

Digital Fabrication of Soft Actuated Objects by Machine Knitting

Lea Albaugh
Carnegie Mellon University
Human-Computer Interaction
Institute
lea@cs.cmu.edu

Scott Hudson
Carnegie Mellon University
Human-Computer Interaction
Institute
scott.hudson@cs.cmu.edu

Lining Yao
Carnegie Mellon University
Human-Computer Interaction
Institute
liningy@cs.cmu.edu



Figure 1: Left: a sweater with actuated sleeve. Center: a reconfigurable lampshade. Right: a responsive plush toy. These objects have been machine-knit using a collection of techniques discussed in this paper, such as shape and stiffness manipulation, combined with integrated tendon actuation.

ABSTRACT

With recent interest in shape-changing interfaces, material-driven design, wearable technologies, and soft robotics, digital fabrication of soft actuatable material is increasingly in demand. Much of this research focuses on elastomers or non-stretchy air bladders. Computationally-controlled machine knitting offers an alternative fabrication technology which can rapidly produce soft textile objects that have a very different character: breathable, lightweight, and pleasant to the touch. These machines are well established and optimized for the mass production of garments, but compared to other digital fabrication techniques such as CNC machining or

3D printing, they have received much less attention as general purpose fabrication devices. In this work, we explore new ways to employ machine knitting for the creation of actuated soft objects. We describe the basic operation of this type of machine, then show new techniques for knitting tendon-based actuation into objects. We explore a series of design strategies for integrating tendons with shaping and anisotropic texture design. Finally, we investigate different knit material properties, including considerations for motor control and sensing.

CCS CONCEPTS

• **Human-centered computing** → *Human computer interaction (HCI)*; • **Applied computing** → *Computer-aided manufacturing*.

KEYWORDS

Soft materials; additive manufacturing; computational crafts; soft actuator

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1 INTRODUCTION

Soft fabrication is increasingly relevant to human-computer interaction, with applications ranging from soft and shape-changing interfaces to wearable technologies. However, the fabrication options for soft matter are limited in terms of an end-to-end pipeline. For 3D printing, available soft materials often have weak mechanical integrity (e.g. Tango series materials for Object), are tricky to work with (e.g. Ninja Flex for FDM printers), or are not elastic/stretchy enough. Soft interfaces made of silicone elastomer or non-stretchy air bladders [23, 27, 34] require a labor-intensive casting process, or are only partially manufactured, with customized tools. Additionally, these materials are unconventional or even uncomfortable for on-body applications and have a limited range of surface characteristics.

In contrast, fabric is flexible and lightweight as well as breathable, relatively strong, and pleasant to the touch, making it popular for a wide variety of objects in our day-to-day lives, from clothes and plush toys to furniture and architectural coverings—the vast majority of our time is spent touching it. Textile processes can incorporate fibers with a widely variable properties such as strength, stretchiness, thermal resistivity, electrical conductivity, tendency to felt, solubility, and of course, color and surface characteristics.

While all three main categories of textile manufacture (knitting, weaving, and “nonwoven” production—i.e., felting, electrospinning, and heat-bonding processes) are most commonly used to produce flat sheets of fabric that must be cut and sewn, glued, or welded to produce three-dimensional objects, knitting additionally has the potential to produce complicated shaping with minimal post-processing [21]. Industrial computer-controlled knitting is also very fast—a fully-shaped glove might be produced in five minutes, and a flat sheet of the same size might take under a minute.

However, industrial knitting pipelines target mass manufacturing, and they do not often push the boundaries of what is possible with knitting. Hobbyist and research use of computationally-controlled knitting is still in early stages, largely because machine knitting is not a straightforward analogue of other digital fabrication techniques.

In this paper, we consider techniques that expand the usefulness of machine knitting as a fabrication method for interactive objects. We first provide an overview explanation of flat-bed weft machine knitting. We then explain three contributions: 1) a holistic strategy for composing embedded tendons, shaping, and textural variations to achieve a variety of shape changing effects, 2) our novel use of horizontal yarn inlay for actuation, 3) a novel complementary technique for integrating tendons in the vertical direction. Finally, we show example applications and discuss the design guidelines and fabrication parameters for achieving them.

2 RELATED WORK

Digital Fabrication for Textiles

Various approaches have been taken toward supporting computationally-fabricated textiles or hybrid textile processes. Notably, Hudson’s “teddy bear” needle-felting printer [15] and Peng’s layered fabric printer [25] used textile materials as the basis for output that was soft to the touch. However, the output objects from these printers are necessarily thick and somewhat limited in material options, making them significantly dissimilar from the familiar fabrics used in garment, toy, and home goods production.

Rivera et al’s work on extrusion printing with embedded textiles [26] is a hybrid approach that uses off-the-shelf fabric and custom rigid elements. Our output can be entirely soft, and because our approach starts at the yarn level instead of the fabric, we achieve significantly more variability in shaping and texture. However, our approach could also be re-integrated into such a hybrid fabrication pipeline.

In the realm of machine knitting, McCann et al [20] demonstrate the wide range of shaping possibilities from a limited design vocabulary of tubes and sheets, and Narayanan et al [21] automate these shaping approaches for mesh-based geometric input. These works offer more generalized treatments of the basic shaping vocabulary we describe in this paper, but neither discusses motion or surface texture such as knit/purl patterns or between-stitch interlacement.

“Knitty” and “Knitting a 3D Model” [16, 17] introduce production assistants for hand crocheting of plush toys from sketched input and 3D models, respectively. We focus on machine knitting; while there are obvious conceptual similarities to hand knitting, specific design strategies often differ in response to differing constraints. For example, a hand knitter may consider a sewing step to be trivial, whereas we would avoid sewing in pursuit of end-to-end machine knitting.

Soft Actuation and Shape Changing Interfaces

The field of soft robotics is greatly concerned with the actuation of soft materials. The use of pneumatic actuators for shape changing interfaces has been established in projects such as PneuUI[34], aeroMorph[23], and printFlatables[27]; 3D printable pneumatics have been explored by Self Assembly Lab [5]. While pneumatic structures have shown great promise, they are often challenging to fabricate and have rubbery surface characteristics which may not be suitable for all use cases. Other soft materials have been used to create either reversible or non-reversible actuations, such as pH-responsive chemical materials [18], shape memory thermoplastics[22], and biological materials[33, 35]. Each of these projects occupies a unique design space with its own technical advantages. We consider our work an addition to the toolbox of soft material actuators.

