Evaluation of a Circumferential Extending Antagonist Actuator in a Soft Arm

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***Abstract*— This paper presents a novel circumferential pneumatic actuator to be used as an antagonist in soft bending arms. The design is based on a McKibben actuator, and the circular shape is inspired by octopus musculature. The performance of the presented actuator is evaluated through characterization of individual actuators, as well as experimental analysis of the actuator's effect on the behavior of an existing soft bending arm segment. A stack of 16 circumferential actuators is capable of producing a force of 37 N when pressurized to 32 kPa and deflected to -15% strain. When the actuators are integrated into a 75 mm diameter soft arm, the arm is able to successfully lift 600 g (285% of its own mass) to 54% of the arm's original height, which is 2.2 times the maximum load for the arm without antagonistic actuators. When the soft arm with antagonistic actuators lifted 250 g at 40 kPa, the segment returned to 101% of its original height, compared to 59% for the arm segment without antagonistic actuators. Compared to existing antagonistic systems, this circumferential actuator produces high extension strokes and high forces at pressures below 100 kPa. The presented actuator is simple to manufacture and the design is complementary to the geometry of many soft arms, which makes the actuator a suitable choice to improve the arms' maximum load.**

I. INTRODUCTION

Cephalopods use limbs of muscle, referred to as *muscular hydrostats*, which have no rigid structures but are still capable of reaching and moving objects like a skeletal limb. Muscular hydrostats, which also include the tongue of a lizard or the trunk of an elephant, are highly complex and consist of tightly bundled groups of muscles that, when they interact, can simulate the effects of a muscle attached to a bone. These muscles apply forces against each other to provide the support that a bone would otherwise offer, and this phenomenon is known as an antagonistic muscle system.

Soft robotic limbs often imitate the structure of muscular hydrostats to apply forces and manipulate objects while remaining malleable. However, mimicking the form of these limbs is difficult given their complexity, and existing soft arms have been simplified in order to be feasibly manufactured with current technology. This simplification has resulted in artificial soft arms that fall short of the load and range-of-motion capabilities seen in biological soft arms.

A major objective in the development of soft arms is to be able to lift and apply loads to interact with environmental obstacles and objects of interest. Cephalopod arms bend and

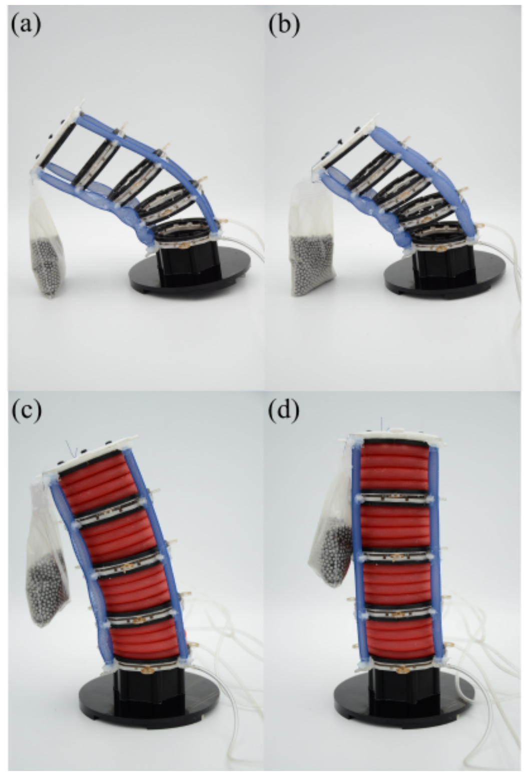

Fig. 1. Comparison of a 75mm diameter soft arm made only from longitudinal McKibben actuators – (a) and (b) – and an arm made with longitudinal and circumferential actuators – (c) and (d). Each arm has a 400 g mass suspended from the top. On the left, each arm is unpressurized, and on the right the arms are pressurized. The longitudinal and circumferential McKibben actuators act against each other to form an antagonistic system.

lift by engaging opposing muscle groups antagonistically, effectively varying their stiffness [1]. Antagonistic systems added to existing soft arms have increased the maximum lifting or resisting load of those arms, but these systems are frequently tailored to an individual arm design, such as STIFF-FLOP's jamming core or adding antagonistic tendons [2], [3]. The challenges of creating a soft antagonist system can also lead to other disadvantages, such as integration of hard components or a smaller range of contraction, extension or bending [4]. Existing pneumatic antagonistic systems, in particular, require high pressures (150 kPa to 500 kPa) to produce a significant antagonist force [5], and these pressures are beyond the capabilities of miniaturized pumps.

Our previous work developed a modular arm segment made from contracting longitudinal actuators, which was

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capable of bending and contracting [6]. However, the segment could not lift significant loads. The arm's weakness can largely be attributed to the fact that the design consisted of one type of actuator. Although the design mimics a cephalopod arm's longitudinal muscle group with McKibben actuators, it lacks an analog to the transverse muscles.

