# Digital Fabrication of Soft Actuated Objects by Machine Knitting

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*CHI'19 Extended Abstracts, May 4–9, 2019, Glasgow, Scotland UK*



ACM ISBN 978-1-4503-5971-9/19/05.
https://doi.org/10.1145/3290607.3313270

**KEYWORDS**
Soft materials; additive manufacturing; computational crafts; soft actuator

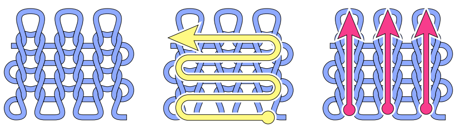

**Figure 1: Left: A basic knit swatch. Center: row-wise connections along the yarn path. Right: column-wise connections of loops holding loops. The structure is formed under gravity, progressing from the bottom to the top.**

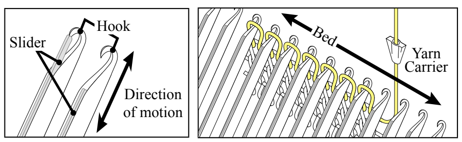


**Figure 2: Left: Slide needles. Right: A bed of slide needles holding a knit swatch in progress.**

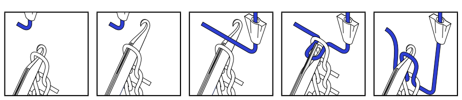

**Figure 3: A basic *knit* operation as performed by a knitting machine.**

**Figure 4: A horizontal tube with decrease shaping to bend the tube into a v-shape.**

## 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. In this work, we explore a series of design strategies for machine knitting actuated soft objects by integrating tendons with shaping and anisotropic texture design.

## Introduction

Soft fabrication is increasingly relevant to human-computer interaction, with applications ranging from soft and shape-changing interfaces [3, 4, 7] to wearable technologies [5, 6]. 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 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 [2]. 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 work, we consider techniques that expand the usefulness of machine knitting as a fabrication method for interactive objects.

### The Structure of Knitting

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. 1. Each loop in a column is formed by pulling yarn through the previous loop in the column. A flat-bed knitting machine forms a knitted structure using rows (*beds*) of parallel needles (Fig. 2). 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.

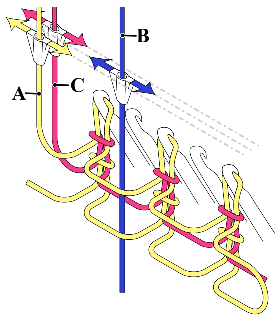


**Figure 5: "Tangling" technique for embedding vertical tendons.**

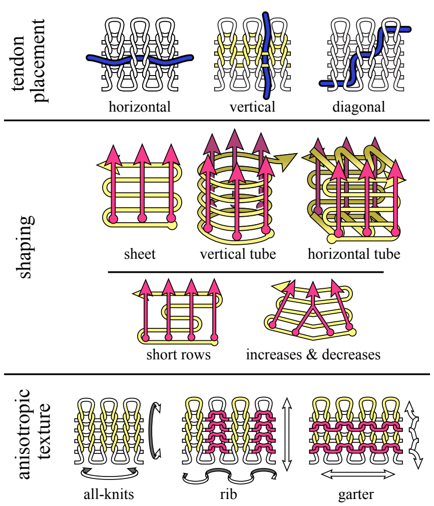


**Figure 6: A menu of knitting strategies.**

## Tendon Placement

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

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. 7).

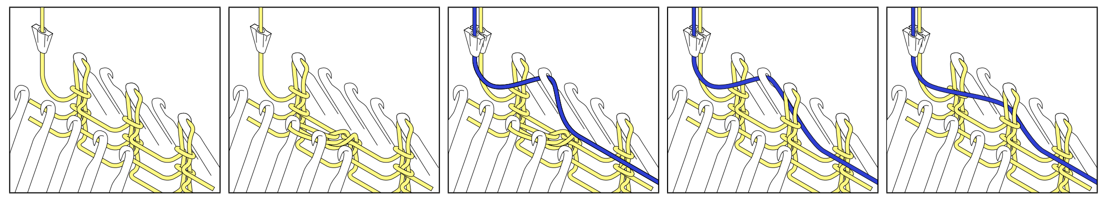

**Figure 7: Inlay technique for embedding horizontal tendons. 1) Stitches formed on the back bed; 2) Every other stitch temporarily moved to the front bed; 3) Inlay yarn pulled across; 4) Stitches returned to the back bed.**

Producing tendons in the column direction requires interlacing with the row-wise connections of the main knit structure. This is a result that in conventional use of the machine 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.

## Knit Shaping and Texture Strategies

We identify three composable categories of knit actuation design elements suitable for machine knitting (Fig. 6). 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 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. 4 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.

We manipulate the local anistropic texture inherent to knitting via the use of knit/purl patterns. These can be quite complex—Glazzard [1] discusses their use in making auxetic textiles—but we use

**Figure 8: Using areas of differing knit/purl patterns to form a hinge or pleat.**

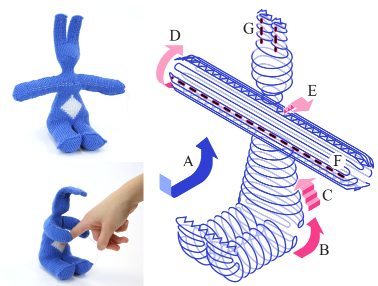


**Figure 9: A bunny with conductive belly and separately actuated ears and arms.**

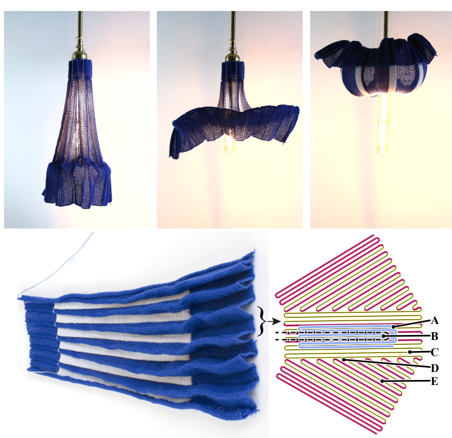


**Figure 10: Top: the lampshade in action. Bottom: The lampshade laid out flat, with schematic of one section.**

the effect in this work primarily to create areas of directed bending in order to form a localized hinge or pleat, Fig. 8.

### Complete Objects

The bunny, Fig. 9, combines both tube types, both tendon types, both shaping techniques, and sensing.The lampshade, Fig. 10, 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. 10(bottom-right). This section was repeated six times for the complete lampshade, Fig. 10(bottom-left).

### 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, shaping, and surface textures to achieve particular effects.

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