A particularly relevant set of soft robotic methods are those that use tendon actuation [24]. Bern et al [9] automate the design of embedded tendon actuators within fabric for plush toy interactions. Kono and Watanabe [19] show the use of gathering fabric for interactions. Both of these works use sewn actuators that are added to an existing fabric, however, their approaches could be extended with our methods.

Dynamic Textiles

Han and Ahn’s “blooming knit flowers” [14] and Scott’s biomimetic architectural knits [28] integrate shape memory effects into knitted structures for subtle motion. Both works use an overall shrinkage effect, not tendons; additionally, Han and Ahn’s flowers provide one-time motion, and Scott’s forms are actuated via rigid wooden veneer elements. ShapeTex[12] uses thin-film thermal expansion for similar effects. Glazzard’s thesis on auxetic knits [13] is not itself actuated, but it discusses knit textures that could amplify the actuation effects we discuss. The work of ten Bhömer et al [29] explores the use of anisotropic knit structures in designing body-worn interfaces, prototyped using cut-and-sew methods; Scarfy [31] demonstrates soft output as part of an interactive scarf using nitinol-actuated crumpling. Fashion designer Hussein Chalayan is known for using dynamic textiles in his runway work, with the most directly applicable example being his *Spring/Summer 2007 [11] presentation incorporating tendon-driven silhouette changes*. Our work could extend these works by demonstrating the feasibility of these design approaches directly in machine knitting.

Substantial prior research has been done on textile circuitry and soft sensors [8, 10, 31, 32]. Many of these prior techniques can be combined with the techniques described here. However, because of the maturity of that research, we do not concentrate on those techniques here beyond one illustration using a conductive yarn used as a touch sensor.

3 BACKGROUND

The Structure of Knitting

In this paper, we discuss *weft knitting*, which is one of the two main kinds of industrial knitting. It produces structures which are conceptually of the same kind as hand knitting, but typically at a different scale, using different mechanical processes, and with a different aesthetic result. We present here a simplified description of the operation of flat-bed weft knitting machines; a deeper coverage of these topics can be found in Underwood [30] and McCann et al[20].

Knitting is a way of forming a surface out of rows and columns of loops of yarn. In a minimal case, a knit structure can be formed from a single continuous length of yarn, Fig. 2. Each loop in a column is formed by pulling yarn through the previous loop in the column.

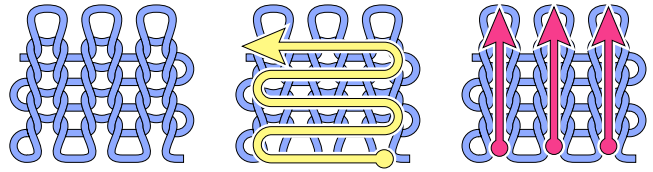


Figure 2: Left: A basic knit swatch. Center: row-wise connections along the yarn path. Right: column-wise connections of loops holding loops. The structure is formed under gravity, progressing from the bottom to the top.

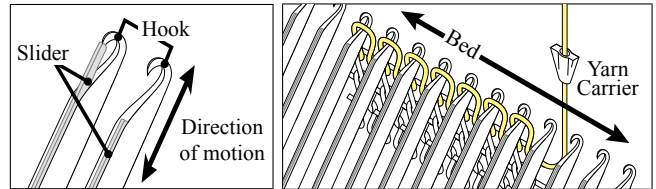


Figure 3: Left: Slide needles. Right: A bed of slide needles holding a knit swatch in progress.

Machine Knitting Basics

A flat-bed knitting machine forms a knitted structure using rows (*beds*) of parallel needles (Fig. 3). These *slide needles* have two major parts each: a hook, which holds the topmost stitch or stitches in a column, and a slider, which can be independently actuated to close the hook.

The machine additionally has a number of *yarn carriers*, through which yarn flows after passing through a tensioning apparatus. The yarn carriers are synchronized to the needle action to provide yarn to new stitches being formed.

A *v-bed* knitting machine has two beds of needles that meet in an inverted ‘v’ shape; Fig. 6 shows a side view.

Each needle can be actuated to perform a *knit* operation (Fig. 4): reach forward, grab yarn from a yarn carrier and form it into a new loop, and pull the new loop through the previously-held loop. (This same sequence of motions would *drop* the previous loop if no yarn carrier were involved.) Needles can also perform a *tuck* operation (Fig. 5), which holds the new yarn in the needle without pulling the existing loop through it. A third needle operation, available to machines with more than one bed, is a *transfer* (Fig. 6), in which a stitch is passed from a needle on one bed to a corresponding needle on the other bed.

4 OVERVIEW

We identify three composable categories of knit actuation design elements suitable for machine knitting (Fig. 7).

The first is the placement of actuatable tendons: horizontal, vertical, or diagonal with respect to knitting time. The second is a set of basic shapes (sheets, vertical tubes, and horizontal tubes) and techniques for modifying them (short rows and

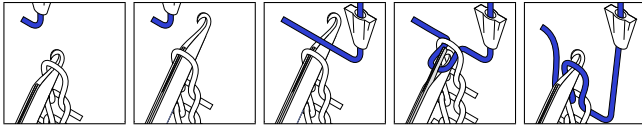


Figure 4: The *knit* operation: 1) before the operation; 2) the needle and slider move up, and any loops in the hook slide down past the slider; 3) the yarn carrier moves past the needle, laying yarn into the hook; 4) the needle moves back down, closing the hook and allowing any previous loops to fall off the tip of the hook; 5) after the operation.

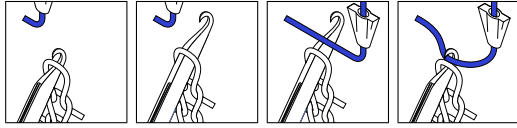


Figure 5: The *tuck* operation: 1) before the operation; 2) the needle slides forward, but the slider stays down; 3) yarn is laid into the hook; 4) the needle slides back down, having captured the new yarn without dropping any existing stitches.

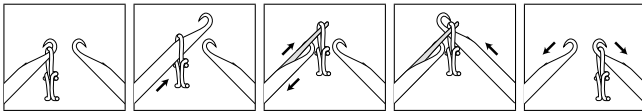


Figure 6: The *transfer* operation: 1) before the operation; 2) the first needle slides forward to nudge its loops onto the slider; 3) the slider moves past its hook; 4) the other needle's hook grabs the loop[s]; 5) both needles return down.

increases/decreases). The third is an approach to using the inherent anisotropy of knit stitches to produce areas of the knit surface with contrasting tendencies to curl, to produce local bending and pleating effects.

