ABSTRACT
This research explores the development of seamless pneumatically actuated systems whose motion is controlled by the combination of differentially knitted textiles and standardized thin-walled silicone tubing. This work proposes a fundamental material strategy that addresses challenges ranging from soft robotics to pneumatic architecture. Research in soft robotics seeks to achieve complex motions through non-mechanical monolithic systems, comprised of highly articulated shapes molded with a combination of elastic and inelastic materials. Inflatables in architecture focus largely on the active structuring of static forms, as facade systems or as structured envelopes. An emerging use of pneumatic architecture proposes morphable, adaptive systems accomplished through differentiated mechanically interconnected components. In the research described in this paper, a wide array of capabilities in motion and geometric articulation are accomplished through the design of knitted sleeves that generate a series of actuated “elbows.” As opposed to molding silicone bladders, differentiation in motion is generated through the more facile ability of changing stitch structure, and shaping of the knitted textile sleeve, which constrains the standard silicone tubing. The relationship between knit differentiation, pneumatic pressure, and the resultant motion profile is studied initially with individual actuators, and ultimately in propositions for larger seamless assemblies. As opposed to a cellular study of individual components, this research proposes structures with multi-scalar articulation, from fiber and stitch to overall form, composed into seamless, massively deformable architectures.
INTRODUCTION

This paper documents research in characterizing the motion behavior of knit-constrained silicone tubes. This is particularly focused on the development of wale-wise tubular knits as the constraining sleeve for the silicon tubing. The wale direction of a knit refers to the horizontal loop or stitch direction, while course-wise refers to the vertical direction of the knit or the direction containing rows of stitches (Figure 2). A wale-wise tubular knit means that the length of the sleeve is defined by the number of wales or stitches. Course-wise defines the length of the sleeves by the number of courses. Given the asymmetry of a knitted stitch, very different strategies are needed to both construct the tubular knit and introduce the necessary stitch variations in order to produce the desired bending behavior. A range of wale-wise knit structures within the seamless sleeve are explored to form an actuated ‘elbow.’ The knit-constrained actuator is subjected to a ramping pressure profile in tests up to 80 psi to examine the full range of motion and its nonlinear behavior. While initially exploring planar motions, particular knits are developed to create multi-axial movements.

This research in knit-constrained actuators exhibits the ability of the knitted constraint to allow for extremely thin-walled uniform silicone tubes (1/32” wall thickness) to be pressurized up to ten times their working pressure. In combination with differentiation in the knit structure, the isotropic tubes can generate a high degree of geometric articulation while accomplishing a wide range of motion, in some cases over 360 degrees, for an eight-inch-long, approximately half-inch-diameter actuator, when fully inflated.

The motivation for this work is to advance concepts in soft robotics as well as appropriate fundamental technological developments for application to the field of pneumatic systems in architecture. First, this research proposes the use of an elastomeric material as the vessel for inflation. Such is typical for actuators designed to accomplish linear, bending, and twisting motions, where a strain-limiting element is embedded within the elastomeric material (Galloway et al., 2013). By contrast, architectural systems utilizing air to activate a closed membrane as a tensile, structural volume are made of inextensible polymer foils (Knippers et al., 2011).

This poses a considerable distinction where the architectural pneumatic system operates as a structural system only in a singular geometric state. Projects such as PneuSystems seek to introduce geometric variability by working with interlocking pneumatic ethylene tetrafluoroethylene (ETFE) components (Velikov et al., 2014a). In a variant of the PneuSystems project, NervousEther utilized a control system that varied pressure within each pillow to drive transformation of the overall assembly (Velikov et al., 2014b). Introducing a flexible ‘muscle’ within a pneumatic component allows for the Adaptive Pneus project to alter its local geometric orientation (Garleghi and Sadeghy, 2009). Investigations have also looked to mimic the material methodology and control systems for soft robotics, using...
shown. Such integration opens up an additional degree of transformability, not only focusing on the actuator motion but also the activation and gradient behavior of the surfaces in between actuators.

