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Anisotropic 3D-Knitted Sleeves as Inverse Pneumatic Artificial Muscles for Soft and Wearable Robotics

Thomas P. Dean, Joshua Davy, Jane Scott, Pietro Valdastri and James H. Chandler

***Abstract*— Inverse Pneumatic Artificial Muscles (IPAMs) have emerged as an alternative to traditional artificial muscle approaches due to their exhibited high deformations. However, existing IPAM designs often require complex fabrication processes involving fiber winding or embedding around inflatable components, limiting adaptability and scalability. In this study, we present a novel approach to IPAM design using digitally designed 3D-knitted sleeves as seamless external shells. These sleeves, made from a combination of Elastane and cotton threads, exhibit tailored anisotropic strain properties to achieve high axial strain of up to 117% and force output up to 3.2 N while minimizing radial expansion. Our method simplifies assembly by eliminating the need for bonding or mechanical tensioning between the sleeve and the inflatable bladder, enhancing modularity and ease of modification. We compare three sleeve designs created through digital knitting to demonstrate the versatility of this technique. The optimal design is further characterized for repeatable strain and blocked force performance, and we show how minor structural modifications enable programmable shape formation. This work establishes a foundation for scalable, cost-effective production of adaptable IPAMs, suitable for soft robotics and wearable technology applications.**

I. Introduction

Soft pneumatic actuators represent a highly versatile approach within the field of soft robotics [1]. By controlling strain development resulting from a pneumatic pressure change, designs can produce independent or combined motion primitives including contraction, extension, bending or twisting [2]. This is typically made possible with combinations of specific internal and external geometry design [3], and/or through the integration of materials with differing mechanical properties [4]. Pneumatic Artificial Muscles (PAMs) fall under the latter case, with designs such as the McKibben actuator consisting of a simple inner tube surrounded by an outer mesh that constrains ballooning motion to cause axial contraction under application of sufficient pressure, operating in a similar fashion to biological muscles [5]. Numerous approaches have been developed for contracting PAMs to suit different applications, including foldable PAMs for low hysteresis [6], series PAMs for steering of continuum robots [7], and pleated PAMs for high contraction force and displacement range [8].

More recently, axially extensible (rather than contraction) designs have been proposed, forming Inverse Pneumatic Artificial Muscles (IPAMs). Approaches have included fiber-wrapping of soft tubing for high strain capabilities [9], casting of helical designs with embedded conductive silicone tubing for self-sensing IPAMs [10], and double helix fiber integration combined with pre-straining for dynamic control

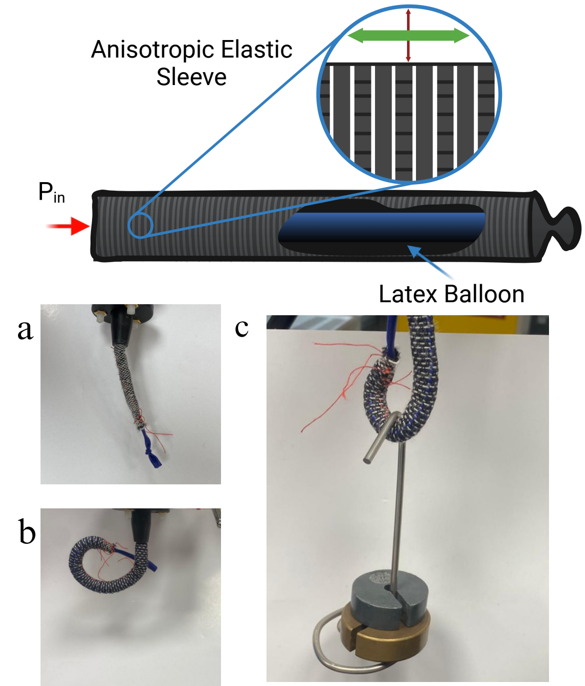

Fig. 1: Overview of the proposed IPAM design. An anisotropic knitted sleeve with internal latex balloon extends axially under pressurization. a) Extension of the actuator under pressurization. B) Bending actuation via sewn-in inelastic thread. C) Use of the actuator for lifting and supporting a load.

