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ORIGINAL ARTICLE

Soft Robots and Kangaroo Tails: Modulating Compliance in Continuum Structures Through Mechanical Layer Jamming

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Abstract

We present a new approach to creating biologically inspired, variable compliance continuum robot sections. Variable compliance is used to great effect in natural continuum structures, such as the arms of octopuses and the tails of kangaroos. We introduce a new approach to variable compliance robots based on mechanical layer jamming. The new design actively tightens and loosens mesh coverings of interleaved surface layers. This mechanical approach to layer jamming avoids problems arising from previously proposed pressure (pneumatic)-based layer jamming implementations. Experiments using a prototype of the new design demonstrate the potential of the approach to produce novel soft and compliant robots.

Introduction

The past few years have seen a surge of interest and research in the area of soft robots.[1,2] This activity has been inspired in large part by perceived and observed limitations in the performance of traditional robots,[3,4] whose bodies are constructed with rigid elements and present a mechanically ''stiff'' interface to the surrounding environment. While ideal for providing the precision and repeatability required in predictable factory environments, stiff structures based on rigid elements are poor at adapting to uncertain, congested, and delicate environments. Robots that inherently exhibit soft environmental interfaces, on the other hand, can adapt their shape and behavior to their environment. This makes them better suited to operate in complex and unpredictable environments (e.g., the environments within which most human endeavors occur).

There has been significant recent development of robots whose bodies may contain some rigid elements, but which present an inherently soft, or compliant, interface to the environment. Prominent in this class of robots are continuous backbone, or continuum, robots.[5–7] These robots are often categorized as the ''tongues, trunks, and tentacles'' of the robot world. Continuum robots are typically biologically inspired, often by biological muscular hydrostats (structures that comprised only muscle, fluid, and connective tissue[8]), for example, octopus arms[9–12] and elephant trunks.[13] The bodies of snakes have also served as inspiration.[14] Able to gently adapt and conform their bodies to the physical constraints of their surrounding environment, continuum robots have found a niche in a variety of applications precluding traditional robotics, most notably medical procedures.[15]

In this article, we present a new approach to the mechanical design of compliant variable stiffness section, continuum robots. The new approach, which allows the robot structure to change its environmental interface from soft to stiff and anywhere in between, is more compact and more easily and quickly controllable than previously suggested designs. We implement the resulting robot hardware as a robotic kangaroo tail. This choice is inspired in part by strategies adopted by kangaroos while boxing,[16] in which the animals stiffen their tails to create support when rising off the ground (Fig. 1[16]). We demonstrate the ability of our robot tail hardware to emulate this capability while retaining the capability of alternatively presenting a soft environmental interface.

There has been some previous work in the creation of robotic tail-like appendages.[17] For example, swinging tails to assist robot locomotion have been inspired by the cheetah[18] and the kangaroo.[19] However, all of these efforts have focused on exploiting tail swing to aid locomotion and have included neither environmental contact or variable softness and compliance. Initial research considering the potential of continuum appendages as legs has been conducted.[20] That work established the first demonstration of continuum limbs

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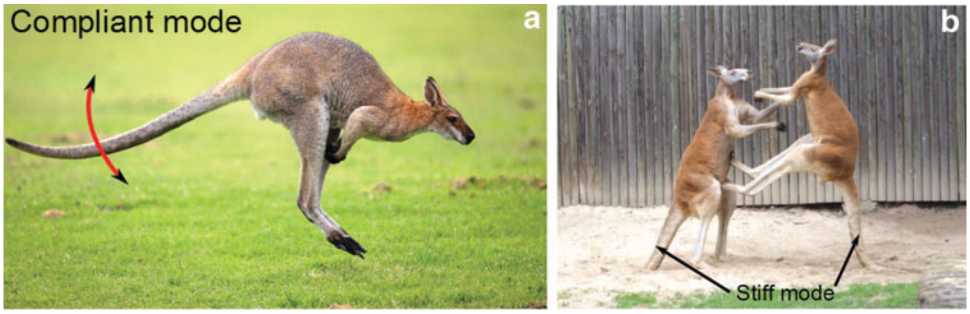

FIG. 1. Stiffness variation of kangaroo tails: **(a)** less stiff compliant tails for legged locomotion. The tail helps to maintain balance by appropriately varying the center of gravity and storing energy for efficient locomotion. **(b)** Stiffening tails for environmental support while boxing. Image credit: Wikipedia. Color images available online at www.liebertpub.com/soro

as legs for quadrupedal robot locomotion, inherently involving active environmental contact. However, actively varying the stiffness of the appendages was not considered.[20] Environmental contact modeling for continuum structures has been conducted.[21] However, the active exploitation of variable stiffness sections in continuum robot environmental interaction has not been considered previously, to the best of the authors' knowledge.

