A 3D Printed Soft Robotic Gripper With a Variable Stiffness Enabled by a Novel Positive Pressure Layer Jamming Technology

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***Abstract*—In this research, a soft robotic gripper with a variable stiffness enabled by a novel positive pressure layer jamming technology was developed and fabricated in two materials using customized additive manufacturing. A novel positive layer jamming technology was developed for tuning stiffness of the gripper. Positive pressure layer jamming has a higher performance potential than conventional vacuum layer jamming since a higher pressure can be applied, approximately 1.6x higher in terms of payload capacity. Two different thermoplastics materials are printed together to form a relatively hard backbone and a relatively soft airtight actuation bellows. The implementation of positive layer jamming will be described, along with the additive manufacturing techniques used to produce the gripper and the test results of the final design. Experimental tests show that this soft gripper was able to vary its stiffness about 25x fold with the positive layer jamming. This work demonstrates that the positive pressure jamming offers a novel method for varying soft robot stiffness with higher payload capacity than the conventional vacuum based layer jamming technology.**

***Index Terms*—Additive manufacturing, grasping, grippers and other end-effectors, soft robot applications, soft robot materials and design.**

I. Introduction

Soft robots are a rapidly growing field in modern robotics with a wide range of potential uses. Compared to traditional robots, soft robots have inherent compliance and are designed to undergo high strain as part of their operation [1]. Soft robots are typically fabricated from elastomeric or flexible materials with a monolithic construction [2]. Research has been done on the design of soft robots for food handling, package handling and minimally invasive surgeries, and many more applications. These designs frequently draw inspiration from octopi and elephant's trunks, whose appendages lack skeletal structure and discrete joints like those found in humans [1].

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Soft robots have two main advantages over traditional, "hard" robots: safety and simplified control. Through their compliance, soft robots are inherently safer for operation around humans. Additionally, through material and design choices, some control functions of a soft robot can be handled by the robot itself. This idea is called morphological computation [2]. For example, while a "hard" robot might require several degrees of freedom and force sensors to safely pick up a small item like a box, a pneumatic soft gripper of a similar footprint could be controlled with a single solenoid valve and would conform to the box, allowing for less precise grasp planning.

However, due to their compliance, soft robots are limited in how much payload weight they can carry. Because of this, much research has been performed on technologies that can be used to vary the stiffness of soft robots. Methods for controlling stiffness can use low-melting-point alloys [3], granular jamming [4], [5], layer jamming [6], [7], or a number of other solutions [8]. Jamming refers to a class of variable stiffness technologies which rely on compression of a substrate in the joint to produce a locking effect through friction [8]. The substrate is commonly granules such as ground coffee, or layers such as plastic strips, and locking is often achieved by vacuum compression, although alternate methods and materials, such as tendon-based compression [5] and fiber substrates [9] have been researched.

Research has also been performed on optimized design and manufacture of soft grippers. For example, Mosadegh *et al.* produced an optimized soft pneumatic actuator design with 25x higher actuation speed and 8x actuation force over contemporary designs [10]. While the most commonly used method for producing soft grippers is silicone molding, increasingly, research has been done on using additive manufacturing with soft thermoplastics instead. Yap *et al.* discussed several different soft actuator designs printed from TPU and showed fatigue and performance testing [11]. Additive manufacturing allows for features that cannot be produced by molding such as complex internal geometry, or multi-material features like mounting hard points or sensors. For example, Hainsworth *et al.* utilized multi-material printing to produce a soft finger with an integrated strain gauge to measure curvature [12], and Howard *et al.* demonstrated granular jamming grippers which could be printed and used without further assembly [4].

II. Motivations and Design Overview

A. Motivations & Background

Soft grippers have been shown to be effective in industrial applications for package and food handling. They have weight and simplicity advantages over traditional robots, containing a much lower number of components, and requiring less complicated control schemes. Despite these advantages, they are significantly limited in payload capacity. Integrating a variable stiffness technology into a soft gripper would provide a solution to this problem, allowing the gripper to conform to payloads when grasping them and stiffen to carry heavier loads.