These techniques can be composed to produce more-complicated shapes. For example, Fig. 8 shows a composition with a horizontal tube, a horizontal tendon, and decreases at the center of the tube to pull it into a v-shape. Short rows are used to taper the edges of the tube.

5 TENDON PLACEMENT

Our method for adding tendons to a knit structure takes advantage of two knit-time techniques, which we will call *inlay* and *yarn carrier tangling*.

Horizontal Tendons

The simplest tendon arrangement, horizontal, leverages an existing knitting technique: inlay. Inlay technique is commonly used to introduce yarns that could not be directly knit due to their stiffness or fragility, and it is typically accomplished using special yarn feeders. Using inlay technique for actuatable tendons is a contribution of this work.

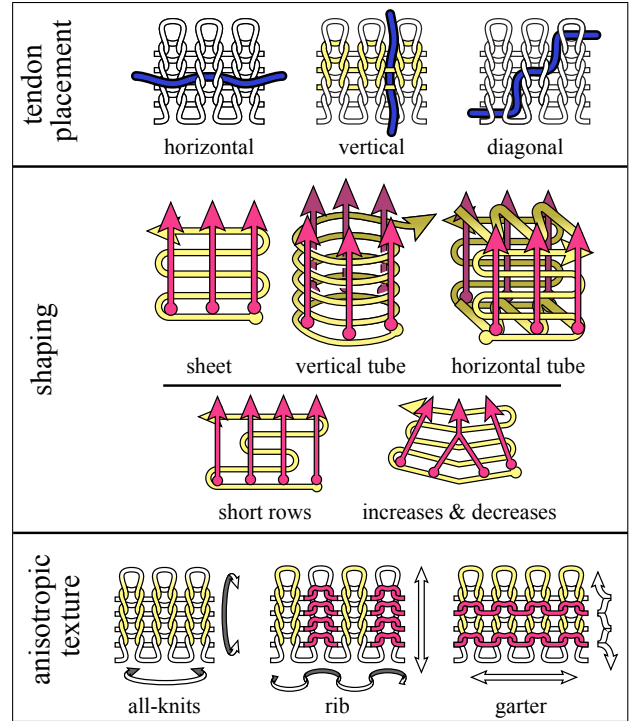


Figure 7: A menu of knitting strategies.



Figure 8: A horizontal tube with inlaid tendon and decrease shaping to bend the tube into a v-shape.

A yarn can be inlaid horizontally into a row in a way that is analogous to weaving: a subset of the stitches are moved temporarily to the other bed, the inlay yarn is pulled across, and then the displaced stitches are moved back to their main needles (Fig. 9). In order to keep the inlay yarn tidily in place while the knit stitches are transferred back over it, it is temporarily tucked onto reserved “holding” needles at the beginning and end of its trajectory as well as at intervals between the two. We find for our 15 gauge machine that tucking every third holding needle is sufficient. These temporary tucks are dropped after the main knitting is transferred back into place.

At the end of this procedure, the inlay yarn is *interlaced* with the stitches—it has crossed in front of some stitches and behind others. Notably, this interlacement happens between the needles: the inlay yarn is never *knitted* into the structure.

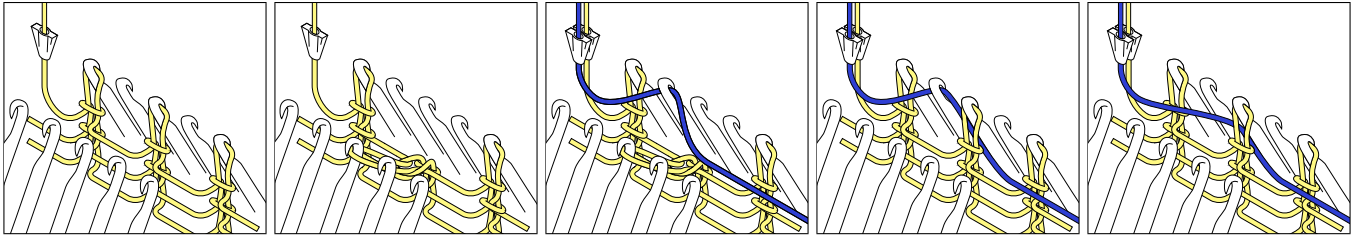


Figure 9: Inlay technique for embedding horizontal tendons. 1) Stitches formed on the back bed; 2) Every other stitch temporarily moved to the front bed; 3) Inlay yarn pulled across; 4) Stitches returned to the back bed; 5) Temporary tucks dropped.

Vertical Tendons

A limitation of inlay technique is that it only allows for a horizontal orientation, across a row of knitting.

Producing tendons in the column direction requires interlacing with the row-wise connections of the main knit structure. In conventional use of the machine, such entangling is likely undesired, especially as it can be produced by simply swapping which carrier is used for a particular part of a structure. We invoke this behavior deliberately for vertical tendons.

The situation arises from the arrangement of multiple yarn carriers on a knitting machine. A knitting machine can have multiple yarn carriers, typically to supply different colors or types of yarn to different parts of a knit job. These carriers move along rails as they synchronize with the needles; on nearly all machines, each carrier has its own rail. These are arranged in parallel from the closest to the front of the machine to the closest to the back of the machine. Often the carriers simply pass by each other when they need to; however, if a carrier has just supplied yarn to one of the beds, the end of the yarn is necessarily attached to that bed. That carrier can then trap a yarn from a carrier that is closer to that bed than it is.

We can thus interlace vertical tendons using three carriers arranged as in Fig. 10: a tendon carrier (“B”) which stays in place, passively supplying yarn into the resulting fabric in a vertical column, and two main knitting carriers, one of which moves in front of the tendon carrier (“A”), and one of which moves in back (“C”). When “A” knits a row, it passes in front of the tendon carrier; when “C” knits a row, it passes behind; by alternating carriers for the main knitting, rows can weave around the tendon.

Fig. 10 shows a single face of fabric being produced on the back bed. To extend this technique to make it suitable for producing tubes, on both beds, the other face of the tube must also be knit entirely from the carrier that does not entangle with the tendon. For example, in the case when the tendon runs up the front of a tube, the back face of the tube must be knit with the back carrier. Therefore, if a tendon is called for on each of the front and back faces of a tube, another

knitting carrier must be added that is positioned between the front and back tendon carriers (Fig. 11), making for three knitting carriers and two tendon carriers. A machine with ten carriers can thus produce eight vertical tendons in the same face, or seven vertical tendons across two faces.