Several continuum robot design approaches to date have explored variable stiffness structures. Early efforts featured variation of pneumatic pressure within the core of a hollow flexible backbone, with tendons used to effect bending.[22–24] However, the range of stiffness achievable proved relatively low. In particular, these structures could not be ''locked'' into an essentially ''rigid'' state. The Shape-Lock[25] and Stiff-Flop[26] strategies each focus on ''rigidizing and derigidizing'' continuum backbone structures. However, these approaches in their originally proposed forms result in essentially ''binary'' states of either stiff or compliant sections, without active continuous regulation of the stiffness in between these states.

A more recent innovation, offering a broader regulation of stiffness, is through layer jamming. The concept was originally proposed by researchers at MIT.[27] In this approach, a continuum section is covered by a series of overlapping layers, all within a sealed pneumatic chamber. The spacing between the layers is controlled by varying the pneumatic pressure within the chamber. At a vacuum, the friction resulting from the high surface contact area of the (now ''jammed'' together) layers causes the section to become quite rigid. However, at higher pressures, the layers can slide over each other and the friction can be modulated, allowing a controllable range of stiffness. This original work has inspired further efforts and variants of the approach, including granular jamming[28–30] and the more recent notion of scale jamming.[31]

In this article, we present a new ''mechanical'' approach to layer jamming, which does not require the use of fluidic actuation. Instead, layers are brought together and loosened by direct mechanical actuation. This design produces comparable stiffening performance with faster control and more compact hardware, removing the need for a pressure source, associated connectors and plumbing, or sealed section chambers. The results in this article build on and extend our initial work in a conference paper,[32] which established the concept of a mechanical approach to layer jamming. This article extends our earlier contribution[32] by the following: (1) introduction of a completely new and more effective method for mechanical layer jamming; (2) demonstration of the effectiveness of the proposed layer jamming approach; and (3) application example of the hardware in environmental interaction modes, through integration in a novel robot kangaroo tail.

The following section introduces our new design concept for mechanical layer jamming, focusing on the development of a hardware prototype of the design. The Results section contains results obtained using the new prototype. Discussion and conclusions are presented in the Discussion section.

Materials and Methods

Layer jamming is based on controlling the friction between specially designed and constructed compressed layers. The resultant structure's stiffness is directly proportional to the amount of friction between the layers and depends on the friction of the particular material the layers are made of and the forces acting normal to the area of overlapping layers. To facilitate the linear and bending deformation during operation, the bounding layered structure has to be of suitable shape. This was originally achieved[27] by creating a double-sided flap pattern that was sewn together with a monofilament wire and compressed together with a latex membrane connected to a pneumatic vacuum source.

When bending, this continuum section[27] was made to assume the low stiffness state (by relaxing the latex membrane around the layer structure in the atmospheric pressure). Then, the tube could be actuated to bend in various orientations. Once the desired spatial shape was reached, the section could

FIG. 2. Core spring backbone element. Springs are inherently compliant and easily available in a range of sizes to choose from and hence provide a suitable choice for the proposed robot's structural support.

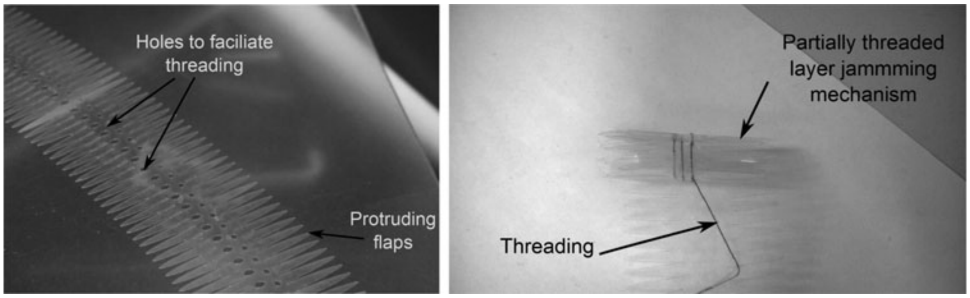

FIG. 3. Scale layers. *Left:* flattened material. *Right:* folding and sewing scales.

be stiffened by inducing a vacuum in the latex membrane, which squeezed the flap structure together because of the pressure difference. The stiffness controllable shape deformation of the section[27] offers much promise, particularly in object manipulation and minimally invasive surgical applications. However, the use of a vacuum source poses problems pertaining to the portability and reliability of the system. In addition, the thin membranes the arm has to rely on to maintain the vacuum can be easily damaged during operation due to the contact with rough edges in the workspace or the layer flap tips. Furthermore, the prototype[27] relied on the linear stiffness of the layer mechanism of the continuum section to return to the original state once the tensile forces of the tendons and vacuum sources are removed. However, the high amount of hysteresis arising from the interlayer friction forces is much larger than the layer stiffness and therefore makes the motion rather slow. This significantly hinders the section's true potential. Therefore, a more compact and less hysteretic design, which can be applied to a variety of other potential applications, is motivated.