**BACKGROUND**

This research concentrates primarily on the characterization of knit-constrained actuators for bending and twisting, as opposed to linear actuation as in a McKibben actuator (Ball et al. 2016). Commonly, bending actuation is accomplished through the combination of an elastomeric air chamber and an inextensible but flexible strain-limiting layer, such as woven fiberglass cloth. A swelling constraint is additionally added by winding high strength fibers, such as Kevlar, around the air chamber. The uni- or bi-axial direction of winding for the swelling constraint is utilized to induce either twisting or bending, respectively (Maeder-York et al. 2014). In comparison to robotic systems with rigid mechanical joints, such soft mechanisms for motion are ideal for human interaction, though they currently lack a comparable level of articulation and predictability. A particular challenge in soft robotics is the ability to isolate a particular bending movement within the length of a single actuator, and additionally to combine different motions within a singular element. In the work of Galloway et al. (2013) and Maeda-York et al. (2014), this is accomplished through a multilayer, multi-component assembly, either by the application of a constraining sleeve to isolate bending, or by the assembly of multiple segmented actuators to introduce different bending motions. In the research shown in this paper, such differentiated articulation is generated through a single knitted constraint utilizing continuous variation in stitch structure.

Industrial dual-bed weft knitting is proposed as a unique solution for producing a differentiated, textile reinforcing sleeve for a pneumatic actuator. First, weft knitting allows for significant differentiation in the structure of a textile at the scale of the stitch. The density of stitches can be dramatically altered within a single course and between courses, referred to as multi-gauge knitting. Where the gauge of a machine defines the number of needles per inch, multi-gauging infers the number of stitches knitted per inch. For instance, an all needle structure can be combined with 1 x 1 knitting, or knitting on every other needle (Figure 3a). This creates a local differentiation in the stretch of the textile. It is important to understand, though, the counterintuitive nature of such a condition. An increased density of stitches introduces more stretch, as there are more loops of material allowing for a greater geometric reconfiguration when an external force is applied. Second, differentiating the number of stitches between courses, referred to as shaping or goring, allows for the production of a seamless non-planar textile
geometry (Figure 3b). Third, the two beds of a weft-knitting machine allow for efficient production of seamless tubular structures. Elaborate topologies of seamlessly interconnected tubular structures through weft knitting have been shown in the research for complex textile hybrid architectures, structures formed of interacting tension, and bending-active elements (Ahlquist 2015). The research in textile hybrid structures utilizes course-wise tubular textiles, while, as mentioned previously, this research in pneumatic actuators focuses in more depth on the development of wale-wise tubular knits. Of most importance, the wale-wise strategy allows for an infinite number of sleeves to be integrated within a single continuous textile, along with the seamless introduction of different materials between sleeves.

METHOD

Pneumatic Control System

Pneumatic valves can be roughly divided into two primary types: on/off valves, and proportional valves. Proportional valves offer the highest degree of control, and operate by translating an electrical input signal and an input air pressure into a controlled pressure at the output within the rated flow limit. By calibrating the resulting state of the actuator to this pressure, a repeatable open-loop positioning system can be created. With the addition of integrated sensing or external position feedback, a servo-pneumatic positioner can be created to adapt to external loads.

The disadvantage of proportional technology is its high cost. A typical system requires a proportional valve and an analog output channel for each pneumatic circuit (Figure 4). An alternative, as used here in the experimental setup, is to use solenoid on/off valves, which are available in numerous configurations, and a single proportional valve. On/off valves operate simply by opening or closing; the downstream pressure will match the upstream pressure once the system reaches steady state. By precisely controlling the “on” time of a valve, partial inflation states can be achieved. While an on/off control methodology is considerably cheaper per circuit, in the range of 25–50% the cost of a proportional system, it is significantly more challenging to create a continuously variable position-controlled system. For the characterization of the knit actuators described below, a proportional system was used to control the pressure according to a calibrated input signal.

Differentiated Knit Constraints

The knitted constraints are developed in the textiles lab at the University of Michigan’s Taubman College of Architecture and Urban Planning, utilizing a STOLL 822 HP 7.2 multi-gauge knitting machine. Whether course-wise or wale-wise, the basic strategy for generating an actuated elbow involves producing a region where there is more material on one side of the tube versus the other. This is controlled by increasing the number of stitches on one side to produce the extensible region and reducing the number of stitches on the other side to produce the restricting region or inner radius of the elbow (Figure 5). The wale-wise knits have an additional control along the backbone of the knit, noted as condition 01.A and 02.A in Figure 5. This backbone consists of a series of long stitches oriented in the
The proportional valve used in this test is an open-loop device. The program triggers a camera at regular intervals according to the change in pressure. This differs from a system where the camera is triggered at a fixed time interval, though in a perfectly linear system these should match. By using a pressure-based trigger, the intent is to better capture the nonlinear sections of the inflation tests.