Among the existing soft actuators, there is a lack of a suitable low pressure, simple pneumatic actuator that extends and integrates well into a contracting arm. Extending McKibben actuators or radially constrained FREEs produce low forces and buckle when compressed [7]. Stacked pouch actuators have the desired motion [8], but they owe their high stroke to their initial thinness, which makes them time-consuming to manufacture and difficult to integrate.

This paper presents a circumferential extending actuator that maintains the higher force production of contracting McKibben actuators over extending actuators [7] and significantly improves the ability of the arm to lift loads (Figure 1). These circumferential actuators are formed by connecting the two ends of a longitudinal McKibben actuator to generate circumferential contraction and height extension, which is similar to cephalopod arms' transverse or circumferential muscle group. The paper describes the design, manufacturing and integration of the actuator and experimentally characterizes the individual actuator and a single segment of an integrated antagonistic system. Without the proposed antagonist, a 75 mm diameter arm was capable of lifting 250 g to 59% of the arm's original height with actuators pressurized to 40 kPa. With the circumferential actuators integrated, the same arm at the same pressure lifted 250 g (119% of its own mass) to 101% of the arm's original height. The arm was able to lift a maximum of 600 g (285% of its own mass) to 54% of its original height.

The contributions of this paper are:

1) Development of a novel circumferential McKibben actuator capable of producing forces greater than 30 N at pressures lower than 40 kPa.
2) Development of a method for integrating the antagonist actuators that can be applied to other soft arms constructed with contracting actuators.
3) Characterization of force and stroke of the circumferential actuators alone.
4) Characterization of the circumferential actuators' effect on the contraction, extension, curvature, and lifting capabilities of three soft arms with different diameters.

This paper is organized as follows. Section II begins by reviewing existing extending actuators and soft antagonistic systems. Section III describes the manufacturing process to create the circumferential actuators and integrate them into a soft arm segment. Section IV presents the results of the actuator and arm testing. Finally, the paper concludes and considers future work in Section V.

II. RELATED WORKS

Soft actuators can be driven many ways, including motor-driven cables, heat and air. Cables or tendons can be used antagonistically to provide variable stiffness to a pre-set position, or as direct actuation [3], [9]. However, tendons must be routed, which often requires the use of co-located mechanical or rigid parts such as motors and pulleys [10]. Shape memory alloy actuators (e.g., NiTi) use coiled springs that change shape with temperature, but often require high currents to operate and are slow to actuate [11], [12].

Pneumatic actuators are the focus of this work due to their easily available input, inexpensive testing, relatively high force, and natural compliance from soft materials [13], [14]. Pneumatic actuators act as reinforced balloons and change shape through inflation to induce actuation. Pneumatic actuators may be comprised of extremely soft materials reinforced by threads or sleeving [15], or they may be made of thin but otherwise stiff films heat sealed to form bellows. Thin film or pouch style actuators have high strokes but are not as inherently malleable as other types of actuators, and their initial thinness requires many connected pouches to generate significant motion [16]. Fiber reinforced actuators (FREEs) are comprised of an inner elastomer tube reinforced by threads that determine whether the actuator contracts, extends or twists when pressurized [17]. Extending FREEs have a higher stroke than McKibben actuators, but produce a lower force for an equivalent pressure and they risk buckling under compression [7]. Longitudinal extending FREEs can act as an antagonist in a contracting arm, but they require high pressures and large diameters to resist buckling.

Existing antagonistic systems in soft arms most commonly consist of longitudinal actuators resisting or supporting other longitudinal actuators [2], [5], [18]. STIFF-FLOP, while known for resisting high loads, uses a jamming core in conjunction with fluid-driven actuators to stiffen in place, which does not generalize to actively lifting high loads [2]. Tendons have been used to act against pneumatic actuators, though this implies the previously noted drawbacks of tendons [3]. Fully pneumatic systems have also been implemented, using extending pneumatic actuators to act against contracting ones [5], [18]. While successful, these arms have required extremely high pressures (up to 550 kPa) to operate and are physically large, which is likely required to avoid buckling the extending actuators [5].

Antagonism in cephalopod arms comes from the combination of longitudinal and transverse muscle fibers [1], which has rarely been implemented in soft arms. Transverse actuators have been connected to a braided structure to create extension, but this structure was not materially soft [10]. The most complete replication of cephalopod musculature with McKibben actuators [19] included a version of the transverse muscles, but the effect of this actuator group was not well studied. Implementing a materially soft transverse-style actuator in a bending arm would be a step towards mimicking the biological complexity of cephalopods that enables such varied motion. This paper analyzes a circumferential variant of a McKibben actuator to determine if this architectural complexity is viable and advantageous.

III. MANUFACTURING AND ASSEMBLY

The soft arms studied in this paper are composed of longitudinal McKibben actuators and the proposed circumferential McKibben actuators. The longitudinal actuators were manufactured using a previously developed process [6], which was modified for the circumferential actuators. This section describes the manufacturing process for the circumferential actuators and their integration into the soft arm.

