Soft Robotics

Kevin C. Galloway, PhD
Wyss Institute at Harvard University

Advantages of Soft Robotics

The primary interest in soft robotics development is to provide systems that offer functionally not found in traditional rigid-bodied robots. Examples include:

- **Delicate manipulation --** Soft material robots can grip, manipulate and flexibly control objects that are fragile or deformable.
- **Safe Physical Human-Robot Interaction --** Inherently safer for humans to work with.
- **Adaptable Morphology --** Inherently more flexible and can be engineered to change their form in response to the environments.
- **Novel Forms of Movement --** Can be designed to move in novel ways formally unavailable to robotic systems including undulation, oscillation, & peristalsis.
- **Inexpensive Development --** Can be engineered relatively easily and at low cost.

Soft Materials Robotics: Ready For Prime Time?, Robotics Business Review, May 12, 2012.

Some Soft Actuator Prior Art

Sept. 26, 1967

3,343,864
MATERIAL HANDLING APPARATUS
AND THE LIKE
James I. Baer, 1033 Success Ave., Lakeland, Fla. 33803
Filed Oct. 7, 1965, Ser. No. 493,758
9 Claims. (Cl. 294—99)

The principal object of the present invention is the provision of a new and improved material handling apparatus and the like which is capable of gripping an object by an element which curls about the object in response to fluid pressure applied to the interior thereof to embrace the object for transportation or handling thereof.

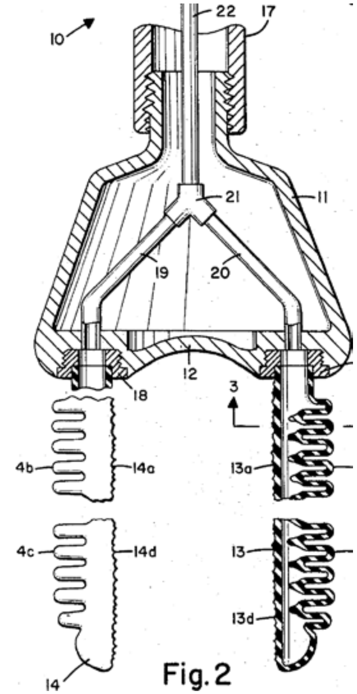


Fig. 2

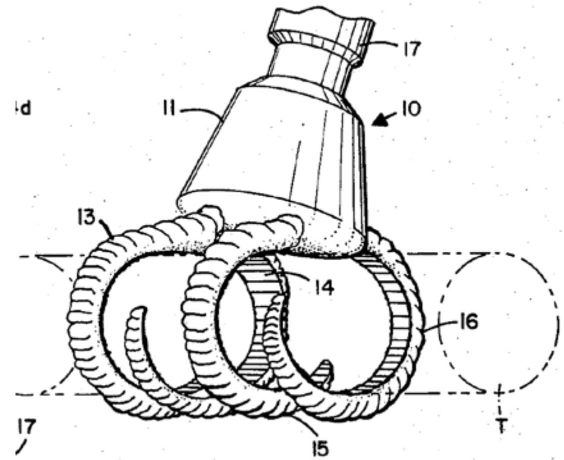
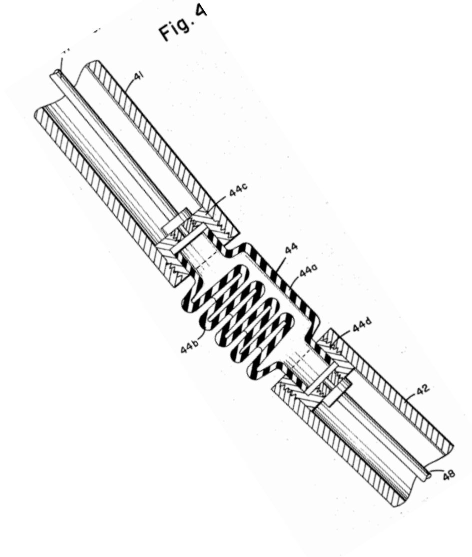
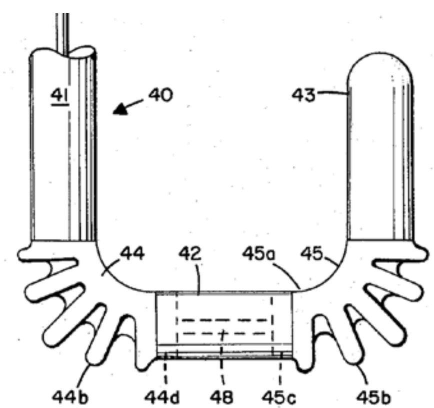


Fig. 4





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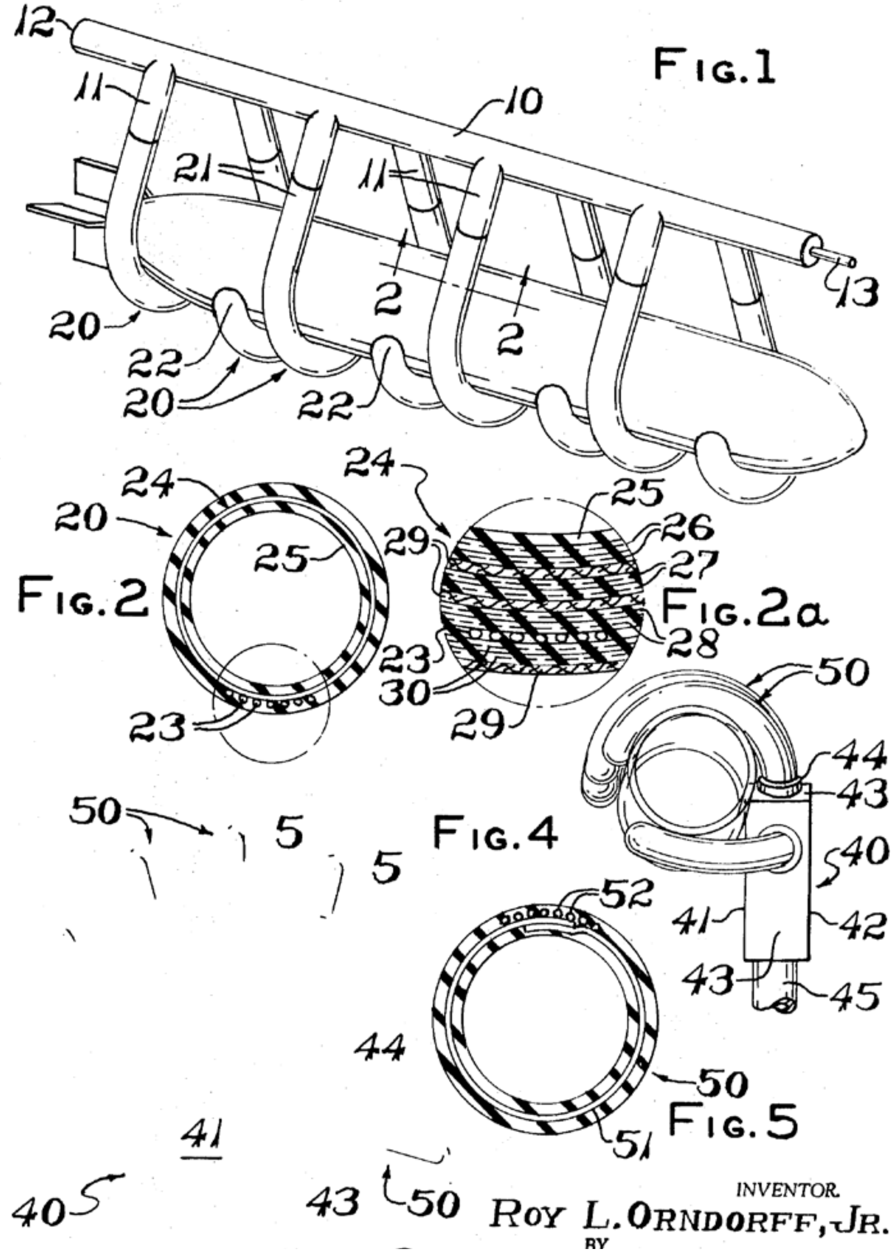
3,601,442

[72]	Inventor	**Roy L. Orndorff, Jr.** **Kent, Ohio**
[21]	Appl. No.	**5,594**
[22]	Filed	**Jan. 26, 1970**
[45]	Patented	**Aug. 24, 1971**
[73]	Assignee	**The B. F. Goodrich Company** **New York, N.Y.**

[54] **GRIPPING DEVICE**
7 Claims, 6 Drawing Figs.

[52] **U.S. Cl.** **294/99,** 3/1.2, 92/91, 92/92
[51] **Int. Cl.** **B25b 11/00,** B66c 1/42
[50] **Field of Search** 294/86.15, 88, 99; 3/1.2; 92/91, 92

ABSTRACT: A gripping device having a plurality of closed end "fingers" of elastic tubing extending from a common pressure manifold, each finger having a portion of the transverse wall section provided with longitudinal cords of tension resistant material embedded therein along only one side of the tubing. In the relaxed state, the fingers are substantially linear, but upon introduction of a pressurized fluid therein, the fingers curl toward a common central region for gripping. Upon release of the pressurized fluid, the elastomeric fingers of the device return to substantially a linear state releasing the grip.



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3,981,528

Sept. 21, 1976

[54] **ROBOT FINGER**

[75] Inventors: **Paul Andorf,** Wettstetten; **Dietmar Franz,** Lampertheim; **Alfred Lieb,** Dossenheim; **Gerd Upper,** Gorsheimertal, all of Germany; **Walter Guttropf,** Winisch, Switzerland

[73] Assignee: **Firma Carl Freudenberg,** Weinheim, Germany

[22] Filed: **May 19, 1975**

[21] Appl. No.: **579,113**

[30] **Foreign Application Priority Data**

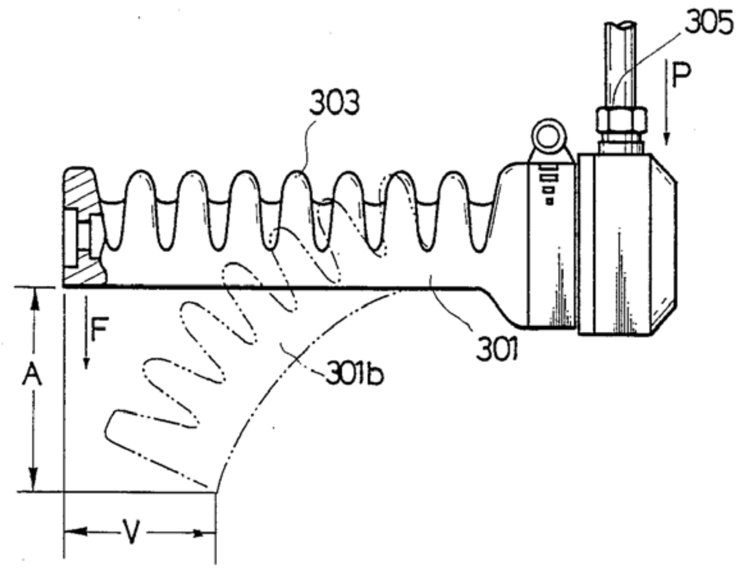
May 30, 1974 Germany.......................... 2426086

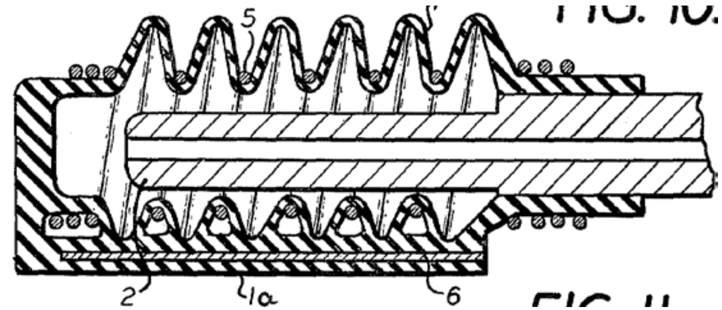
[52] **U.S. Cl.**.................................. **294/99 R;** 3/1.2; 294/86 R

[51] **Int. Cl.²**...................... **B25J 15/00;** B66C 1/46

[58] **Field of Search**................. 294/63 A, 86 R, 88, 294/93, 99 R, 106; 3/1.2, 12, 12.7; 46/126; 214/1 CM

A robot finger comprising a substantially enclosed, hollow elongated body, which body has integral therewith and running lengthwise exteriorly thereof a gripping pad, said hollow body being deformable by fluid pressure in the direction of said gripping pad, said gripping pad being nondeformable in the direction of said body by said fluid pressure, said elongated body having a fluid injection inlet in a wall thereof.





