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# Selective Stiffening of Soft Actuators Based on Jamming

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*Abstract*— **The ability to selectively stiffen otherwise compliant soft actuators increases their versatility and dexterity. We investigate granular jamming and layer jamming as two possible methods to achieve stiffening with PneuFlex actuators, a type of soft continuum actuator. The paper details five designs of jamming compartments that can be attached to an actuator. We evaluate the stiffening of the five different prototypes, achieving an up to 8-fold increase in stiffness. The strength of the most effective prototype based on layer jamming is also validated in the context of pushing buttons, resulting in an 2.23-fold increase in pushing force.**

## I. Introduction

Soft robotic mechanisms have advantages over traditional, rigid ones: for example, they are inherently safe and light, have a high degree of compliance without the need for explicit control, are robust to impact and collision, and can be designed and built quickly at low costs. In our prior work, we have leveraged these characteristics to build soft robotic hands [1] based on the soft PneuFlex actuator [2].

PneuFlex actuators are made of fiber-reinforced silicone rubber. Inflating the actuator expands the top part, while the non-stretchable bottom part maintains its length. As a result, the actuator bends. One of the strengths of these actuators—in particular when employed in robotic hands—is their effectiveness in using the inherent compliance to robustly establish and safely maintain contact between the hand and the environment. This has been shown to be an important contribution to robustness in grasping [3].

There are situations, however, in which softness and compliance become a disadvantage. The softness of the PneuFlex actuator (or any other soft actuator) limits the amount of force it can exert onto the environment, for example, when lifting a heavy object or when pressing a switch. To alleviate this limitation, we propose soft actuators capable of changing their stiffness by employing jamming [4].

Jamming is a physical process in which materials consisting of numerous smaller pieces, such as grains or sheets, change from a flexible to a solid-like state. This effect is achieved by increasing the density of the material, i.e. by "jamming" the material together. We extend the original PneuFlex design by adding a jamming chamber to the top of the actuator. This compartment can alternate between a passive, flexible state and a jammed, fixed state. In conjunction with the inelastic bottom side of the actuator, this creates a sandwich-like stiffened structure.

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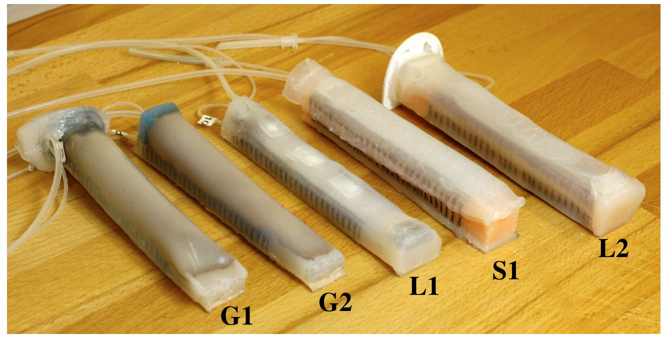



Fig. 1. Five PneuFlex actuators with different jamming designs: G1 and G2 are based on granular jamming, L1, S1, and L2 employ layer jamming (S indicates the fish-scale-like layer design)

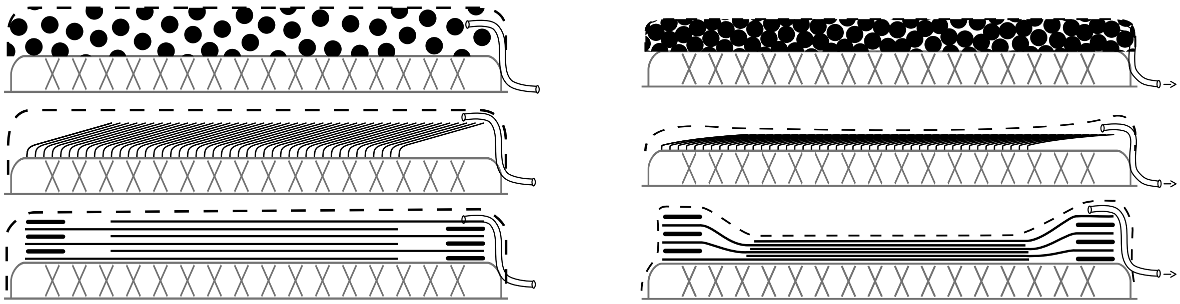
We evaluate five different designs based on two jamming methods. After a brief overview of related approaches in Section II, we will describe the individual designs in Section III. The attainable change in stiffness is quantified in Section IV. In a second experiment (Section V), we put the best-performing prototype (L2 in Figure 1, based on layer jamming) to test in a reference task of exerting a force onto the environment with the tip of a straight, stiffened finger.