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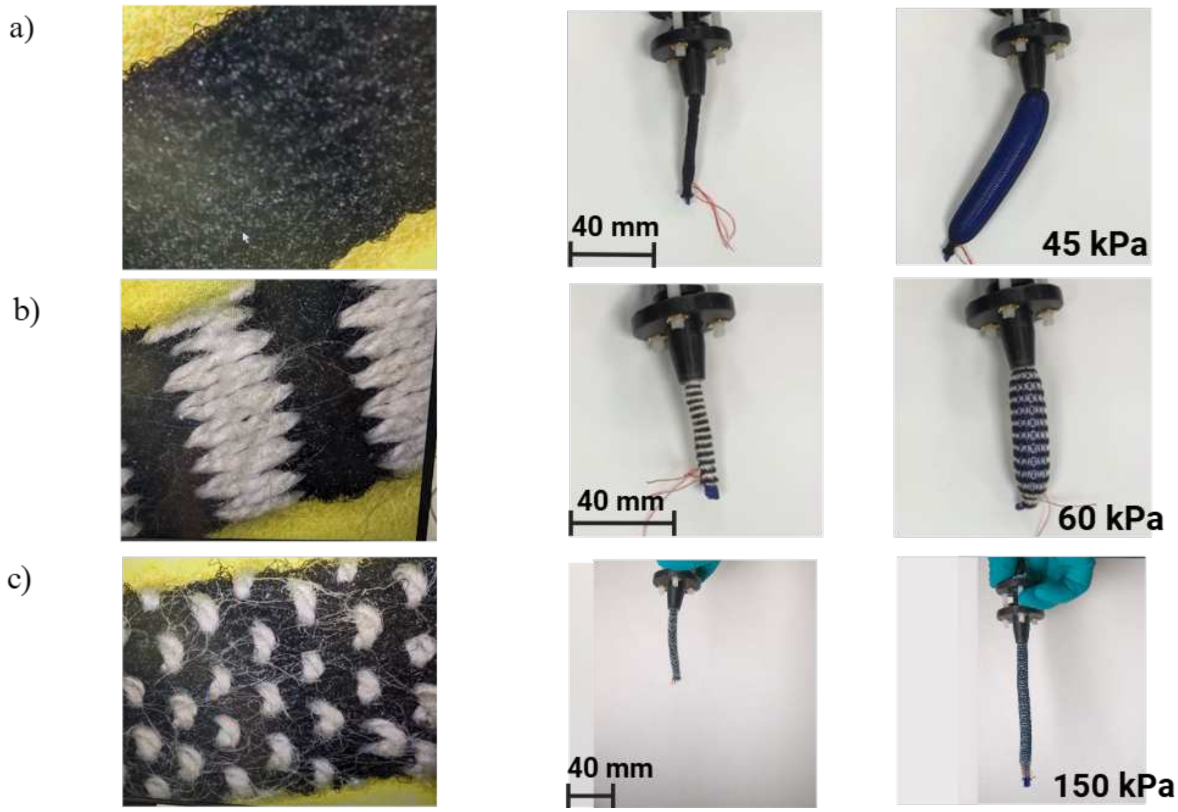

Fig. 2: Comparison of the three tested knitted sleeves. The sleeves are formed from combinations of elastic and non-elastic yarn. After insertion of the latex ballon they are then testing until close to material failure. a) Sleeve 1 consisting purely of Elastane thread with a plain knitted pattern. b) Sleeve 2 consisting of stripped alternative cotton and Elastane thread c) Sleeve 3 consisting of a combination of cotton and Elastane to create anisotropic behavior.