The goal of our new layer jamming design was to improve upon the functionality of existing designs by introducing mechanical layer jamming as well as simplifying the actuator package for the robot. Modifying the pneumatic-based layer jamming concept of constriction from internal and external forces to a mechanical design without need for a vacuum is feasible by using a spring backbone. By using a linearly and torsionally deformable but radially stiff object (i.e., a spring) to be contained within the layer jamming structure, the external mechanical constriction applied at the surface could be opposed by the internal backbone. We selected a spring of appropriate stiffness (Fig. 2), which provided a good hard skeleton core onto which the jamming layers could be tightened. Its high linear stiffness was selected to enable fast recovery from deformed to undeformed states, which helps to reduce hysteresis.

To design the flaps, also termed scales herein, we began with the original design concept.[27] We wrapped the strips around the spring and evaluated the extent to which the spring was stiffened when the strips were twisted tighter against the spring backbone. Following numerous iterations, view foil or projector transparencies were identified as an extremely effective material for the flaps. The flaps were laser cut. Figure 3-left shows the resulting cuts.

The flaps were then sewn together (Fig. 3-right) with a needle and fishing line in order for these ''scales'' to cover the whole length of the spring backbone. The result was a light and compact structure that, in its loosened state, allowed both bending and extension of the structure around the enclosed spring backbone (Fig. 4).

Our core innovation of mechanical layer jamming is to mechanically tighten the scales together by use of a sheath that encases the scales. Our initial approach to this[32] was to rotate a tensioning cable that was attached to the sheath so that the sheath tightened and squeezed the layers against the steel spring backbone and stiffened the structure. However, one key issue encountered was this torque transmission cable mechanically restricted bending of the sections, significantly reducing bending, length variation, and stiffness regulation on the plane where the torque cable lies.

Therefore, in this article, a new and unique mechanical solution for stiffening is introduced. The key innovation is in using a mechanically woven mesh sheath (of the type often used for artificial muscle exteriors also known as braided meshes). These mesh sheaths increase and decrease significantly in radius when they are contracted and extended longitudinally respectfully (Fig. 5). Use of the mesh as a sheath provides the means to compress the flaps underneath by compression by mechanically pulling the sheath.

The implementation of the concept was achieved through enveloping the flaps within a braided tubular mesh and then folding each of the ends of the mesh tube (of the maximum

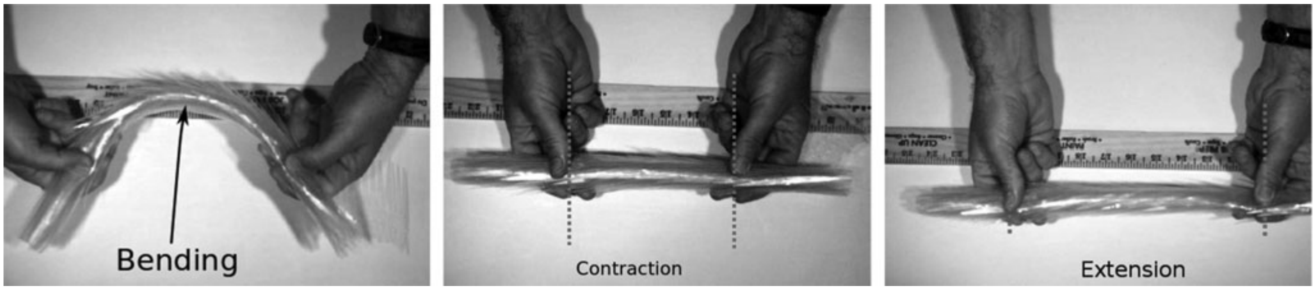

FIG. 4. Bending and extension capability of scales.

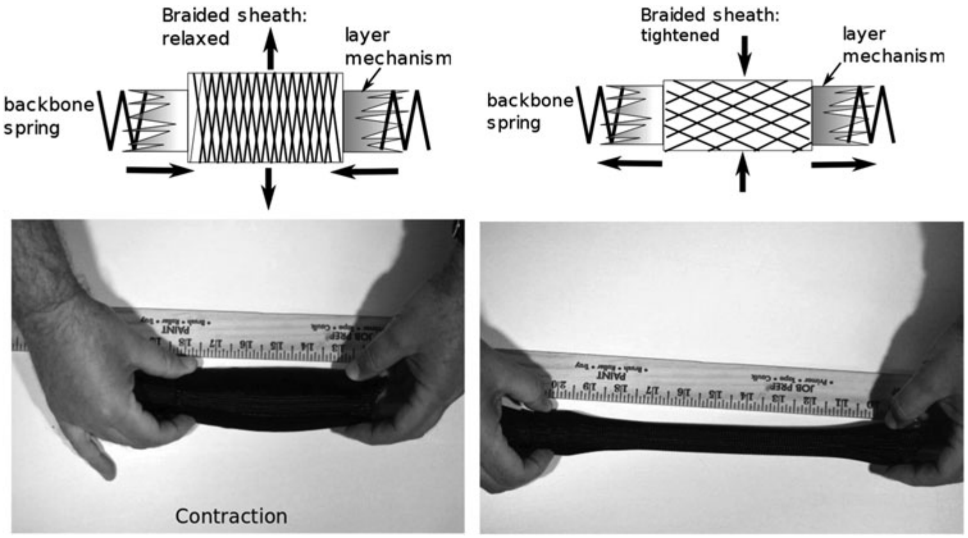

FIG. 5. Braided mesh. *Left:* contracted (large diameter) relaxes the layer jamming mechanism and results in low stiffness. *Right*: extended (small diameter) tightens the layers together and results in high stiffness.