## II. Related Work

As the focus of this paper is to change the stiffness of mechanisms, we will review the different methods by which this can be achieved.

The most common variable stiffness approach is to use closed-loop impedance or admittance control. An example for this strategy in robotic hand design is the i-HY Hand [5]. It uses the motors that drive the flexor tendonds to modulate joint stiffness. Transferring this approach to the pneumatically actuated PneuFlex is problematic, as even high quality, electromagnetic valves are too slow for the required control frequencies.

Alternatively, a second approach uses antagonistic actuators, coupled to the controlled mechanisms via springs. By co-actuating the antagonists, the stiffness of the joint can be increased by loading the springs. This method is employed with pneumatic artificial muscles [6] and with tendon-driven hands [7]. Antagonistic actuation is also possible with PneuFlex actuators by joining two actuators at their passive, bottom sides. But because the current design is optimized for forward bending, the actuator is unstable when bending backwards and thus prone to fold unpredictably.



(a) Unjammed, flexible compartment

(b) Jammed, stiff compartment after evacuation of air

Fig. 2. Working principles of three jamming compartments tested on top of a PneuFlex actuator: granular jamming (G), layer jamming with overlapping fish-scale-like layers (S) and layer jamming with two stacks of three interleaved layers (L); the Pneuflex actuator is shown on the bottom, the jamming chamber is indicated by dashed lines.

The third approach—and the approach we will take in this paper—is to add structures that can harden or soften in their current configuration. This transition from soft to stiff can be realized in place with a single control channel for many degrees of freedom, keeping control simple. A particularly effective method is to use the solid-liquid phase transition of certain materials e.g. low-temperature melting metal alloys, which can provide a huge change in stiffness [8]. Unfortunately, cooling times to solidify even small structures are on the order of seconds and subject to ambient temperature; this is too slow for most manipulation tasks.

Another way to effect phase change is to actively compress granular materials, such as sand [4]. Individual particles get jammed together, locking each other in place. Hence, this method is called granular jamming. It has been used with great success for a simple yet effective gripper design [9], and has also been applied to a tubular, tendon-driven continuum robot [10]. By testing various materials (coffee, glass beads, sawdust, and diatomaceous earth), Cheng et al. found that ground coffee provides the most effective stiffening [10]. Figure 2 illustrates the principle of granular jamming and how it can be integrated with a PneuFlex actuator.

Layer jamming replaces granular material with sheets that stiffen when pressed against each other. This design has been employed in tubular continuum robots [11], [12], but also as brakes in tendon driven finger joints [13]. Forces between individual sheets are spread over a large area of contact, greatly reducing the pressure required to maintain stiction. The structure then effectively behaves like a single sheet. Layer jamming potentially uses the available volume more efficiently than granular jamming, but is more complex to manufacture. The layers can take the form of interleaved stacks of sheets [11], [13], partially overlapping layers arranged similar to fish scales [11], or interlocking fibers [12]. Figure 2 illustrates the first two variants and shows how they can be integrated with a PneuFlex actuator.

To engage jamming, the material is compressed by evacuating a flexible, airtight compartment it is contained in, essentially using the ambient air pressure as the compressive force. This method can also share the pneumatic control system of the actuator, simplifying integration.