applications [11]. Although effective, these require winding and/or embedding of the strain limiting fibers around the inflation unit, which can increase fabrication complexity and reduce design repeatability and adaptability. As an alternative approach, IPAMs may be designed with a separate strain limiting external sleeve/shell design and simple inflatable bladder; an approach more analogous to traditional PAM designs. In this case, the use of textile-based anisotropic sleeves can offer a high degree of design freedom due to versatility in yarn material, manufacturing methods and integration [12]. Most soft robotic approaches using textiles have followed a 2D-to-3D approach, where sheet textiles are cut and joined through sewing or bonding to form shell structures [13]. For example, Guo et al. [14] produced pneumatic actuator designs based on sewing layers of anisotropic knit material together using pre-designed encoded seams to form 3D textile shells that, once inflated with a pneumatic bladder, produce a wide range of programmed deformations. Additionally, Yang et al. [15] describe a 2D trilayer knit which introduces a polyester yarn inlay into a looped polyurethane-polyester yarn knit to create a high anisotropic stiffness profile between course and wale directions. Through flat seam joining of the trilayer knit and sewn-in polyester, programmed bending and spiralling was achieved. As an available alternative to 2D-3D approaches, 3D knitting offers the potential to create seamless 3D designs with continuously variable geometry and yarn distributions. Sanchez et al. [13] investigate 3D knitting to create monolithic pneumatic soft robotics by adjusting knit structure and yarn properties within the knit tube for various combined motion primitives. Recent advancements have thus demonstrated some of the potential benefits of 2D and 3D knitted textiles for soft robotic applications. However, for the efficient development of sleeve-based IPAMs, knit structures should maximise axial strain while minimising radial strain, avoid or minimize additional post-fabrication steps and undesired anisotropic defects from sewing/bonding, and retain extensive design freedom for application-specific optimization.

In this study, we consider the use of digitally designed 3D knitted sleeves as seamless IPAM shells. We consider elastic loop yarns (elastane) with inelastic inlay yarn (cotton) to produce desirable anisotropic strain characteristics, see Figure 1. This approach allows the production of small scale (7 mm diameter) IPAMs with high strain and force output that are easy to assemble, modify and offer the potential for simple manufacturing scale-up. This approach avoids the need for direct bonding or mechanical tensioning between the strain modifying structure and the inflation unit, allowing either to be modified or replaced. We highlight the diversity offered in this approach by comparing three designs with digitally-defined and machine-produced knit patterns. For the optimal sleeve design, IPAM performance is further characterized

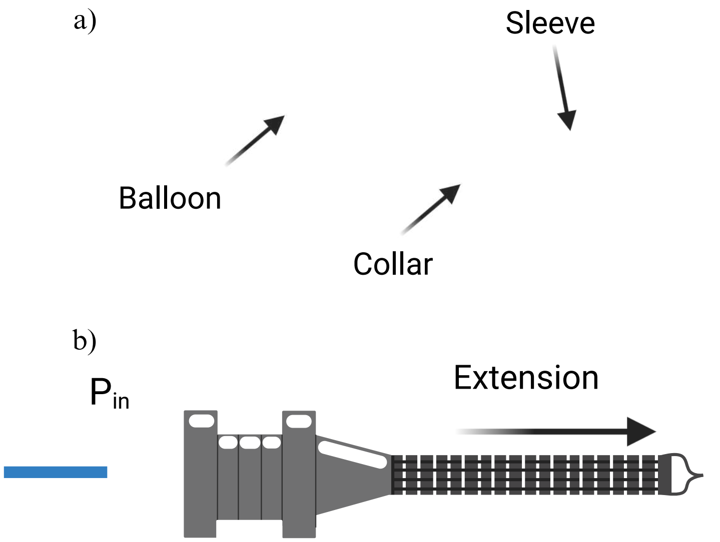

Fig. 3: a) Assembly of the 3D printed collar for clamping the sleeve with internal balloon. Three M5 bolts and matching nuts (not shown) are used to secure the collar. b) Pressure is applied at the proximal end causing extension of the muscle.

for strain and blocked force output repeatability, and we demonstrate how simple modifications to the knitted sleeve structure through the addition of inelastic thread allows for arbitrary shape formation. This work lays the foundation for digital production of simple, adaptable and affordable IPAMs as base actuators in applications such as soft and wearable robotics.