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4,976,191

Dec. 11, 1990

[54] **ELASTICALLY DEFORMABLE FLUID ACTUATOR**

[75] Inventors: **Koichi Suzumori,** Yokohama; **Takafumi Matsumaru,** Tokyo; **Shoichi Iikura,** Yokohama, all of Japan

[73] Assignee: **Kabushiki Kaisha Toshiba,** Kawasaki, Japan

[21] Appl. No.: **422,742**

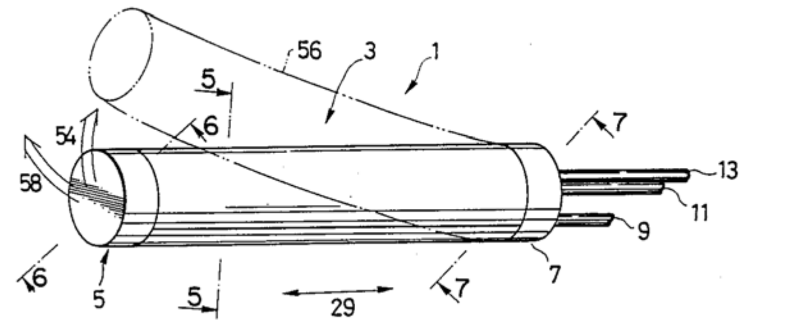
[22] Filed: **Oct. 17, 1989**

[30] **Foreign Application Priority Data**

Oct. 17, 1988 [JP] Japan 63-259391
Oct. 19, 1988 [JP] Japan 63-261314

[51] **Int. Cl.**^{5} **F01B 19/00**
[52] **U.S. Cl.** .... **92/48;** 92/89; 92/103 R
[58] **Field of Search** .... 92/47, 48, 89, 90, 91, 92/92, 103 R

An actuator for use in an arm or hand of an industrial robot comprises a tubular elastic body of which interior is separated into a plurality of pressure chambers by an axially extending partition, and means for adjusting respective pressures of the pressure chambers to render the tubular elastic body to take a motion at a multi-degree freedom. At least the outer peripheral part of the tubular elastic body has an anisotropic characteristic with respect to modulus of elasticity. The axial direction of the tubular elastic body is a direction small in modulus of longitudinal elasticity, while the direction perpendicular to the axial direction of the tubular elastic body is a direction large in modulus of longitudinal elasticity.



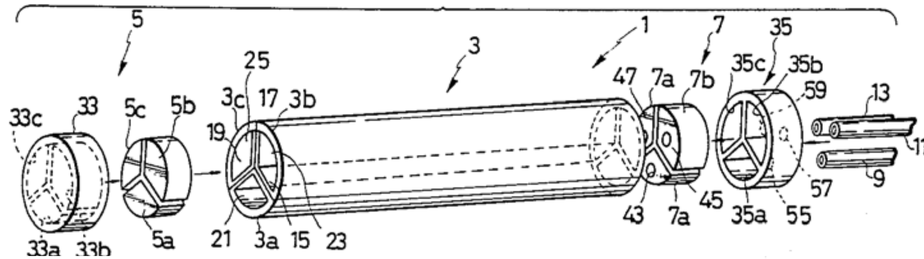


FIG.43 (a)

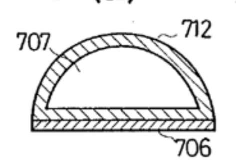


FIG.43 (b)

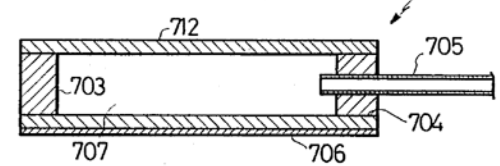


FIG.44 (a)

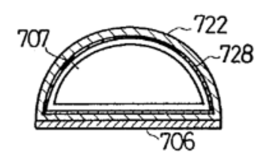


FIG.44 (b)

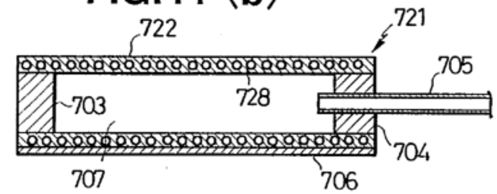


FIG.45 (a)

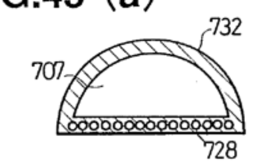
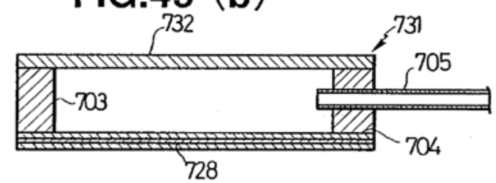


FIG.45 (b)



706 = strain limiting layer 712 = elastic material

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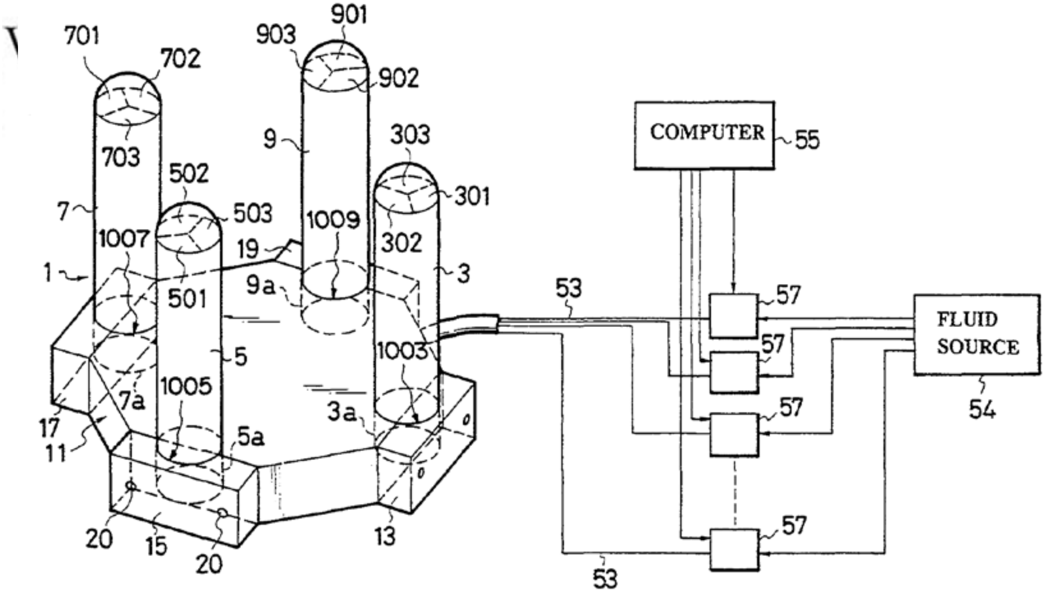
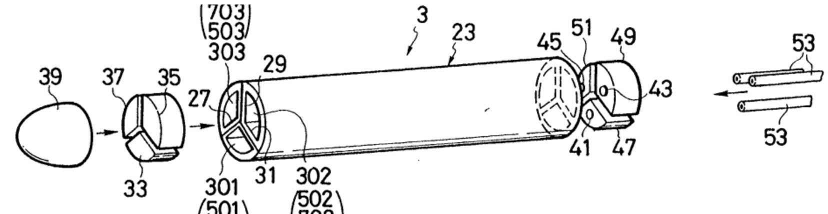
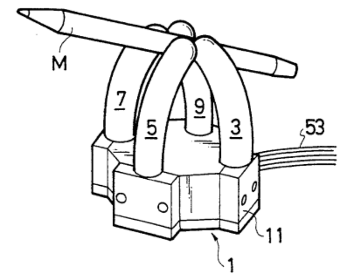
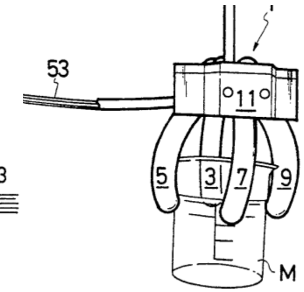








5,385,080

Jan. 31, 1995

[54] **ACTUATOR WITH FLEXIBLE CYLINDERS**

[75] Inventor: **Kohichi Suzumori,** Kanawaga, Japan

[73] Assignee: **Kabushiki Kaisha Toshiba,** Kawasaki, Japan

[21] Appl. No.: **142,122**

[22] Filed: **Oct. 28, 1993**

Related U.S. Application Data

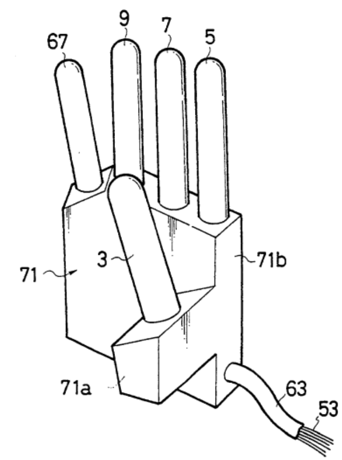
[63] Continuation of Ser. No. 945,267, Sep. 15, 1992, abandoned, which is a continuation of Ser. No. 631,812, Dec. 20, 1990, Pat. No. 5,156,081.

[30] **Foreign Application Priority Data**

Dec. 20, 1989 [JP] Japan 1-328435

[51] **Int. Cl.**[6] **F01B 19/04;** F15B 11/20
[52] **U.S. Cl.** **92/171.1;** 91/525
[58] **Field of Search** 92/48, 61, 64, 89, 90, 92/92, 128, 171.1; 91/521, 525

An actuator comprises a plurality of flexible cylinders arranged adjacent to one another. The inside of each of the flexible cylinder is divided into a plurality of pressure chambers with partition walls that extend axially inside the flexible cylinder. The actuator has a pressure adjuster for adjusting pressures in the respective pressure chambers of the flexible cylinders so that the flexible cylinders may operate at individual degrees of freedom in achieving cooperative motions.



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[11] **Patent Number:** **5,251,538**

[45] **Date of Patent:** **Oct. 12, 1993**

[54] **PREHENSILE APPARATUS**

[75] Inventor: **Christopher M. Smith**, Richland, Wash.

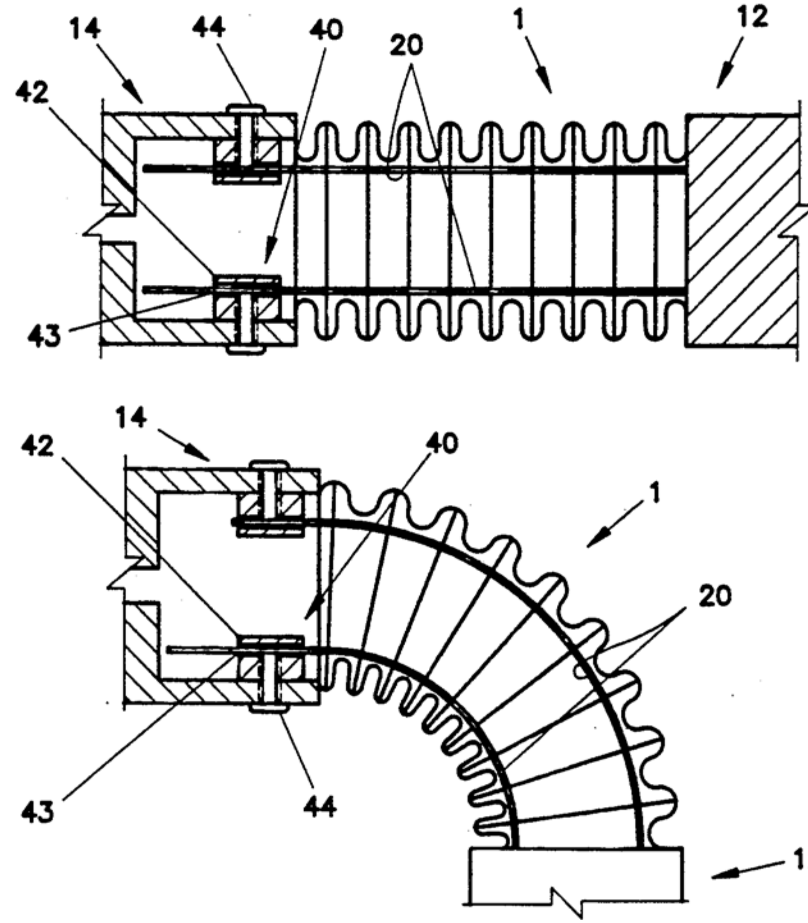
[73] Assignee: **Battelle Memorial Institute**, Richland, Wash.

[21] Appl. No.: **748,989**

[22] Filed: **Aug. 21, 1991**

[51] **Int. Cl.**[5] **F01B 19/00**
[52] **U.S. Cl.** **92/34**; 92/92
[58] **Field of Search** 92/89, 90, 91, 92, 48, 92/34

The present invention relates to an apparatus for handling a workpiece comprising a vessel that is longitudinally extensible and pressurizable, and a nonextensible and laterally flexible member on the vessel. The member constrains one side of the vessel to be nonextensible, causing the vessel to bend in the direction of the nonextensible member when pressurized.



