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R3VAMPs - Fully Recyclable, Reconfigurable, and Recoverable Vacuum Actuated Muscle-inspired Pneumatic structures

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Abstract— **We present a version of Vacuum Actuated Muscle-Inspired Pneumatic structures (VAMPs) that is entirely constructed of polypropylene to be of potential use in medical, or other single use applications where contamination may occur and where the full lifecycle is considered so that many aspects are recoverable, reusable or otherwise use minimal materials. We title these actuators Recyclable, Reconfigurable and Recoverable VAMPs (R3VAMPs). A traditional material for soft robotics like silicone rubber can last for thousands or millions of actuation cycles, but if it was damaged or otherwise contaminated in a way that prevented easy cleaning it is not easily recyclable or recoverable, and that would be extremely financially and environmentally costly. By constructing our soft robotic structure entirely out of polypropylene, the system may be manufactured from recycled materials and/or recycled after use if needed, without costly material separation requirements. The material costs for soft actuators can be as little as $0.25 and the mechanical design and assembly process can allow the basic system to operate as a joint, a muscle or a bone by combining vacuum operation and variable sleeve properties to actuate or jam the R3VAMPs for different behaviors. As such, this solution provides an extremely low cost and more environmentally benign option to introduce soft robotics into single or few use applications because the system has been designed explicitly with the disposal and recovery requirements in mind.**

I. Introduction

Soft robots are becoming increasingly capable of complex actuation, sensing, self-healing and navigation in a variety of environments. To date, silicone rubbers have been the material of choice because of their relative ease of fabrication, variety of mechanical properties, and compatibility with molding within 3D printed molds. More recently, 3D printing has been used to directly manufacture soft robots based on silicone materials [1], but also alternative elastomers like thermoplastic polyurethanes [2], curable ink-jetted resins like Tango Black [3], and thermoplastic elastomers such as styrene-ethylene-butylene-styrene (SEBS) [4-6]. Unfortunately, for both silicones and the majority of 3D printed elastomers used in soft robotics, recycling is not practical because they are thermosetting materials. While thermoplastic elastomers can in theory be recycled, they are far less common than typical commodity polymers, and so their ability to be recycled is more theoretical than practical in the majority of the world because sorting and separation facilities to deal with these thermoplastic elastomers are extremely uncommon.

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As an alternative, commodity polymers - such as polyethylene (both high density and low density), polypropylene and polyethylene terephthalates (PET) - are among the most ubiquitous and low-cost polymers, and specialized recycling facilities for these materials are more widely available as these polymers are uniquely distinguishable on commonly used plastic resin identification codes. Polypropylene (PP) is a commodity thermoplastic, with an intermediate modulus (E ~1300 MPa), low costs and is commonly used in medical applications (Luer-lok™ connectors, plastic syringes, bottles, containers, etc.) as it is tolerant to sterilization and autoclaving temperatures. Polypropylene is also one of the only thermoplastic materials that is very tolerant to repeated bending (up to 1 million cycles in theory), and is commonly used in living hinges and compliant mechanisms [7]. A final aspect of polypropylene of high importance at the moment is its ubiquity in melt-blown fabrics used in surgical masks and N95 style respirators [8], which is an enormous challenge for disposal or need for potential reuse due to the demands created by the COVID-19 pandemic. The combination of useful mechanical properties, wide acceptance in other medical applications, relative ubiquity of facilities for recycling and wide variety of form factors of commercial products and manufacturing processes makes polypropylene an extremely attractive candidate for use in recyclable soft robots in medical/wearable applications where it may eventually be mixed with other waste streams of similar materials.