achievable section length) inside themselves and then using an epoxy to preserve the structural integrity at the ends by coating the folded ends inside (Fig. 6). Once the mesh was slid onto the section so that the underside was sufficiently loose to give room for the mesh to expand, the mesh openings were then attached with epoxy to their respective spacer furthest to the end (Fig. 6) with the other end left free to be pulled by a braided steel cable. A metal crimp was then used to secure the braided steel cables to one end of the sheath through the holes in the spacers to their respective motors that were then secured to collars onto the motor shaft. Physical parameters of the resulting prototype are provided in Table 1.

To actuate bending of the two section robot, remotely driven tendons were fed through and terminated at the end of each section. Three tendons, spaces at 120° apart radially, were used, for each of the two sections to generate spatial motion. To guide the tendons and tensioning wires, spacers were created, which could be screwed into the extension spring tightly. The spacer in Figure 7 was designed out of soft ABS polymer, and the resulting two section prototype is shown in Figures 8 and 9. Additional section coupling discs are shown in Figure 8. Our compact actuation package (a laser cut acrylic box in Fig. 9) contains six servo motors to drive the tendons (three for each section), two DC motors for driving tensioning cables to constrict the sheaths of each section, power supply units, and embedded controllers.

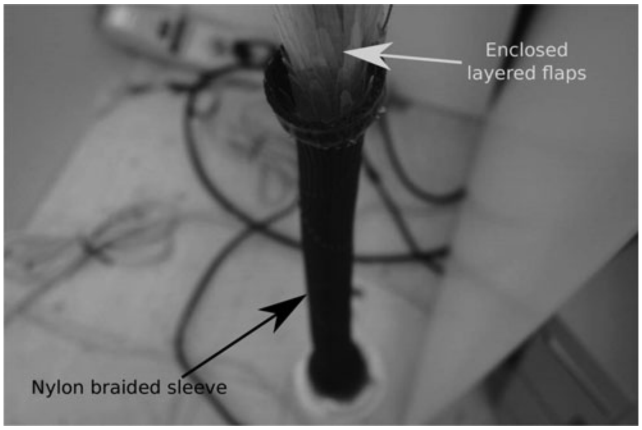

FIG. 6. Braid mesh overlay integrated with scales/spring backbone.

Results

The net result of using the mesh concept versus the original locally torsioned sheath was a significantly more distributed stiffness package, which allowed an increase in overall section stiffness without restricting bending. We encountered initial issues with some flaps getting caught in the holes in the exterior mesh, which impeded the ability of the associated section to unstiffen. However, a simple redesign of the shape of the flaps (to make them wider and their tips rounder and more blunt) eliminated this issue, eliminating the flap/mesh penetration, and allowing the sections to release their stiffness easily.

The effect of layer jamming mechanism on linear and bending stiffness

To quantify the achievable stiffness and their range from stiffened to relaxed, we measured the stiffness parameters during relaxed and stiffened states. The linear stiffness measurement was taken by applying a few known forces at the tip or each section and then taking the strain. The strain values were then plotted against the forces, and a linear curve fit provided the linear stiffness coefficient. The data are listed in Table 2. The origin was also considered as a data point for calculating the stiffness confident through curve fitting. As the proximal section is mechanically identical to the distal section (Table 1), the values derived in Table 2 can be extended to the

Table 1. Details of Prototype Two Section Robot

Item	*Mean diameter (m)*	*Minimum length (m)*	*Maximum length (m)*
Spring core	0.02	0.76	0.86
Proximal section	0.032	0.33	0.36
Distal section	0.032	0.37	0.41

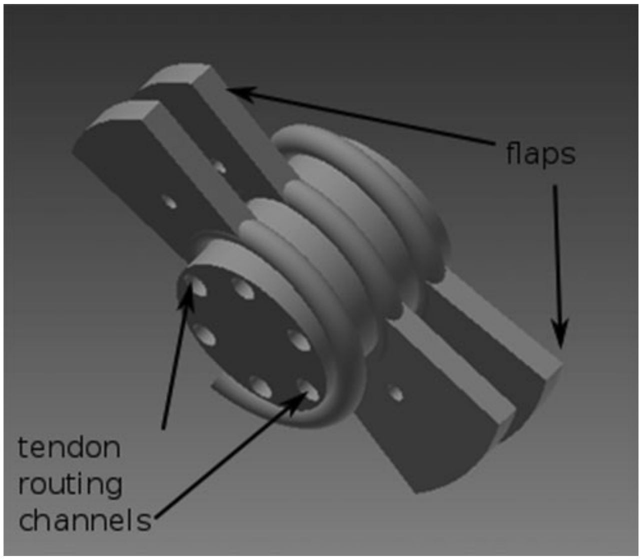

FIG. 7. Spacer element designs. Note threading for connection to spring backbone. Center holes for tendons to bend sections, and outer holes for tendons for tightening/loosening mesh for variable compliance. Once threaded, the spacer discs are secured in place with epoxy and the outer flaps are removed.

proximal section. The results show that the stiffness modulation through layer jamming mechanism can increase the linear stiffness up to 4 times than the value at rest.