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US 6,484,601 B1

Nov. 26, 2002

(54) **BELLOWS ACTUATION DEVICE, SPECIALLY FOR ROBOTIC MANIPULATOR, AND METHOD TO OPERATE SAID DEVICE**

(76) Inventor: **Vincenzo Arrichiello**, Via S. Antonio 7, La Spezia (IT), I-19121

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/762,172**

(22) PCT Filed: **Aug. 4, 1999**

(86) PCT No.: **PCT/IB99/01544**

§ 371 (c)(1), (2), (4) Date: **Feb. 2, 2001**

(87) PCT Pub. No.: **WO00/07781**

PCT Pub. Date: **Feb. 17, 2000**

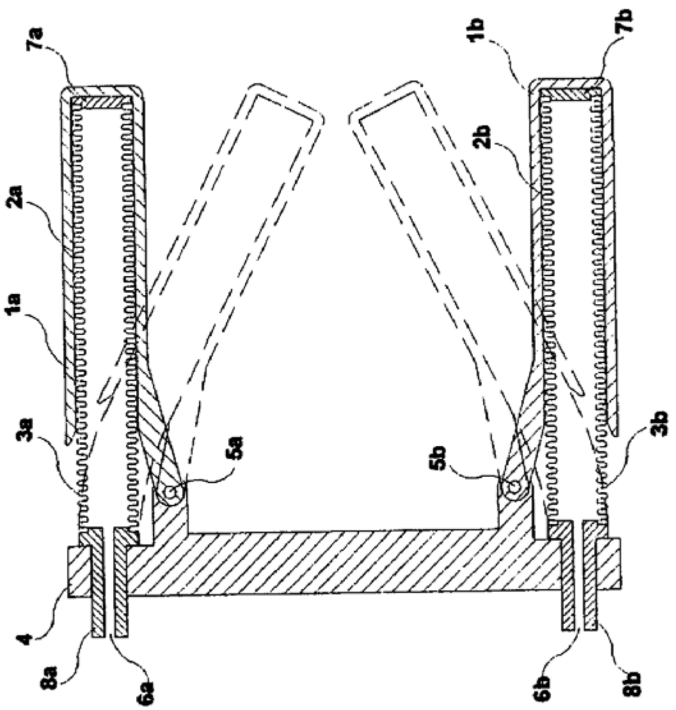
(30) **Foreign Application Priority Data**

Aug. 5, 1998 (IT) JP98A0006

(51) **Int. Cl.**[7] **B25J 15/00**; B25J 9/14; F01B 19/00; F16J 3/04

(52) **U.S. Cl.** **74/490.04**; 92/34; 92/37; 92/44; 294/106; 294/119.3; 414/740

(58) **Field of Search** 74/108, 490.04, 74/17.8; 92/34, 37, 39, 44; 901/22, 37; 414/739, 740; 294/106, 119.3



An actuation device uses, for the active element, a flexible bellows operated by a pressurized fluid (usually, but not necessarily, at a pressure higher than the ambient one). The bellows is housed, for the most part of its length, inside a cylindrical cavity having the inner diameter slightly larger than the outer diameter of the bellows, so that the bellows is free to vary its length, but is restrained to bend sideways and therefore can be operated by high pressure.

Soft Actuators & Applications

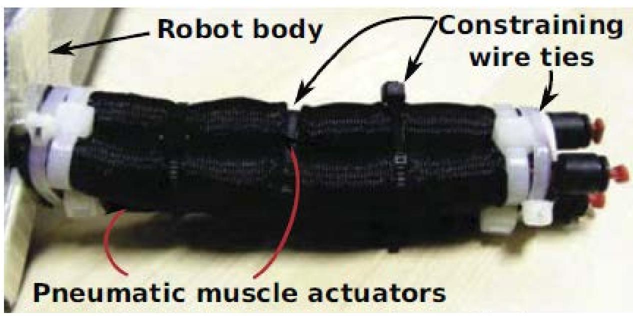
Wyss Institute

2012 IEEE/RSJ International Conference on Intelligent Robots and Systems 2012

Locomotion with Continuum Limbs

Isuru S. Godage, Thrishantha Nanayakkara, and Darwin G. Caldwell

This paper presents the kinematics, dynamics, and experimental results for a novel quadruped robot using continuum limbs. We propose soft continuum limbs as a new paradigm for robotic locomotion in unstructured environments due to their potential to generate a wide array of locomotion behaviors ranging from walking, trotting, crawling, and propelling to whole arm grasping as a means of negotiating difficult obstacles. A straightforward method to derive the kinematics and dynamics for the proposed quadruped has been demonstrated through numerical simulations. Initial experiments on a prototype continuum quadruped demonstrate the ability to stand up from a flat-belly stance, absorb external disturbances such as maintaining stability after dropping from a height and after being perturbed by a collision, and crawling on flat and cluttered environments. Experiment results provide evidence that locomotion with soft continuum limbs are feasible and usable in unstructured environments for variety of applications.



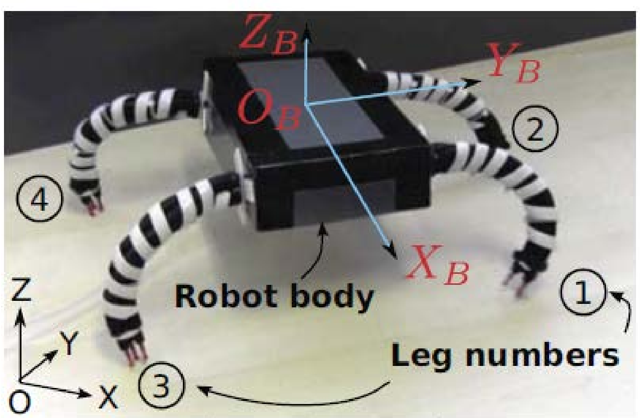
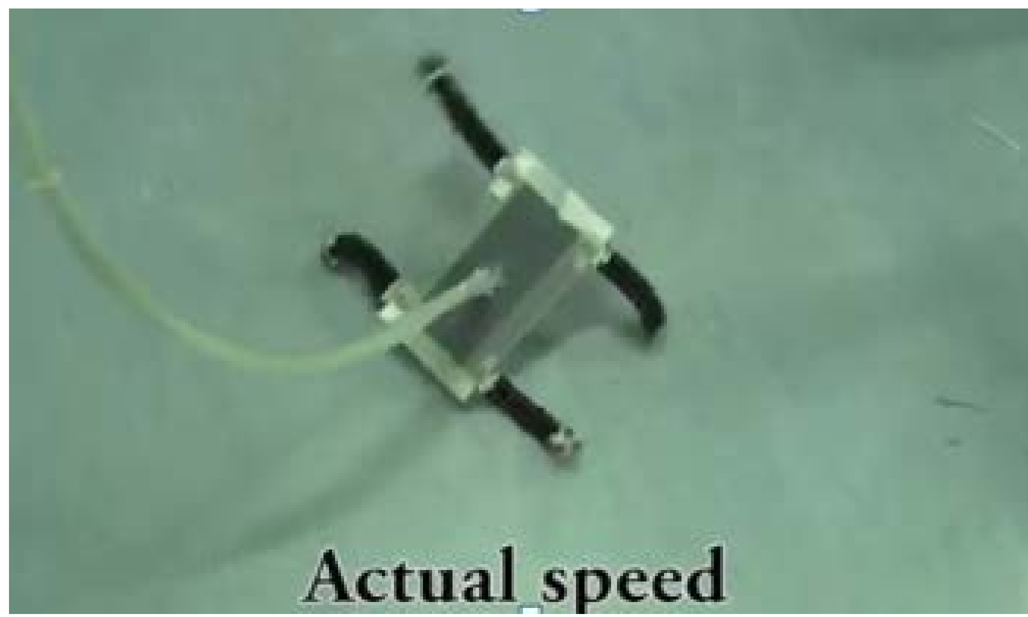


Fig. 3. Prototype robot with floating base representation.



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Enhanced Flexible Fluidic Actuators for Biologically Inspired Lightweight Robots with Inherent Compliance
Gaiser et al., 2010

Abstract—The actuation principle of spider legs has served as an analogue for several technological fields. The current generation of Flexible Fluidic actuators (FFA) follows this principle and pushes their performance to meet industrial requirements. These new actuators are fabricated in a new two step vulcanization process with specially developed rubber compounds. In the first step the inner rubber boot is manufactured. The second step bonds the fiber reinforcement and the metal connectors to the inner rubber boot. The Actuators can carry a statical internal pressure of 20 bars and withstand up to 1.200.000 load cycles at an internal pressure of 6 bars. The new manufacturing process allows applying the biomimetic spider leg approach even for structural robotic links with variable stiffness. In order to exploit the potential of FFAs a compliant mechanism with integrated position sensor was developed. This flexural joint exhibits highly integrated sensors, small weight, and low friction. Over all, actuators and structural links with variable stiffness and inherent compliance as well as light weight composite joints were developed. These components serve as a platform for applications in the field of service robotics, artificial hands, prosthetics, orthotics, and human-robot interaction.

Fig. 11. RFH Fiber Preform

Fig. 12. Molded RFH

Fig. 13. RFH and FFA

Fig. 14. RFH and FFA cross-section

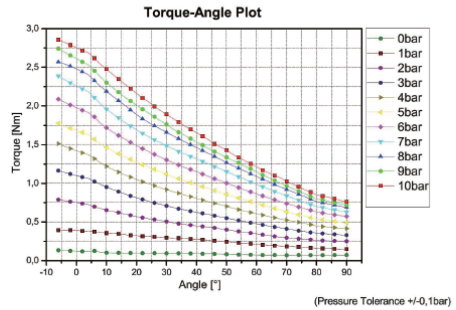


Fig. 22: Torque vs. Angle Plot for different operating pressures for an 18mm actuator

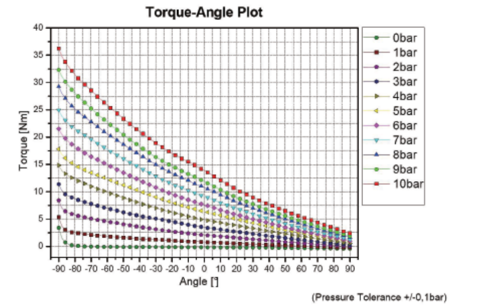
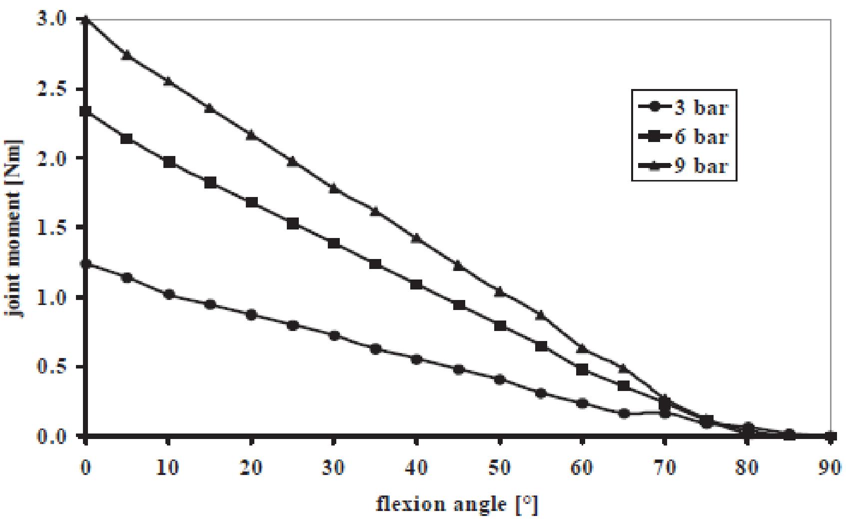


Fig. 23: Torque vs. Angle Plot for different operating pressures for a 35mm actuator

Fig. 25: Fluidic Arm (large picture) and Humanoid Robot ARMAR III with Fluidic Robotic Hands FRH 4/5 (small picture)

Design of a Flexible Fluidic Actuation System for a Hybrid Elbow Orthosis
Pylatiuk et al., 2009

Abstract— In this article the design of a new upper limb rehabilitation system will be presented. A lightweight, modular, and portable system is achieved by the combination of electromyographic (EMG) control, functional electrical stimulation (FES), and the use of miniaturized flexible fluidic actuators (FFA) integrated in an elbow orthosis. First, the state of the art of upper limb rehabilitation devices will be discussed and requirements extracted. Then, the design concept of the new prototype upper limb training system will be presented. Subsequently, a miniaturized fluidically driven actuation system, including its mechatronical components, will be highlighted



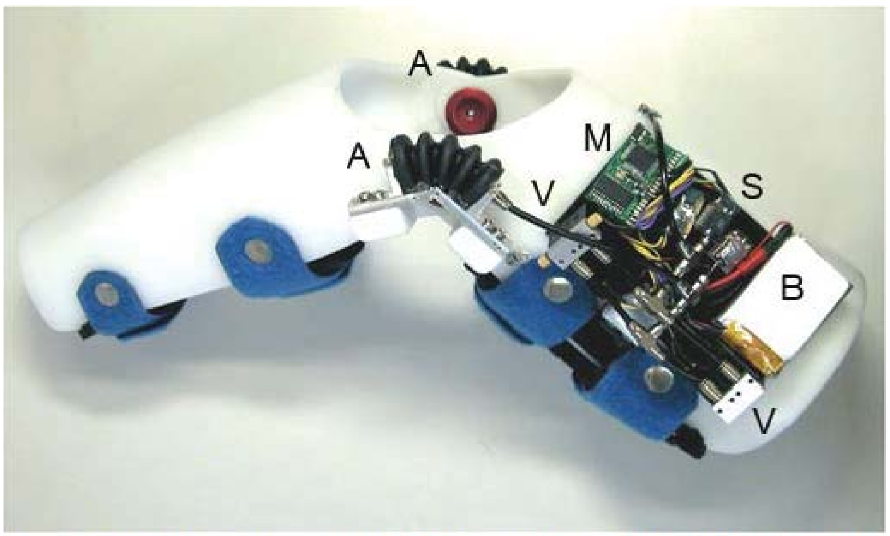
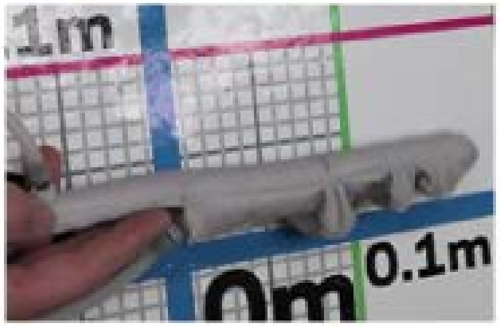


Fig. 2. Components of a fluidically driven elbow training system prototype. A= flexible actuator, M=microcontroller and drivers, V=valves, B=Battery, S= pressure sensors.