The circumferential actuators are made of three elements: an elastomeric bladder, an annealed sheath and a custom t-joint cap. The circumferential actuator bladders were manufactured using the process noted above. The same bladders were used for the circumferential and longitudinal actuators, and each was made from Ecoflex 00-30, had a 6 mm outer diameter and a 1 mm wall thickness.

Forming a circular mesh by annealing. The expandable polyester (PET) sheathing was annealed into a helix to eliminate reaction moments from bending the sheath. A 6mm diameter rubber cord was threaded through the sheathing, and the cord-and-sheathing were wound around a metal rod, which set the actuator's diameter. The cord-and-sheathing were clamped in place, and the assembly was heated to 140 C at a rate of 20 C/hr. The assembly was held at 140 C for 2 hours before cooling to 25 C at a rate of 10 C/hr. The annealed helical sheathing is shown in Figure 2(a).

Assembling a circumferential McKibben actuator. The annealed sheathing was cut into individual circles, and the Ecoflex bladders were slid into the sheathing. The actuators were assembled on cylindrical stands (shown in Figure 2(b) and 2(c)) with the same outer diameter as the annealing rods to maintain consistent actuator sizes. This step was critical to avoid slip between actuators when integrated into the arm.

A custom t-joint cap and nozzle that had the same initial curvature as the circumferential actuators was printed on a FormLabs resin printer. The curved t-joint maintains the actuator's circular shape, as opposed to an off-the-shelf, straight, t-connector. The two ends of the bladder and sleeving were fit onto the t-joint, secured, and sealed with cable ties and clear RTV. A single, complete circumferential actuator is shown in Figure 2(d), passive, and 2(e), pressurized.

Assembling an arm segment. The modular design of the arm segment is similar to prior work [6]. Longitudinal actuators were connected via keys to a set of interchangeable Delrin plates. Curved tracks were adhered to both sides of these plates to prevent slip between circumferential actuators.

Physical connections (screws, bolts, clamps, ties, etc) between the actuators and the arms were intentionally avoided to minimize restrictions on actuator expansion. Instead, the circumferential actuators were stacked on a core of supercushioning polyurethane foam to align and secure them (Figure 2(f)). The foam core flexes with the arm, but reduces slip between the stacked actuators. Force transmission through a stack of circumferential McKibben actuators relies on alignment; non-aligned actuators will expand into gaps

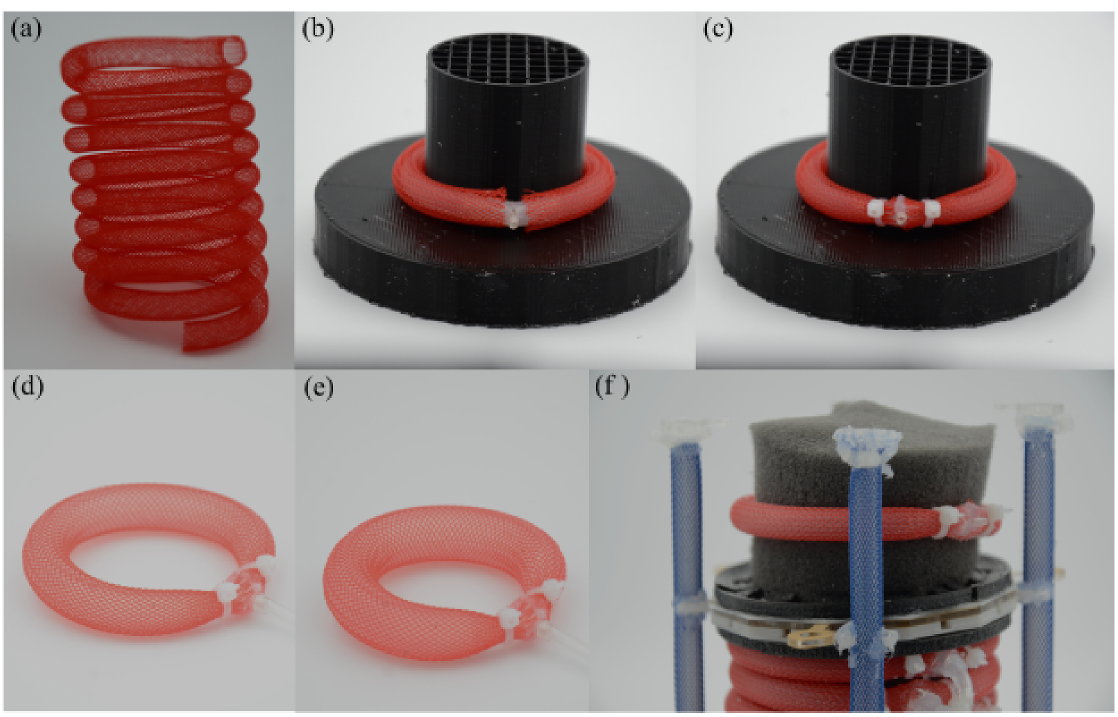

Fig. 2. The process of manufacturing circumferential McKibben actuators and integrating them into a soft arm segment. (a) The polyester braided sleeving is annealed to a low-angle helix of an approximately correct diameter. (b) The sheathing is cut into individual circles, and a Ecoflex 00-30 bladder, manufactured with a previously developed process [6], is inserted. (c) Custom curved t-joints are inserted at the seam, which caps the actuator and allows air in. The t-joints are secured with zip ties while the actuator is around a 3D-printed jig to maintain size and shape. The caps are sealed with clear RTV. (d) The uninflated actuator. (e) The inflated actuator. (f) The actuators are integrated into the arm by stacking around an ultrasoft foam core.