While R3VAMPs use a more inherently stiff material compared to the silicone rubbers often used as structural materials in soft robots, other soft robotics work has successfully introduced structured compliance or combination of stiff and soft materials to produce lightweight and structurally strong actuators [9-11]. Of these, the Vacuum-Actuated Muscle-inspired Pneumatics (VAMPs) [11] and Fluid-driven Origami-inspired Artificial Muscles (FOAM) were the primary inspiration due to their conceptual simplicity, inherent safety compared to positive pressure driven systems, and in the case of the FOAM actuators, the mechanical reconfigurability and potential reusability of the internal structures if the sleeve is damaged or contaminated provides a motivating factor. Mechanical reprogramming of function was previously demonstrated in Slit-in-Tube (SLiT) actuators [9] and provides a conceptually simple but powerful technique to change the function of a soft robot, without necessarily changing the input type (in our case a single negative pressure line). While the VAMPs, FOAM and SLiT actuators reported previously are used to produce force/displacement, another major use of negative pressure

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actuation has been stiffness switching via jamming transitions of particles [12], layers [13] or fibers [14, 15] with an recent review covering many of these specific jamming modes [16] . More recently, honeycomb jamming has been a mechanism by which the interior of a structure is designed to act as a sandwich core composite and can be more lightweight [17]. Our solution has the benefit of being able to switch actuator behavior with identical core design simply by altering the relative stiffness of the sleeve in different areas and thus improves its reconfigurability and reusability.

II. Materials and Manufacturing

A. Materials

The materials used in this work are almost exclusively polypropylene and polypropylene co-polymer, received from different sources. Polypropylene filament (TREED P-LENE 4 and 15 (white and natural colors)) was purchased from Filaments.ca and used as received. Polypropylene lay flat tubing (4” wide, 2 mil thick) was purchased from Uline.ca (part number S-15656). Some polypropylene was thermally bonded with a t-shirt hot press (Colorsub 15x15” Heat Press) between silicone rubber layers to form 4 mil thick sections for tests. Polypropylene pipette tips (10 µL clear white from Copapa) were used to make connectors from silicone tubing to the lay flat tubing. Silicone tubing, which interfaces with the soft robots, was purchased from McMaster-Carr (1/32nd, 1/16th or 1/8th inch ID, part numbers 5236K203, 5236K811, and 5236K831). The silicone was reused and is not considered part of the actuators themselves. The 3D printing of polypropylene isn’t as well established as with materials like Polylactic Acid (PLA) and Polyethylene Terephthalate Glycol modified (PET-G) polymers.

B. Equipment

The internal structures of the polypropylene actuators were printed on FDM printers from Creality and Geeetech (Ender 3 and A10). Polyolefins, including polypropylene, are very difficult to bond well to conventional build plates, so two options were used to enhance this parameter and achieve nearly warp free PP parts. An ultra-high molecular weight polyethylene (UHMWPE) tape (JVCC UHMW-PE-3 UHMW Polyethylene Film Tape from Findtape.com) was used on the printing bed which allowed for acceptable adhesion of PP prints while also allowing easy releasing of the parts. Printing on the UHMWPE side was found to be a good solution for a variety of printing temperatures using PP and minimized warping. Printing temperature was set to 230 °C with 100% fan setting, while speed was set to 20 mm/s for the initial layer and 30 mm/s for subsequent layers. The nominal wall width was 0.4 mm and layer heights for printing were 0.2 mm. The bed could be heated with this tape up to approximately 80 °C but for most prints, heating the bed was found to be unnecessary. An increased flow setting of 110% was found to be necessary to correct for under extrusion compared to PLA with identical e-steps on the same printer. UHMWPE tape is relatively expensive (~$80 USD for a 4” wide, 36-yard roll), and an alternative included direct printing on duct tape (McMaster-Carr part 7612A8 which provided larger printing area for lower cost (~$30 USD). This 3” wide tape has a cloth reinforced LDPE backing layer and also provided reasonably strong but reversible bonding for PP when printed with a small brim (four lines widths at 0.4 mm per line) and can even be a reasonable substrate for polyethylene printing with optimized settings [18]. The adhesive on duct tape is not strong at elevated temperatures however, so substrates were kept at room temperatures and initial print temperature was lowered to 220 °C when printing on this material.