Custom executable software was developed to interface between the various components in the experiment. In order to facilitate high frame rate capture, the software is written in C++, utilizing the camera’s SDK (Spinnaker), OpenCV, and the TwinCAT ADS protocol. The executable starts the ramping pressure profile, captures the image via a trigger in the PLC program, queries the PLC for the current pressure, and then stores pressure data along with the image. In order to reduce the storage required by the raw file capture, after the completion of a test, the executable then reopens, compresses, and saves the images.

The images are then batch processed in image processing software, and used to extract data for the shape of the actuator against the recorded pressure. Currently the data is limited to the estimated angle at the end of the tube, but future work intends to gather more complex shape information, such as radius of curvature, or multi-jointed hinge measurements.

RESULTS

Course-Wise Studies

An initial set of studies were developed using the course-wise tubular knit structure to create an actuated, stiffened boundary that subsequently formed a tensile saddle-like surface. The textiles are knitted with two ends of a high-performance 725 denier/192 filament polyester yarn. The bladder is a silicone tube, Durometer (hardness) 50 Shore A, with a 1/2 inch inside diameter, 1/16 inch wall, and a maximum operating pressure of 5 psi. Because of the knitted constraint, these exemplars are able to operate in the range of 25 to 50 psi. The elbow motion is generated through two interconnected alterations in the knit structures: (i) the number of stitches are reduced, knitted as a multi-gauge 1 x 1 knit, to create the inextensible region, and (ii) the expandable region is formed by knitting on all needles, as well as knitting two courses for every one course in the opposite side of the elbow, shown in Figure 5, diagram 03.C. Variants of this strategy include the utilization of different yarn combinations: (i) polyester only, (ii) polyester with bands of stitches using nylon-elastic yarn (referred to as nylastic) isolated at the elbows, and (iii) combined polyester and nylastic stitches across the entire textile, where the stitch structure is varied at the elbow to express extensibility with more nylastic stitches and inextensibility with primarily polyester stitches (Figure 6).
Observationally, the prototype with nylastic isolated at the elbows (Figure 6, center) generated the most significant motion, being tested up to 40 psi. This method of knitting, in knitting with a particular yarn only in isolated regions across the width of the textile, is limited for tubular structures in the course-wise direction, and is referred to as intarsia. Depending on the number of yarn feeders in the machine, only a limited number of separate regions knitted in the course direction can be achieved. Therefore, a larger prototype was developed utilizing the combined polyester and nylastic strategy (Figure 6, right). In the

5 Diagram comparing wale-wise and course-wise strategies for knitting differentiated sleeves.

6 Comparison of different elbow constructions in a course-wise tubular knit: (left) all polyester, (center) inset areas of nylastic at the elbow, and (right) nylastic and polyester knitted throughout the textile.

7 Inflation tests for single knit with four independent course-wise sleeves in a hexagonal configuration, (top) detailing inflation of all bladders, which structures the surface to an approximate height of five inches, and (bottom) phasing the inflation from one bladder to the next, which produces a sideways movement of approximately one inch per cycle.
This method is deployed within the SpringFORM software developed by the author (Ahlquist et al. 2014). To explore the potential of a simplified design tool while approximating the material differentiation of the knitted sleeve, a regular quad mesh is utilized with an overlay of differential spring lengths (Figure 8). As opposed to a typical mass-spring-based simulation, the springs strengths are nonlinear, being increased as they approach their target length. This is primarily due to the area factor, where as area increases, so does the magnitude of force. Where there are greater differences in area between faces, as happens in the "elbow" of the mesh, the simulation can tend to "explode," in that inflation forces on larger faces increase infinitely. The parameters that compute the relationship between factors defining the magnitude of inflation forces and the spring mesh itself are made to be manipulable during the form-finding process in the SpringFORM software. This is critical in both visually understanding the ramifications of adjusting the individual parameters and being able to tailor their relationship for a particular topology and articulation at the "elbow" of the inflation model. Further development looks to explore the construction of non-uniform meshes where a quad-face can represent the approximation of a certain grid of stitches.