rather than transmitting force through the stack. The foam sits freely within the center of the arm, and a plate is screwed onto the top of the arm to make sure the foam does not fall out. Exactly sized foam did not sufficiently restrict slip, and therefore the foam was intentionally oversized 2 to 5 mm with respect to the inner diameter of the arm. The foam was cut and sewn to achieve desired diameters.

The modified design is still modular. While this work matched the circumferential actuator size to the arm, undersized actuators can also be used. The foam slides out of the top of the arm, and the circumferential McKibben actuators can easily be installed through gaps between the plates. This structure makes for easy assembly of the arm segment in this paper, but also allows for integration into other arm designs. The arm segments in this paper are studied as single sections of a longer arm, which may have the same or different diameters along the length. This work examines three arm diameters: 55 mm, 65 mm, and 75 mm.

IV. TESTING AND RESULTS

The circumferential actuators were characterized as an individual stack and within the arm. The passive compression force and the pressurized force output of the actuator was first tested (Section IV-A). A single arm segment was tested to determine the contraction and extension (Section IV-B), unloaded curvature (Section IV-C) and load resistance (Section IV-D). The deformed shape of the arm was tracked via an OptiTrack, with markers attached to the segment's radial plates. The test set-up is shown in Figure 3.

A. Actuator characterization

The circumferential actuators were initially characterized alone, to determine their passive stiffness and actuation force. These characterizations offer an isolated view of the proposed actuators and can be used to analyze the performance of the antagonistic system. Three actuator diameters were tested, and each test sample consisted of 16 actuators stacked around a foam core, capped by Delrin plates. The actuator stacks were tested on a Mark-10 ESM1500 tension-compression test stand, connected to a 50 N load cell.

The passive compression force for all three diameters is shown in Figure 4. The actuators and foam together add significant passive stiffness, which accounts for the higher passive support for loads visible in Figure 1(c) as opposed to (a). The changes in contraction and curvature due to this passive stiffness are tested in Sections IV-B and IV-C. The slight jumps in each curve in Figure 4 are likely from small slips between actuators; no buckling was observed during compression testing.

When the actuator stacks are pressurized, they are capable of reaching up to 40 N of support. The force vs pressure for each actuator size is plotted in Figure 5. The actuators were held at set strains to isolate the effect of pressure on the force produced. Generally, larger strains and bigger diameters yielded higher forces. However, there were some instances of larger strains yielding lower forces. These lower forces are likely due to actuator slip which results in misaligned

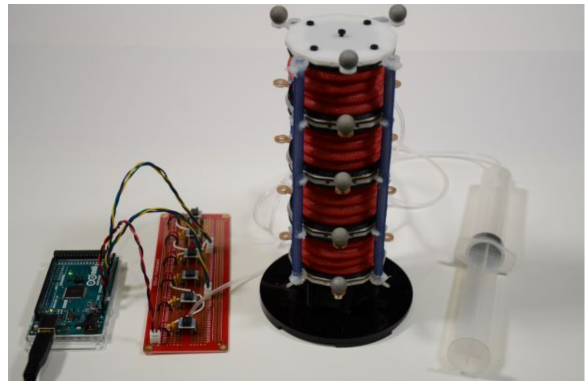

Fig. 3. The test set-up used to record positions values for this paper. OptiTrack cameras tracked the position of markers that were attached to the arm's radial plates. Actuator pressures were recorded using a Honeywell TruStability pressure sensor read through an Arduino Mega.

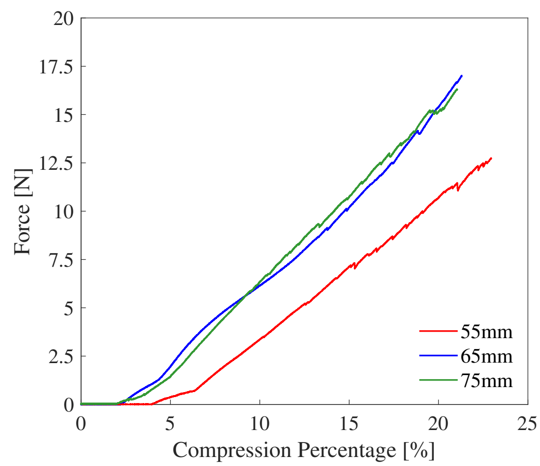

Fig. 4. Passive compression percentage of the arm versus the compression force that is applied, for all three diameters.

actuation force and extension. The small dead zones present at lower strains are not due to slip, and are more likely caused by the slight gap between the bladder and sheath: the bladder must expand and contact the sheath before the actuator will produce a force.