Once internal structures were completed, they were removed from the substrate, and inserted into PP sleeves. A pipette tip was placed inside the sleeve before the perimeter was bonded with an impulse sealer. A silicone tube was pushed over the pipette while it was in the sleeve, which stretched - then punctured - the thin sleeve and created a relatively leak-proof seal without requiring any adhesives or extra materials – a major element in the design for recyclability. This bonding method was found to work well with PP sleeves up to ~100 µm (4 mil) thick. Positive pressure tests on single thickness PP sleeves connected with this method found that failure would be frequently through rupturing the sleeve rather than the bonded interface or the pipette connection method although the maximum pressure was only 10 psi for the size of the actuators tested (see Fig. 1).

As part of the motivating factor of using these actuators, we considered the basic costs of each part used. Virgin PP resin can be purchased for approximately $1.25 kg from commodity polymer suppliers so in theory an 8-gram actuator could cost as little as a penny. In practice, the manufacturing cost is more complex, and each type of PP component used has its own associated manufacturing costs built in. A breakdown of the part cost, either per gram or per part is listed in Table I. The total costs are dominated by the infill (which is variable mass depending on the geometry and is based on $40 USD per 1 kg filament spool). A total average material cost for our most commonly used actuators is approximately $0.25 which accounts for 1 gram of sleeve material, one pipette tip, 4 grams of infill and approximately 1 inch of silicone tubing for an interface. Nearly 25% of the material cost comes from the silicone tubing, despite its small size. For comparison, a typical pneumatic network (PneuNet) style silicone actuator previously reported from our lab [19] consists of approximately 25 grams of silicone at ~ $40/kg (Dragonskin 30). When manufacturing time is considered as well, the comparisons are even more favorable for the R3VAMP actuator given that printing time can take less than an hour, and assembly takes a few minutes, while the silicone curing time alone is nearly 16 hours (if not accelerated by elevated temperature) followed by multiple adhesive bonding steps. Should a leak occur in the silicone PneuNet, repair is challenging (requiring silicone adhesives) and is often ineffective because positive pressure expands the actuator and applies tension on previously formed holes or tears. For the R3VAMP actuators reported here, every portion but the sleeve can be recovered and reused should leaks be caused by improper assembly or damage during operation and the process may take only a few minutes to complete.

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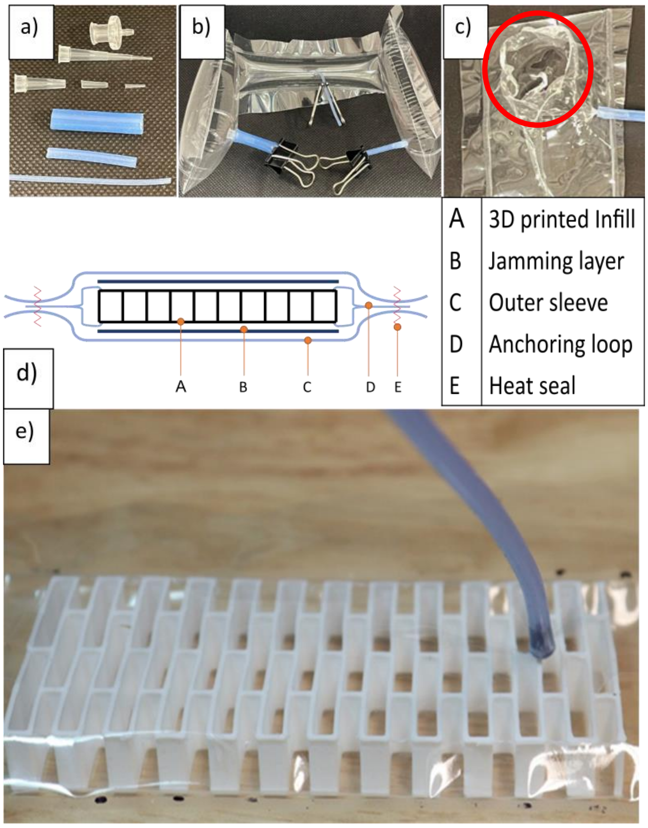