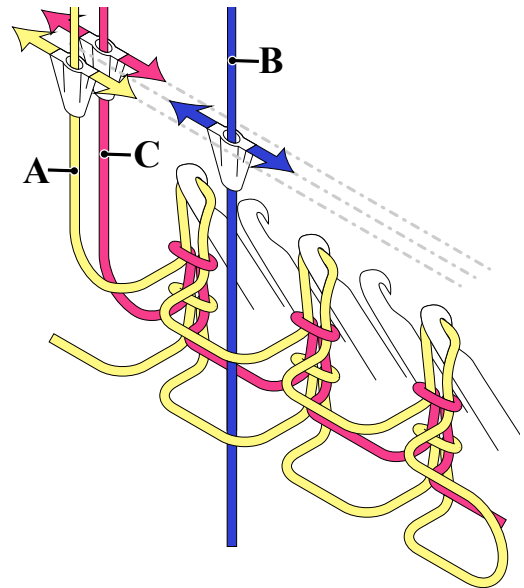


Figure 10: “Tangling” technique for embedding vertical tendons. When carriers must pass each other going right or left, each can only move along on its own rail.

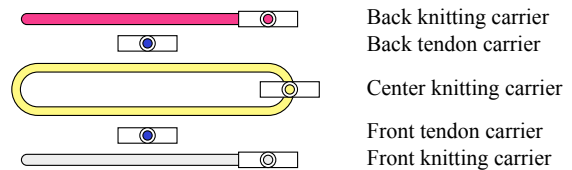


Figure 11: Birds-eye schematic of the relative positions of the five carriers required to produce a tendon on each of two faces of fabric.

Diagonal Tendons

Diagonal interlacements can be accomplished with either the yarn carrier tangling or inlay technique by applying the methods described above in a stair-step fashion—working for a small distance, then moving in the orthogonal direction for a small amount, then returning to application of the technique. For example, to use the inlay technique, the tendon can be interlaced with just one or two stitches per row, before moving up a row to interlace one or two more stitches, etc. To use the tangling technique, the tendon carrier’s position can be changed every few rows.

6 SHAPING

Basic Topologies: Sheets and Tubes

Knitting can be arranged into flat sheets, or tubes composed of a front and back face, connected either at the sides by a continuous spiral of yarn, or at top and bottom by a yarn path that zigzags between the faces (Fig. 12). For our purposes—creating tendon-driven soft actuation within knitting—tubes are notable because they can contain elements that provide restoring force after activation, such as stuffing or strips of springy material.

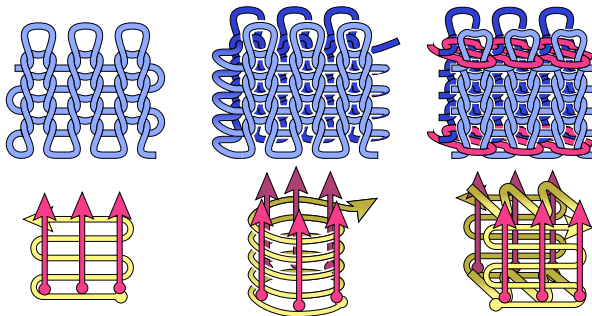


Figure 12: Left: A sheet, as shown in Fig. 2. A simplified representation of the row and column connections is shown below. Center: a vertical tube of knitting. The lighter-colored front face could be formed on the front bed of the knitting machine, and the darker back face on the back bed. Right: a horizontal tube, joined at top and bottom by a zig-zagged yarn path.

Tubes and Half Gauge

On a v-bed knitting machine, tubes are knit flattened into two faces, each knit on its own bed. However, several of the techniques we discuss in this paper, such as knit/purl texture and inlay technique, rely on the availability of both beds of the knitting machine to construct a single face of fabric. Therefore the *combination* of tube knitting with either or both of these techniques on a v-bed machine requires a scheme called “half gauge” in which only every other needle is used to form stitches for that face of the fabric. The

remaining needles are allocated as “holding needles” that may be used temporarily in the construction of the other face. This is similar to the use of half gauge to support fully general transfer planning in McCann et al[20].

Combining Tendons with Tubes

As discussed in the section on tendon insertion techniques, tendons can be integrated into both the front and back face of the tube for bending in each direction, as seen in Fig. 13A. A single tendon can also interlace with both faces sequentially, producing an s-shaped bend (Fig. 13B). A diagonally-set tendon can produce an asymmetric bend (Fig. 13C); two diagonal tendons placed opposite each other can produce twist (Fig. 13D).

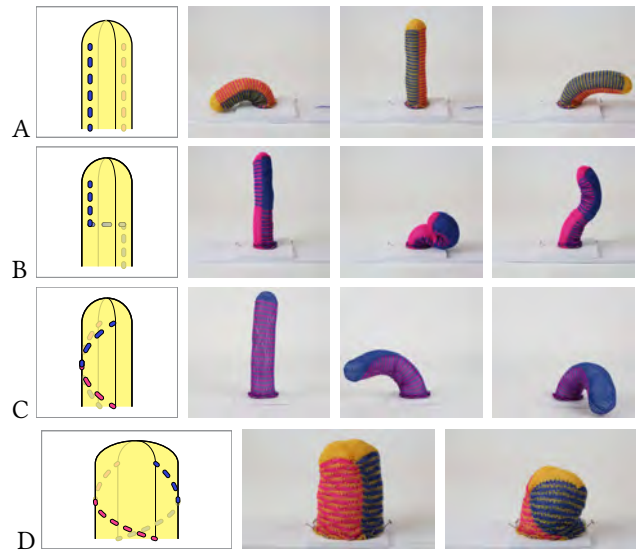


Figure 13: A: Separate tendons for front and back faces. B: a tendon which interlaces with the front face for the first half of the tube and interlaces with the back face for the second half of the tube can create an s-shaped bend. C: Two diagonally laid tendons on the front face create a twisted bend. D: Two diagonally laid tendons, one on each face, create shear twist.

