**; • **Modeling and simulation**; • **Simulation types and techniques**; • **Interactive simulation**; • **Human-centered computing**; • **Visualization**; • **Visualization systems and tools**; • **Human-computer interaction**;

Additional Key Words and Phrases: Computation, design, emergent behavior, textiles, visualization

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1 INTRODUCTION

While the weaving process typically results in flat, rectilinear panels, the use of active yarns is a well-established method of manipulating shape to create 3D-form in weaving. With the complex interaction of active yarns and variable weave structure, woven fabric may undergo a dramatic transformation from flat, smooth loomstate to a highly-textured surface topography when removed from the loom and activated, such as with heat. This class of self-shaping textiles has seen limited use for decorative apparel, but their varied textures, shapes and depths of surface suggest a broader range of applications including weave-to-fit upholstery and systems-integrated architectural panels. The practice of weaving shape-changing textiles has been predominantly empirical, necessitating extensive physical sampling before the desired behavior is captured. Whereas the construction of complex knitted textiles has enjoyed considerable interest from the computer graphics and computational fabrication communities [Narayanan et al., 2018, Yuksel et al., 2012], current weaving software has not evolved to facilitate the design and exploration of these dimensional textiles.

We have developed a workflow for designing self-shaping wovens that gives agency to and aligns with the working practices of textile designers. This includes a process for simulation-assisted drafting, in which textile behaviors can be visualized and iteratively refined in advance of loom setup and fabrication. From this, we generate a library of woven behaviors which forms the basis for a functional vocabulary for weaving these textiles into designed objects and by which we can effectively collaborate as a multidisciplinary team of textile designers, furniture designers and computer scientists. Our demonstration project is the design and fabrication of textile-centric chairs that unify ergonomic, aesthetic and assembly considerations into a single woven piece.

2 TOWARDS A DESIGN METHODOLOGY FOR WEAVING SELF-SHAPING TEXTILES

2.1 About Weaving

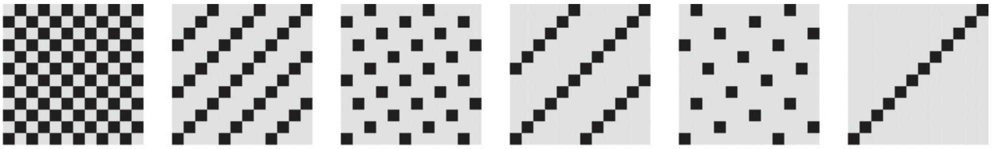
In Jacquard weaving, perpendicular warp and weft yarns are interlaced with independent control over every yarn crossing, allowing for complex pattern and multi-layer fabrics. The process of weave drafting involves creating a multicolor graphic, then assigning a unique weave structure to each color in design software, generating a 2D binary image. This “card image” drives the Jacquard loom but carries no information about the behavior of yarn within the fabric [Pointcarre, 1988], which is especially limiting when weaving self-shaping textiles that look significantly different after finishing than on the loom.

2.2 Weaving Techniques and Practices

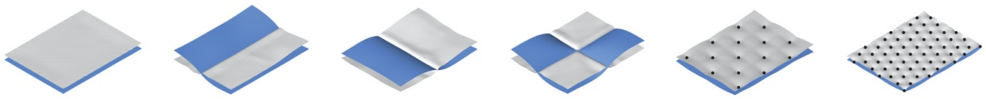
The dimensional qualities of these woven textiles arise from the interplay of weave structure and material and can be differentiated from other types of dimensional weaving such as 3D-weaving in which volume is attained through a special loom setup and the interaction of numerous layers of material [Harvey et al., 2019, Wu et al., 2020a,b]. We identified two yarn types that drive shape change: high-shrinkage and high-stiffness. Yarns that shrink after weaving, including spandex and thermoplastics, create differential shrinkage in fabric, causing buckling and other deformations. Stiff yarns, including linen or nylon monofilament, are useful for creating hardened zones of material.