While Zeng *et al.* [13] demonstrated a layer jamming joint with a stiffness increase of 75x, their design partially relied on a parallel beam design, which is less applicable to compact grippers. Applied to soft grippers in a smaller form factor, Wall *et al.* demonstrated a 3.5x and 2x stiffness increase using layer and granular jamming respectively [6]. Fiber-based jamming grippers have also shown a similar stiffness increase of 3x [9]. Other stiffness variation methods, such as Low-Melting-Point Alloys (LMPA) have been shown to increase stiffness by a factor of 477x in soft manipulators [3]. However, because LMPA activation can require approximately 10 seconds [3], jamming is desirable for applications requiring faster response times. Limited research has been performed on positive pressure jamming solutions, but it has been been used with granular jamming to create a novel variable stiffness revolute joint [14]. Positive pressure has also been used in conjunction with a vacuum granular jamming gripper to forcibly eject payload from the gripper [15].

B. The Principle of Positive Layer Jamming

To achieve maximum stiffness variation in a soft gripper, the stiffening mechanism should be placed away from the bending axis of the gripper. Because of this, as the gripper curls, the stiffening mechanism will be required to extend by an amount proportional to its distance from the bending axis. Of the three commonly researched types of jamming (granular, fiber and layer), layer jamming has the greatest potential for extension-because the layers overlap, they can move relative to each other and still provide effective jamming. Compared to designs like the "Jamsheets" produced by Ou *et al.* [16], placing layers away from the bending axis maximizes peak stiffness.

When considering a layer jamming soft gripper, the distance between the layers and the bending axis of the gripper can at most be the thickness of the gripper, so to increase performance, other parts of the design must be considered. From prior research, it is known that layer jamming joint stiffness increases as more vacuum pressure is applied to the layers, and that the typical mode of failure (yielding) is slip between the layers [13], [17]. In characterizing Layer Jamming loading performance, Zeng *et al.* identified three distinct phases: Phase 1, Pre-slip, Phase 2, Transition and Phase 3, Slip [13]. In Phase 1, the layers are locked together by friction and the stiffness of the jamming joint is dependent on joint material stiffness [13]. The Transition Phase marks where the applied load exceeds the friction force between the layers and they begin to slip relative to each other [13]. Finally the Slip Phase indicates continuous slip between the layers [13].

Most current layer jamming designs use vacuum to lower the pressure in the membrane containing the layers, compressing the layers at a maximum of 14.7 psi (101.4 kPa), atmospheric pressure [16]. Because atmospheric pressure cannot be increased, we propose a design wherein the jamming layers are unenclosed and compressed instead by an inflatable membrane or jamming bag. In this concept, the jamming bag can be inflated to any pressure and is only limited by the air supply and material strength of the bag. Then a higher compressive force can be applied to the layers, producing higher friction forces and raising the force required to cause the layers to slip relative to each other. To implement this design, several changes are made from vacuum layer jamming. The layers are placed in a segmented, rigid constraint frame on the top side of the gripper. The rigid constraint frame is required to react against the expansion of the jamming bag and direct the force into the layers, as shown in Fig. 1.

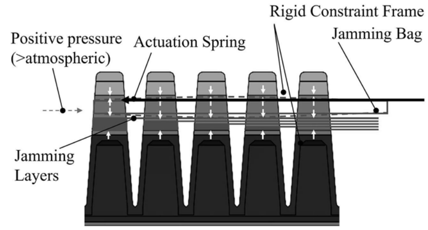

Fig. 1. Sectional View of the Proposed Positive Layer Jamming Constraint Frame.