7 SHAPING VARIANTS: SHORT ROWS, INCREASES, AND DECREASES

In addition to straight tubes with consistent cross-sectional geometry, we incorporate “short row shaping” and “increase/decrease shaping” Both techniques are common in hand knitting, where they provide such shaping as the heel of a sock (short rows) or the taper of a hat (decreases). We use them here to increase the diversity of shapes we can achieve for our soft actuators.

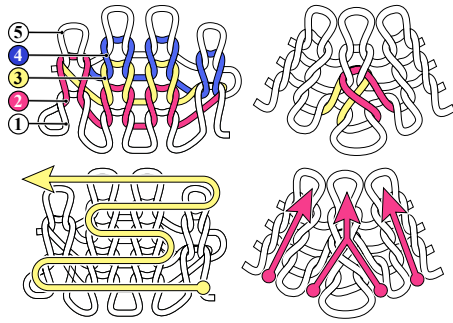


Figure 14: Left: Short rows. The second, third, and fourth rows (counting from the bottom) are highlighted and contain fewer than a full row’s count of stitches. Right: A decrease. Two stitches in the second row are overlapped and thus share a descendant stitch in the third row. Below: the effects these methods have on the row and column arrangements, respectively.

Short Rows

“Short row shaping” (Fig. 14) refers to a technique in which some of the rows of the knit structure do not extend the full width of the structure (Fig. 14, left). In other words, they are a way to distort the row/column grid. This distortion can be used to create local curvature out of plane, or, if used with “matching” nearby short rows to fill the gaps, to create rows that meander across the fabric (Fig. 15).

Increases and Decreases

The row/column grid can also be distorted via the introduction of *increases* or *decreases*: adding a column of stitches, or merging two columns into one (Fig. 14, right). For example, this can be used to make vertically-oriented tubes branch or merge (such as the thumb on a glove), or horizontally-oriented tubes bend (Fig. 8).

On the knitting machine, increases and decreases require the “transfer” operation. For a decrease, a stitch must be transferred onto its neighbor (Fig. 16); for an increase, an empty needle must be made available for the new column of stitches. See McCann et al [20] for details.

8 ANISOTROPY: KNIT/PURL TEXTURE

In addition to tendons and shaping, stitch-level anisotropy can play a critical role in actuation behavior. Knitting terminology draws a distinction between a loop that has been pulled through its parent from the nominal back of the fabric to the nominal front, typically just called a “knit,” and a loop that has been pulled through from the nominal front of the fabric to the nominal back, often called a “purl” (Fig. 17).

Patterns of knit and purl stitches have specific anisotropic profiles because every stitch has a tiny bit of intrinsic springy

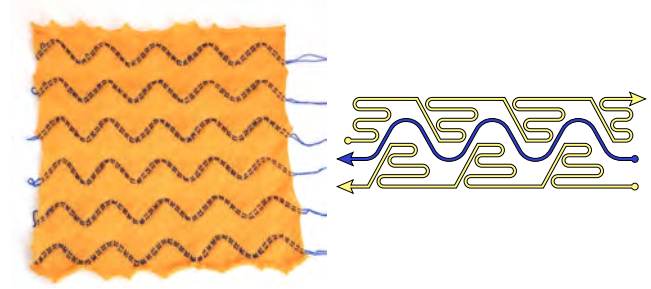


Figure 15: Left: Short rows distorting the stitch grid into waves. Right: diagram of knit rows.

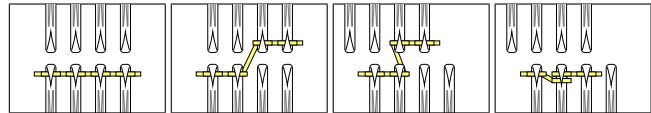


Figure 16: The transfer operation being used to move a stitch to a different place on the same bed: 1) stitches on the front bed; 2) the rightmost two stitches are transferred to the back bed; 3) the back bed moves leftward relative to the front bed; 4) the stitches are transferred back to the front bed, now leftward by one of where they started.

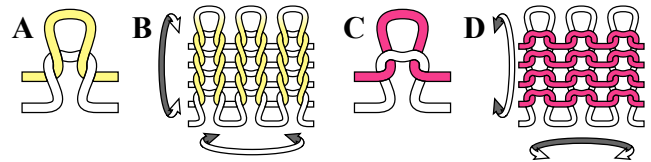


Figure 17: Knit vs purl. A: a single “knit” stitch. B: an area of all knit stitches, which has a tendency to curl forward along the vertical axis and backward along the horizontal axis. C: a single “purl” stitch. D: an area of all purl stitches, with the opposite tendencies.

curvature: each “knit” stitch has a tendency to curl forward in the vertical direction and backward in the horizontal direction, and each “purl” stitch does the opposite. This small amount of curvature accumulates with more stitches: a knit fabric made entirely of just one of the two variants will curl visibly.

However, knit structures can be designed to use knits and purls in equal or near-equal quantities; these are called “balanced knits” in both hand- and machine-knitting. A common knitting structure, “ribbing,” alternates between knits and purls in a row; since the direction of curl is switched for each vertical “rib,” the fabric tends to draw in sideways but not curl from top to bottom; this makes it popular for use in the cuffs and hems of sweaters. Another common knitting structure, “garter stitch,” alternates between full rows of knits and full rows of purls: the fabric is extra stretchy top to bottom and resistant to curling laterally.

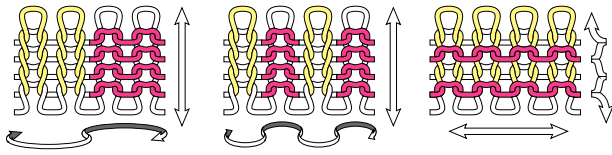


Figure 18: Left: A “rib” pattern that alternates two knits with two purls. Like all rib patterns, this pattern will tend to curl forward and backward (pulling inward) horizontally and be stable vertically. Center: A rib pattern with one-stitch-wide ribs. Right: A “garter” stitch pattern that alternates between a row of knits and a row of purls. This pattern will pull inward vertically but be stable horizontally.

Combining Tendons with Texture

The design of knit/purl patterns can be quite complex—Glazzard [13] discusses their use in making auxetic textiles—but we use the effect in this work primarily to create areas of directed bending. In contrast to the usual knitting emphasis of balancing knits to prevent curling, we deliberately introduce sections of all-knits or all-purls in order to form a localized hinge or pleat, Fig. 19. The curl direction of each stitch as shown in Fig. 17 means that a vertical hinge of purls or a horizontal hinge of knits will result in a “valley fold,” whereas the opposite arrangements will result in a “mountain fold.”