Figure 1. a) A single pipette tip is shown next to a 1/16" barb fit luer-lok connector for scale. The single pipette tip can be cut to size for three separate connection tubing diameters. (1/32", 1/16" and 1/8" ID). b) an image of PP sleeves inflated with 5 psi via the three tubing sizes shown in a). c) a failure of a PP bonded actuator from 10 psi positive pressure, showing a rupture in the sleeve rather than at the tubing or sealing interfaces. d) schematic of assembly of R3VAMP actuator with variable infill and reinforced sleeve material. e) a picture of an assembled R3VAMP with 10 cm length and 40 mm width for the infill.

III. Actuator Designs

Actuators were primarily inspired by Vacuum Actuated Muscle-inspired Pneumatics (VAMP) and Fluid-driven Origami-inspired Artificial Muscles (FOAM), with the internal structures designed similar to VAMPs, but the internal structural skeleton separate from the sleeve, which is more inspired by FOAM actuators. Vacuum driven actuators are attractive in medical applications because they will not exhibit large expansion/inflation during actuation so they can operate in a physically constrained environment, and catastrophic failures cannot result in an explosive rupture, but a slow leak typically [11]. Care was taken to minimize the complexity of PP infill designs and reduce printing of isolated structures, which could introduce excessive stringing and under-extrusion issues.

To ensure the infill appropriately connects to the sleeve for linear actuation, a small loop of PP feeds through the infill on each end and connects to the sleeve through thermal bonding. Being able to disassemble a R3VAMP and recover its infill structure is a far better feature in recycling/reuse as this is the most expensive and time-consuming portion to produce. Unlike VAMPs, our R3VAMPs can be mechanically reconfigured on the inside, with a truss structures that can be modified to act as a linear muscle/actuator, a bending actuator or a stiffness tunable foam core composite. Borrowing concepts from the FOAM actuators, our system can insert the skeleton structure into a sleeve that may or may not be reusable, but unlike the origami inspired systems demonstrated in FOAM actuators, our system can be produced directly through modification of infill parameters in several open source FDM slicing software packages, and the function of the actuators do not need to be mechanically pre-programmed through complex folding operations. As a result, it is even more accessible and inexpensive to produce than previously demonstrated vacuum driven actuators.

All internal structures were created using rectangular prisms as a primitive in Ultimaker Cura 4.8. The structures were generated by selecting print options with only infill (no walls or top/bottom printed), zig-zag infill structure settings at 0 and 180 degrees for distinct blocks placed side by side. By changing the size of the blocks or the infill spacing parameters, simple generation of offset rectangular blocks was possible and the use of retractions and unneeded travel moves was minimized, which increased quality and uniformity of printing with PP. In the future, alternative infill designs may be employed, or alternative software, like Full Control GCode [20] used for further customization of the infill. In our system however, it is extremely easy to modify designs for our actuators without ever having to access expensive CAD software and furthers our groups' efforts at using infill as a functional component in fused deposition modelling (FDM) produced parts [21]. Infill parameters for the R3VAMPs tested are listed in Table II. Each type of infill had either 2 or 4 mil thick PP sleeves tested, with *A,C,E,G*, and *I* using 2 mil and the remainder 4 mil. For actuation, there was little benefit in the 2 mm spacing for *A* and *B* as they were outperformed by variation C and used more infill material, and the majority of 4 mil thick sleeves jammed rather than actuated with the exception of infill variation J. As a result, only a smaller subset of the tested variations that could either actuate effectively or jam are reported here.