C. Design Overview

In this work, the goal of a soft gripper with high stiffness variation is approached with two solutions: novel positive layer jamming and the use of multi-material additive manufacturing. The proposed design for this gripper consists of a thin, PETG strain limiting backbone, soft TPU bellows used for actuation, and a PETG jamming constraint frame, which contains the jamming layers, TPU jamming bag and actuation spring, as shown in Fig. 2. While not monolithic, this gripper primarily consists of 3D printed parts, and requires minimal assembly, particularly when compared to multi-part mold silicone jamming grippers like those shown by Wall *et al.*

The layers are constructed from 0.13 mm thick sheets of Mylar plastic, selected based on its use in previous research [13]. A single layer is adhered to each segment of the gripper and sized so that they protrude from the base by an equal amount. With this configuration the layers overlap, meaning that the layer fixed at the tip sits on top of all other layers, preventing any from escaping through gaps in the constraint frame during actuation. One additional layer is attached at the base of the gripper and fixed at its sides to allow the other layers to freely slide past it. This gripper has 11 segments, so with the layer fixed at the base, a total of 12 layers are used per finger. The rectangular cross section TPU jamming bag detailed in Fig. 2(c) is placed inside the constraint frame and fixed at the tip of the gripper so it can slide in and out of the constraint frame with the jamming layers. With dimensions shown in Fig. 2, gap (space not occupied by the jamming bag or layers) in the constraint channel varies from 4.17 mm at the tip to 2.74 mm at the base, where all 12 jamming layers overlap.

While most soft grippers require pressure to close on an object, and rely on material elasticity to open, this gripper acts in the opposite way. A 3.7 N constant force spring (McMaster-Carr 9293K113) is fixed at the tip and base and used to pull the gripper into a curve, as seen in steps 2–4 of the cycle shown in Fig. 3. While this force is relatively low, similarly sized springs are available up to 10.2 N of force, so grip strength can be readily adjusted and increased. A common inflatable bellows actuator similar to those shown by Mosadegh *et al.* is used to act against

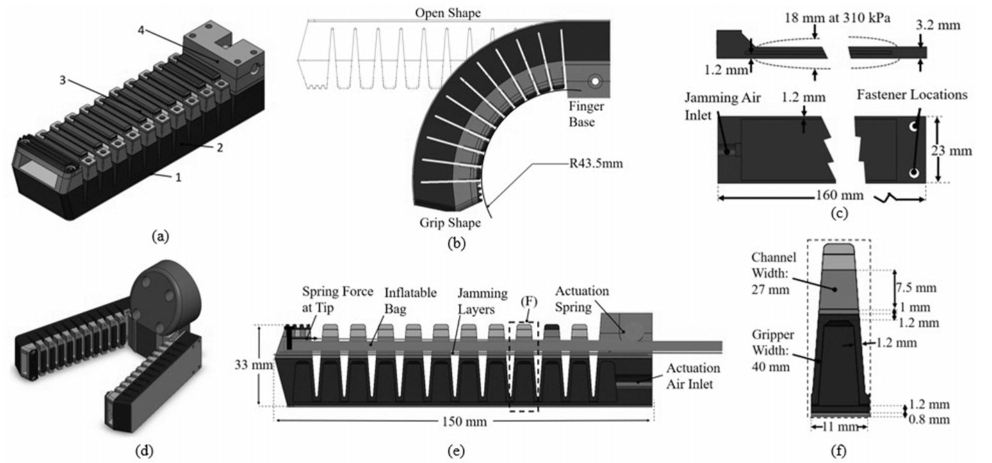

Fig. 2. Design Overview. (a) Isometric View of the Positive Pressure Jamming Gripper Showing (1) Strain Limiting PETG Layer, (2) TPU Bellows, (3) Jamming Constraint Frame, (4) Actuation Spring Bearing Mount. (b) Open and Closed States. (c) Jamming Bag Key Dimensions. (d) Dual Finger Gripper Designed for UR5 Robot. (e) Gripper Sectional View. (d) Detailed View of Inflatable Bellow.