Forming knit/purl texture requires the transfer operation. In machine knitting, we can use either the front or the back bed to pull a loop through, provided that the parent has been formed on or transferred to that bed. “Front bed knit” and “back bed knit” can be understood as synonyms for “knit” and “purl” for a fabric with its nominal front oriented to the front of the knitting machine. To switch between knits and purls in a column of stitches, the column must be transferred to whichever bed will be used to form the next stitch. For example: because garter stitch alternates between knits and purls in a column, stitches must be transferred before every row of knitting.

9 FABRICATION AND MATERIALS

All examples in this paper were designed as compositions of the knitting strategies defined in Fig. 7. Code to generate low-level Knitout format instructions[3] was written using a set of modular Javascript functions based on the strategies. Examples of these Javascript functions and the resulting Knitout are included in our supplemental materials. The Knitout format was then translated into machine-specific operations for knitting on a Shima Seiki “Wholegarment” SWG091N2 v-bed 15 gauge knitting machine using half gauge.

Materials Selection Guidelines

For repeatable motions, it is important that a mechanism can return to its original position. In a soft material tendon



Figure 19: Using areas of differing knit/purl patterns to form a hinge or pleat. Top: A sheet with a pocket, which is part of the lamp example 28. The blue area is a single layer of knitting, primarily garter stitch, and the white is a second layer that connects to the blue layer at the top, bottom, and right edge, forming a pocket. Just above and below the pocket, full rows of all-knits define pleats that will bend forward (valley fold). Bottom: hinge areas allow the active position of a sheet-shaped sample to fold along pleat lines.

system, the recovery force must normally be supplied by a stuffing material; this force must be great enough to overcome both the friction along the tendon and the stiffness of the main knitting: for good recovery, we might ideally have a fairly stiff stuffing material, a fairly limp covering material, and a fairly slick tendon material. However, there are tradeoffs: a stuffing material that is too stiff might lose some of the benefits of soft actuation, depending on context. A covering yarn may have additional constraints on its appearance or other properties, such as conductivity. A tendon that is extremely slippery may slip out during the fabrication process, or be too weak to actuate without breaking.

Friction

We tested several tendon materials: the same Tamm Petit acrylic yarn we were using for the main knitting, a 2/60 weight pure silk yarn, Superior Threads “Omni” polyester-wrapped quilting thread, and a 0.045” nylon monofilament.

Of these materials, the fine silk yarn was the slickest, and thus offered the best recovery for cluster-stuffed objects. However, the quilting thread was stronger so we chose to use it for actuating objects stiffened with PETG. The nylon monofilament was neither stronger nor slicker than the silk or quilting thread, and additionally was stiff enough to periodically fail to knit cleanly, so we dropped it from consideration.

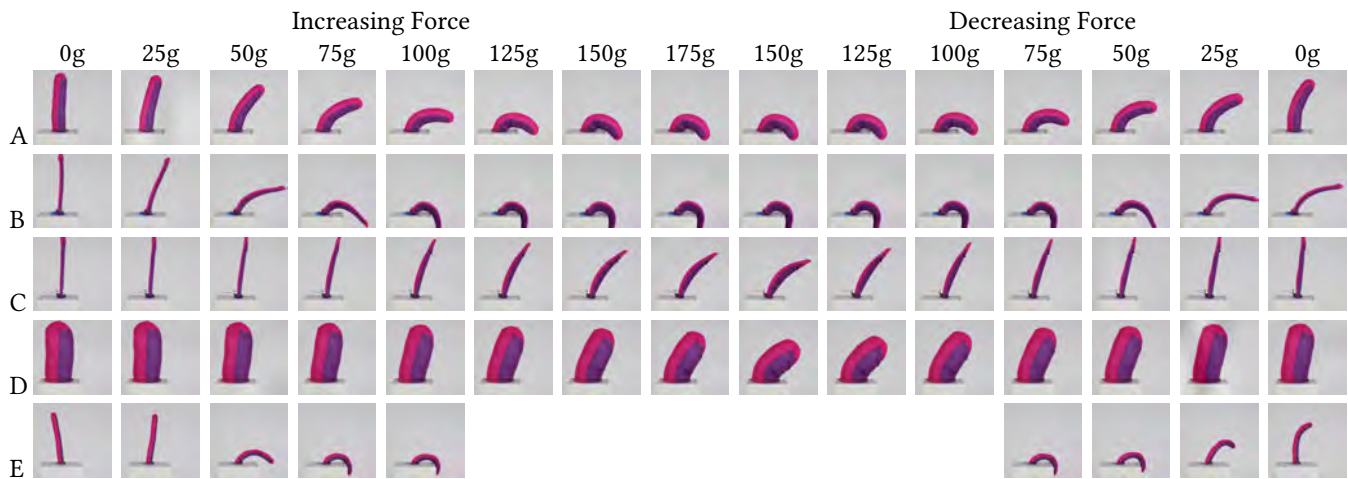


Figure 20: Comparison of different stuffing materials, A-C, and different cross-sectional areas of stuffing, D-E. Sample A is 1.5'' and stuffed with “Cluster Stuff.” Sample B is 1.5'' and stuffed with 3mm craft foam. Sample C is 1.5'' and stuffed with 0.30'' PETG sheet. Samples D and E are both stuffed with “Cluster Stuff”; D is 3'' and E is 0.75''. To show the hysteresis in recovery position, we incrementally loaded the tendon until a maximum curvature was achieved, then we decremented the load. We show the full actuating range of Sample A; some other samples achieved their fully-bent state at higher or lower end forces. The full data are plotted in Fig. 21.

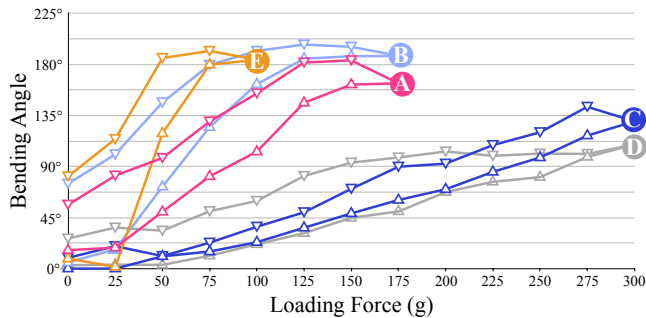


Figure 21: A plot of the data captured in the experiment described in Fig. 20.