The circumferential actuators' extension was measured separately, under no load and without foam (Table I). The arm segment and actuator stacks extend less, due to the passive resistance from the foam and longitudinal actuators.

TABLE I
FREE EXTENSION OF CIRCUMFERENTIAL ACTUATORS

Number of Actuators	Percentage Extension
1	42%
4	41%

B. Arm contraction and extension

Contraction and extension were measured in the OptiTrack by pressurizing either longitudinal actuators (contraction) or circumferential actuators (extension). Arm contraction was measured with and without the circumferential antagonists integrated. The percent contraction and extension vs pressure for each diameter are plotted in Figure 6. The cross sections included in Figures 6-8 show which actuators were in the arm when the given test was done, and the actuators highlighted in yellow were those that were pressurized for that test.

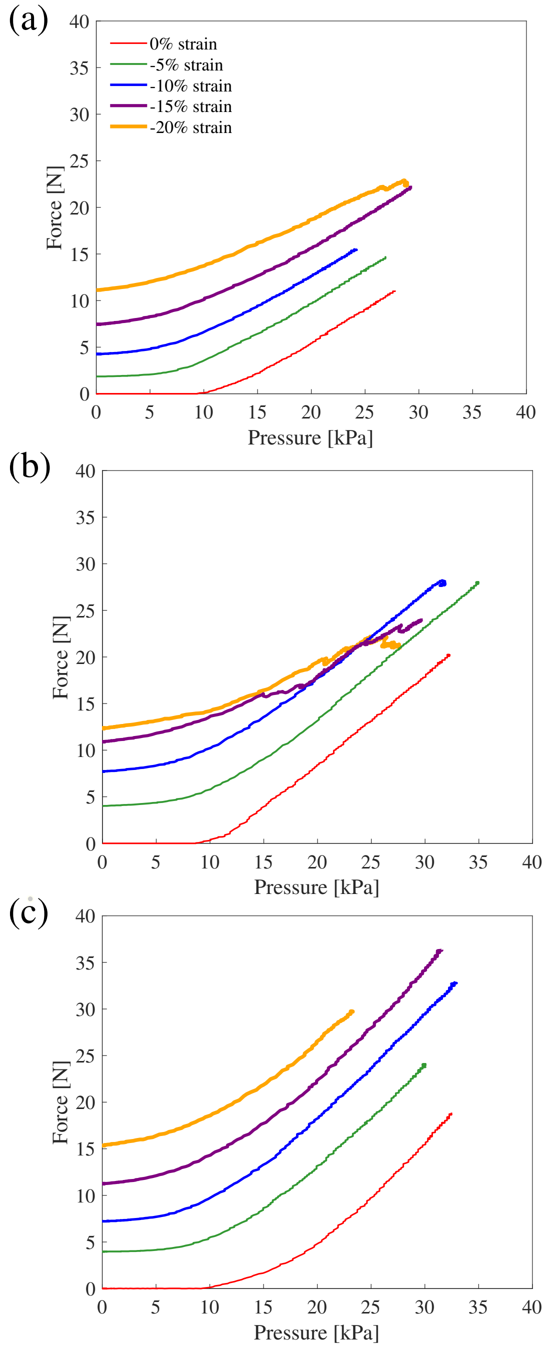

Fig. 5. Plots of the pressure vs force produced by a stack of 16 circumferential actuators constrained to a given strain. (a), (b), and (c) are for the 55mm, 65mm, and 75mm diameter arm respectively. The strains tested were 0%, -5%, -10%, -15%, and -20%.

Comparing arm contraction with and without the circumferential actuators measures one effect of their presence. Contraction percentages of the three arms without the circumferential actuators reached between 23 and 25%. With a circumferential actuator-and-foam core, the arms reached 17-18% contraction. The maximum contraction drops with larger diameters when the circumferential actuators are integrated into the system. This drop occurs because larger circumferential actuators produce a higher resistive force, whereas the longitudinal actuators are unchanged. The three arm variants only lose 7 - 10% of their contraction when the antagonistic actuators are integrated, which still leaves them capable of manipulating objects and lifting loads.

The previous arm did not extend [6], and while the extension is limited by the stiffness of the longitudinal actuators in