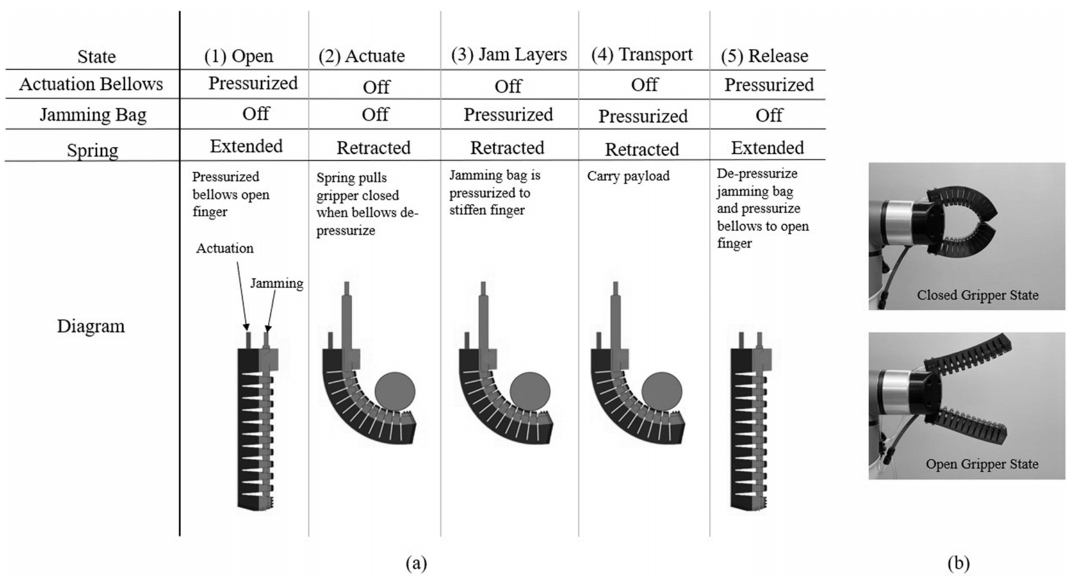

Fig. 3. (a) Functional Cycle of the Gripper Consists of Five States. (b) Gripper Actuation States.

the spring and open the gripper into its straight state [10]. With this design, the layers can be placed opposite the bending axis of the gripper to maximize their effect on stiffness change. Because the jamming layers are placed on the inside radius of the gripper, they are placed in tension when under load, thus avoiding the layer buckling failure mode observed in other research [13].

III. Manufacturing Methods

Most current research on soft pneumatic actuators utilize a silicone molding process to produce prototypes, frequently with 3D printed molds. While this process is effective, it often requires significant post processing and cannot be easily used to produce airtight actuators with complex internal geometry. In the design of this gripper, multi-material 3D printing was used to significantly reduce post processing time and reliably produce small internal features. For example, soft grippers commonly use a piece of letter or plastic glued into the actuator as a strain limiting layer [10], [6]. As shown in Fig. 4, this can simply be printed with the actuator in one process. Also printed in place and shown in Fig. 4 is the rigid constraint frame, a hard plastic feature that would need to be glued onto a silicone actuator. Finally, the small 2 mm air channels shown in Fig. 4 would be

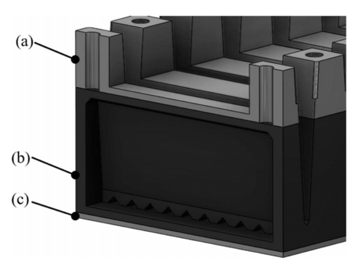

Fig. 4. Print in Place Features. (a) Rigid Jamming Constraint Frame. (b) Strain Limiting Layer. (c) 2 mm Wide Air Channels.