Weave structure controls how yarn behaviors are expressed in fabric, and local variation in weave structure creates variable fabric behavior even though yarns are typically continuous throughout the fabric. The number of interlacings between warp and weft yarns in a weave structure indicates how physically constrained the yarns are. In plain weave, the tightest weave structure with maximal interlacings, friction between yarns tends to suppress shrinkage and increase stiffness. Structures with fewer interlacings impose less constraint on yarns, allowing shrinkage to occur. They also have lower stiffness, a feature that is useful when introducing creases into a tightly woven fabric.

Fig. 1. Examples of self-shaping wovens. (©VTRG 2022)



(a) Tightest weave structure Loosest weave structure



(b) Interactions between woven layers

Fig. 2. (a): plain weave,1/3 twill, 5 satin, 1/5 twill, 8 satin, 1/11 twill. (b): double cloth, pockets (vertical, horizontal, blocks), tiedown points, fully tied down fabric. (©VTRG 2022)

Interactions between woven layers also create local variations in fabric behavior. A common design in this category consists of two layers, a shrinking and non-shrinking one; the arrangement of “tiedowns", or connection points between layers, can dramatically change fabric topography. Fabric regions with tiedowns typically suppress shrinkage and have higher stiffness than layers woven separately. The density of tiedown points within the region can modulate stiffness and surface texture.

2.3 Current Computational Tools

Weaving fabric, whether on a manually-controlled or industrial loom, requires a card image to program the loom. Pointcarré is the industry-standard textile CAD software which allows assignment of weave structures to selected color zones and outputs a corresponding card image [Pointcarre, 1988]. This interface, representative of commercially-available software, does not address yarn or fabric behavior. This lack of predictive capability is the primary contributor to the material, labor and time intensity of the physical sampling process, especially for weaving dimensional fabrics.

To fill this gap, we looked outside of the textiles field, in particular to 3D-tools with simulation capabilities. AEC (Architecture-Engineering-Construction) workhorses such as Rhinoceros now incorporate real-time physics-based simulation. We use the Kangaroo simulator, a plug-in for Rhinoceros that uses “goals” defined as functions acting on a set of points [Piker, 2014]. These include components such as stiffness, stretch and shear, which are then applied to geometry, describing how they will behave in a relaxed state. A more fabric-focused platform is CLO3D, an apparel-design program in which panels of fabric can be joined, fitted onto a model and simulated, showing the effects of gravity, compression and wearer’s movements [CLO3D, 2009].

The accessibility of these physics-based solvers enables non-experts in simulation to experiment with relatively high-quality outcomes. The textile designers on this team developed a process with these widely-available design platforms to digitally sketch key qualities of self-shaping woven fabric. The challenges encountered in turn enriched a dialogue with computer scientists on the team who are concurrently developing a new yarn-level simulation tool for woven fabric. Yarn-level simulation can complement the larger-scale simulations used in the current project, providing predictions of how yarn properties and weave structures determine fabric properties [Cirio et al., 2014, Kaldor et al., 2010, Leaf et al., 2018, Sperl et al., 2020]. However, existing yarn-level simulations are not as reliable, usable, or efficient as they need to be to serve this application (Figure 4).

2.4 Our Approach

Our workflow prioritizes ideation and prediction. Its main component, created with Grasshopper and Kangaroo for Rhinoceros, enables simulation-assisted sketching of woven behaviors. A rectangular grid represents a single-layer woven fabric and line segments represent groups of warp and weft yarns. The input parameters reflect fabric behavior; weave structures and interlacings are not depicted, and properties such as shrinkage and stiffness are assigned to line segments using Kangaroo goal components. With repeated calibration of these parameters to physical samples, an output surface exhibits key qualitative features seen in physical fabric. The user can draw regions with distinct properties, similar to creating a multicolor graphic for Jacquard weaving, to observe how the defined surface relaxes into shape (Figure 5). Multi-layer interactions are possible through tie-downs and layer exchanges set within user-defined regions. By iteratively adjusting the placement of these regions, the designer can fine-tune the output surface topography, gaining insight into how a physical fabric will behave.