TABLE I. Actuator Cost Breakdown

Actuator Materials cost breakdown (costs in USD)				
	Pipette $/piece	***Infill $/gram***	***Sleeve $/gram***	***Silicone tubing $/ft***
Unit cost	~0.01	0.04	~0.02	0.48
Amount used	1	4 grams	1 gram	1 inch
Total cost	$0.01	$0.16	$0.02	$0.04

TABLE II. Designs of R3VAMP Infill

	PP infill unit cell geometry		
designation	***Height (mm)***	***Length (mm)***	***Width (mm)***
A, B	5	2	20
C, D	5	4	20
E, F	10	4	20
G, H	5	8	20
I, J	10	8	20

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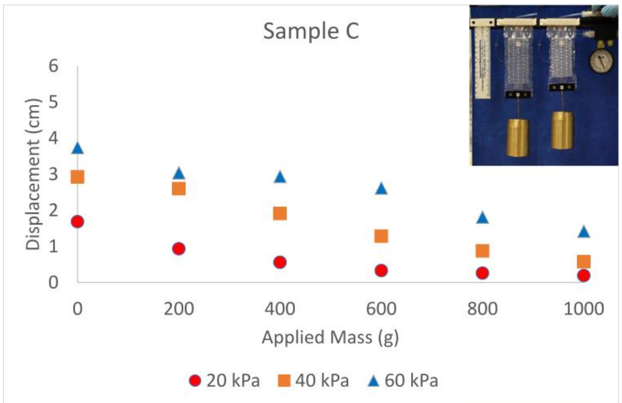
IV. TEST PROCEDURES

Three distinct modes of operation are possible R3VAMP actuators: linear actuation, bending actuation and bending stiffness switching via jamming. The linear actuation is conceptually simplest and easiest to achieve – a vacuum is applied to the sleeve containing the structured infill and the whole device contracts to provide substantial forces and displacements in the axial orientation. Bending actuation occurs if one side of the sleeve is stiffer than the other, which preferentially results in collapse of one side of the actuator and limits the dimension change of the other, during the application of vacuum. If the sleeve is uniformly too stiff to collapse into the unit cells of either side of the actuator, the result is a sandwich composite material that is stiffened in bending due to friction between the sleeve and the infill.

The honeycomb interior used in this work is preferentially deformable in a single axis, but alternative infills such as auxetics may be considered in the future which can bend or actuate in more than one axis easily. Speed of actuation is not considered an important variable in this work, as it is primarily defined by the volume in the sleeve and the resistance to flow by the tubing in series. On average the actuation time is approximately 1 second but can be more or less depending on the input vacuum source – our tests were run in a quasi-static condition.

A vacuum regulator (McMaster-Carr part 41585K43) was used to set different vacuum pressure levels (-60, -40 and -20 kPa) and determine actuator displacement while lifting different masses. A high contrast feature on the actuator was used a trackable point so that displacements for different loads and pressures could be determined. Pictures of the actuator under each pressure/loading condition were taken with a Canon EOS Rebel SL3 at 6000x4000 pixels at least three times and then batch processed with a macro script in ImageJ using the particle detection function to measure the difference in position between actuated and relaxed states. The performance of two actuators C and I are shown in Fig. 2 for typical performance. Maximum displacements were found with thicker actuators and higher vacuum levels as anticipated, with worst performance with variation A, which was only 5 mm thick and had smallest gaps between walls (2 mm).

For blocked force measurements, the actuators were connected on a linear positioner (RATTMOTOR part # CBX1605-100A) with a 10 lbf load cell (Transducer Techniques MLP-10) and an amplifier module (Transducer Techniques TMO-1) connected with an Arduino Uno to record output voltages and calculate the resulting forces. The linear stage was positioned to eliminate slack in the actuator and different negative pressures were applied while holding the actuator at a constant length. Each measurement was taken three times and the average value was used to find the blocked force. If the actuator acted like a regular VAMP, the blocked force pressure should be the pressure difference multiplied by the cross-sectional area (either 5x40 mm or 10x40 mm nominally). It was determined that the majority of tests achieved values that were higher than this theoretical maximum blocked force, with the exception of infill design A, which had the smallest spaces between support walls. The