Hydraulic operation of the training system allows for designing an autonomous wearable system, whereas a pneumatic system should be given preference for patients that permanently use a wheelchair, as the heavy pressure supply can be mounted to it. However, the inherent compliance of pneumatic actuators has to be considered when designing the control.

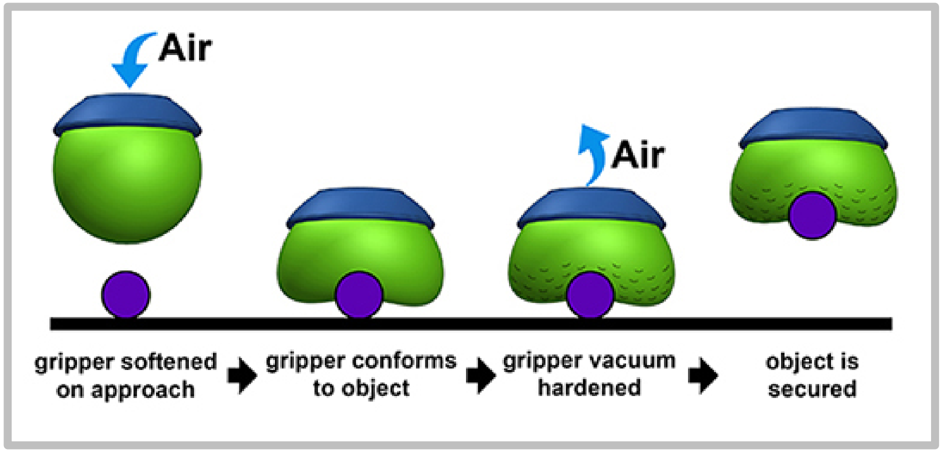
Wyss Institute

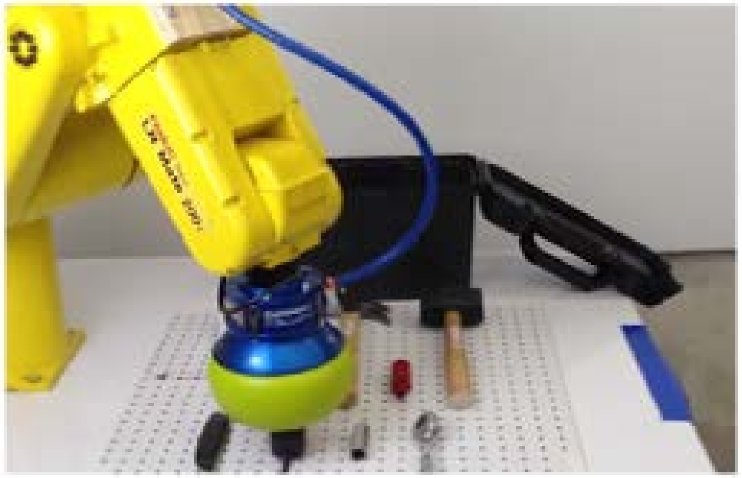
OtherLab



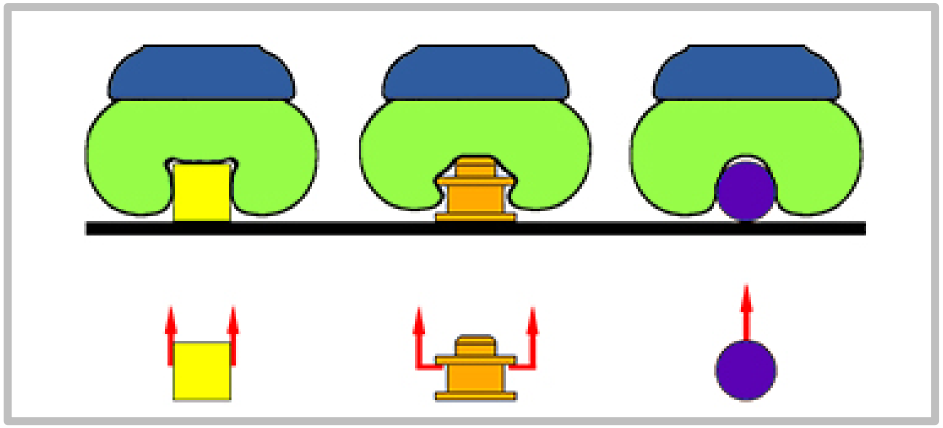
Empire Robotics

How it works





Gripping Forces



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SOFT ROBOTICS

Adaptive Gripping Platforms

Introducing the adaptive gripping platform by Soft Robotics Inc. A set of highly modular and interchangeable graspers able to tackle a wide variety of objects. This platform is able to handle tasks ranging from the incredibly delicate manipulation of a mushroom or pastry liner to unstructured environments where objects may be wet, submerged, sharp, cluttered, or occluded by nearby obstacles. Overall, Soft Robotics is a highly scalable platform that offers light weight, unprecedented safety, and extremely low cost.

Introducing a large scale soft robotic manipulator from Soft Robotics Inc. capable of diverse tasks ranging from the handling of fragile items to large and unwieldy targets. Soft robotics is a highly scalable platform that offers light weight, unprecedented safety, and extremely low cost.

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Soft Robotics Online Resource

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HARVARD School of Engineering and Applied Sciences

soft robotics toolkit

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http://softroboticstoolkit.com/

soft robotics toolkit

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What is soft robotics?

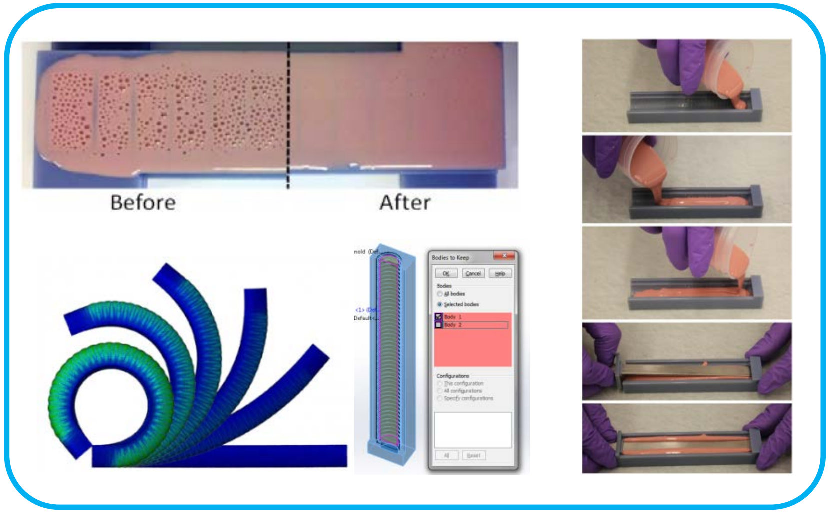
Soft robotics is a growing field that takes inspiration from biological systems to combine classical principles of robot design with the study of soft, flexible materials. Many animals and plants are composed primarily of soft, elastic structures which are capable of complex movement as well as adaptation to their environment. These natural systems have inspired the development of soft robotic systems, in which the careful design of component geometry allows complex motions to be "pre-programmed" into flexible and elastomeric materials. The use of compliant materials to embed intelligence in the mechanics of the body enables designers to simplify the more complex mechanisms and software control systems used in traditional, rigid robotics. The inherent compliance of soft robots makes them highly adaptable to a wide range of tasks and environments. In particular, they are ideally suited for interactions with humans, from assisting with daily activities to performing minimally invasive surgery.

HARVARD School of Engineering and Applied Sciences

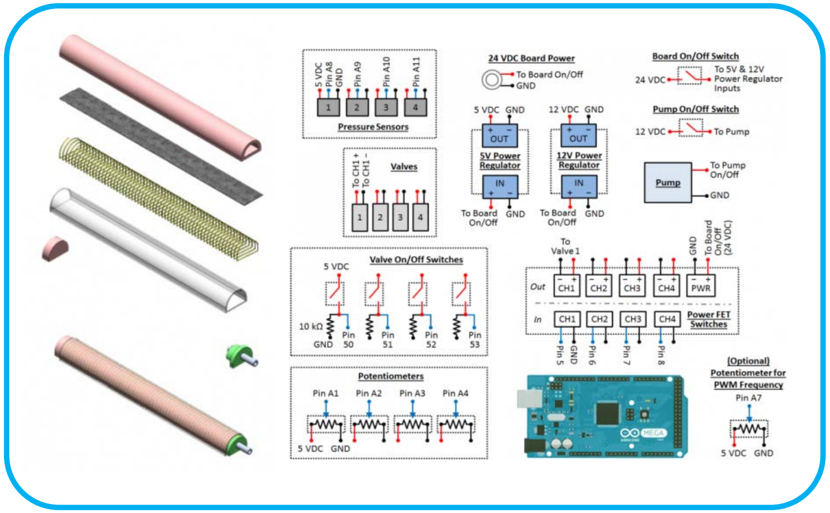
soft robotics toolkit

WYSS INSTITUTE

Open-access intellectual toolkit to support hands-on engineering design education



Multimedia tutorials covering design, fabrication, and analysis of soft robotic components



Case studies, CAD files, schematics , source code, and bills of materials

Aimed at high school, undergraduate, and graduate students.

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soft robotics toolkit

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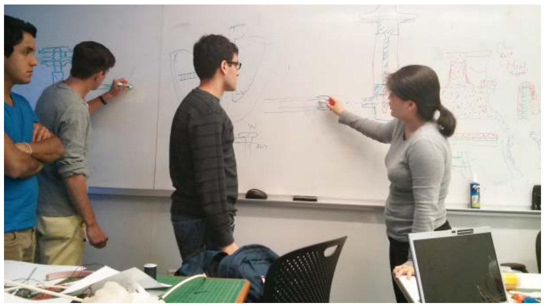
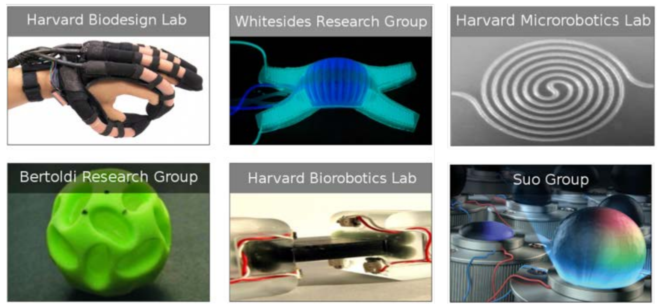
Background:

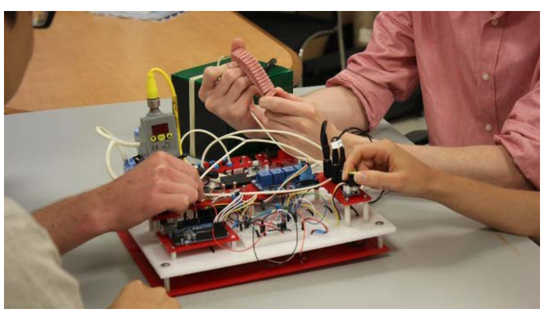


Developed as part of a PhD project on pedagogical needs of engineering students



Content draws on material from 6 research labs (and growing)

Tested with non-engineering students to ensure content is appropriate for novices



Used by 2 cohorts of students in a medical device design course at Harvard

Used by students in a medical device summer program in India

AMERICAN SOCIETY FOR ENGINEERING EDUCATION ASEE

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Research published in leading journals and conferences

Pneumatic Networks (PneuNets)

Soft actuator using pressurized fluid

- Typically constructed from a combination of elastomeric (i.e. rubber) and inextensible, flexible (i.e. woven and non-woven) materials.

- Upon pressurization (pneumatic or hydraulic), channels or chambers expand in directions with the lowest stiffness and give rise to linear, bending, and twisting motions.