After identifying a promising assignment of physical properties to fabric areas, the designer translates the surface into weavable form by selecting structure-material combinations that achieve those properties. Leveraging the multicolor graphic derived from user-drawn shapes (Figure 9), weave structures are assigned to each color in Pointcarré, using variable tightness of weave to suppress or enhance the behavior of each weft type. This simulation-assisted drafting is a significant departure from typical drafting, where evaluation is only possible after weaving. Through simulation, textile designers can be deliberate in their use of dimensional effects, confident that the physical outcome will reflect design decisions. As we progressed to larger-scale for specific use, we added CLO3D to our workflow, adapting its simulation feature to see promising designs

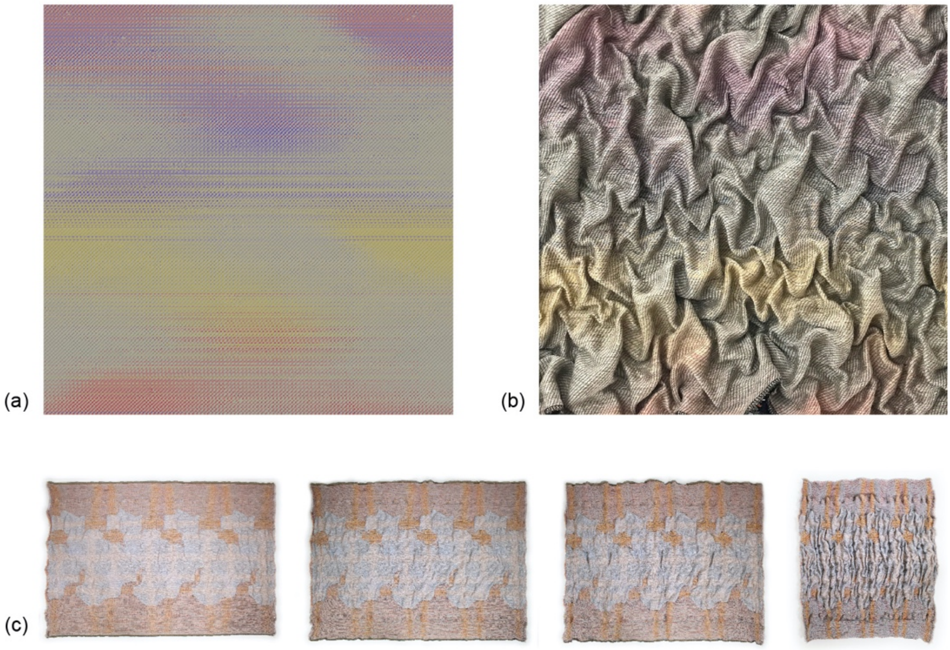


Fig. 3. Simulation in Pointcarré (a) is representative of color and pattern on the face of loomstate fabric, but doesn't capture the textures that emerge after finishing (b) or the progression from tensioned to relaxed states (c). (©VTRG 2022)

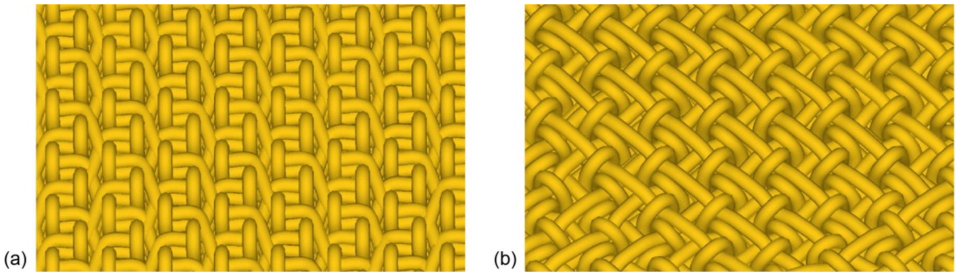


Fig. 4. A simple woven pattern (a) is simulated to a relaxed state (b), using a previous yarn-level simulator taking 25,000 timesteps and careful, on-the-fly tuning. (©VTRG 2022)

on furniture frames. Comparisons between modeled surfaces and physical samples became the basis for evaluating the predictive capabilities of our chosen simulators, and valuable input for the computer scientists on our team in their development of a new fabric simulation tool.

Capturing key geometries that produce predictable effects in a library of woven behaviors has been a fruitful step towards developing designs for experimental weaving techniques in prior research involving a multidisciplinary team [Harvey et al., 2019]. This visual representation of anticipated outcomes, far more than abstract weave drafts, becomes the common vocabulary to communicate within and amongst visual design fields.