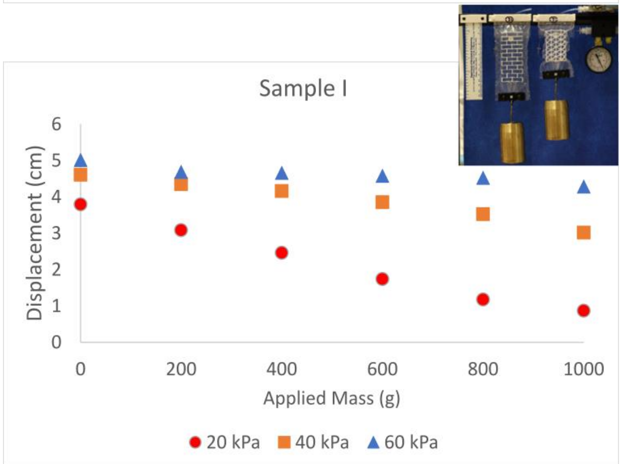


Figure 2. Typical dead-lift performance of R3VAMP actuators. Thicker and wider spaced support walls produce larger forces and stroke for equivalent applied negative pressure.

reasons for these higher than theoretical blocked forces measurements are similar to what was reported in FOAM actuators – the negative pressure on the sleeve results in a tension within the sleeve between each supporting wall that is added to the net forces caused by vacuum acting over the cross-sectional area of the actuator. For some of our trials, this results in nearly three times the expected forces from pure vacuum actuation alone (Fig. 3). Our test system is not advanced enough to run complete cycle tests on these actuators yet, but similar to FOAM actuators, the expected maximum static forces for a given applied pressure would be reduced as the actuator contracts and eventually reduce to either the vacuum pressure multiplied by the cross-sectional area, or zero if the spring forces within the actuator are balanced by the applied vacuum.

While the actuator can be disassembled and reassembled with different sleeves for different performance, an alternative involves simply repositioning an inner sleeve within the actuator itself, because the negative pressure actuation doesn't require that the infill be bonded to the sleeve or other internal features. This borrows from the mechanical reprogramming demonstrated in SLiT actuators [9] where the function of the system depends on the relative positions of mechanical reinforcements. The sleeve must be stiff enough to not collapse into the unit cells of the R3VAMP, which is a function the width and length of each cell, the thickness and modulus of the sleeve and the applied

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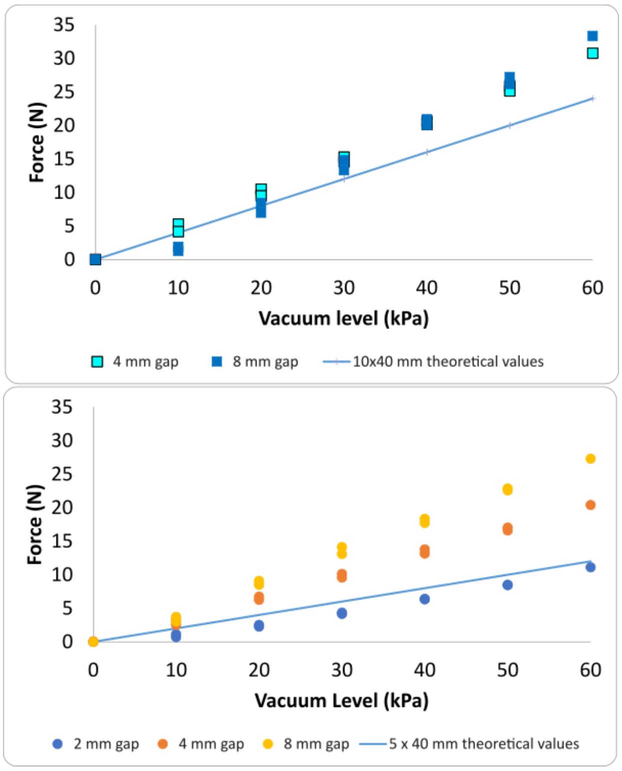