Stiffness

The stiffness of a knit object is determined primarily by the material that is used to stuff it, along with its height and thickness. We tested three stiffeners (samples A, B, and C): “Morning Glory” brand “Cluster Stuff” polyester fiberfill, 0.30'' PETG sheet, and 3mm EVA craft foam. Additionally, we tested the effect of larger or smaller stuffing areas when using cluster stuffing (samples D and E). For each sample, we measured the bending angle of the sample under increasing loads from 0g until maximum curvature was achieved, then decreasing loads back to 0g. The samples are shown in Fig. 20 and a plot of the data is shown in Fig. 21.

The PETG sheet offers the most complete and quick recovery, but required the most force to fully bend at the thickness tested; it may thus be too stiff for smaller-scale actuations.

The craft foam was too weak to recover fully at the size tested, but it required the least force to actuate so it is suitable for smaller-scale motions that are desired to be relatively flat—for example, we use it in the ears of our toy bunny. The cluster stuffing offered less recovery force than the PETG sheet, but it has the advantages of being fully soft and appropriate for filling three-dimensional volumes, such as the arms of our gripper and bunny examples. The recovery ability of cluster stuffing is greatly influenced by its available volume. A very thick tube, such as Sample D, can return to very nearly its home position whereas a very thin one (Sample E) cannot.

We tested four yarns for the main knitting:

Brand	Name	Fiber	Weight
Yeoman	Volga 50/50	wool/polyester	7,143 m/kg
Yeoman	Polo	merino wool	15,000 m/kg
Yeoman	Supersheen	acrylic	15,000 m/kg
Tamm	Petit	acrylic	16,390 m/kg

There are many systems for characterizing the thickness of yarn. Yarn that is sold on cones for machine knitting is often labeled by “the yarn count system” which describes the number of strands spun together (“plies”) in the yarn as well as the thickness of each ply relative to a standard thickness. While the “Supersheen” and “Petit” yarns have different mass per meter, they have very similar thicknesses; both are characterized as “2/30” (two plies, with each ply 1/30

of the standard) in the yarn count system. The “Volga” yarn is about twice as thick. While the thickness of the “Volga” yarn made for a perceptually stiffer and more opaque fabric than the others, this stiffness was not enough to affect the motion of cluster-stuffed mechanisms. We ultimately chose yarns based on visual design characteristics; for example, the “Supersheen” yarn lends a lacy appearance in the lamp example, and the “Volga” yarn provides a denser look to the sweater.

Because the exact characteristics of the main knitting yarn does not greatly affect the mechanical properties, it is possible to use specialty yarns in this role. For example, we use conductive yarn to create a capacitive touch sensor in the bunny example.

10 EMBEDDING INTERACTIVITY

Motor Control

Motor control can be accomplished with a servo or DC motor setup like the one documented in the Soft Robotics Toolkit [1]. As shown in our stiffness experiments (Fig. 21), the force required to actuate our samples ranged from 100 to 300g. Assuming a 1.5” diameter reel, this requires 190-570 gram centimeters or 2.6-7.9 ounce inches torque, well within range of a standard servo or DC hobby motor[4, 6, 7].

Sensing

We integrate three sensing mechanisms. First, we used the capability of the tendons themselves to transmit forces by coupling the tendons to a linear encoder. We used a simple string potentiometer made from a 10-turn potentiometer and the return spring from a badge lanyard [2]. By attaching a sensor to each of four tendons—front face vertical, back face vertical, clockwise diagonal, and counter-clockwise diagonal—we can sense forward and backward bend and twist (Fig. 22).

Two other sensing approaches involve knitting with a conductive yarn. First, an area of conductive knitting can be used as a contact pad for capacitive touch sensing (Fig. 24). Second, because the loop structure of knitting makes variable contact as a knit swatch is stretched, an area of conductive knitting can be used as a resistive strain sensor [8, 32]. We saw resistance values of 1.29 mΩ at 0% stretch, 499 kΩ at 25% stretch, and 193 kΩ at 50% stretch for a swatch that was 2.5 cm by 4 cm between the test leads, knit from Bekaert 50/2 Cotton (Fig. 23).

Conductive yarns are often brittle and therefore difficult to knit reliably. To make a more physically robust sensor, the conductive yarn can be “plated” with another yarn. Plating is a technique in which two separate yarn carriers both contribute yarn to the same stitch. Because two separate carriers are used, the yarns don’t twist around each other; instead, one yarn is always closer to the nominal front of the fabric

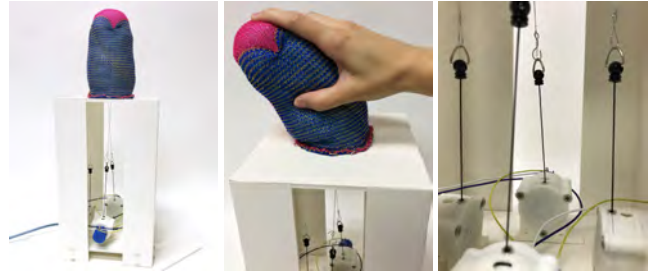


Figure 22: Bend and twist sensing using string potentiometers coupled to front, back, and diagonal tendons. Each tendon is coupled to a string potentiometer (right), which acts as a linear encoder.



Figure 23: A swatch knit with Bekaert 50/2 Cotton plated with a hair-thin latex elastic, shown at 0%, 25%, and 50% stretch.

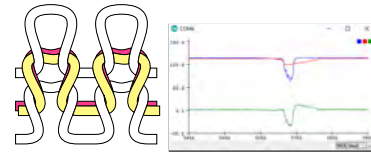


Figure 24: Left: Two yarns knit into the same stitches using “plating.” Right: a plot of the capacitive touch response of the “bunny” toy (Bekaert VN35X4 plated with Tamm Petit) using an Adafruit MPR121 board.

and the other backs it (Fig. 24). For the capacitive touch sensor in the bunny’s belly, we plated the conductive yarn with Tamm Petit yarn for strength. For a strain sensor, we plate with an elastic yarn to ensure that the swatch returns to its original shape after stretching.

11 COMPLETE OBJECTS

Tentacle

The three-way tentacle, Fig. 25, combines vertical tendon and shaping techniques: it has three vertical tendons and is shaped with decreases at the top.