For measuring the bending stiffness, known moments were applied at the tip of distal section. Forces were applied normal to the neutral axis of the robot section to ensure pure moments. The bending angles were then plotted against the moments and a linear curve fit provided the bending stiffness coefficient. The values obtained from these experiments are shown in Table 3. Similar to the linear stiffness, bending stiffness was also increased by about 1.5 times. Thus, this mechanism is capable of significantly and continuously modulating both the linear and bending stiffness properties of the robotic arm. This feature can therefore effectively assist in general tendon operated continuum arm manipulation tasks. For instance, the tendon coupling observed in tendon actuated arms could affect the kinematics of the arm to generate undesired shapes that can hinder some applications such as inspection operations in crowded spaces. The reason for this phenomenon is the force/moment propagation between sections. The stiffness modulation present at section level can mitigate these undesired behaviors by effectively eliminating the coupling by stiffening chosen sections.

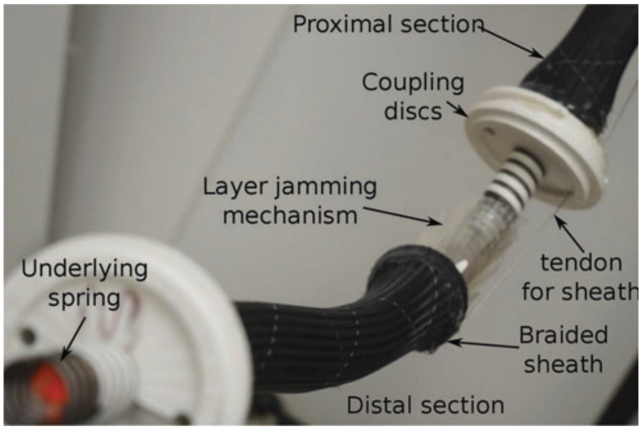

FIG. 8. Two section robot prototype showing overall construction. Color images available online at www.liebertpub.com/soro

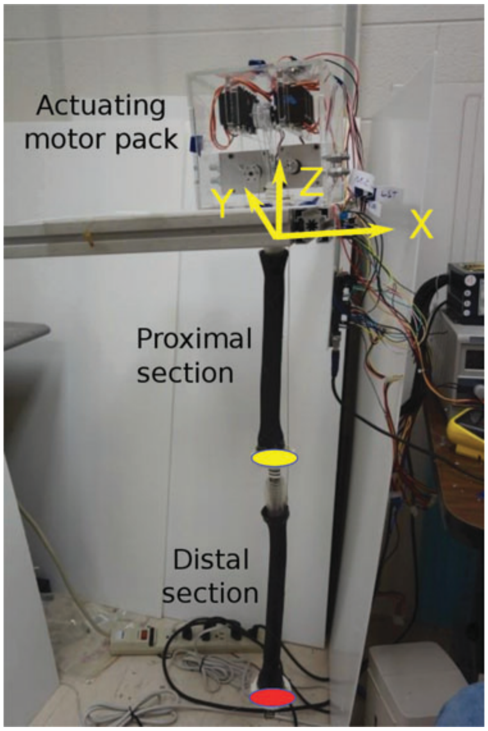

FIG. 9. Two section robot prototype showing actuation package (*top*), section tips (*yellow*—proximal, *red*—distal), and the inertial coordinate frame with respect to which the displacement of the tips are measured. Color images available online at www.liebertpub.com/soro

Experiments on spatial operation

To evaluate the spatial operation of the new design, we conducted a variety of experiments. First, to evaluate the prototype configuration and work spaces, we deployed two

Table 2. Linear Stiffness Coefficient Variation of Distal Section

Force (N)/ strain (m)	*Layer jamming OFF*	*Layer jamming halfway actuated*	*Layer jamming ON*
4.90	0.0065	0.0025	0.001
9.81	0.009	0.0045	0.002
Linear stiffness [N/m]	1023	2071	4095
Stiffness ratio	1	2.02	**4.00**

A fourfold stiffness increase is observed upon actuating the layer jamming mechanism.

Bold highlights improvement of stiffness regulation.