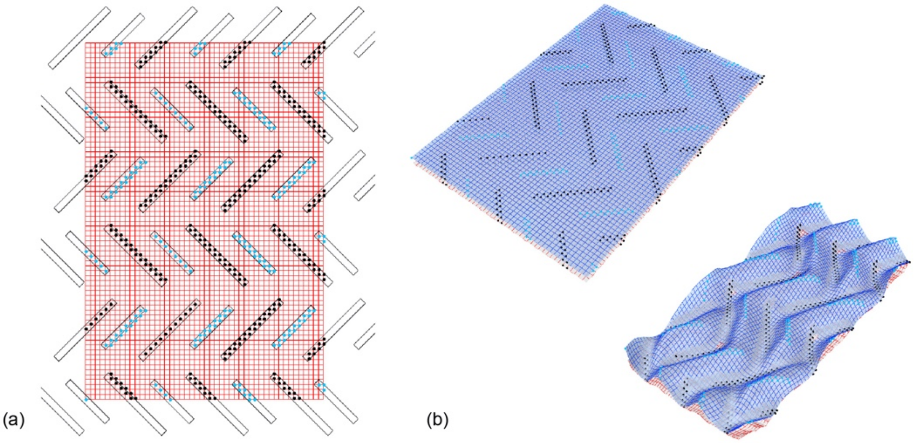


Fig. 5. A typical workflow: (a) drawing shapes and defining them as zones, (b) setting parameters and relaxing the surface. (©VTRG 2022)

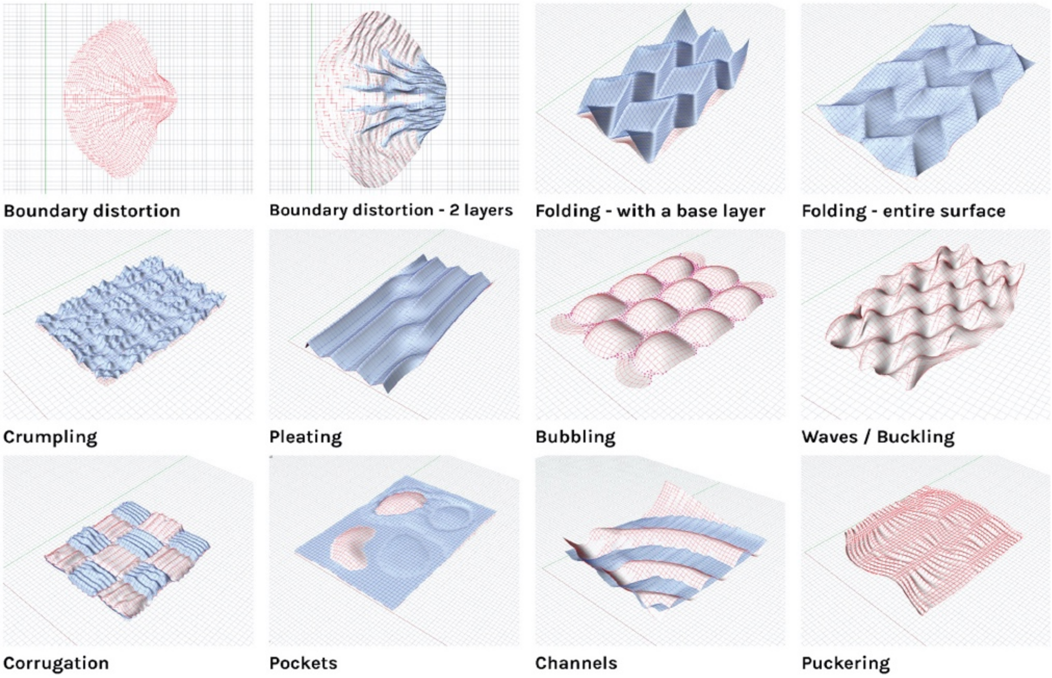

Boundary distortion
Boundary distortion - 2 layers
Folding - with a base layer
Folding - entire surface
Crumpling
Pleating
Bubbling
Waves / Buckling
Corrugation
Pockets
Channels
Puckering

Fig. 6. Surface behaviors designed with simulation-assisted process, representative of dimensional fabrics in their relaxed state. (©VTRG 2022)