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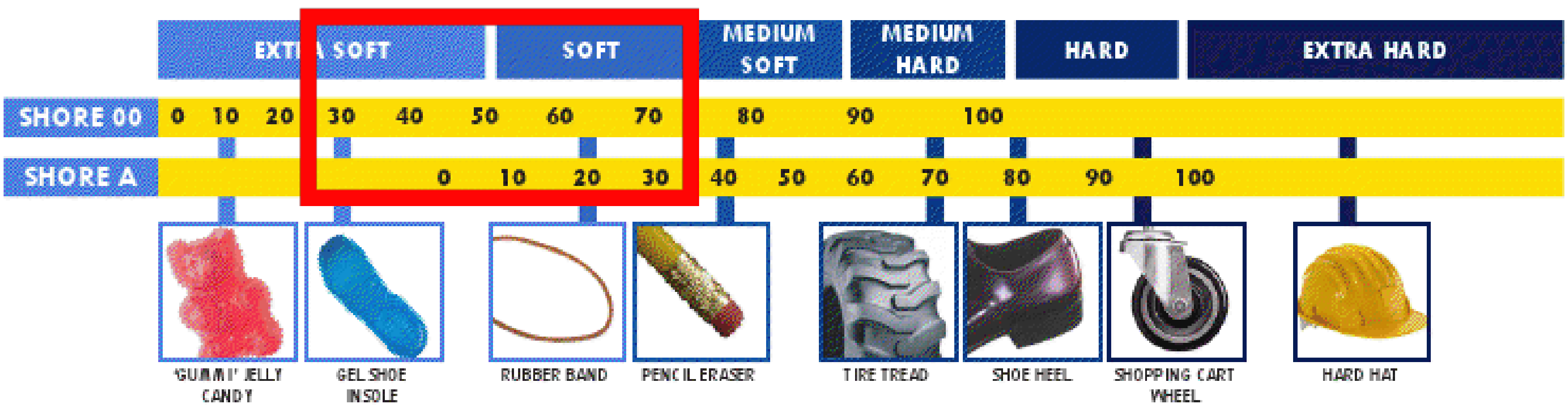
Materials Selection

Material	Shore Hardness	Elongation % at Break	Tear Strength (pli)
Ecoflex 003	00-30	900%	38
Ecoflex 5	5A	1000%	75
Dragon Skin 10	10A	1000%	102
Dragon Skin 20	20A	620%	120
Dragon Skin 30	30A	364%	108
Elastosil M4601	28A	700%	>171



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The Material Trade-off

- *The pressure requirement to achieve a particular amplitude of actuation scales with the stiffness of the material.*
- That is…
  - Soft materials will respond (i.e. bend, extend, contract) with low pressure (~<10 psi); however, the output and load capacity will be low.
  - Stiffer materials require higher pressures (~10-80 psi) to achieve similar amplitude of actuation to soft materials and can deliver more output force and support larger loads; however, must be careful not to exceed the material's strain limits.

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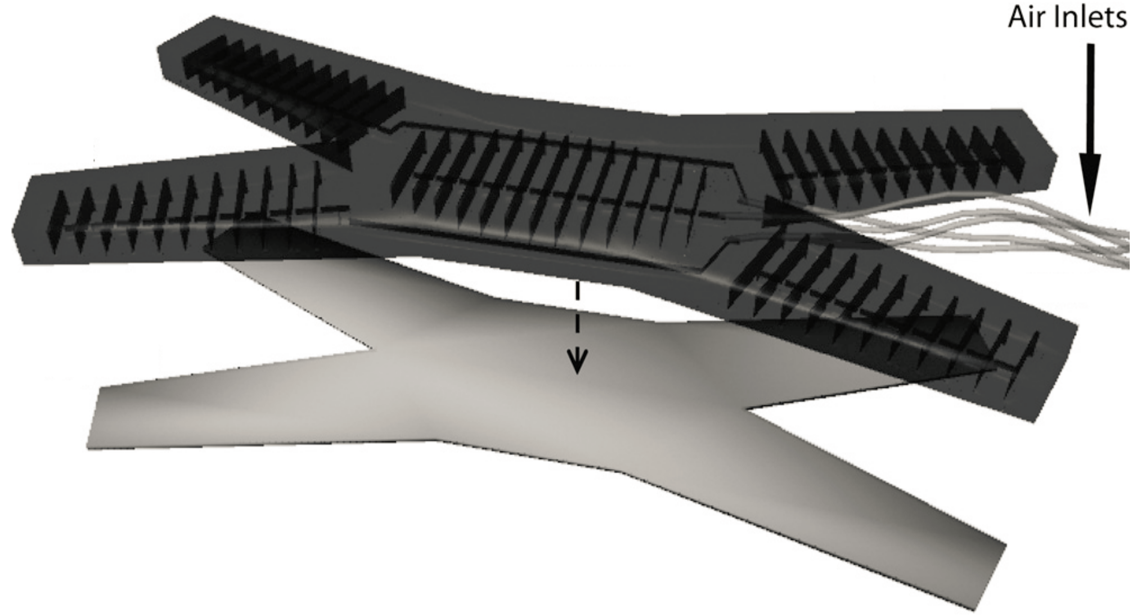
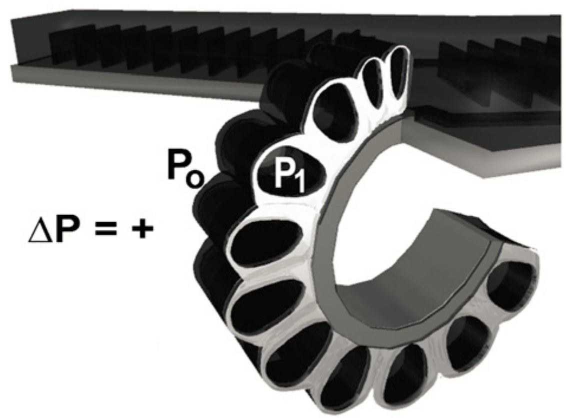
PneuNets

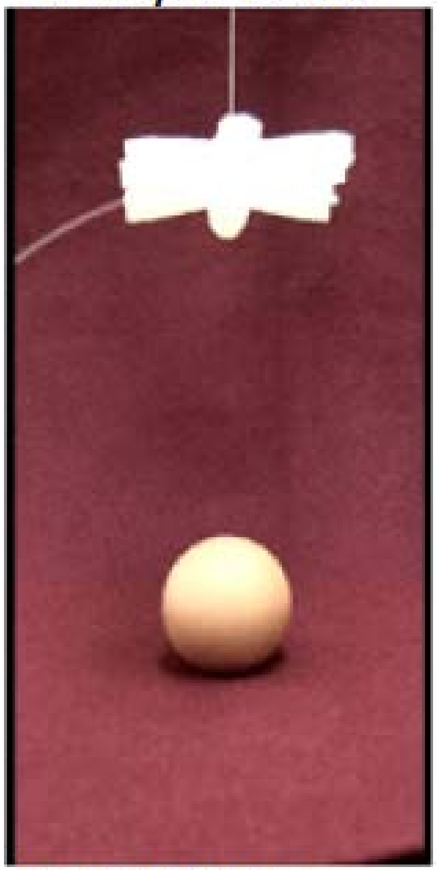
- Compressed air inflates pneumatic network of air channels.
- Differential strain induces curvature
- Material stiffness and thickness affect bending
- Complex motion requires only a single source of pressure.





PneuNet Examples

Manipulation



*Ilievski et al. (2010)

Locomotion

1.5X playback

*Shepherd et al. (2011) *PNAS*

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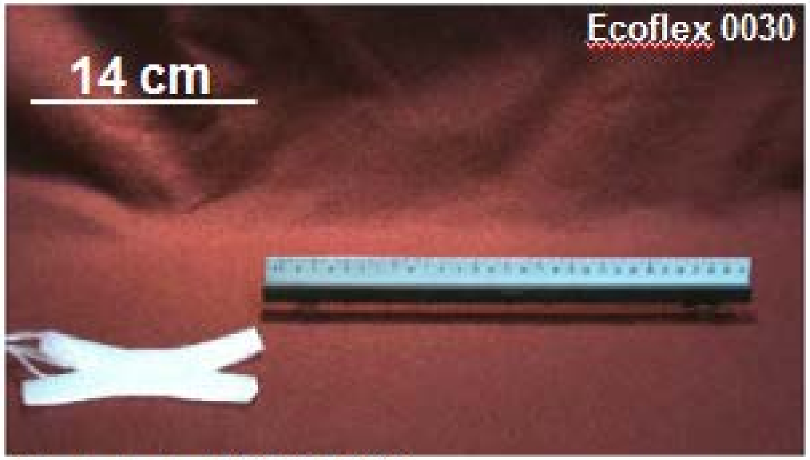
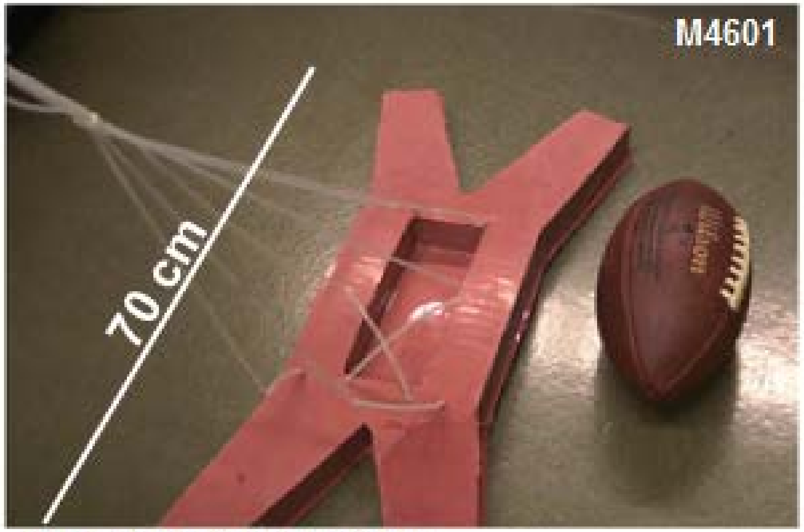
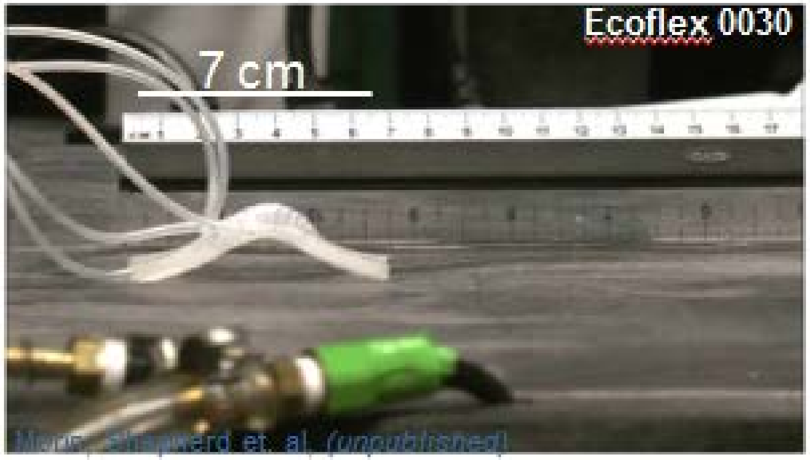
Scalability



Shepherd et. al, *PNAS* (2011)



Shepherd et. al, *(unpublished)*



- **10x increase in size w/predictable actuation responses.**
- **Materials selection varies with size: tougher materials for larger robots**

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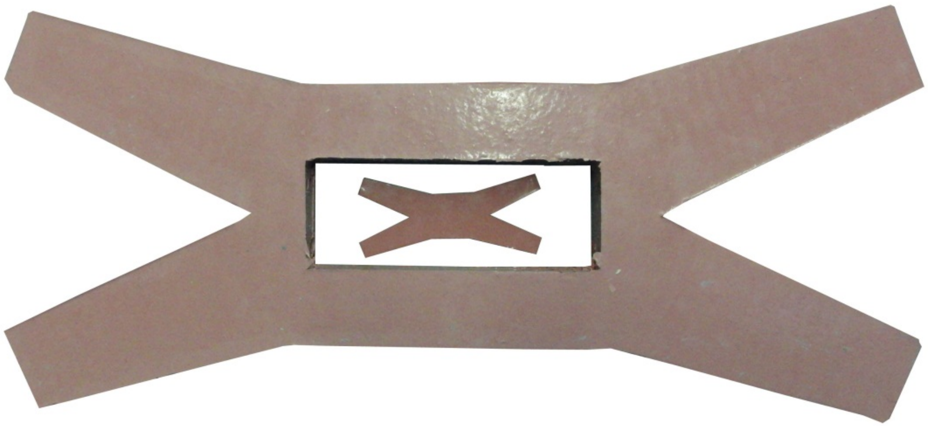
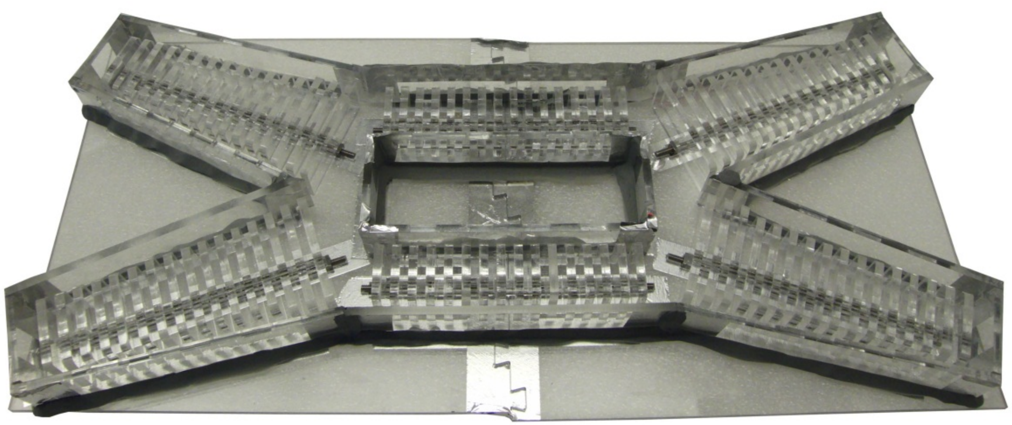
Laser Cut Mold

65 cm





Robot Body Weight: 3.5 kg (7.7 lbs)

- Scalable molding technique
- Entire mold can be disassembled to facilitate demolding.
- Laser cut features enable rapid iteration of internal and external molded features.
- Reusable and less expensive alternative to 3D printing or CNC machining.