We will compare the effectiveness of the proposed designs with state of the art variable stiffness actuators, focusing on those that are used in robot hands or use jamming methods. The Awiwi hand can mechanically stiffen its joints up to a factor of 12.5 [14]. Kim et al. were able to achieve a factor of up to 16 with their jammable rotational joint [11]. Schubert and Floreano achieve a factor of 25 using low-temperature melting alloys [8], though its applicability is limited by the time consuming cooling process. The AwAS actuator is able to stiffen by a factor of 50 [15], but the method requires rigid parts and cannot be applied to soft actuators.

The simple activation, mechanical compatibility with the actuator, and simple manufacturing make jamming the most promising approach to add variable stiffness to PneuFlex actuators.

## III. Stiffening Mechanism

The wealth of motions possible by a fiber reinforced soft continuum actuator such as the PneuFlex has been enumerated by Bishop-Moser et al. [16]. A typical PneuFlex actuator is straight, has a flat bottom, and when actuated, curves in a plane without twist. In its simplest form, it has a uniform cross section geometry, which results in a uniform actuation ratio (curvature per internal pressure). The actuators used in this paper are made with SmoothOn DragonSkin 10 silicone. The design of the PneuFlex actuators and instructions for manufacturing are freely available[1]. Similar actuator designs are the pneu-net actuator [17] and Bi-bellows [18]. With minor changes, the proposed jamming designs can be adapted to these actuators too.

An effective way to stiffen the PneuFlex actuator in any bending state is to restrict the motion of the elastic top side. Together with the flexible but non-stretchable bottom side, this creates a much stiffer sandwich structure. We achieve this by adding a jamming compartment on top of the actuator, as depicted in Figure 2. The chamber contains granular material or stacked sheets, for the granular jamming and layer jamming methods respectively. It is built by bending a sheet of silicone (Ecoflex 10, 1 mm thick) over the top

[1] `http://www.robotics.tu-berlin.de/menue/research/compliant_manipulators/pneuflex_tutorial/`

to form a cylinder and attaching the sheet to the side walls of the actuator. The ends are sealed with rubber caps. One of the caps also embeds a tube to inflate or evacuate the jamming compartment. Jamming is engaged by evacuating the compartment to $-85$ kPa.

### A. Granular Jamming Prototypes

The granular jamming method was used for two candidate designs shown in Figure 1, G1 and G2. We used ground coffee, as it works well and is of acceptable weight density [10]. The design G1 uses a cylindrical compartment, whereas G2 uses a conical compartment to provide more material at the base where higher forces are expected to occur due to leverage. The conical shape also stabilizes the hull, minimizing unwanted displacement of the granules within the compartment. Both prototypes use 7.5 g of ground coffee within a volume of 22 $cm^3$ (G1) and 7 $cm^3$ (G2).

### B. Layer Jamming Prototypes

We investigated two distinct structures based on layer jamming. Prototype S1 uses a series of overlapping layers akin to fish scales and is similar to a design that has been used for stiffening a tube [11]. The jamming compartment is filled with a stack of polyester scales (24 mm by 15.5 mm) cut from 100 μm PET foil. Each scale is individually anchored to the PneuFlex actuator below, 2.55 mm apart from each other. The scales lie flush on the actuator as shown in Figure 2.

The second design (L1) uses two interleaved stacks of sheets that are anchored to each end of the actuator, as shown in Figure 2. The sheets are made from 100 μm PET foil and are separated from each other by 800 μm within a stack. Each stack consists of eight interleaved layers, resulting in 16 layers total. Each sheet overlaps its counterpart by 75 mm in the straight actuator.

The third candidate design (L2) improves on the L1 design by using a laser-cut form illustrated in Figure 3. The cut can be folded into a reproducible stack of sheets. The separating distance between sheets in a stack was reduced to 400 μm and the number of sheets reduced to five each. Additionally, the topmost sheet is made elastic using a special cut pattern. This sheet acts as a dry lubricant to keep the rubber hull from sticking to the moving sheets, improving compliance of the actuator in the unjammed state. The pattern was adopted from stretchable electronic circuits [19].

The layer jamming chambers have approximate volumes of 14 $cm^3$ (S1), 19 $cm^3$ (L1) and 20 $cm^3$ (L2).