Wale-Wise Studies

Two variants of the wale-wise strategy were explored: (i) the use of multi-gauging to generate the inextensible region (Figure 9), and (ii) the use of shaping to expand and contract the circumference of the wale-wise tube, relying on the backbone, as referred to earlier, to drive the bending motion (Figure 12). The multi-gauge studies explore the length of the articulated region to determine the bending behavior under a range of pressures up to 50 psi on an approximately 7.5 inch long actuator. The multi-gauge sleeves are knitted with the same polyester yarn as the course-wise studies, but in a lighter 325 denier/22 filament weight. They utilize a silicone tube, Durometer 50 Shore A, with a 1/4 inch inside diameter silicone tube, 1/16 inch wall, and a maximum operating pressure of 5 psi. At 50 psi, the actuator is expanded to an approximate diameter of 0.72 inches, almost two times its initial 0.375 inch outer diameter. With the initial examination of a wale-wise knit with no stitch articulation at the elbow, the motion behavior is minimal. The initial un-inflated state exhibits curvature driven solely by the backbone of the wale-wise tubular knit. But when the bladder is inflated, the actuator geometry is mostly straight, primarily exhibiting rotation because of the degrees of freedom at the fixture (Figure 10). The backbone of the wale-wise knit in this example is mostly ruled out from producing a bending behavior. Therefore, any articulation within the knit will isolate the bending motion to that location.
12 Detail of inflated wale-wise tubular knit, showing (a) shaped area of the knit that minimizes bending motion, and (b) unshaped region where significant bending motion occurs.

13 Overlay of analysis of rotation, with sampling at a step of 3.0 psi up to 80 psi, for an actuator with an unarticulated wale-wise tubular sleeve (left), and a sleeve with more structured stitches along a certain length of the backbone of the knit (right).

14 Comparison of pressure to rotation angle at the end of each actuator, where the multi-gauge knits are captured in grey and the shaped knits are shown in red.

15 Comparison of studies between actuators, pressurized up to 80 psi, with two (left), three (middle), and four (right) shaped regions where the elbow condition occurs between each of the shaped areas defined by the knit.

16 Spiraling motion at 24 psi, 54 psi, and 84 psi, generated by shaping the body of the wale-wise sleeve in relation to the "backbone" stitches.
Articulation for the elbow is introduced by knitting all needles on one side of the elbow and knitting every fourth needle on the opposite side, as shown in Figure 4, diagram 02.B. The width of the articulated area is varied from sample to sample from 33 to 125 needles wide (Figure 11). Examining the full range of movement across all samples, there is an initial “s” curvature and then a nonlinear transformation to a more natural bending motion. By approximately 30 psi, the non-articulated portion of the knit is straight and the bending geometry is concentrated in the multi-gauged area of the knit.

The next set of studies, in the use of shaping to drive the bending behavior (Figure 12), are designed to operate at higher pressures, tested up to 80 psi, while using a thinner-walled bladder and a higher-strength yarn. The bladder is a silicone tube, Durometer 50 Shore A, with a 1/4 inch inside diameter, 1/32 inch wall, and a maximum operating pressure of 10 psi. The sleeves are knitted with a Kevlar yarn. The unarticulated actuator exhibits very different behavior from the previous studies. In this example, the backbone of the wale-wise knit is clearly the driving factor in generating the bending motion (Figure 13). This is confirmed in the testing of a knit where the stitches along a certain length of the backbone of the sleeve are more highly structured. The bending motion is significantly constrained in this region (Figure 13, right).

Shown across the array of tests, the overall motion behavior is more linear in comparison to the multi-gauge prototypes (Figure 14). One critical factor that drives the distinction between these two sets of studies is the size of the sleeve in comparison to the outside diameter of the silicone tube. In the unarticulated sleeve shown below, at 50 psi, the diameter of the actuator is 0.375 inches, only 1.2 times larger than the 0.3125 inch outer diameter of the silicon tubing. This is in comparison to the approximately two times factor for the previous studies. The expansion of the silicone tube is constrained in the circumferential direction, allowing it more ability to expand along the extensible region of the knit: the backbone.