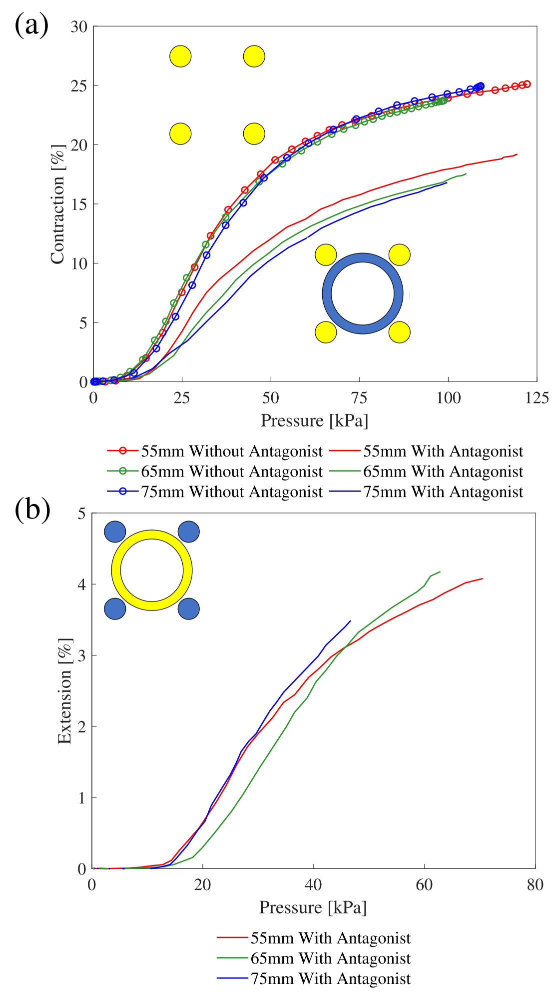

Fig. 6. (a) Percent contraction vs pressure of the three tested arms when only the longitudinal actuators are pressurized, recorded with and without the circumferential actuators integrated. (b) Percent extension vs pressure of the same three arms when only the circumferential antagonist actuators are pressurized. Note that extension and contraction both show a dead zone similar to the actuator characterization tests (Figure 5), caused by the slight gap between the bladder and sheath. The cross-sections included in the figure indicate which actuators were present in the arm during the given test, and the actuators that are highlighted yellow were those that were pressurized.

extension, any amount is an increase over the prior architecture. Figure 6 shows that all three arms reach approximately 4% extension at their highest pressure. The circumferential actuators are capable of reaching larger extensions when unconstrained (Table I). In general, for a soft arm to show extension and contraction, the longitudinal actuators must be as passively extensible as the circumferential antagonists are passively compressible.

C. Unloaded arm curvature

The unloaded arm curvature was measured to determine the curvature lost due to the circumferential actuators' passive stiffness. Each arm diameter was tested with and without circumferential actuators integrated, while pressurizing only the longitudinal actuators. Two cases were tested: pressurizing one longitudinal actuator, which is a conservative estimate of possible curvature in any direction, and pressurizing two longitudinal actuators equally, which limits bending to two orthogonal planes. The results for the four cases are shown in Figure 7.

As expected, curvature at equivalent pressures decreases when circumferential actuators are integrated into the arm segment. The percent change in curvature at 100 kPa are given in Table II. The percent loss increases as the circumferential actuator size increases, due to the higher passive stiffness. The loss of curvature is compounded in larger arms, which naturally curve less than narrower arms. Pressurizing two actuators doubles the force acting against the circumferential actuators and thus reduces curvature loss, though it also reduces the number of directions the arm can bend.

TABLE II
CURVATURE CHANGE DUE TO CIRCUMFERENTIAL ACTUATORS, MEASURED AT 100 KPA

Diameter	One Long. Actuator	Two Long. Actuators
55 mm	-15%	-8.4%
65 mm	-25%	-8.6%
75 mm	-41%	-22%

Bending, quantified by curvature, is a critical action for soft arms because it enables a broader workspace. Integrating