II. Methodology

IPAM actuators were constructed from a combination of 3D knitted sleeves and separate internal bladders. Knitted sleeve designs were formed from combinations of elastic and non-elastic yarn to produce differing anisotropic stiffness distributions. For the proposed designs, the elastic thread was selected as black Elastane (16.74% lycra, 83.26% nylon cover, yarn count 52 Nm) with a maximal extension of 356 % (Elastane, Uppingham Yarns, UK), and the non-elastic thread was selected as a common 2-ply white cotton (100% cotton, yarn count $2/30$Nm), (Ecoloop, Uppingham Yarns, UK). Designs were programmed using specialist knit design software (Apex3, Shima Seiki, Japan). The yarns were formed into sleeves using a commercial knitting machine (Mach2 XS, Shima Seiki, Japan, 15gg gauge), based the software-defined knitting patterns. To consider design variation using the 3D knitting approach, three knit patterns were considered (Figure 2). The first design was formed purely of the Elastane thread with a plain knitted pattern as shown in Figure 2a. The second design was formed as a striped tubular weft knit fabric consisting of four courses of knit stitches (in cotton) and four courses purl stitches (in Elastane), alternating in the wale direction to create a striped appearance (Figure 2b). The third design represents a more complex pattern, consisting of a tubular weft knit fabric (in Elastane) with a cotton inlay every 3 courses. The inlay was introduced horizontally by a separate feeder during knitting process. As shown in Figure 2c, the inlay is off-set within the pattern with alternate stitches securing the inlaid yarn within the knit structure.

Manufacturing the designs using the 3D knitting machine allows for sleeves of arbitrary length to be rapidly produced. In the presented case, 1 m lengths were manufactured to allow sufficient material for production of a small number of IPAM designs. Test actuators were formed by sub-dividing sleeves into shorter sections to produce IPAMs with a static length of 50 mm. An internal bladder was formed using a 25.4 mm diameter latex modeling balloon that was knotted at its distal end. The balloon was pulled through the sleeve section and the knot subsequently secured by stitching it in place. This approach ensured that the sleeve and the bladder stay aligned during actuation, minimizing relative motion or 'slipping' whereby the balloon slides through the sleeve. A custom three-part retaining collar and clamp was designed and 3D printed to secure the balloon and the sleeve, and to provide air tight seal for bench-top evaluation. Given the seamless 3D knitted sleeve design and simple assembly, IPAM actuators were able to be fully assembled in under ten minutes (see Supplementary Video 1). For pressure testing, the clamp was designed to connect directly to a pressurized air supply via 4 mm tubing (See Figure 3).

III. Results

A. *Comparison of knitting patterns*

The ideal sleeve for the IPAM would feature a large axial to radial elastic ratio and high maximum strain. This would allow for the greatest deformation given the elastic limit of the internal bladder while minimizing radial expansion. Three sleeve designs, as detailed above, were formed into actuators by insertion of the latex bladder and clamped for connection to the pneumatic supply. For each sleeve, air pressure was increased using a pressure regulating valve (AR30K-N03B-Z-B, SMC, Japan) until close to material failure, which was evident as the internal bladder began to visibly protrude from the gaps between stitching. In Figure 2, the effect of pressurization of the actuators can be observed. The first actuator design, shown in Figure 2a, was formed of the Elastane-only sleeve and realized a maximal pressure of 45 kPa, an axial strain of 70% and a radial strain of 214%. Although a moderate axial extension was demonstrated, it was combined with large undesirable radial expansion. This represents a failure of the single material sleeve to restrict the internal bladder, with the deformation profile broadly following that of the latex balloon without a sleeve. The second actuator design, shown in Figure 2b, supported a slightly higher pressure of 60 kPa, with a small axial strain of 20% and radial strain of 119%. The alternating yarn pattern of the sleeve shows improved radial constraint but also restricts high axial extension. The third actuator design, shown in Figure 2c, performed significantly better, achieving a maximum pressure of 150 kPa, a high axial strain of 120 %, and a low radial strain of 30 %. This illustrates how the strong anisotropic sleeve design with circumferential cotton inlay best meets the desirable criteria for general purpose IPAMs, and was therefore selected for further analysis. The higher maximum pressure of this design can be attributed to it's ability to better constrain strain of the inner balloon and prevent bursting.