Table 3. Bending Stiffness Coefficient Variation of Distal Section

Layer jamming OFF		*Layer jamming ON*	
Moment (Nm)	*Bending angle (rad)*	*Moment (Nm)*	*Bending angle (rad)*
0.81	0.62	1.17	0.83
1.1	0.97	1.57	1.21
1.3	1.25	1.84	1.43
1.6	1.67	2.01	1.61
Linear stiffness (Nm/rad)	0.756	Linear stiffness (Nm/rad)	1.10
Stiffness ratio	1		**1.46**

It was observed that the bending stiffness of increase around 1.5 times that of the amount at rest when the layer jamming mechanism in operation.

Bold highlights improvement of stiffness regulation.

cameras oriented at 90° with respect to each other, at the same height and same distance away from the origin of the tendril for reconstructing spatial data. MATLAB was used to motion track the tendril at two colored points (yellow and red) marking the distal section endpoints (Fig. 9). Refer to article[33] for a detailed description of the experimental setup and procedure.

The results of one representative experiment are presented in Figures 10 and 11. Figure 10 shows plots of the tracked coordinates with respect to the robot coordinate frame (Fig. 9). In these experiments, the robot was not stiffened and operated at its natural stiffness, mostly governed by the spring stiffness. In this experiment, the distal section of the arm was bent by applying tension to one of the tendons actuating the distal section. This caused the section to bend. Because of the coupling present in tendon actuated systems, the tension caused the proximal section to slightly bend as well as illustrated in the temporal evolution of the tip coordinates. The natural passive compliance caused slight oscillatory behavior that is shown in the coordinate plots indicating very low stiffness.

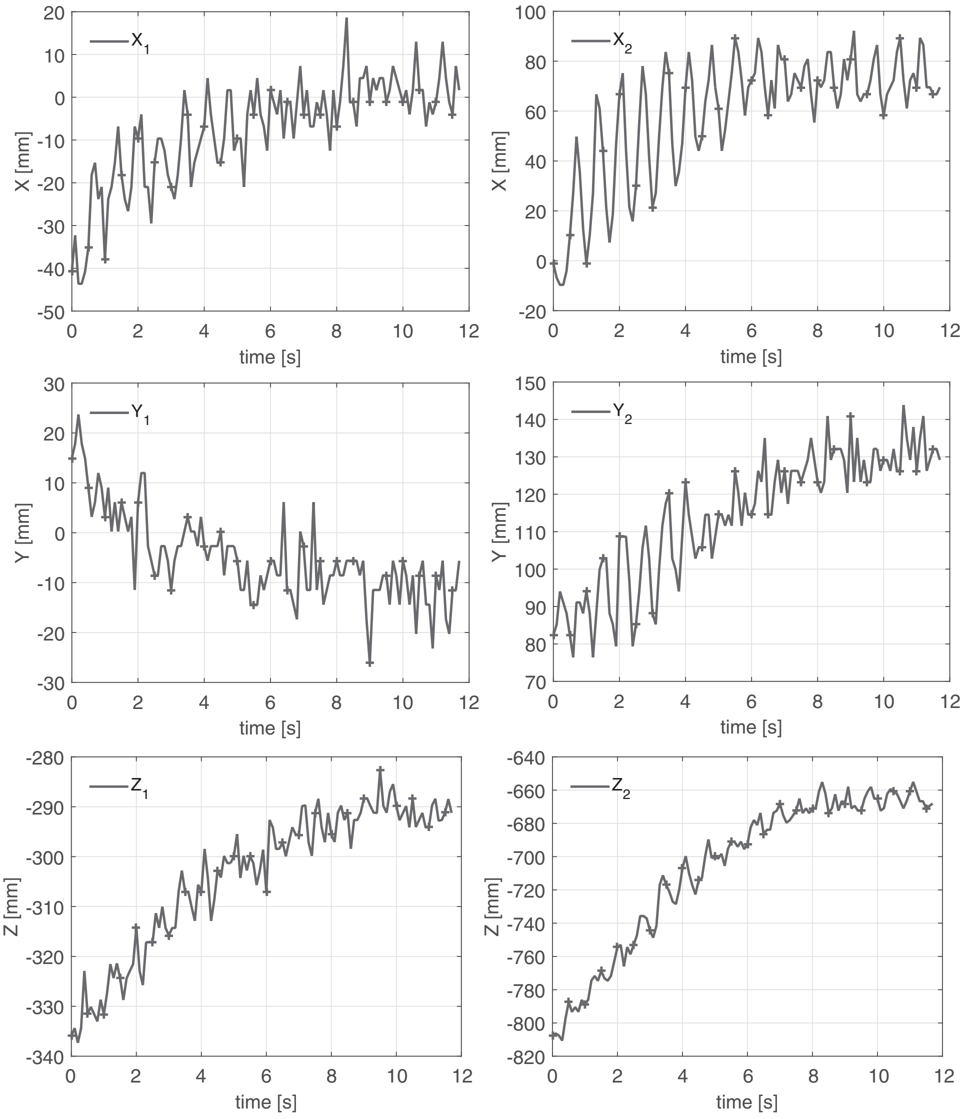

FIG. 10. Experimental data for bending the distal section. The plots show the temporal evolution of the tips (proximal section and distal sections subscripted 1 and 2, respectively) in the robot coordinate frame (Fig. 9). The results show small oscillatory behavior, which is due to the low stiffness of the arm.