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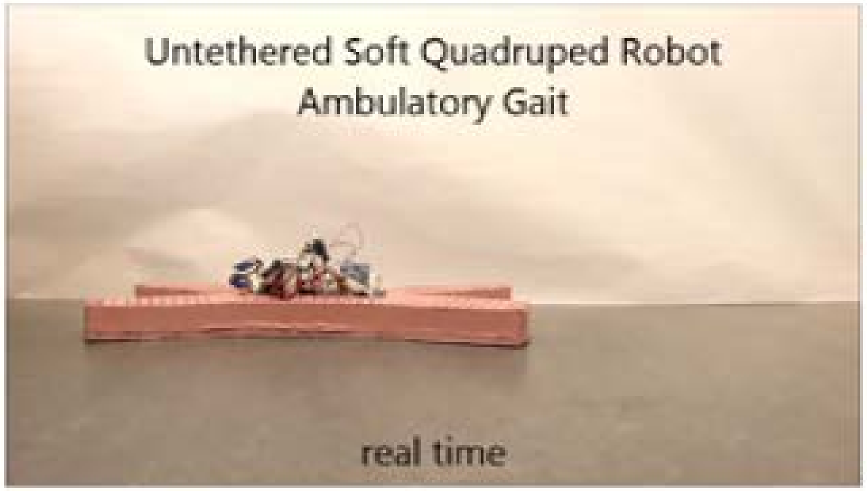
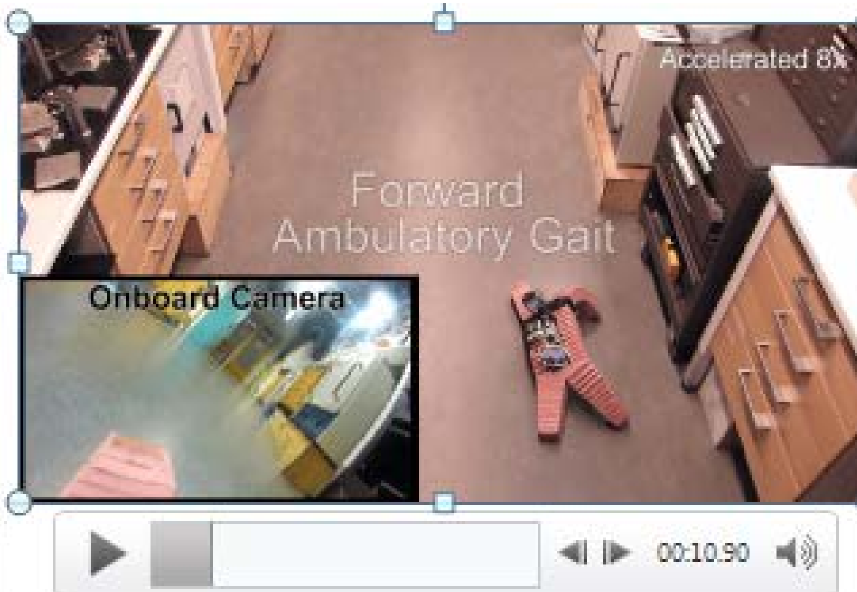
Soft Quadruped





M. Tolley, R.F. Shepherd, B. Mosadegh, K.C. Galloway, M. Wehner, M. Karpelson, R.J. Wood, and G.M. Whitesides, "A Resilient, Untethered Soft Robot," SOFT ROBOTICS Volume 1, No. 3, 2014.

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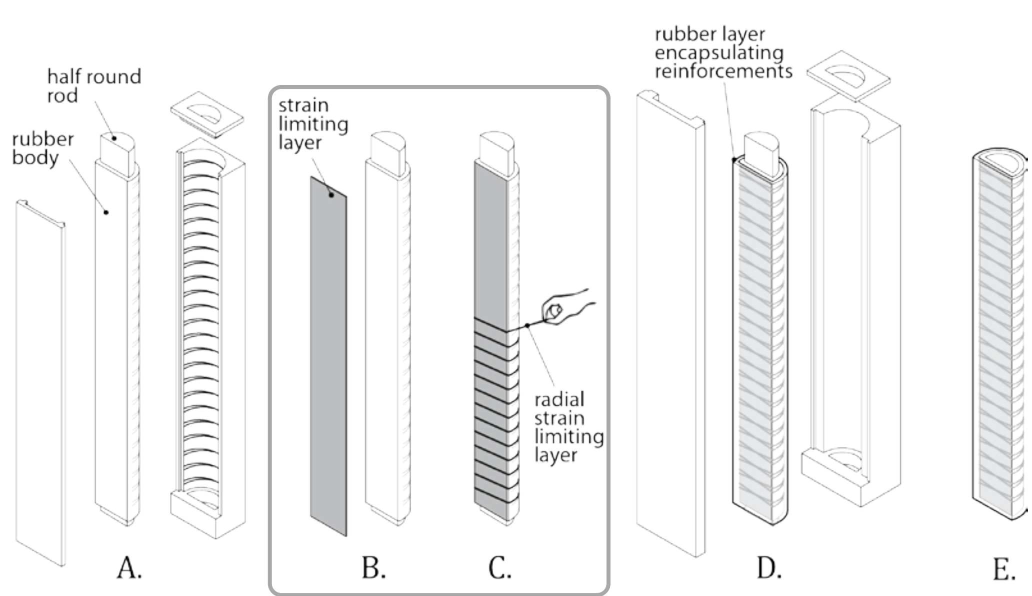
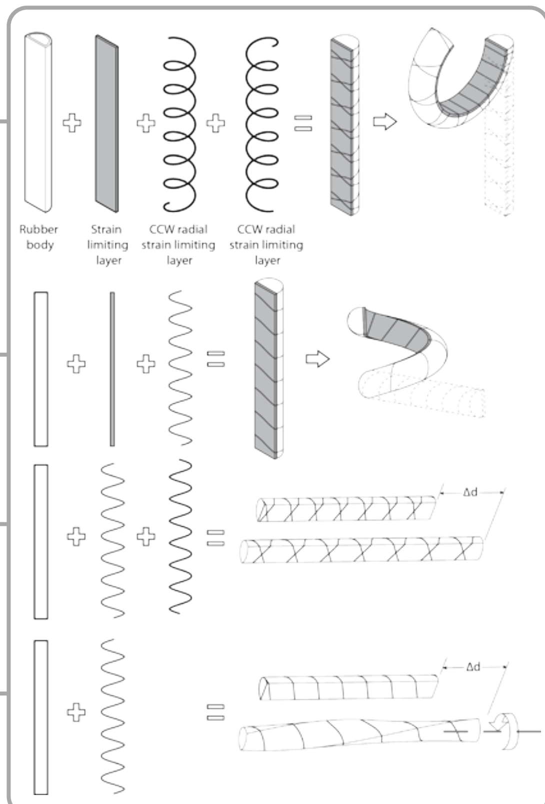
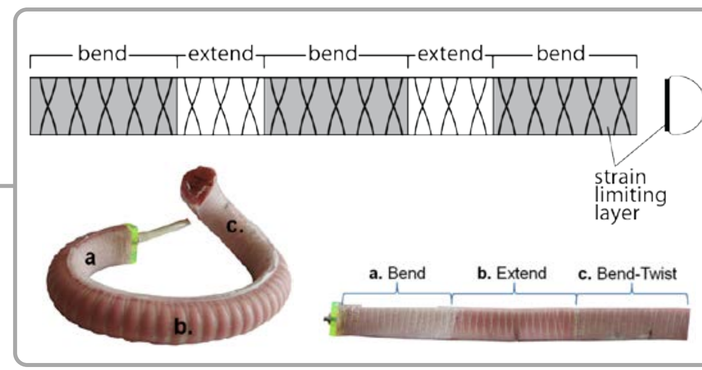
Fiber Reinforced Soft Actuators





Multi-segment FR



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One way to make a fiber reinforced soft actuator

Refer to http://softroboticstoolkit.com/ for the fabrication steps.

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Polymer Mixing Trick: Silicone Thinner

A non-reactive silicone fluid that will lower the mixed viscosity.

Advantages:

- A lower mixed viscosity (A+B) means that the rubber will de-air faster when vacuuming.
- Mixed rubber (A+B) will flow better over intricate model detail.
- Will lower the ultimate shore hardness (durometer) of cured silicone rubber.
- Pot life (working time) is increased in proportion to the amount of Silicone Thinner used.

Disadvantages:

- Ultimate tear and tensile strength are reduced in proportion to the amount of silicone thinner added.

Value	Mold Max 30 0% silicone thinner	Material Property Changes	Mold Max 30 10% silicone thinner
Mixed Viscosity	25,000 cps	45% ↓	13800 cps
Shore Hardness	30A	23% ↓	23A
Tensile Strength	400 psi	18% ↓	330 psi
Tear Strength	130 pli	15% ↓	110 pli

Max. recommended amount of silicone thinner is 10% of mixed (A+B) weight .

Notes on 3D printed molds

- **If you bake your part in the oven be careful not to apply significant forces to the outside of the mold.** For example, a clamp – even a small one – can locally deform the mold.
- **If you are not certain about tolerances for mating faces, don't add any.** You can use either a razor blade to scrape off tiny layers from the mold or an abrasive surface (i.e. file or sand paper) to get the needed fit. Its easier to subtract material than to add it.
- **If you break a part on your mold, try using Loctite to repair it**. The goal is to get as many uses out of a mold as you can so that you can test out different ideas, record these findings, and include these insights in the next mold.

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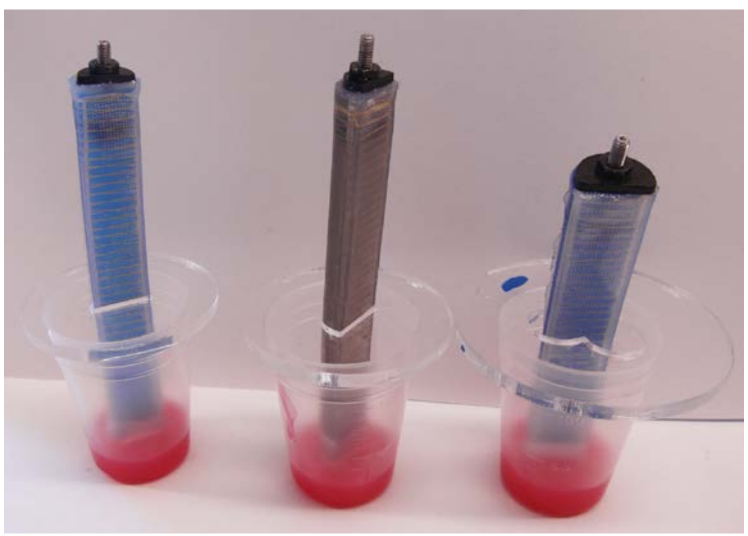
Capping Actuator Ends



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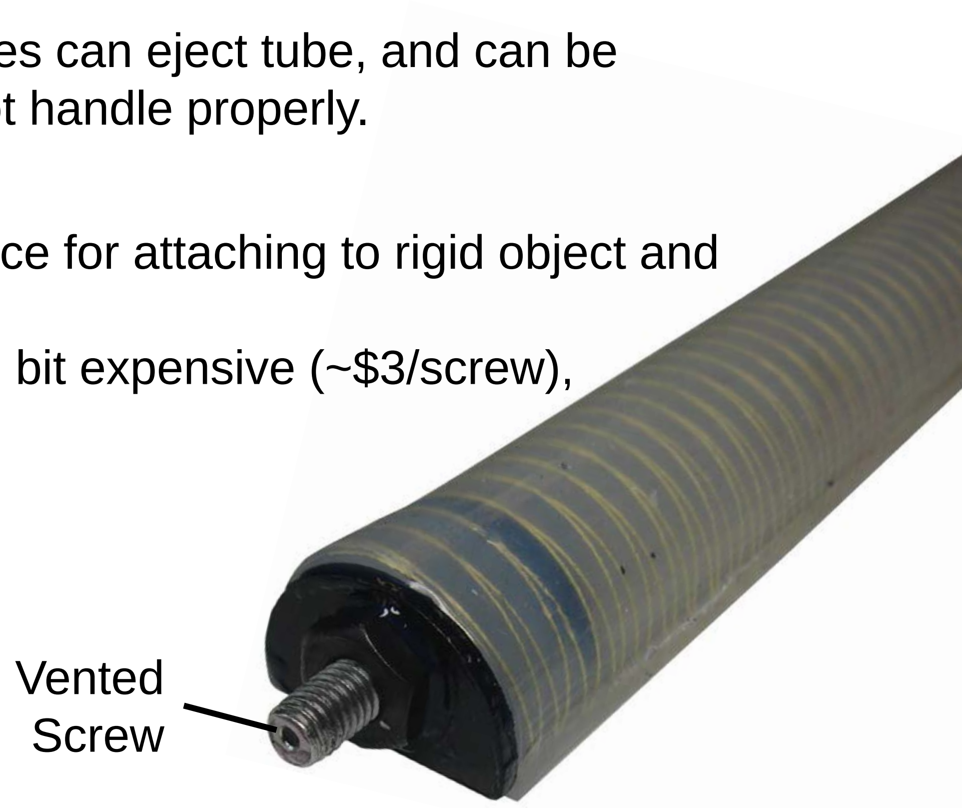
Connecting to Pressure Source

Silicone does not bond well to other materials.
This makes interfacing with the material challenging.