B. *Characterization of Axial and Radial Strain*

To more thoroughly characterize the strain profile of the selected IPAM actuator design, it was pressurized incrementally between 0 and 150 kPa over four repeat cycles while images were recorded to determine the resultant axial and radial deformation profile. Images were corrected for camera distortions and measurements of length, extended length, diameter and extended diameter were determined vs a fixed reference rule (Figure 4a). Figure 4b shows the axial strain response of the actuator over the pressure range, demonstrating minimal deformation change up to approximately 50 kPa, a rapid increase between 50-100 kPa, and a reducing strain rate towards 117 % between 100-150 kPa. Figure 4c shows the corresponding radial strain response over the same pressure range. It can be observed that there is an increase in radial strain between 20-75 kPa as the macroscopic loose knitted structure expands, followed by a saturated maximal radial strain of 30 % as the highly inelastic cotton yarn becomes dominant in constraining radial expansion. The IPAM actuators were also tested up to a failure pressure of 190 kPa, whereby the inner bladder broke through the knit sleeve and rapidly inflated and ruptured; the beginning of this failure process is shown in Figure 5.

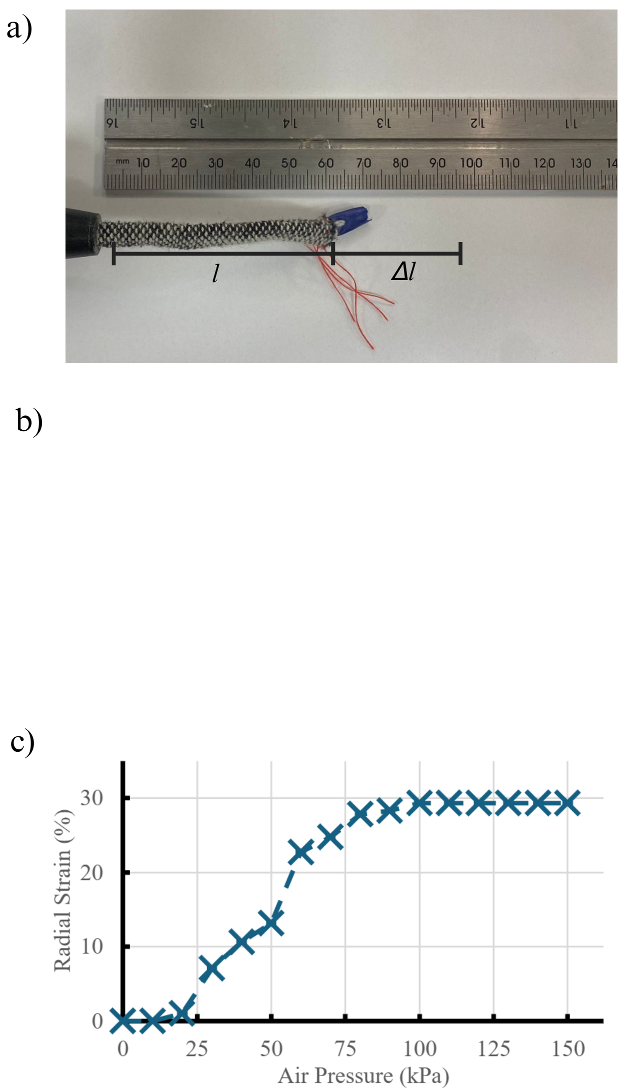

Fig. 4: a) Diagram showing how strain is calculated for the actuator with sleeve type 3. b) Axial strain under pressurization c) Radial strain under pressurization

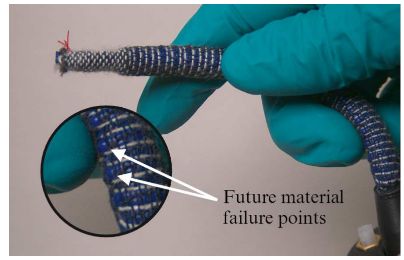

Fig. 5: Beginning of material failure. The latex balloon bladder begins to seep through the sleeve knits.