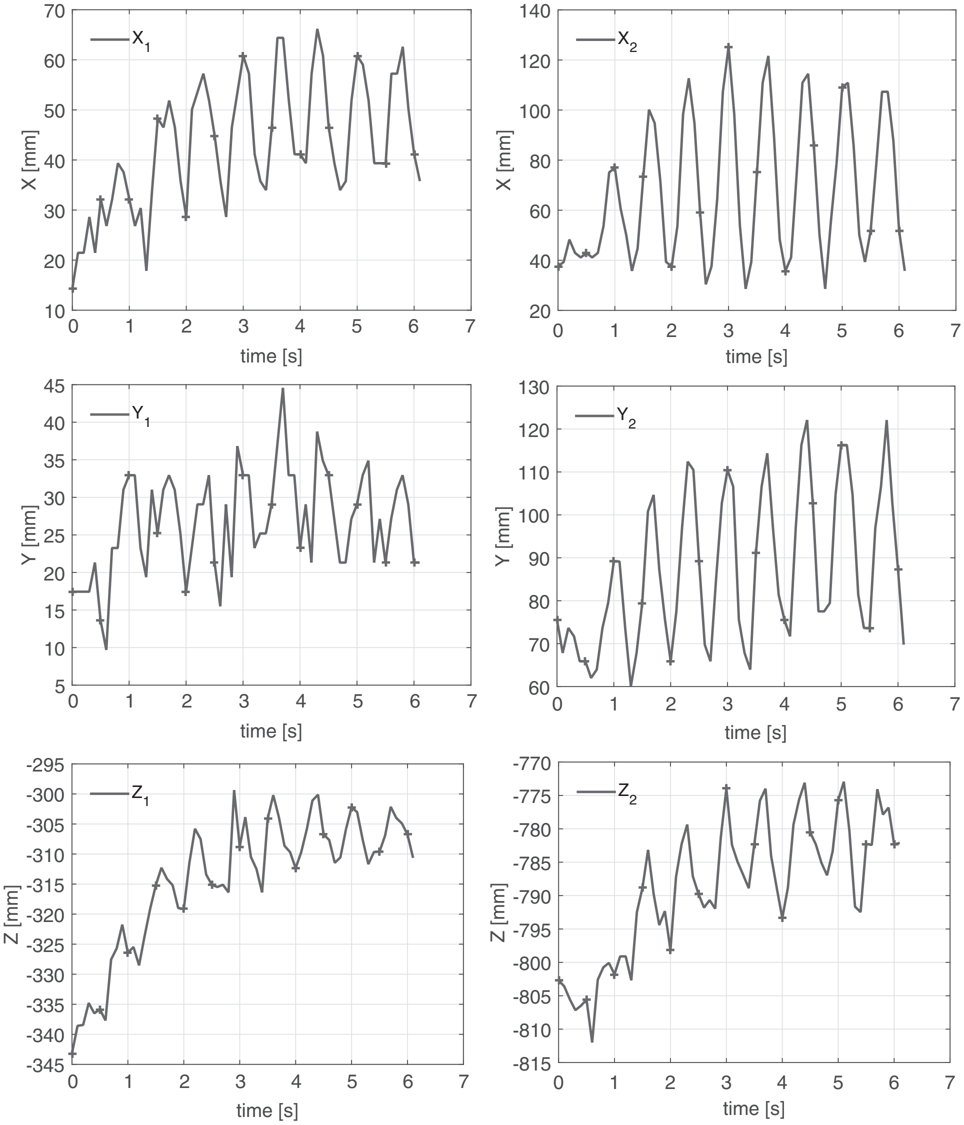

FIG. 11. Experimental data for bending the proximal section. The plots show the temporal evolution of the tips (proximal section and distal sections subscripted 1 and 2, respectively) in the robot coordinate frame (Fig. 9). The results denote high oscillatory behavior due to the low compliance of the entire structure. This results in passive oscillations at the distal end.

Similarly, Figure 10 represents the coordinate value evolution when the proximal section is subjected to bending while the distal section is kept unactuated. As expected, the motion of the proximal section propagated the motion to the distal section, causing it to oscillate significantly. This is analogous to the low stiffness state of a kangaroo tail when it is running. As seen by the plots, the new design (in comparison to the previous realization) showed significantly more deformation without hindering the bending. Note that the robot is capable of significantly more bending, but the motors utilized in the experiments were not capable of providing enough torque to drive it to its limits. A complete set of experimental results, ranging across the robot workspace, is presented in the thesis of the first author.[34]

Robotic kangaroo tail: an application example of stiffness modulation

Finally, to provide an intuitive demonstration of the stiffening capabilities of the design, the robot system was integrated into a stuffed kangaroo toy (Fig. 12b). As noted previously, the (biological) kangaroo tail is an excellent example of successful use of variable stiffness continuum structure in nature. The goal of the experiment was to achieve the ''standing/boxing'' state of Figure 1-right, using a robotic tail that is also capable of being inherently soft.