1. **Stab with a tube**
   - *Advantages:* quick and easy.
   - *Disadvantages:* high pressures can eject tube, and can be unintentionally pulled out if not handle properly.

2. **Insert vented screws**
   - *Advantages:* threaded interface for attaching to rigid object and for attaching barbed fittings
   - *Disadvantages:* limited sizes, bit expensive (~$3/screw), adds a rigid component.



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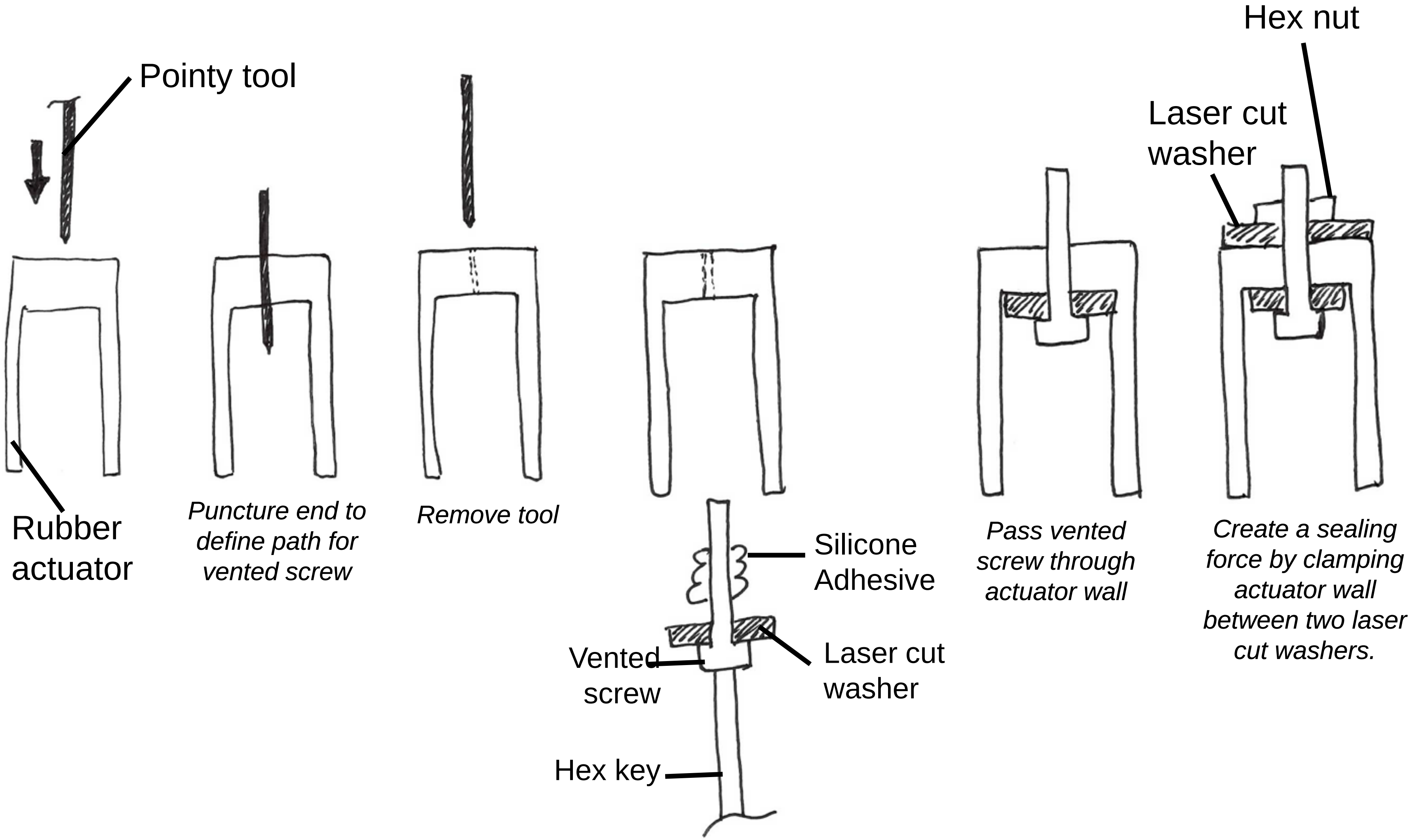
Installing a Vented Screw



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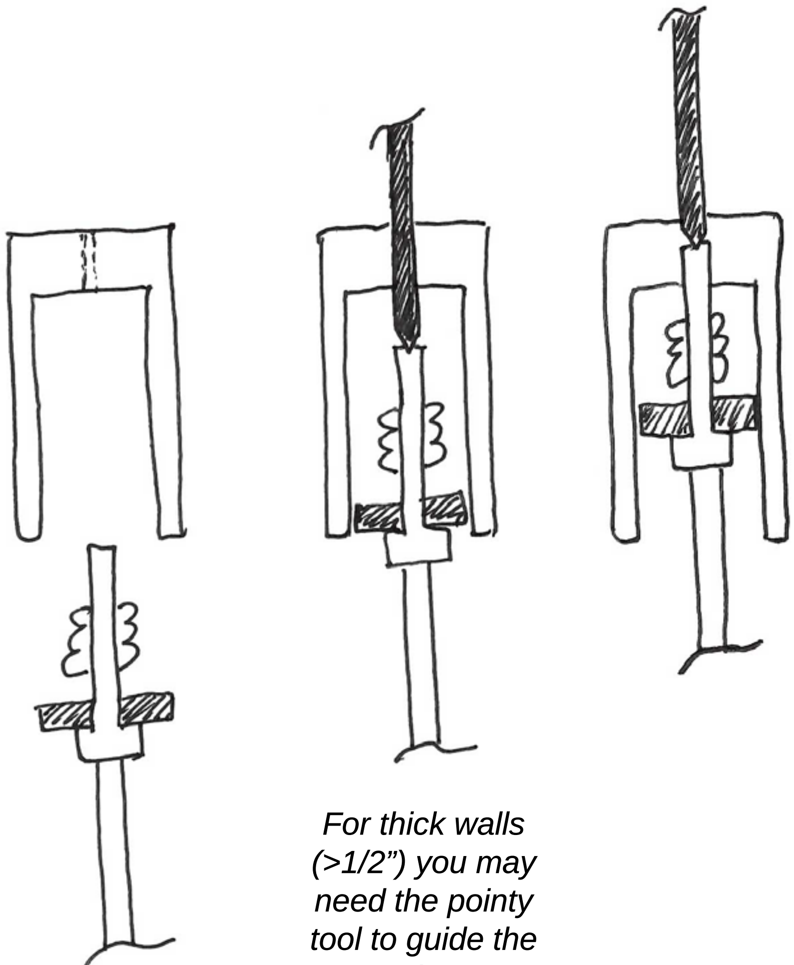
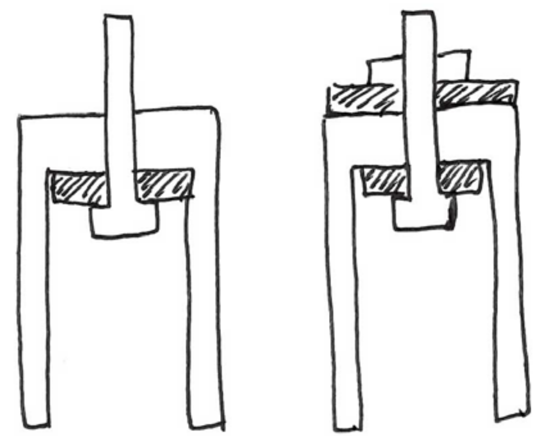
Installing a Vented Screw: Thick Wall





For thick walls (>1/2") you may need the pointy tool to guide the vented screw.

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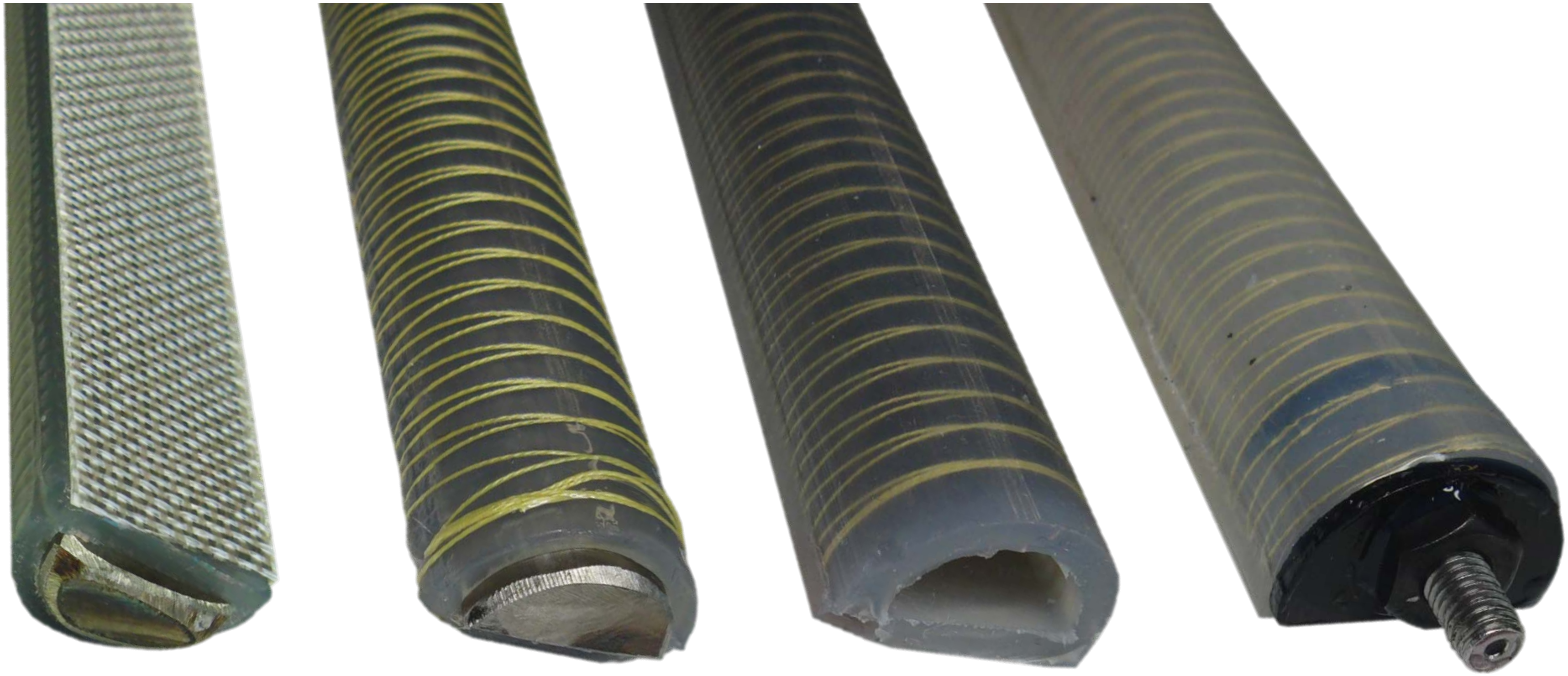
Fiber Reinforcing



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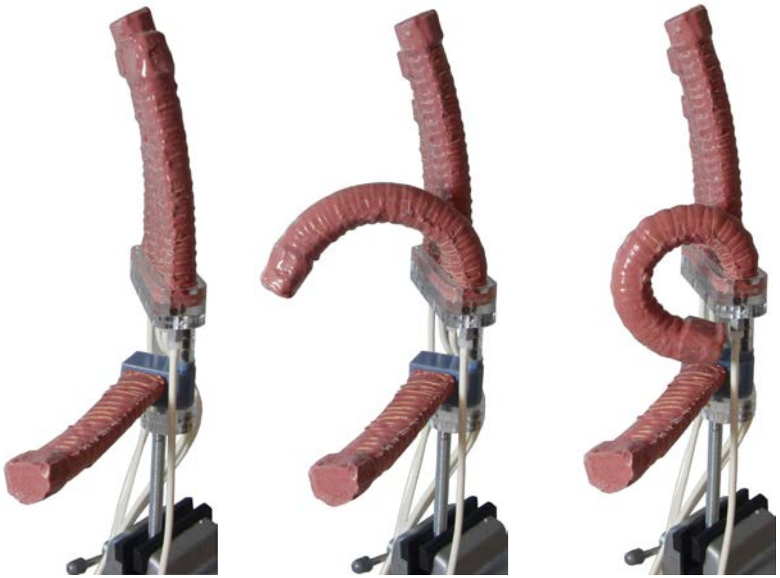
Soft Robotic Manipulator