## IV. Evaluation of Stiffening Capability

To evaluate the stiffness change caused by jamming on our five prototypes, we must first define stiffness in the context of bending actuators. The stiffness of a PneuFlex actuator can best be described for infinitesimally thin segments along the actuator, as illustrated in Figure 4. For each segment the cross section geometry determines the change of moment $\Delta M$ necessary to attain a change in curvature $\Delta c$, this local stiffness can be expressed as $k = \frac{\Delta M}{\Delta c}$.

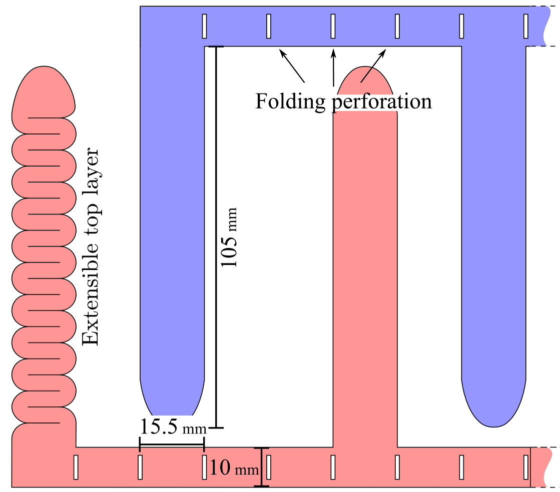
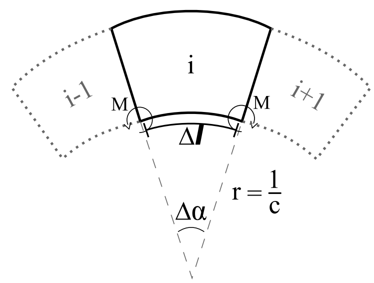



Fig. 3. Cutting template to fold two stacks of layers for prototype L2. The design of the layer on the left (top layer) prevents sticking between the stack of layers and the rubber hull of the jamming chamber.




$$k = \frac{\Delta M}{\Delta c} = \frac{\Delta M}{\Delta \alpha} \cdot \Delta l$$

Fig. 4. The actuator can be approximated by short, discrete segments with constant cross section and a constant curvature $c$. Between adjacent segments, a moment $M$ is transmitted. Local stiffness $k$ relates the latter two variables.

Computation of this local stiffness gets biased by noise in the curvature measurement. To circumvent this problem, we use fingertip rotation $\alpha$ versus force $F$ applied perpendicularly at the finger tip. For a given actuator position, $\frac{F}{\alpha}$ linearly relates to the local stiffness $k$ up to a constant factor, which is sufficient to estimate the stiffening factor $\frac{k_{jammed}}{k_{unjammed}}$. In our experimental setup, shown in Figure 5, a constant force is applied to the tip using a spring scale, while tip orientation is tracked visually using spherical markers. The 2D tracking setup uses a 10 Megapixel DSLR camera and corrects for perspective distortions using a calibration pattern.

The average stiffening factor for each prototype was calculated from five repeated measurements at five different loads and three different initial curvatures in jammed and unjammed state, yielding 750 data points in total. Figure 6 gives the resulting average stiffening factors for each tested prototype. The best results are achieved with layer jamming using interleaved sheets. Prototype L2 is the best of all and achieves an up to eight-fold increase in stiffness when being jammed. Prototype S1 shows the worst performance, achieving 2.2-fold stiffening at best at 0° actuation and jamming is practically ineffective when highly curved.

The granular jamming prototypes achieve about half the stiffening of the layer jamming ones, while sharing compa-