TABLE I
3D PRINTING PARAMETERS

Parameter	TPU 85A	PETG
Nozzle Temperature	225°C	250°C
Bed Temperature	85°C	85 °C
Volumetric Flow	1.5 mm^3/s	7.5 mm^3/s
Layer Height	0.2 mm	0.2 mm
Extrusion Width	0.4 mm	0.4 mm
Infill	100%	100%
First Layer Speed	12 mm/s	12 mm/s
Perimeter Speed	20 mm/s	20 mm/s
Cooling Fan	100%	15%

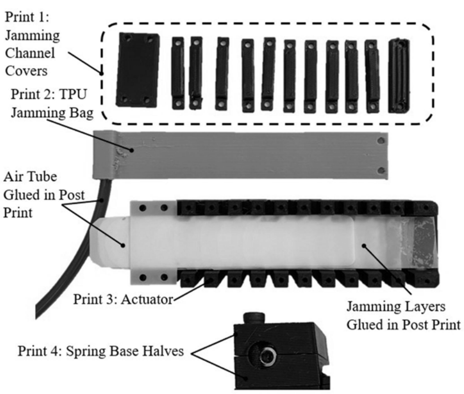

Fig. 5. An Overview of the Separate Prints and Post-processing to Fabricate the Gripper.

difficult to reliably mold but can be easily produced with 3D printing.

Using customized additive manufacturing to produce soft actuators does, however, introduce other challenges. While the softest commercially available FDM filament has a hardness of 60 A, molding silicones are commonly available as soft as 10 A shore hardness. While the actuator designs were not identical, 28 A silicone actuators have been found to withstand up to 10^6 actuation cycles, with similar 3D-Printed 85 A TPU actuators failing at 600 cycles [10] [11]. Additionally, reliably printing soft filament requires specialized hardware and low print speeds. The print parameters used to produce this finger can be found in Table I.

Producing the gripper presented here requires four prints and minimal post-processing. Multi-material prints are most reliably airtight when the divisions between materials are planar, so that the print heads do not need to be switched for every layer of material. Because of this fact, while it would be possible to produce all components with one print, the prints were divided as shown in Fig. 5 to maximize reliability. The main body of the gripper is designed to accommodate this, requiring only two automated print head switches throughout the print: PETG to TPU to print the bellows on top of the strain limiting layer, and TPU to PETG to print the lower half of the jamming constraint frame on top of the bellows. After printing, air tubes are glued into the TPU jamming bag and gripper, and mylar jamming layers cut to the width of the jamming frame are glued to each segment of the actuator. Finally, screws are used to fasten the spring mount covers, TPU bag and actuator together.

IV. TESTING & RESULTS

A. Gripper Stiffness

To test the stiffness of the gripper at different jamming pressures, it was fixed to a rigid base and allowed to fully retract into a curve, then deflected using a force sensor mounted to a linear stage, as shown in Fig. 6(a). The gripper was deflected by 6 mm, then allowed to return to its initial position. This was repeated five times at each pressure, and by plotting the recorded force and displacement, the stiffness of the gripper at different pressures can be compared.

Based on the plotted averaged force-displacement data in Fig. 6(b), gripper stiffness is roughly saturated for the first 2 mm of deflection at a jamming pressure of 10 psi (69.0 kPa). Despite this, in Fig. 6(b) we can see that average gripper stiffness increases with every increase in pressure, although the rate of increase does slow. While gripper stiffness at 10 psi (69.0 kPa) is comparable to higher pressures at low displacements, it begins slipping around the 2 mm of deflection, while at 45 psi (310.3 kPa) no distinct slip is seen over the entire 6 mm range. To compare with vacuum layer jamming, we can examine finger stiffness at 14.7 psi (101.4 kPa) of jamming pressure, which should be equivalent to a similar finger jammed with best case (limited to atmospheric pressure) vacuum pressure of −14.7 psi (101.4 kPa). In layer jamming, pressure is applied to the layers to increase friction force. Pressurizing the jamming bag to “vacuum pressure” should compress the layers with the same pressure as vacuum jamming. This comparison can be used to demonstrate that increasing the pressure on the layers beyond “vacuum pressure” can further increase joint stiffness and performance.