Gripper

The gripper, Fig. 26, combines both tube types and both tendon types: a horizontal (inlaid) tendon is set into a horizontally-formed tube, and a vertical (yarn tangling) tendon is set into a vertically-formed tube. An eyelet at the intersection of the tendons makes it easy to pull the strings through to a Bowden tube. The gripper is stuffed with cluster stuffing.



Figure 25: A three-way tentacle.



Figure 26: A soft gripper.

Bunny

The bunny, Fig. 27, combines both tube types, both tendon types, both shaping techniques, and sensing. It is formed similarly to the gripper, but shows off the shaping complexity that is achievable with short row and increase/decrease shaping. Vertical tendons can actuate the ears, which are stuffed with craft foam. The rest of the bunny is stuffed with cluster stuffing, and horizontal tendons can actuate the arms in a hugging motion. The bunny is primarily knit in Yeoman Yarns “Volga” wool/polyester blend yarn, with an inlay of conductive yarn (Bekaert VN35X4) knit using the “plating” technique with Tamm Petit yarn for strength. We show its response as a capacitive touch sensor with an Adafruit MPR121 board in Fig. 24.

Lampshade

The lampshade, Fig. 28, combines horizontal tubes, sheets, horizontal tendons, short row shaping, and anisotropic bending techniques. Each horizontal tube is extended above, below, and to the side by a sheet to form a “sheet with a pocket.” The tendon is inlaid into the pocket, which can contain a PETG sheet. Each sheet section has short row shaping to form it into a wedge—one such wedge is diagrammed in Fig. 28(left). This section was repeated six times for the complete lampshade. Within the wedge, the main knitting is done in a stable garter stitch; areas of all-knit and all-purl form pleats when the lampshade is relaxed. The lampshade was knit out of Supersheen, which was the visually thinnest of our yarns, to give it a lacy appearance.

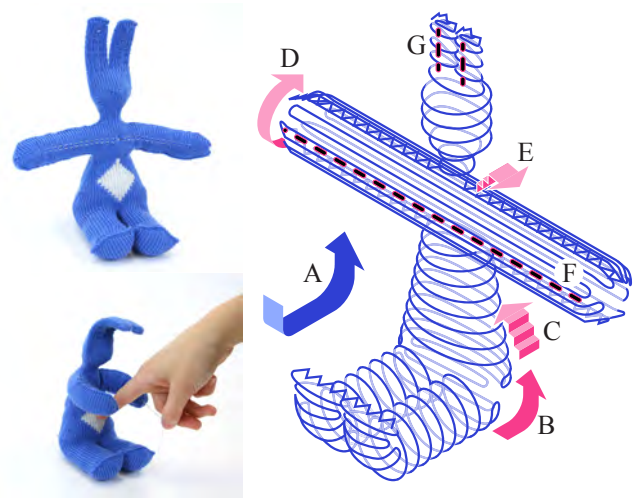


Figure 27: Left: A bunny with conductive belly and separately actuated ears and arms. Right: schematic of bunny (not to scale). A: direction of knitting. B: Short rows bend the legs and torso. C: Decreases to shape the torso. D: Short rows at the edges of a horizontal tube provide roundness. E: Increases to shape the neck and head. F: Horizontal tendon for arms. G: Vertical tendons for ears.

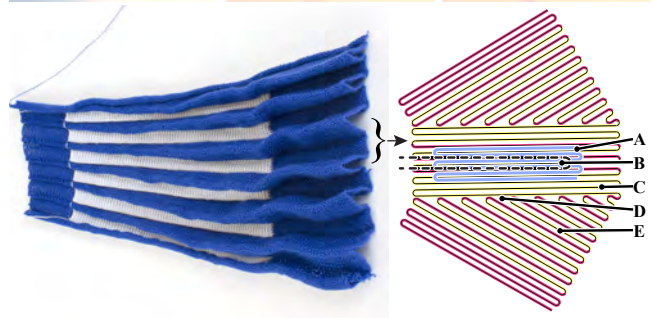


Figure 28: Top: the lampshade. Bottom Left: The lampshade laid out flat, seen from the back. Bottom Right: schematic of one section of the lampshade (not to scale). A: Double-layer pocket. B: A horizontal tendon; doubled over. C: All-knits. D: Short rows so that each section is wedge-shaped. E: Garter (alternating knits and purls).



Figure 29: A sweater with actuated sleeve.

The lampshade and the sweater sleeve were both knit with doubled-over tendons—a tendon was laid horizontally leftward, then, one row later, the tendon was laid back rightward again. Because of this, no knotting is needed to anchor the tendon in the knit fabric.

Sweater

The sleeve of the sweater, Fig. 29, like the lamp, combines horizontal tubes, sheets, horizontal tendons, short row shaping, and anisotropic bending techniques. The body of the sweater shows typical sweater shaping with ribbing at the hem and collar. The sweater was knit primarily out of Volga yarn to give it an appropriate heft as a garment, with the pink sleeve inlays knit out of Supersheen to encourage them to buckle back into place more easily.

12 LIMITATIONS AND FUTURE WORK

Our system has several limitations related to material properties: the inherent trade-offs between material softness, range of motion, and recovery force, as well as the difficulty of machine knitting reliably with delicate fibers such as conductive yarns. We additionally do not present comprehensive data on the repeatability of an actuated motion over time. While we actuated some basic objects (such as Sample A in Fig. 20) for hundreds of cycles and found little difference after the first complete cycle, much higher numbers of repetitions, or prolonged periods in the active configuration, may surface different results.

Another limitation is that, like any design vocabulary, our actuation strategies do represent a constrained domain within knitting. For example, we focus our attention to local texture on the anisotropic properties of knit/purl structures. A future exploration could include decorative textural effects such as eyelet lace patterning, or multi-layered surfaces such as interlock.

Additionally, as an experimental approach, our examples were designed directly in code which generated low-level Knitout files and our results do not include an end-user visual design system. This is an area which could benefit from an algorithmic approach, for example by adapting Narayanan et al’s work toward automating complex shaping on knitting machines [21] alongside Bern et al on simulating and automating tendon actuation within textile forms [9].

13 CONCLUSION

Textiles are an important category of materials for human interaction, particularly in on-body and furniture-scale contexts. Computer-controlled knitting can produce soft objects out of a variety of input materials. We show how actuation can be embedded directly in the knitting process, and provide recommendations for materials and surface textures to achieve particular effects.

We hope that this work will spur a deeper consideration of computer-controlled knitting as a fabrication method for interactivity, across applications and levels of expertise, from hobbyists to the runway.

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