C. *Blocked Force Tests*

To characterize the IPAM actuator force, we placed the actuator within a constraining tube to guide axial extension. A load cell (Nano17, ATI Automation, USA) was placed at the end of the tube and the actuator was pressurized until in contact, as shown in Figure 6a). Given the forces produced in the actuator will be dependent on its length, we studied the actuator as constrained by two different tube lengths. At 62 mm and 93 mm this corresponds to half and three quarter the length of the fully pressurized actuator in free space. The force on the load cell was recorded for each actuation pressure between 50-150 kPa over three repeats, Figure 6b shows the average produced force of the actuator as a function of actuation pressure. The maximal force of the actuator produced at half extension is 2.0 N and at three-quarter extension 3.2 N at 150 kPa.

D. *Application Suitability*

Based on the high axial strain and blocked force values, the IPAM design may be utilized as a linear pneumatic actuator for different applications. However, it is also possible to provide simple modifications to the knitted sleeve structure to create a broader range of actuators with arbitrary shapes under actuation. By addition of a cotton thread into the sleeve structure in the axial direction in three different configurations, we demonstrate three diverse bending patterns under actuation, as shown in Figure 4. This cotton stitched into the sleeve constrains the deformation on one side of the actuator causing curvature under expansion. We demonstrate application of this approach to create actuators with a J, S and C shapes. To demonstrate the utility of these modified designs, We evaluated the holding capacity of the C shaped a)

b)

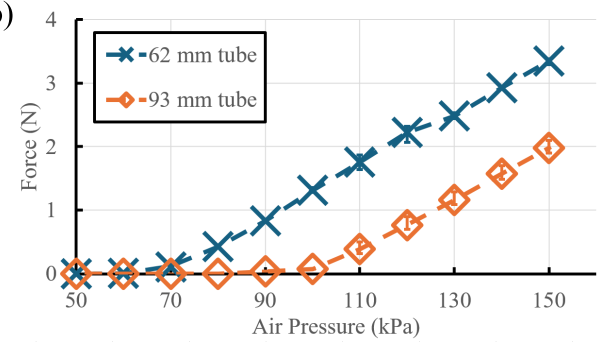

Fig. 6: a) Blocked force testing setup. The actuator is extended in a cylinder and force measured using a load cell (93 mm tube test shown). b) blocked force versus pressurization for two constrained extension lengths of the actuator.

a)

b)

c)

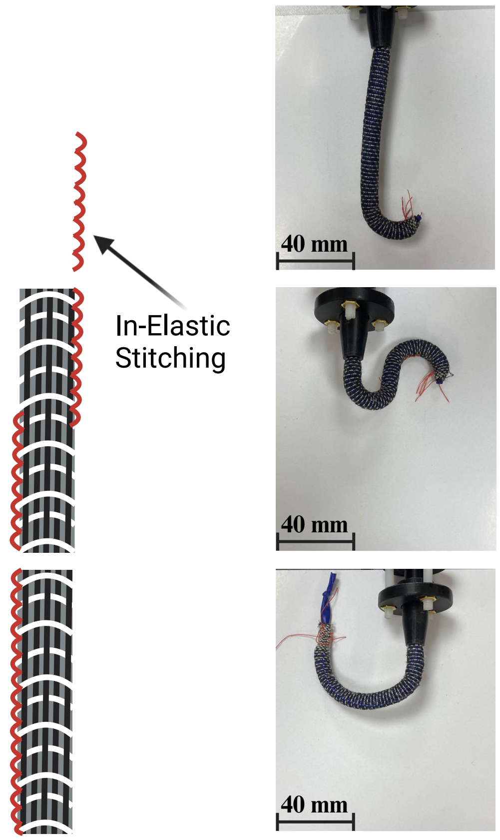

Fig. 7: Arbitary shape forming via strain limitation. Cotton thread is used to constrain the actuator bending allowing for J, S and C shapes under pressurization

actuator when active as a pneumatic grasper (See Figure 8). After pressurizing to 150 kPa to form a tight coiled grasping shape, successively larger masses were added to the actuator until it failed to support them. The grasper was capable of holding masses of up to 900 g.