In Fig. 6(d) it is clear that jamming the finger at 45 psi (310.3 kPa) offers a performance increase over vacuum-equivalent jamming at 14.7 psi (101.4 kPa)- average stiffness increases by 1.85 N/mm and the 45 psi (310.3 kPa) curve exhibits a constant slope, while the 14.7 psi (101.4 kPa) curve shows a distinct stiffness decrease at 4.5 mm of deflection, indicating significant slip. The similarly sized vacuum layer jamming grippers produced by Wall *et al.* showed a stiffness increase of 8x with 12.3 psi (85 kPa) vacuum pressure, comparable to a recorded stiffness increase of 13x produced at 12.5 psi (86.2 kPa) vacuum equivalent jamming [6].

The force-deflection data can also be used to analyze hysteresis of the gripper, with the metric of residual deformation after loading (hysteresis) as defined in Fig. 6(d). This was measured by finding the point where force from the force sensor drops to zero as the gripper is unloaded. This hysteresis originates from the jamming layers slipping relative to each other under deformation. Once the force is removed, the gripper is locked into the new deformed position. During testing at lower pressures it was found that hysteresis was extremely inconsistent. This is because stiffness at low jamming pressure is sensitive to the unpredictable nature of stiction between the layers. However once 35 psi (241.3 kPa) was reached, the layers appear to remain in Phase 1 (no slip) [13] and hysteresis was consistently near zero. More future research is necessary to fully characterize this behavior.

B. Pull-Out Force

To better quantify the grippers real world performance, it was also tested for pull-out force with two of the fingers assembled into a gripper. Pull-out force is defined here as the peak force required to pull an object out of the grasp of the two finger