Some behaviors, such as boundary distortion, inspired end-use application, such as the design of garment sleeves (Figure 7). Fabrics that change from rectangles to specific pattern-pieces while gaining decorative texture present an alternative to cut-and-sew apparel construction and manual

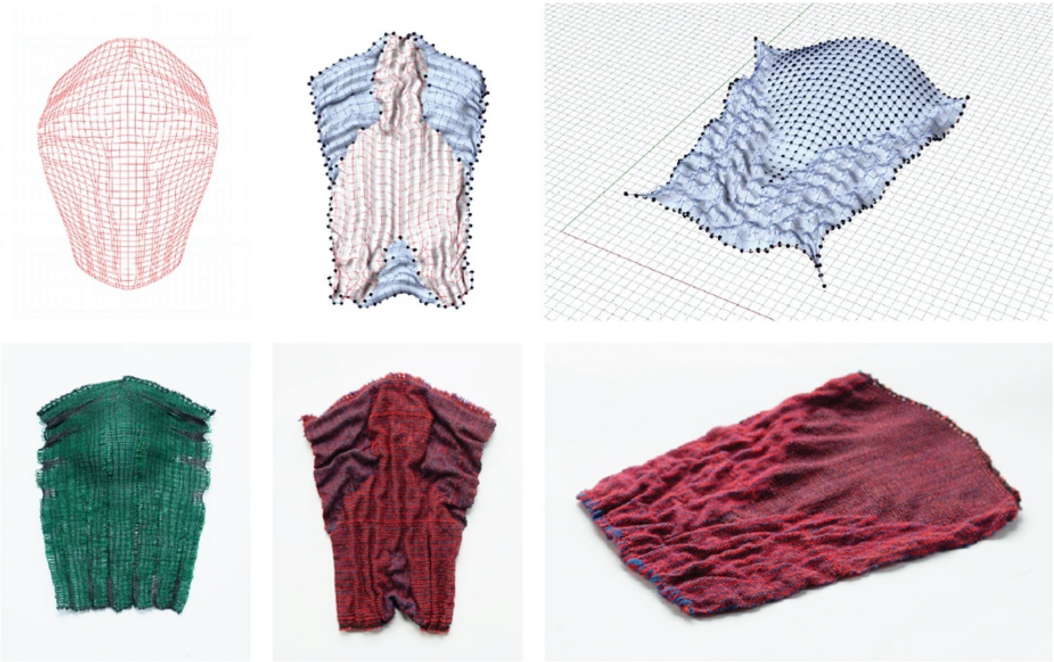


Fig. 7. Variations on garment sleeves, as simulated surfaces and handwoven. (©VTRG 2022)

fabric manipulation. More importantly, this catalog of weavable building blocks invites the possibility of combinations of function and ornamentation, intentionally and more precisely integrated into a single woven textile.

Visual taxonomies for behaviors within the library played an important part of our collaborative workflow. At the initial stages of designing, we undertook a typological characterization of surface behaviors relative to desired functional attributes that we had previously mapped onto zones of generic seating (Figure 8). This type of meaningful early-stage engagement established common awareness of relevant parameters and potential tradeoffs, allowing our team to converge quickly on which behaviors and types of ornamentation to feature and why.

3 CASE STUDY: SHAPING WOVEN BEHAVIOR FOR SEATING

The promise of our workflow is its potential for woven textiles to be designed with intentional behavior and ornamentation built in. Seating emerged as an ideal challenge to design and construct at full scale self-shaping textiles programmed to express behaviors at different zones, and to test the predictive capabilities of our workflow.

3.1 New Furniture Forms

In traditional furniture upholstery, textiles cover and decorate elements like shells, springs and foams. In sling-type seating, for which fabric plays a significant role in supporting the body, there is often a lack of localized ergonomic consideration. We recognized an opportunity to design a single-piece woven textile for sling-type seating, capable of meeting the demands usually fulfilled by an assembly of materials, as an alternative to fixed upholstery. Our library of woven behavior revealed promising candidates when mapped to salient attributes for seating, such as compressibility and depth of surface. Behaviors that meet the criteria for each seating zone can be assigned to regions