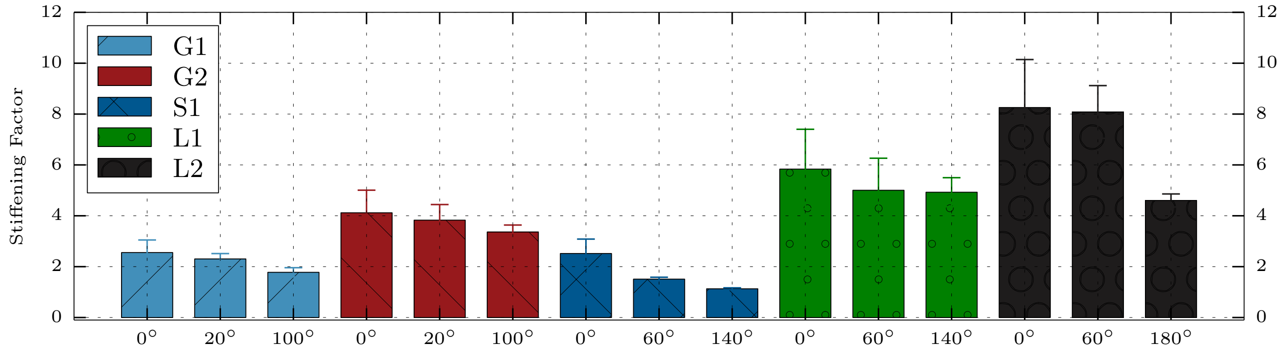



Fig. 6. Stiffening factors of all prototypes, for three tip orientations of the unloaded actuator each. Error bars indicate standard error.

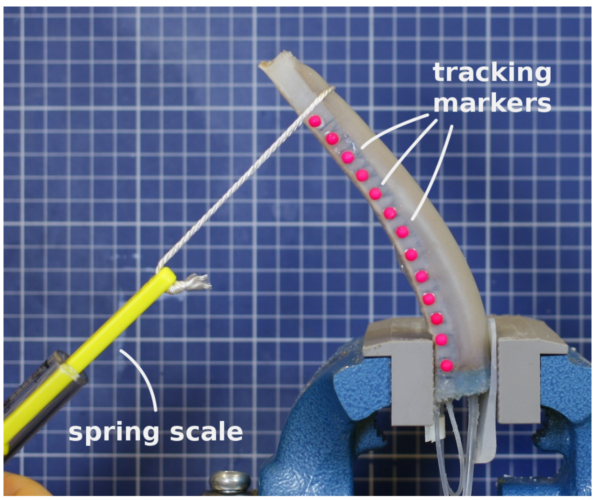



Fig. 5. Experimental Setup: A force is applied to prototype G2, deformation is tracked using colored spherical markers.

rable jamming chamber volumes. Both G2 and L2 show a considerable improvement over their related prototypes G1 and L1, almost doubling the performance.

We also measured the change in stiffness for loads applied sideways to the actuator tip of a straight actuator. A generally lower performance was expected, as the jamming compartment was not designed specifically for this type of load. The results are shown in Figure 7. Stiffening is less pronounced with around a factor of 2, with L2 achieving a factor of 3.5. Notably, G2 does not outperform G1 as it does in Figure 6, which indicates that the changed granular chamber geometry has almost no influence on the sideway stiffness.

## V. Effect of Jamming on Pushing Force

In the RBO hand [2] and the RBO 2 hand [1], the soft and compliant PneuFlex actuators are used as fingers. But for the task of pressing light switches, for example, the fingers need to be rigid enough to not buckle. We therefore set up a robotic experiment to evaluate the usefulness of jammable actuators in the context of applying force with a fingertip. We mounted the best performing jammable PneuFlex design, L2, as a single finger on the wrist of a Meka humanoid robot and pushed the straight finger into a vertical wall. Figure 8

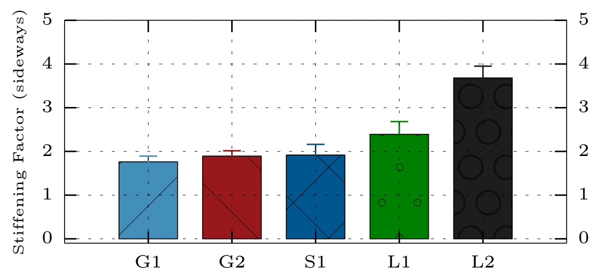



Fig. 7. Stiffening factors of the straight actuators for loads sideways to the actuator tip. Error bars indicate standard error.

shows an example trial in jammed and in unjammed mode. We then analyze the maximum normal force attainable to quantify the achievable improvement. In addition to a straight unjammed and straight jammed actuator, we also tested a third mode where the actuator is jammed first, and then inflated *afterwards* to 75 kPa. Due to the activated jamming, the internal pressure does not cause the actuator to bend, instead it applies pretension to the embedded fibers of the actuator, further stabilizing it.