The two section continuum robot was inserted into the toy kangaroo tail (after removal of the original tail stuffing), with the actuation and control system contained in the body. The power and control signals were provided externally through connected interfacing wires. The demonstration was entirely successful. In the unstiffened state, the kangaroo was unable to support itself (Fig. 13, top) and slowly collapsed on the ground. However, when stiffened, the kangaroo tail provided ample support for the toy animal to successfully stand erect (Fig. 13, bottom).

Note that for this demonstration, we used the assumption, inferred from the skeletal structure of a kangaroo and from images of boxing kangaroos, for example, Figure 1b, that most of the weight is not supported by the distal section. Observing the skeletal structure of a kangaroo in Figure 12a, it can be seen that the tip of the large boned proximal section

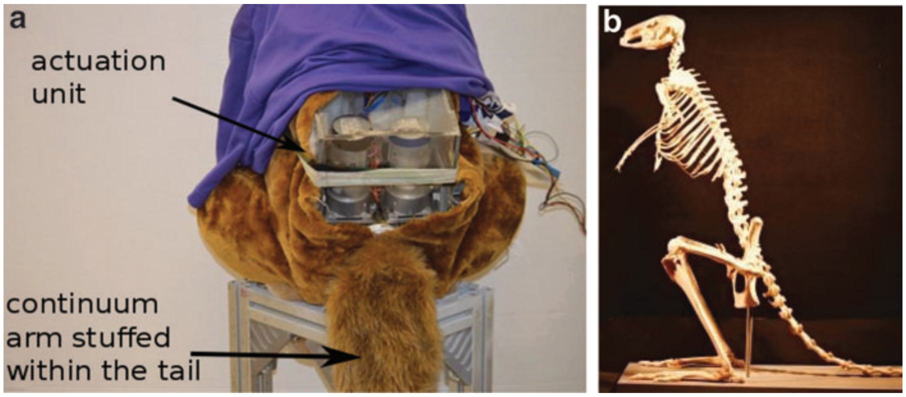

FIG. 12. **(a)** Prototype integrated into toy kangaroo. (Toy back shown opened to illustrate placement.) **(b)** The skeleton of a kangaroo. (Skeleton image credit: www.nhc.ed.ac.uk/index.php?page=24.134.165.255.266). Color images available online at www.liebertpub.com/soro

can be assumed to be where the bulk of supporting forces would occur. Given this, it was important to have enough static friction at that focal point on whichever surface the demonstration would take place, and this was the case in the above demonstration.

The authors further note that if the goal of this robot implementation was to more directly emulate a kangaroo tail, the spring backbone core of the robot should not have been a constant diameter, but instead use a wider diameter spring at the top portion that would taper down into a smaller diameter as indicated by the tailbone/spine of the kangaroo in Figure 12a. In addition, the maximum torque available for each of the six motors bending the sections was equal, which exacerbated the coupling between sections. Ideally, the motors controlling the proximal section should have greater stall and active torques so that actuating the distal section reduced coupling and minimized changes of direction and stiffness of the proximal section.

Discussion

We have introduced a new approach to the design of continuum robot elements, which inherently present soft compliant interfaces to their environments. The new design, through mechanical implementation of layer jamming, enables active control of the compliance, from fully ''soft'' to ''rigid.'' By eliminating the need for fluidic actuation for the jamming, the new design increases the speed of response and reduces the hysteresis, complexity, mass, and volume of the resulting overall system and additionally increases the reliability and portability for field applications.

Experiments were conducted to demonstrate the prototype arm's actuation in varying stiffness settings. Results show that the stiffness regulation mechanism does not hinder the workspace of the robot. Furthermore, the kangaroo tail realization of the new design highlights its ability not only to provide controllable stiffness but also to do so in a compact and reasonably light package. Potential future applications of the design approach introduced here include continuum limbs for legged soft robot locomotion and stiffness controllable surgical tools for minimally invasive surgeries.

In variations of the design, it would be possible to achieve higher friction through greater layer surface area with larger flaps and tighter winding of the flap surface about the spring core. However, increased layer area and tighter wrapping reduce the ability of the sections to bend and extend when relaxed (Fig. 4). In the prototype presented in this article, we empirically arrived at a suitable tradeoff of these factors, wherein high stiffness was achieved, while also allowing smooth extension and bending in the relaxed state. Increased

FIG. 13. Robot functioning as kangaroo tail. *Top:* Kangaroo unable to stand when tail loosened. *Bottom:* Kangaroo stands when tail stiffened. Color images available online at www.liebertpub.com/soro

stiffness, for a given layer geometry, could be achieved by constricting the outer mesh braid tube evenly around its diameter, instead of through a single point contact (the tendon connection). This could be an interesting design modification for future work.

Acknowledgments

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Author Disclosure Statement

No competing financial interests exist.

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