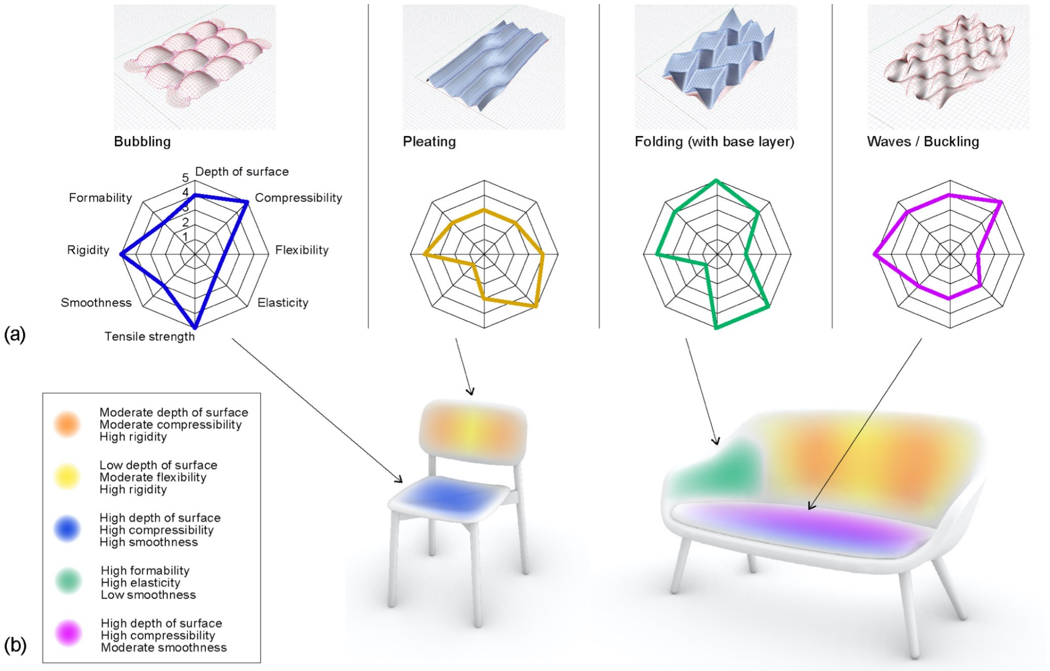


Fig. 8. (a) Typological characterization of behaviors evaluated by key criteria for seating, (b) Desirable fabric properties mapped onto generic seating forms. (©VTRG 2022)

within the textile, integrating a colorful and decorative outer covering, a supportive structure with high tensile strength, and soft padding into one continuous textile.

The strategic connections between furniture frame and fabric were also significant in our design process. Channels are ideal for inserting rigid components into a fabric without cutting or sewing, and high fabric density and tensile strength are necessary in these areas for durability. We defined channels as standalone behaviors that could either be visible on the surface, or added between layers without significantly disrupting the overall surface topography.

3.2 Creative Process

Our process began by mapping functional zones onto a sling form, then selecting woven behaviors that met the profile of desired attributes for each seating zone. We selected a corrugated behavior for its thickness and compressibility, and applied it to the outer bands, which act as armrests, in one design variation and to upper and lower regions, providing cushioning between the frame and the body, in another. For the central band including seat and backrest, we used a pleated behavior with moderate elasticity in warp and weft directions. Designing the interface between behaviors, where layer exchange occurs, was another opportunity for simulation-assisted refinement. Across the fabric, a free-form curve, as opposed to a straight line, results in more tie-downs, inhibiting shrinkage. Scaling the 2D regions that make up each behavior also directly affects depth of surface.

We adapted these initial mappings into sections showing fabric behaviors at full scale, using simulated sketching to refine surface topography and boundary distortion. This workflow helped validate our designs and provided greater confidence in their appearance as finished forms. To weave fabrics consistent with our simulated surfaces, we selected linen for its stiffness and crimped nylon for its high shrinkage. We used the same sequence of stiff and shrinking weft yarns throughout our fabrics, which were woven on a Jacquard loom. The yarn sizes and densities (142 warps and 240 wefts per inch for a 3-layer fabric), comparable to commercial upholstery fabrics, gave our textile the tensile strength necessary to support a person's weight. Selecting the optimal weave structure for each zone required some prior knowledge, established through earlier samples. In some places, we split the linen-weft layer in two, creating continuous channels in the fabric.