Figure 3. Blocked force performance of different R3VAMP variations that are 10 and 5 mm thick. The actuators can outperform the theoretical performance of a pure vacuum linear actuator when the gaps between the support walls are large compared to the thickness of the actutor because tension within the sleeve can enhance the total force produced when held in a fixed position during application of vacuum.

negative pressure. A transition point was found for actuators between 4 and 8 mm wide, and between 5 and 10 mm thick. This transition point is complex to determine due to the frictional boundary conditions on the sleeve but demonstrates the critical influence of sleeve bending stiffness on the operational characteristics of these actuators. When the sleeve is stiffer than this transition point and symmetric, the actuator no longer displaces but jams instead into a much stiffer state (Fig. 4). The increase in bending stiffness of an actuator with 5 mm thickness and 4 mm infill gaps in a fully jammed configuration was found to be over 40x based on simple 3-point bending tests. This is higher than the ratio found in other reported honeycomb jamming actuation designs (~7.4x), but in that previous case, the relatively thick silicone rubber sleeve dominated the actuator stiffness in unjammed configurations [17]. That same work found layer jamming of 43 sheets - which in theory should have stiffened by over 1000x in bending - had a worse performance than expected (~7x) again due to the influence of sleeve properties. Both cases indicate that sleeve/jamming layer thickness is an important quality with future optimization still to come to maximize device performance. As shown in Fig. 5, a single infill design can have multiple actuation methods when an inner sleeve is used and repositioned. In Fig.5 A) and B) an actuator is seen to displace only on one half, with the right-hand side unmoved when vacuum is applied due to a symmetric reinforcing layer (blue). When the sleeve stiffness is asymmetric, the R3VAMPs can act as bending

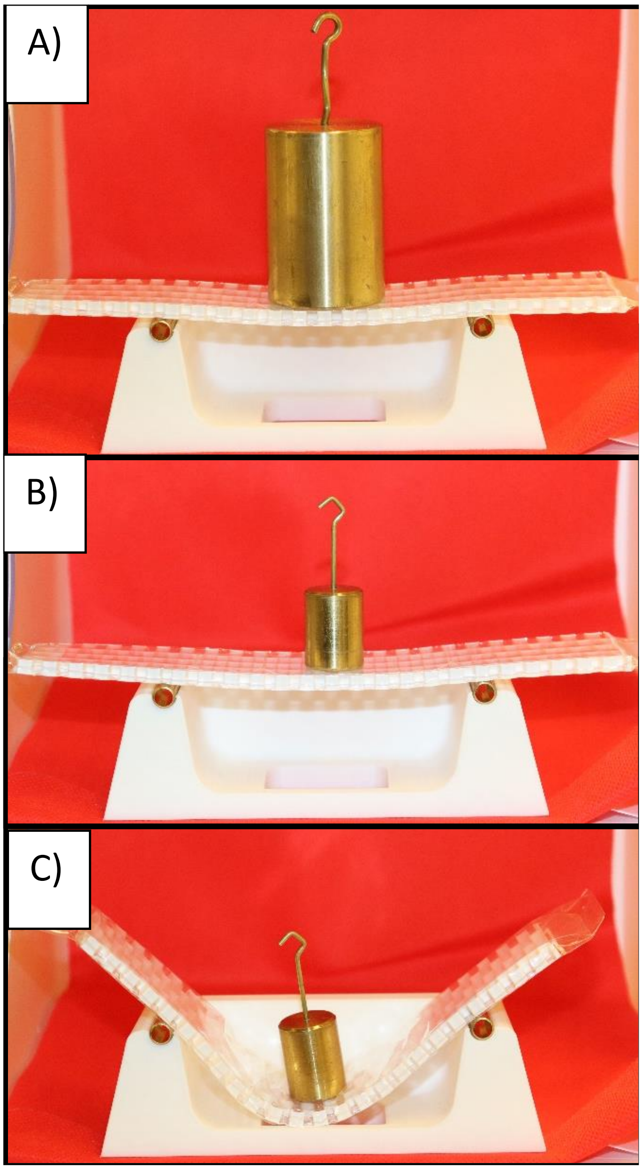

Figure 4. R3VAMP variation C with a double length (20 cm total) and 4 mil inner sleeve operating in jamming configuration. A) shows jammed under -60 kPa.supporting 500 g. B) jammed and supporting 50 g.C) unjammed and collapsed under 50 g load.

actuators (Fig. 5 D). Further development will be directed to optimization of the strength and tunability of these actuators for a variety of applications.