We also introduce wrist pitch as an independent variable to the experiment, as perfectly aligning the wrist with the wall may be difficult in real applications. Varying wrist pitch will also give us an indication of how robustly such an action can be executed under uncertain conditions. The push motion was repeated five times for each wrist position, which in turn was varied from $-35°$ (pointing downwards) to $40°$ (pointing upwards) in steps of $5°$.

Figure 9 shows the measured forces during contact with respect to different wrist positions. The plots are aligned so that the wall contact occurs at $x \approx 0$ cm, after which the normal force increases steadily before it drops due to buckling. The unjammed actuator shows a low slope, indicating generally low stiffness. The highest stiffness is attained with a pitch around 15°. The the jammed actuator shows much steeper slopes, indicating high contact stiffness especially when the actuator is pitched around 20° upwards.

The strongest force applicable to the environment is limited by buckling, which manifests in a force peak in Figure 9. Those peak forces present the strongest force


(a) unjammed actuator


(b) jammed actuator

Fig. 8. Deformation of unjammed and jammed (but not pressurized) actuator during a push trial: at initial contact, during the push, and at the position closest to the wall. The wrist is pitched at 20° to the surface normal.

available for pushing and are aggregated into Figure 10. On average, jamming increases peak force by a factor of 1.43 (standard error: $\pm 0.11$). The jammed actuator is also consistently stronger than the unjammed across all tested finger orientations. Jammed and pressured, the actuator performs even better, resulting in a $1.73 \pm 0.12$ fold increase of maximum push force. The effect is most pronounced in the base scenario with wrist pitch at 0°, where the actuator is able to exert $2.33 \pm 0.26$ times as much force. The improvement is consistent over a large range of wrist pitch angles tested. The data also show, that jamming improves the range of admissible pitch angles that can achieve a specific force threshold.

We observed that in all three modes the finger performed best when oriented slightly upwards at ca. 20° (as shown in Figure 8), and not at 0°. We believe that the cause for this offset is the fabric in the passive bottom layer. It resists forces stretching it well, but easily collapses under compressive force. At the same time the additional silicone from the jamming chamber further strengthens the top part of the actuator, creating an overall assymetric cross section.

## VI. Discussion

The experiments demonstrate that jamming can be integrated with the PneuFlex actuator design and that actuator stiffness can be modified by a factor of eight. This probably represents a lower bound on the performance, as the tested devices are proof-of-concept prototypes. Also, the prototypes G2 and L2 improved considerably with respect to the related initial designs G1 and L1. The fish scale design S1 proved to be difficult to manufacture, the scales also tended to stick to the hull, impeding motion in the unjammed state.

The change in stiffness we were able to achieve is considerable, but it has to be put in perspective. State of the art variable stiffness joints are able to achieve stiffening factors on the order of 12–50 [8], [11], [14], [15]. Compared to these systems, the presented jammable PneuFlex actuator resides at the lower end of stiffening performance. However, the presented method retains the excellent deformability and robustness of the basic actuator, which is necessary for some target applications, such as the use in soft robot hands.

For the examined application of pushing buttons, prototype L2 was able to exert up to 16 N, which approaches the limits of the robotic arm. But also the unjammed actuator could exert a surprisingly large force. We attribute this to the high volumetric ratio of (incompressible) rubber to enclosed air (ca. 90%) of the specific actuator. For an actuator with a lower ratio we can expect a much larger factor of stiffening.

During use of the granular jamming prototypes it became apparent, that the granular material easily gets displaced within the jamming compartment. To avoid this, it may be sensible to subdivide the compartment into several chambers. Though, this increases build complexity, one of the main advantages of the granular jamming method.