After weaving, we activated the fabric by heating with a steam iron until shrinking yarns had contracted fully. A semi-flexible tube clip, inserted into channels near the fabric's top and bottom edges, securely fastens it to the frame. The way the fabric drapes and conforms to the body is a result of the variable thickness and elasticity of the two behaviors. This woven seating design references two distinct furniture typologies–a thin-profile sling suspended from a frame and supportive layers of furniture upholstery–merged into a single-piece, self-shaping textile form.

3.3 Evaluating Predictive Capabilities and a New Computational Tool

These complex woven fabrics, with intentional behavior and use built-in, persuasively demonstrate the possibilities for a simulation-assisted design process. However, there are challenges resulting from the off-the-shelf simulators we use, both in terms of behavioral effects that diverge from predictions as well as larger examples that cannot be handled. In all simulated surfaces that we wove, the general character of behaviors was captured, but some details fell short. In the garment-sleeve wovens (Figure 7), the scale and pleating behaviors are well-represented, but boundary distortion is less accurate and shearing is exaggerated. For the Jacquard-wovens for seating, the specific placement of pleats that emerge spontaneously and the irregular buckling of layers at crease zones are not predicted. Scale and resolution are also significant limitations that complicate our workflow for larger examples, such as full-scale seating prototypes, which we could only simulate as small sections. Additionally, the current simulator works in terms of compound properties of fabric, and does not model how those properties arise from weave structures and yarn characteristics, making the designer responsible for choosing combinations that result in specified properties. This lack of guardrails can lead to the design of simulated surfaces that are difficult to fabricate.

All of the insights gained from bringing a simulated surface to a woven prototype were shared with the computer scientists on our team who are designing a new computational tool that reflects both the yarn properties and the weave structure, and requires minimal manual tuning on the fly. This simulator performs yarn relaxation using numerical continuation, a method that progresses efficiently towards an equilibrium. Rather than following a solution path that is parameterized by time as in previous yarn-level simulators, the continuation method follows a path consisting entirely of equilibrium states, and evolves with a system parameter λ that varies from 0 to 1. The role of λ is carefully crafted to incorporate the key features that drive the shape changes of the woven structures—for instance, to simulate the buckling of the cloth shown in Figure 3 as tension is released upon removing it from the loom, the method would progress from loom tension at $\lambda = 0$ to no applied tension at $\lambda = 1$.

A key benefit of this new approach is that it directly simulates the forces within yarns and between yarns that give rise to dimensional fabrics, and it can reduce or eliminate the need for physical sampling of different weave structures to calibrate the more phenomenological goal-based model. Furthermore, the new approach generates simulation results corresponding to a continuous range of values for a specified parameter, allowing designers to easily explore the space of parameters. The effects of changes to the details of weave structures can be predicted, and subsequently the structures optimized much more flexibly. For textile designers, working directly with simulated weave structures facilitates the translation from design to card image, especially without prior knowledge of structure-material interactions. Effects of weave structure beyond modulating yarn