V. Conclusion

We have demonstrated an all polypropylene actuator (R3VAMPs) that takes inspiration from previously reported negative pressure actuated artificial muscles, but enhances capabilities through mechanical reconfigurability so as to perform different actions, even if the interior geometry remains mostly unchanged. Eventually we propose that systems like this could be building blocks for many types of wearable, collaborative or disposable robotics, because individual elements can be mechanically reprogrammed with ease to repurpose their function, and the system uses an

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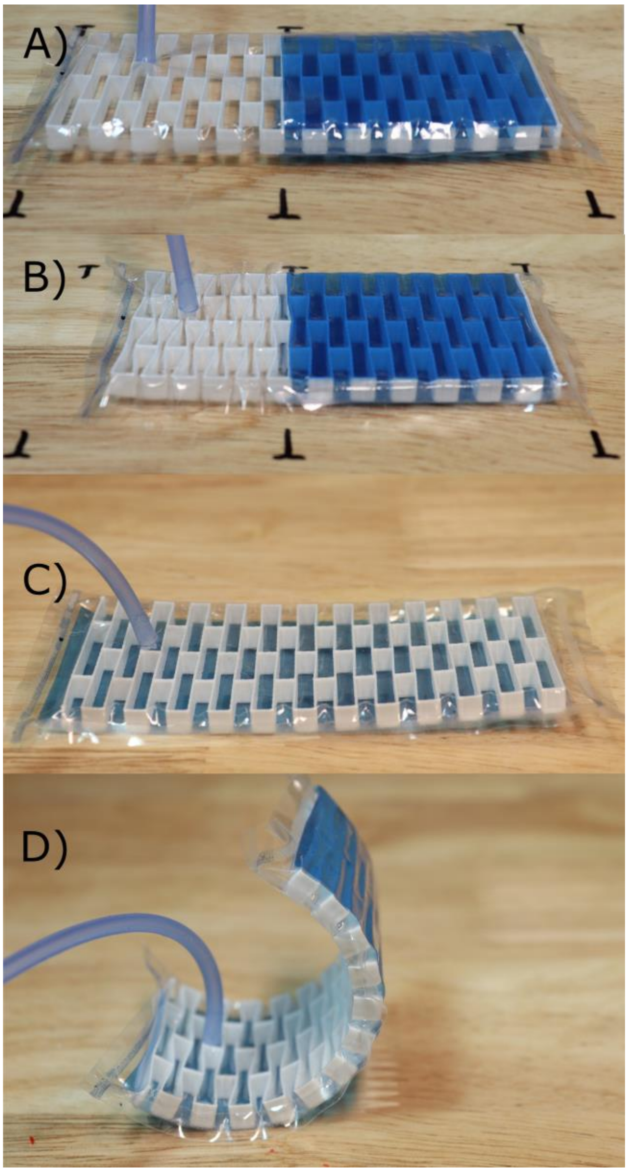

Figure 5. R3VAMP variation C operating as a hybrid actuator. A blue inner sleeve is used to initiate jamming or act as a strain limiting layer. For A) and B) the inner sleeve is symmetric and the left side of the actuator displaces under vacuum while the right side does not. For C) and D) the actuator has an asymmetric inner sleeve (Blue) which converts the motion into bending rather than linear actuation.

extremely simple building block that can be used to create complex designs in the future. All aspects of the actuator design and implementation are designed to be as accessible as possible, requiring only an FDM 3D printer and impulse sealers, no specialized CAD software and only a minimum of non-recyclable/reusable material to connect a negative pressure source.

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