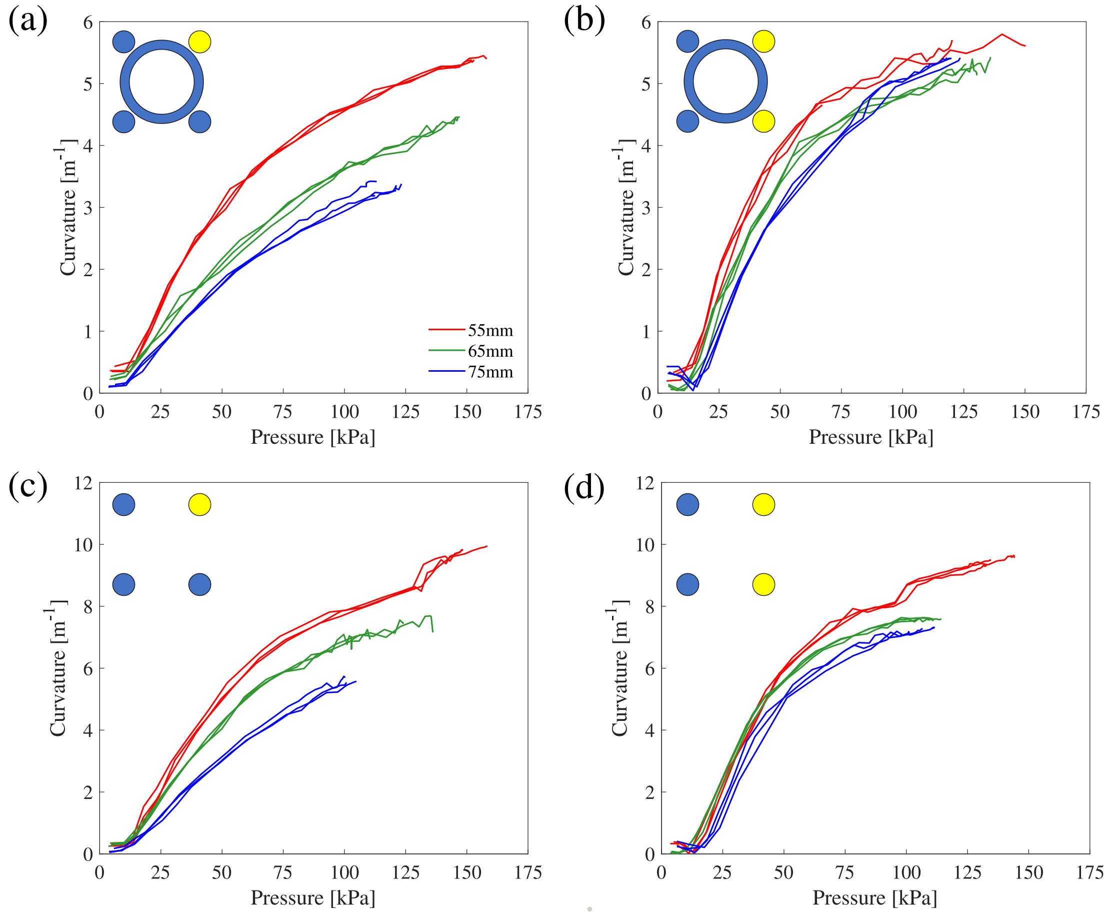

Fig. 7. Soft arm curvature for: (a) one longitudinal actuator pressurized, with circumferential actuators; (b) one longitudinal actuator pressurized, without circumferential actuators; (c) two longitudinal actuators pressurized, with circumferential actuators; (d) two longitudinal actuators pressurized, without circumferential actuators. Curvature was calculated from the position of retroreflective markers attached to each arm's radial plates (Figure 3).

circumferential actuators decreases the curvature at equivalent pressures, but that effect is minimized in smaller, more flexible arms. All arms can reach equivalent curvatures below the with-antagonist maximum curvature, albeit at higher pressures than arms without antagonists.

D. Arm load resistance

The final test compared the arms' ability to lift or resist loads with and without the circumferential actuators integrated. Weights were suspended from the arm's top plate. The weights were lifted two ways: first, pressurizing two longitudinal actuators opposite the load, in an arm without circumferential actuators; second, pressurizing only the circumferential actuators of an antagonistic arm. Note that pressurizing only the circumferential actuators is still an antagonistic engagement, because extension is limited by the longitudinal actuators. The maximum load was determined by testing with increasing masses, in increments of 50 g, until the highest achievable pressure in either the longitudinal or circumferential actuators could not lift the mass off the test bed. Figure 8 compares the arm height to mass lifted, with and without circumferential actuators. Only successful cases are plotted. This test considers arm height measured from the base to the middle of the top plate, without regard to arm shape. Lower loads typically resulted in bending (Figure 1(a),(c) and (d)), while loads near an arm's maximum could result in a combination of bending, contraction and actuator buckling (Figure 1(b)).

The lifting capability of the arm with only longitudinal actuators is counter-intuitively similar across all diameters. The maximum mass achieved was 300 g for the 55 mm diameter arm, and 250 g for the 65 mm and 75 mm diameter arms. This near constant maximum mass is attributed to the loading direction. The force from the suspended mass is parallel to the arm's central axis, which means the arm is loaded partially in bending and partially as a column. Bending stiffness is normally correlated with diameter, but the column load is supported by the axial stiffness of the longitudinal actuators, which does not change with diameter. The maximum mass may be higher for the 55 mm arm because the mass of the arm itself is lower, and it would be easier to lift the applied mass along with its own mass.

When the circumferential actuators were integrated the maximum masses (when pressurized to 40 kPa), in order of increasing arm diameter, were 300 g, 400 g, and 600 g. The circumferential actuators increased the arm's resistive force and the manner in which arms lifted the masses. While the maximum mass of the 55 mm arm was unchanged, the height it was able to lift intermediate loads increased 49%. Larger arms were also able to lift masses higher, in addition to lifting more mass, and were more resistant to actuator buckling. Lighter masses were occasionally lifted to over the original height of the arm, due to arm extension.