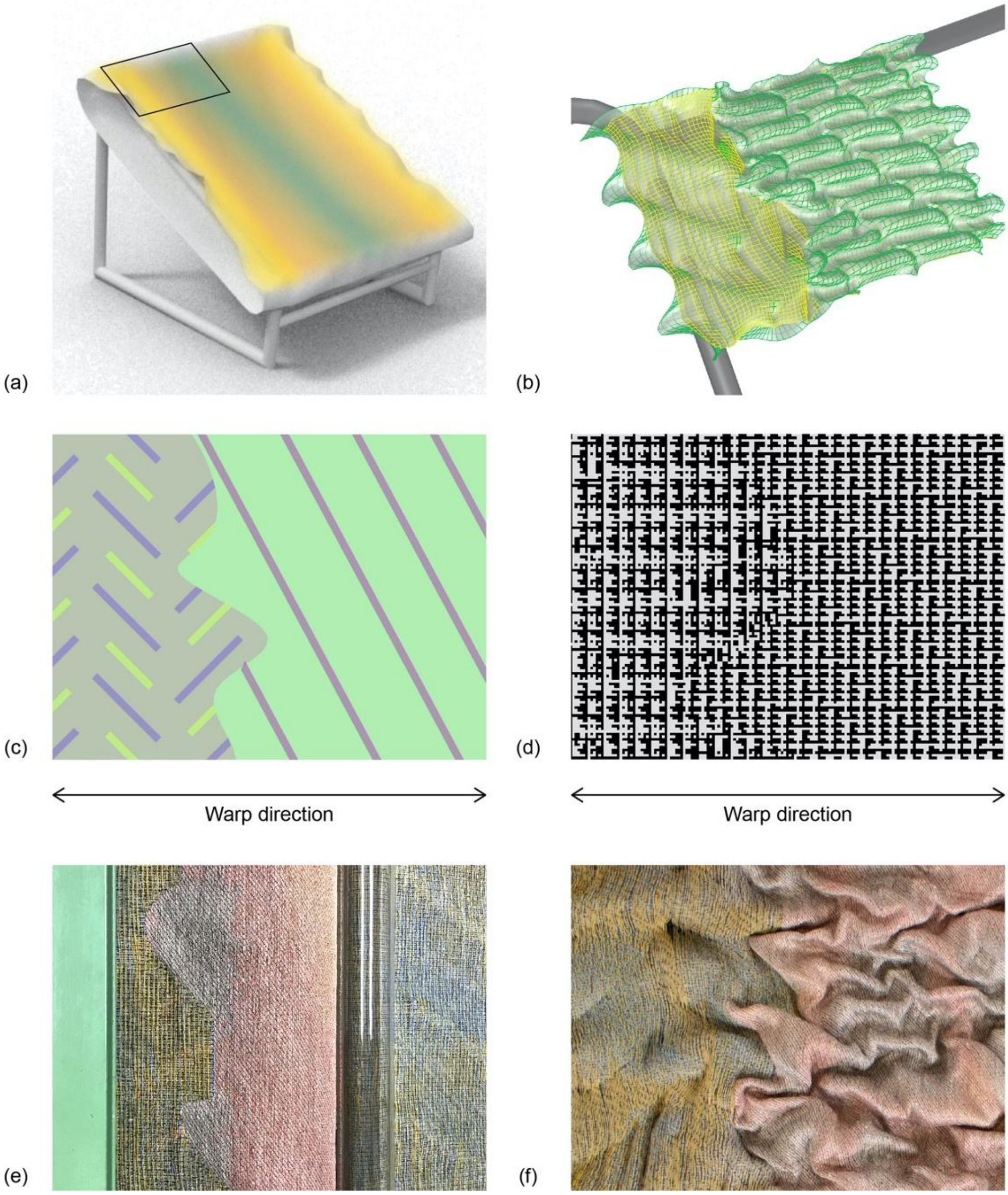


Fig. 9. (a) Mapping desirable properties, such as compressibility (yellow) and flexibility (green) onto sling seating suggests a composition of multiple behavioral zones in a single-piece textile; (b) A section of the design is shown as a surface model; (c) a color graphic generated by the sketching tool; (d) card image (e) loomstate fabric and (f) finished fabric. (©VTRG 2022)

properties, such as the influence of twill direction, can only be captured by yarn-level simulation, and fabric engineering decisions addressing specifics of inner corrugations or batten sleeves can only be fully controlled through this approach.

Fig. 10. Two variations on self-shaping textile seating, woven on a Jacquard loom at full-scale. (©VTRG 2022)

4 CONCLUSION

Our simulation-assisted workflow allowed us to design complex woven fabrics and move to physical prototyping with a reasonably high level of confidence in the outcomes. The library of behaviors we sketched and subsequently categorized served as valuable communication tools in our collaborative work with furniture designers, illustrating potential fabrics without extensive physical sampling and prompting ideas for variations on familiar seating typologies. Our iterative process is part of an ongoing dialogue between design and computer science that will inform the next generation of CAD tools for textiles. Our final prototypes show the potential of this new approach to textile-centric seating, a zoned single-piece construction with minimal assembly that utilizes dimensional weaving techniques with high specificity. With further refinements to our workflow and computational tools, we aim to close the gaps between simulated and physical designs and expand the use cases for this class of fabrics.

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