To isolate the bending motion, a series of shaped regions are introduced along the length of the knit. The shaped regions introduce more material, thus allowing the silicone tube to expand in its diameter, limiting the effect of the backbone to generate a bending motion (Figure 15). This results in a very sharp and concentrated curvature in the un-shaped regions.
17 Aggregated behavior, produced by flipping the “spine” of the tubular knit, generating a range of sine wave bending motions.

18 Aggregate spiraling behavior of interconnected actuators, pressurized to 80 psi.

19 Studies for the aggregated clockwise and counterclockwise spiraling of an individual actuator.
The previous set of studies with shaped actuators show a unique combination of range of movement and degrees of freedom. In the work by Polygenorinos et al. (2015) on a robotic hand assistive device, multiple degrees of freedom are achieved through a “multi-segment actuator.” Combinations of clockwise and counterclockwise fiber reinforcements bonded with the elastic and strain-limiting components are tailored to produce such levels of articulation. The examples above show the ability to capture all the degrees of freedom within the structure of the knitted sleeve. Expanding upon the aggregated behavior within a single actuator, additional knit characteristics are constructed within a single knitted constraint to produce a wider array of movement. Spiraling is achieved by continuously shaping along the length of the wale-wise knit (Figure 16). While this uses the method of shaping, it produces an actuator with a constant cross-section, unlike the actuators shown in Figure 15. A sine-wave motion is produced based upon the sample shown in Figure 13, left. To flip the location of the “backbone” from one side of the tubular sleeve to another, a section is knitted on the opposite needle bed of the knitting machine (Figure 17).

The ultimate goal for this research is to assemble multiple actuators within a seamless system. This exposes the key capacity of machine knitting in creating seamless, 3d, multi-material textile systems (Penciuc et al. 2010). The initial concept is to resemble the basic structural strategy of a textile hybrid system: the interaction of a structurally-active boundary with a tensile, form-active surface. In previous research, this is accomplished with a glass-fiber reinforced polymer rod and woven or knitted textiles (Ahlquist et al. 2013). When the boundary is replaced by pneumatic actuators, the result is a multi-state pneumatic/textile hybrid system, where actuation of the rail allows for the generation of an array of formal and structural configurations (Figure 18).
CONCLUSION
This research establishes fundamental strategies for controlling motion behavior of a pneumatic actuator through the articulation of a seamless knitted constraint. The knitted constraint poses unique advantages over a conventional soft actuator in being able to produce differentiation in shape, material, and structural behavior within a single unit. Weight is an important quality as well, where actuation at pressures up to 100 psi can be accomplished with extremely thin-walled conventional silicone tubing. This research requires exploration at the smallest scales of material construction in the fibers, yarns, and stitch structure, as well as methodologies for knit manufacturing. Thus, this current and ongoing research explores an extensive array of variants in the 1st, 2nd, and 3rd level hierarchies.

The aggregation of motion within a single actuator and integration of multiple actuators within a single system opens up unique opportunities. The proximity between actuators can be designed to, in one instance, activate and transform the geometry of a material spanning between the actuators. In another instance, actuators can be designed adjacent to each other. This would allow for a full spectrum of forward and reverse actuation. Bending, unbending and reverse bending is made possible by controlling the balance of pneumatic pressure. This means, for instance, that what is typically an unloaded state, unable to respond to external loads, can actually be loaded by having an equal balance of pressure between the two adjacent actuators.

Future development looks to address more detailed issues related to the two arguably divergent scales of soft robotics and responsive architectural systems. To better understand the relationships of motion, pressure, and force in the knit-constrained actuators, a more robust computer vision–based analysis tool is necessary. The current system links each snapshot of the actuator with its current pressure, but analysis of geometry and rotation is done manually. Scale is a critical issue when considering its potential as an architectural system. While the multi-gauging technique is clamped based on the maximum scale and spacing of stitches, the shaping techniques are more extensible and should be generalizable for larger scales.

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REFERENCES


**IMAGE CREDITS**

All drawings and images by the authors.

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