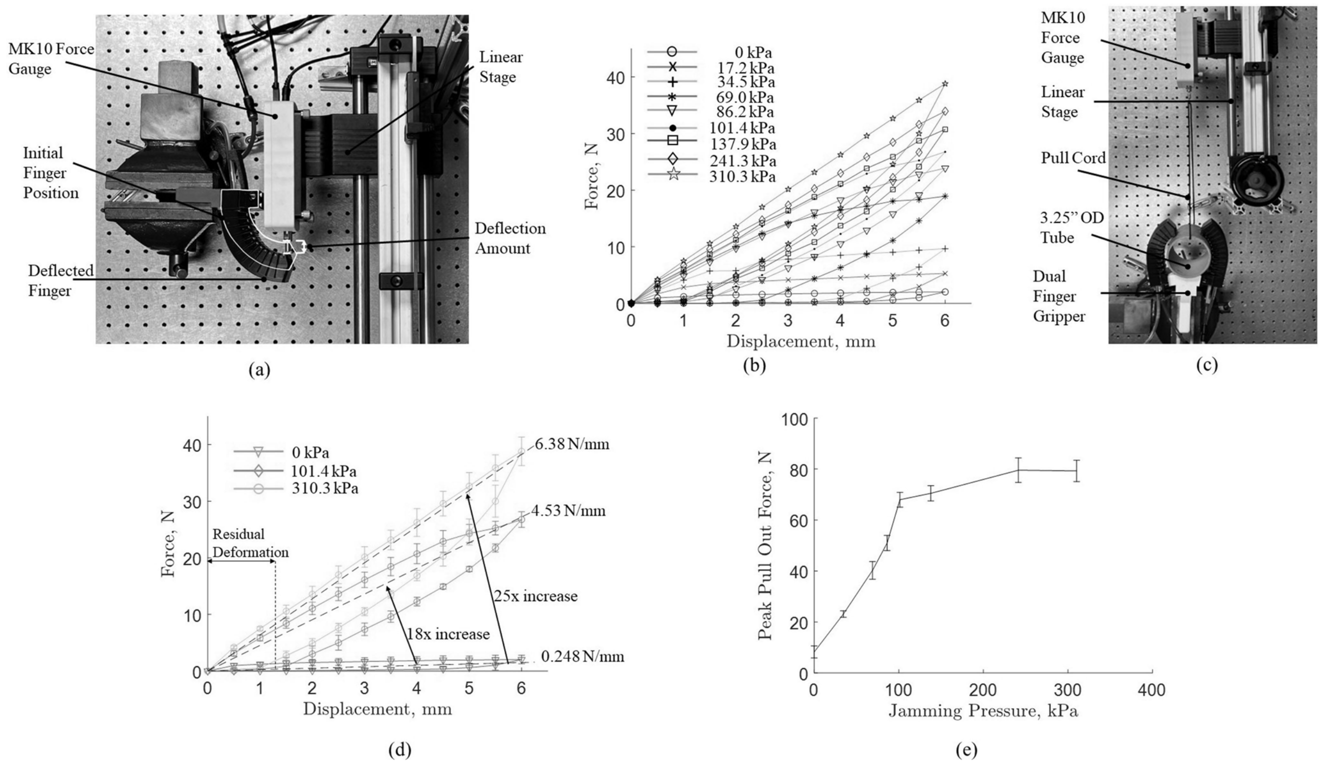

Fig. 6. Finger Stiffness Test Setups & Results. (a) Stiffness Test Experimental Setup. (b) Average Force vs. Displacement of the Finger, 5 trials per pressure. (c) Pull-Out Force Test Experimental Setup. (d) Average Force vs. Displacement of the Finger with Standard Deviation and Stiffness Increases, 5 trials per pressure. (e) Average Pull-Out Force vs. Jamming Pressure, 5 trials per pressure.

gripper. In this test, a cardboard tube was grasped by the gripper with a cord looped through it attached to a force gauge mounted on a linear stage, as shown in Fig. 6(c). The force sensor was traversed away from the gripper until the tube was fully removed from its grasp. This was repeated five times at a range of pressures, and average peak force can be seen in Fig. 6(e). This test further demonstrates the advantage of positive layer jamming, as pull-out force increases above 12.5 psi (86.2 kPa), the limit for many low cost vacuum generators. The payload capacity increased until it saturated at 35 psi (241.3 kPa) with an average force of 80 N. This is a 1.6x increase in force from 12.5 psi (86.2 kPa) and a 1.16x increase in force from 14.7 psi (101.4 kPa). Once adequate pressure is applied to the jamming layers, their stiffness in the Phase 1 (no slip) regime will not increase further [13]. Because the layers do not slip relative to each other in Phase 1, the overall stiffness of the gripper is dependant on the geometric and material properties of the gripper and layers. At lower jamming pressures, the deformation required to remove the tube may cause the jamming layers to slip and enter Phase 3, resulting in a lower pull-out force. However as jamming pressure increases, the deformation required to cause layer slip increases beyond the deformation required to remove the tube, causing payload to saturate. To further increase pull-out force, gripper design could be optimized to increase stiffness in in the Phase 1 regime.

There is slightly higher standard deviation at higher pressures, but this can likely be attributed to the unpredictable nature of both the layers slipping relative to each other and the cardboard tube slipping against the finger as it is pulled out. Liu *et al.* showed testing of a similarly sized soft variable stiffness gripper with vacuum fiber jamming [9]. Their gripper design utilized three radially symmetric fingers and in similar pull out testing was able to achieve a peak pullout force of 12 N at 13 psi (90 kPa) of vacuum jamming pressure [9]. In the commercial space, the mGrip Soft Gripper from Soft Robotics Inc. advertises pickable object masses of up to 3.4 g, or 33.35 N with a 6 finger configuration and no variable stiffness technology from mGrip$^{\mathrm{TM}}$. While the testing methodology for this metric is unknown, our design demonstrates a 2.4x increase in pull-out force compared to the 6 finger mGrip$^{\mathrm{TM}}$ gripper.