The layer jamming design also offers room for improvement. The limiting factor in the jammed state is not the friction between the layers, which was sufficient to basically "fuse" together the two stacks, but rather a buckling of the sheets at the base end of the actuator. There the two stacks do not yet overlap, which effectively halves the number of reinforcing layers. Figure 8 shows this failure mode in the last image. This point of failure could possibly be avoided by shifting the layers against each other.

We also observed a significant increase in stiffness when pressurizing the actuator after jamming. This is in line with observations by Cheng et al. [10], who used cables to pretension their tubular continuum actuator, increasing the weight carrying capability by about eight times. Pretensioning therefore seems to be a crucial method to boost performance of jamming structures and should be taken into account for every hardware design.

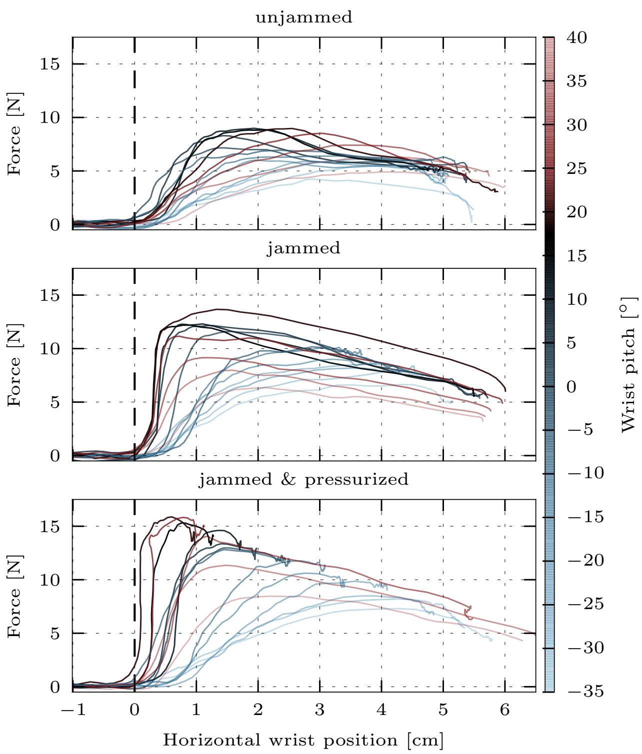



Fig. 9. Normal contact forces measured during a push as a function of the wrist position relative to the first contact with the environment (actuator mode is given in the title of each graph, wrist pitch is encoded in the color)

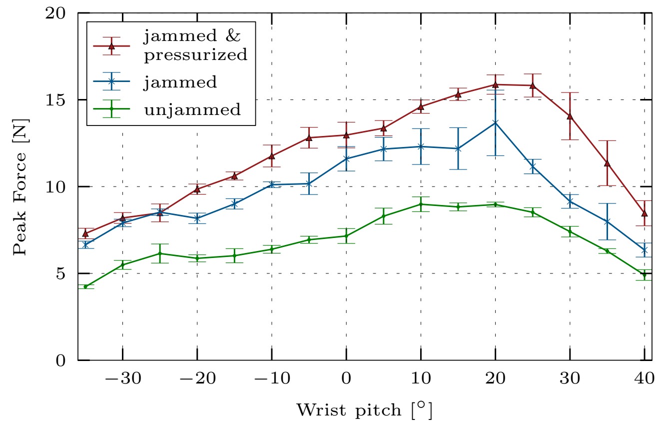



Fig. 10. Peak push forces at different contact angles. Error bars indicate standard error.

## VII. Conclusion

We presented three different mechanisms for increasing the stiffness of PneuFlex soft continuum actuators [1], [2]. These mechanisms are based on granular jamming and layer jamming. We evaluated each using a total of five prototypes. The prototype using layer jamming with two interleaved stacks of sheets performed best, achieving a stiffening factor of approximately eight, about twice as large as the granular jamming prototypes. This prototype was then evaluated in the reference task of pushing buttons, achieving an increase of applicable force by a factor of up to 2.33. We believe this shows that the proposed jamming extension is a promising approach to enable quick and reversible reinforcement of soft continuum actuators, while maintaining the advantages of their compliance, low cost, and ease of manufacturing.

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