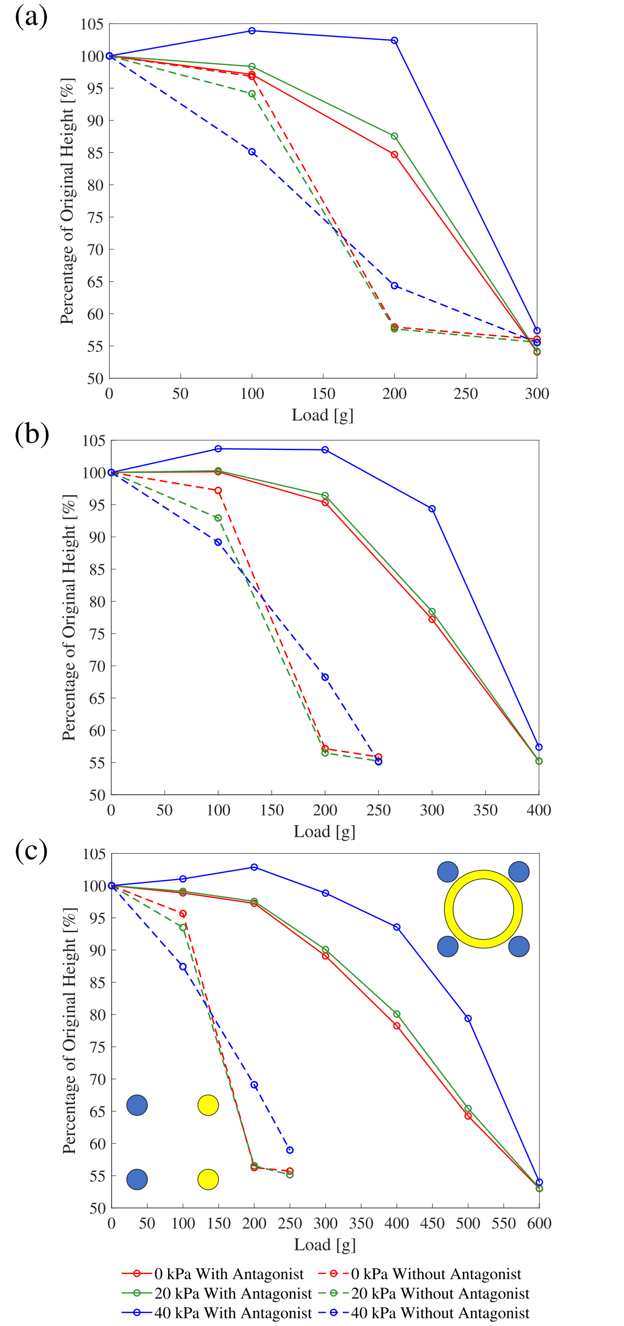

Fig. 8. Percentage of the original height that the indicated masses were lifted to. Trials were done by lifting masses, which consisted of small steel balls inside a bag, in 50 g increments. Arm height was extracted for pressures of 0, 20 and 40 kPa.

When integrated into a soft bending arm as an antagonist, the proposed circumferential actuators provide a trade off between flexibility and resistive force. The actuators reduce an arm's maximum contraction by 7-10%, but allow the arm to extend approximately 5%, which the design was originally incapable of. While the circumferential actuators reduce curvature 8-41%, the actuators increase the maximum lifted mass up to 240%.

V. CONCLUSIONS

This paper has presented a novel design of a circumferential antagonist actuator based on a McKibben actuator. The circumferential actuator connects the two ends of a McKibben actuator together to form a circle which, when pressurized, shrinks radially and extends in height. The actuator and its use as an antagonist are biologically inspired, as the form mimics the transverse or circumferential muscle groups in cephalopod limbs. Unlike existing antagonistic systems, which counter longitudinal actuators with other longitudinal actuators, the proposed circumferential antagonist follows biology, and relies on perpendicular extension from an otherwise contracting actuator.

The circumferential actuators were characterized individually, as a stack around a foam core, and within the arm. Individually, the actuators were capable of extending approximately 40%, but in a stack and in the arm were limited by the foam and longitudinal actuators. As a stack, the circumferential actuators were capable of transmitting forces of 30-40 N. The passive stiffness of the actuators and foam core resulted in 7-10% loss of contraction and a 8-41% loss of curvature. However, the actuators add an ability to extend up to 5%, and increase the arm's ability to resist load up to 240% when inflated to 40 kPa.

The pressure required to operate the proposed actuator is significantly lower than for many existing antagonist systems, which rely on longitudinal actuators that require up to 550 kPa. While the principle of operation is similar, the mechanics of longitudinal systems dictate higher pressures: to avoid buckling, the longitudinal extensors must be large, with thick walls. Higher pressures have practical implications that affect robot mobility; miniaturized pumps typically produce no more than 200 kPa, or perhaps 300 kPa if connected in series. Readily available and inexpensive miniaturized pumps produce less. Higher pressures also challenge the softness and malleability of soft arms. Actuators with thick elastomeric walls inflated to 550 kPa, or 80 psi, are more akin to the tube inside a bicycle tire than to an octopus arm.

Soft arms can excel at flexibility and adaptability in motion and tasks, but often lack the rigidity that allows traditional robots to lift large loads, reach across wide spaces and manipulate objects. Antagonist systems allow for a clear and simple way to bridge this gap, and these systems are readily observed in nature: elephant trunks and octopus arms are capable of the aforementioned tasks, and they do so without a bone structure. The complex interactions of muscle groups within these limbs are what allow this, and the antagonist circumferential actuator presented in this paper is heavily rooted in this idea of varied muscular design. The actuators are shown to improve arm capability, without unduly impeding flexibility.

The next steps in this work are to: (1) further improve integration between the circumferential and longitudinal actuators, and particularly the method of routing air between circumferential actuators; (2) fully characterize the circumferential actuators for a predictive model of the soft arm.

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