C. Actuation

Several aspects of gripper actuation were tested, including repeatability of gripper tip position, gripper actuation speed and pressure required to fully open the gripper. Gripper tip position repeatability was measured using the linear stage & force sensor. The position of the gripper tip was measured before and after cycling it open and closed at 45 psi (310.3 kPa). In this testing, standard deviation of gripper tip position was 0.13 mm. This demonstrates that the gripper has adequate closing force to overcome any un-jammed friction and that its position can be reliably known for automation tasks. Actuation pressure, pressure required to fully open the gripper was also tested. In this test, the gripper was cycled with increasing pressure until it was fully open, which required 45 psi (310.3 kPa). While one finger opened fully at a lower pressure in testing, this is likely due to differences in assembly causing slightly more friction. Actuation time was then tested at 45 psi (310.3 kPa) using an electrically controlled solenoid and slow motion videos. Footage was then analyzed to determine open and close times. Using this method, recorded average open time was 0.24 s, and average close time was 0.29 s. These values are are consistent in order of magnitude with other pneumatic gripper designs and adequate

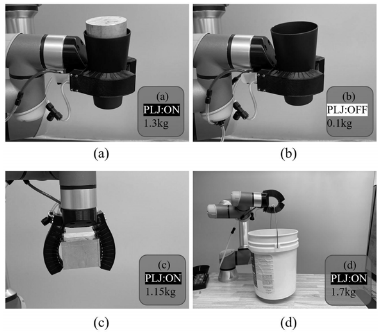

Fig. 7. A Dual Finger Gripper Mounted on UR5 Picking up Different Payloads. (a) A cup with an Aluminum Cylinder (1.3 kg) with LJ enabled. (b) An Empty Cup (0.1 kg) with LJ disabled. (c) An Aluminum Block (1.15 kg) with LJ enabled. (d) A bucket (1.7 kg) with LJ enabled. See the supplemental video for more functional tests.

for real world uses [10]. While the gripper and jamming bag were both tested at pressures up to 60 psi (413.7 kPa), pressure for both was limited to 45 psi (310.3 kPa), the pressure required to fully open the gripper. This was chosen so that both could use the same air source, and in an attempt to minimize fatigue on both the gripper and jamming bag.

D. Functional Results

A base to integrate two fingers into a gripper was designed to test real world functionality. This gripper was installed as the end effector on a UR5 robot arm. Using solenoid valves connected to the UR5 control box, actuation and jamming pressure could be controlled in the UR5 software to pick up a variety of high weight payloads. The objects tested are shown in Fig. 7, and the variety demonstrates both the gripper's potential for heavy duty applications and its adaptability.

V. Conclusions & Future Work

A novel variable stiffness technology based on positive layer jamming was developed and integrated into a soft pneumatic gripper. The pull-out tests showed that the positive layer jamming has more than 1.6x payload than the traditional vacuum based layer jamming. The soft gripper produced in this research demonstrated a very high stiffness change with layer jamming activated. However, because the gripper was tested in the curved, gripping position, grip force was taken into account for the lower stiffness value. Because of this, stiffness change results are not directly comparable with results from vacuum layer jamming research on compliant links. In the future, a positive pressure jamming link will be designed and tested, independent of an actuator in order to optimize stiffness change performance. Parameters such as jamming channel dimensions, number of layers and layer material could be tested. Additionally, due to the inverted design of the actuator and use of an actuation spring, it has a relatively low grip force, limiting it to certain payloads. Future research could find a way to implement this positive jamming into a more standard gripper design to overcome this.

Customized multi-material additive manufacturing was used to rapidly iterate the soft gripper design. Multi-Material additive manufacturing also allowed for printed-in strain limiting features and hard points that would have otherwise required an additional assembly step. While optimized print parameters for airtight printing were developed over the course of this research, future work could be done to improve the robustness of the multi-material printing process to allow more complex geometries. Additionally, work should be performed to better characterize the fatigue life of actuators produced using this method.

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