IV. Discussion and Conclusion

In this conference paper, we propose a novel methodology for creating IPAMs using 3D knitted sleeve structures. By carefully designing the knitting pattern to combine elastic and inelastic yarn, we achieve an anisotropic behavior in the sleeve that can produce high axial strain and limit radial expansion under the application of pressure to the internal bladder. A key advantage of this approach is the simplicity of both form and construction. The 3D knitted sleeve can be continuously manufactured on a commercial knitting machine in a seamless design and be subsequently cut into sections of the desired length to form actuators. The internal bladder, a readily available latex modeling balloon, simplifies production further.

We compare three different knitting patterns and identify one that uniquely exhibits anisotropic properties, achieving axial extensions of up to 117% while minimizing radial strain to 30% (mostly caused due to macroscopic properties of the knit structure). The actuator demonstrates substantial force generation, capable of producing up to 3.2 N. Moreover, by using simple in-line sewing of cotton thread, the deformation shape can be modified, enabling the creation of customized shapes upon pressurization. We provide an example of a simple coiling grasper that can lift weights of up to 900 g.

The proposed design offers a small diameter (7 mm) IPAM that achieve strains comparable to or greater than elastomer-based IPAM designs such as in [10], [11], but less than in alternative designs using direct winding of tubes, as in [9]. However, the flexibility offered by digitally-driven sleeve fabrication using 3D knitting can enable exploration of arbitrary knit structures and better integration with wearable robotics. In the presented work, we limit testing to three basic designs, but future research should explore more complex structures optimized to suit specific application requirements.

In addition, prior work has explored integrated sensing within actuators [10]. This concept could be combined with our approach to create closed-loop systems, potentially integrating electronics directly into the actuator itself. Such a design would parallel the functionality of servo motors, which are widely used in robotics to create complex, adaptive systems. Furthermore, by leveraging a single manufacturing process, multi-chamber knitted sleeves could be produced in parallel, enabling the development of actuators with multiple degrees of freedom and more dexterous deformation capabilities. The 3D knitting process allows production of sleeves with varying diameters along their length, facilitating

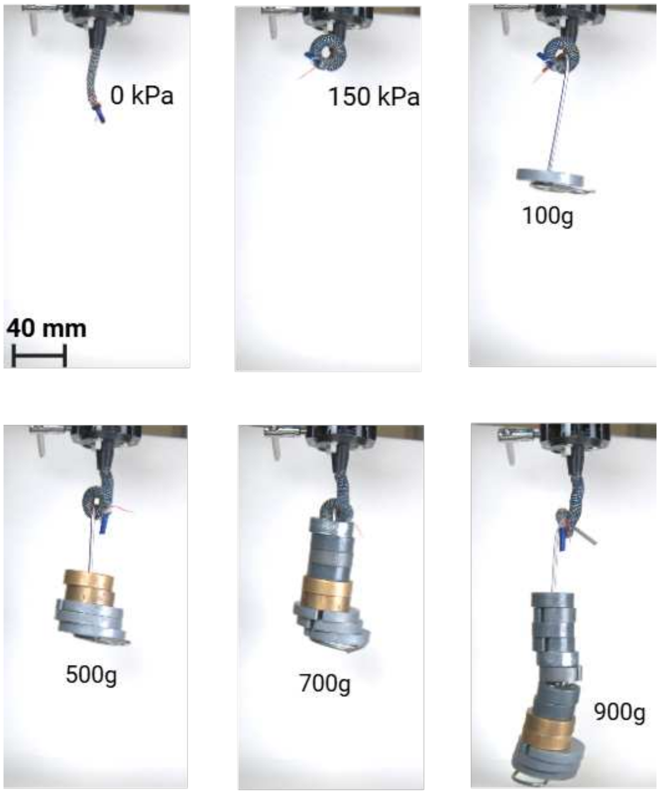

Fig. 8: Hanging of masses using the C shaped actuator. Masses were added until the grasper failed. Failure after loading of 900 g.

the creation of tapered designs or structures with a series of independent bladders.

Given the small diameter of our actuator (7 mm) and potential for design customization, we foresee its potential integration within medical robotics for robust, compliant actuation in minimally invasive procedures such as endoscopy. The actuator's compliant, textile-based form also makes it well-suited for wearable applications, where it could be integrated directly into knitted clothing to assist or augment human movement. This approach holds particular promise for rehabilitation applications.

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