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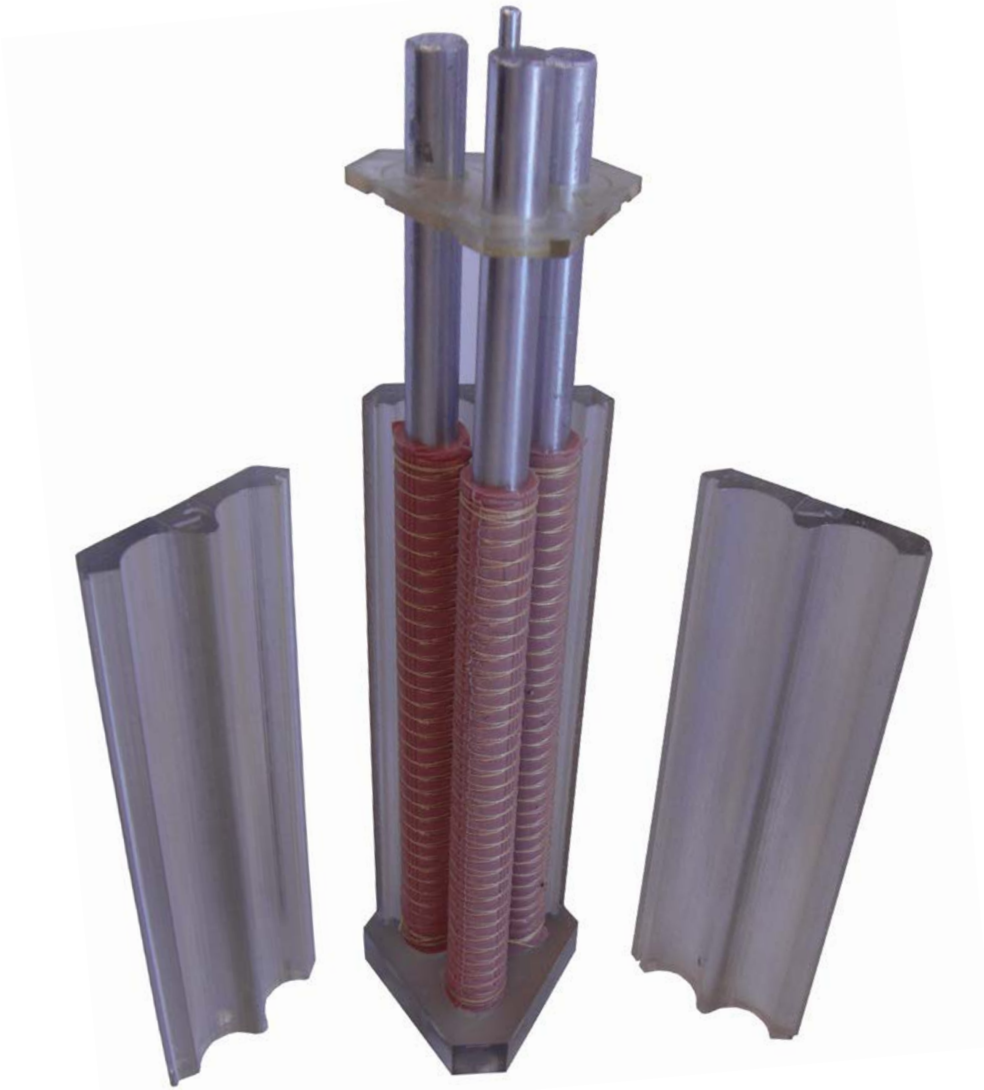
Multi-DOF Bending Actuator

Fiber reinforcements as a Radial Constraint



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Multi-DOF Bending Actuator

Making Soft Bending Joints

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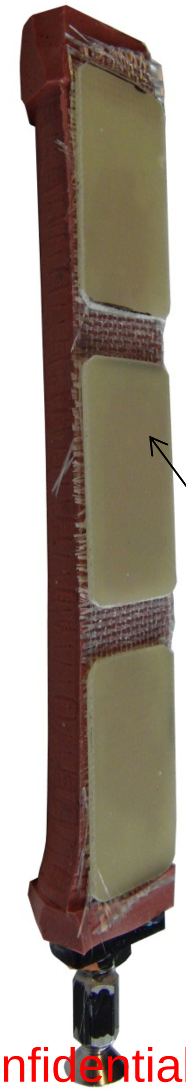
Bending Joint: Mixing Rigid and Soft

single bending joint

failure mode

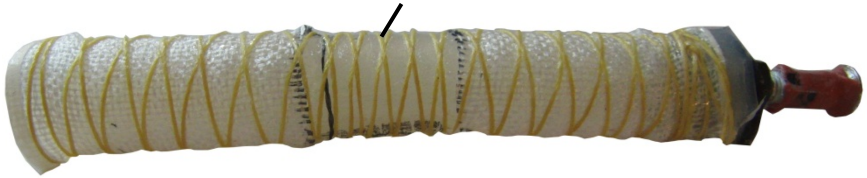


1/32” thick FR4 (fiberglass)

Soft Bending Joints

Selectively Draping FG to create soft joints

1 Joint



2 Joints

35 psi

30A

10A

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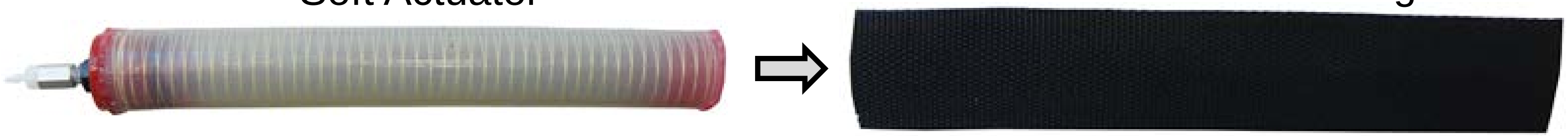
Approach



- Apply a form fitting covering and make cut outs where actuation is desired.
- Overlaying a new reinforcement structure enables rapid programming of actuator bend radius, bend location, and even bend axis.

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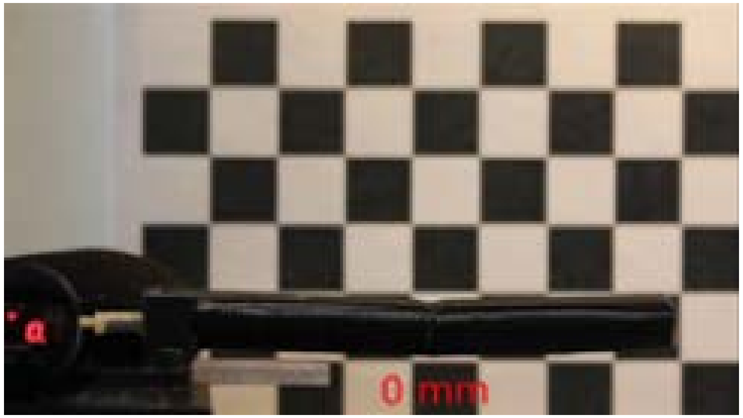
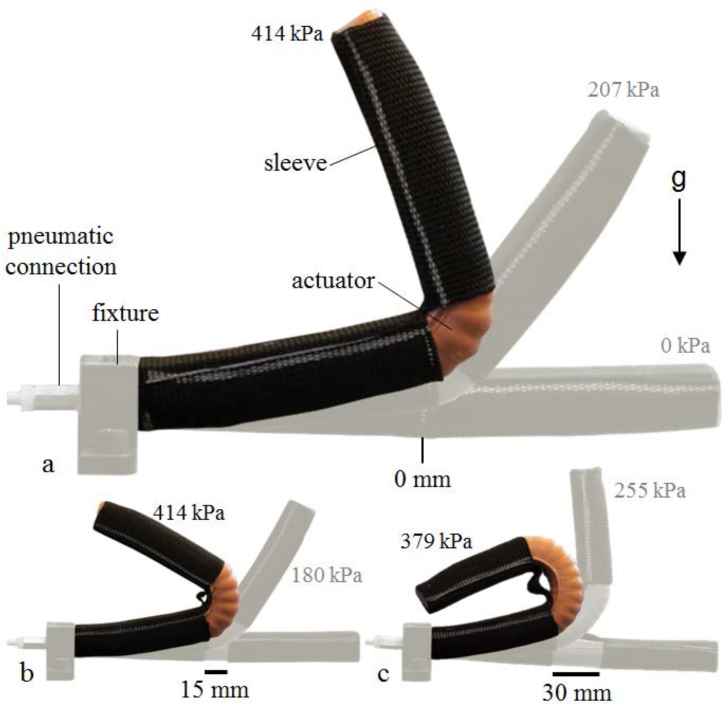
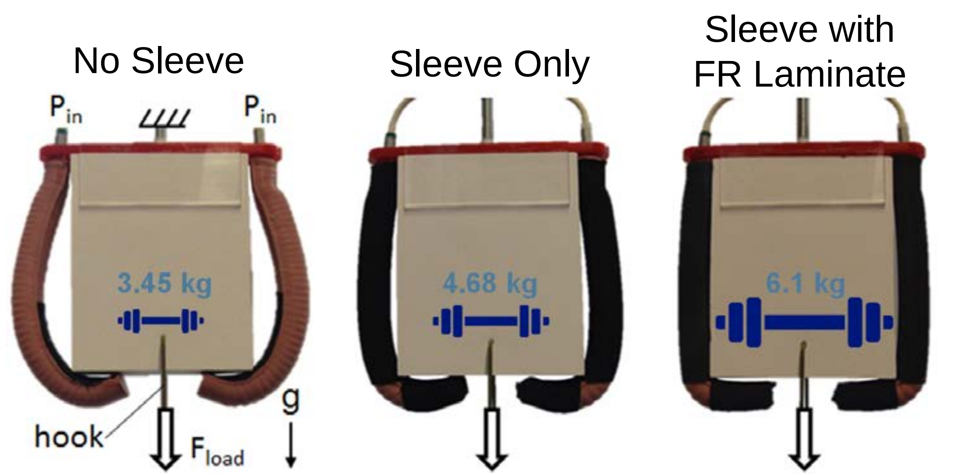
Shape Matching







K. Galloway, P. Polygerinos, C. Walsh, R. Wood, “Mechanically Programmable Bend Radius for Fiber-Reinforced Soft Actuators.” International Conference on Advanced Robotics, 2013.

Grip Glove

Multi-Axis Bender

with a sleeved linear actuator

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Other

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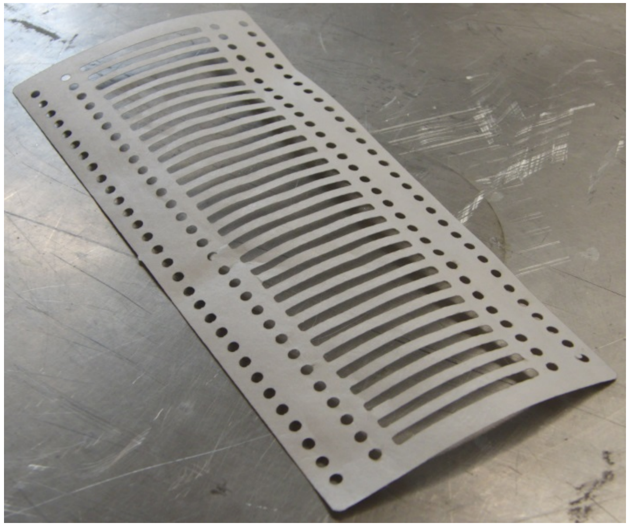
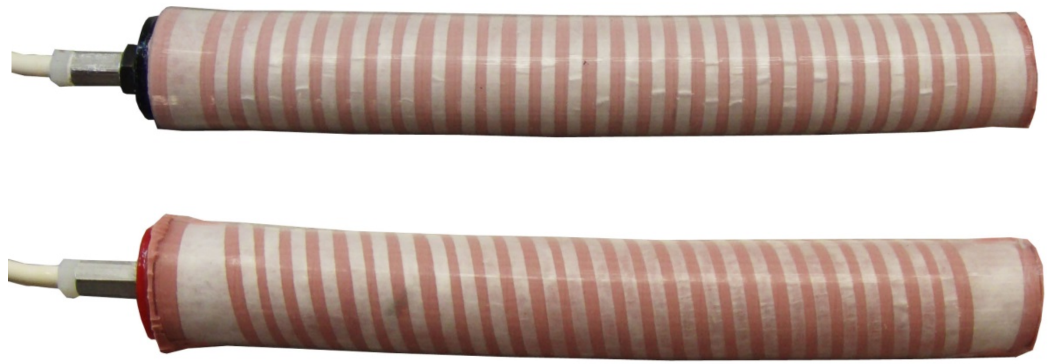
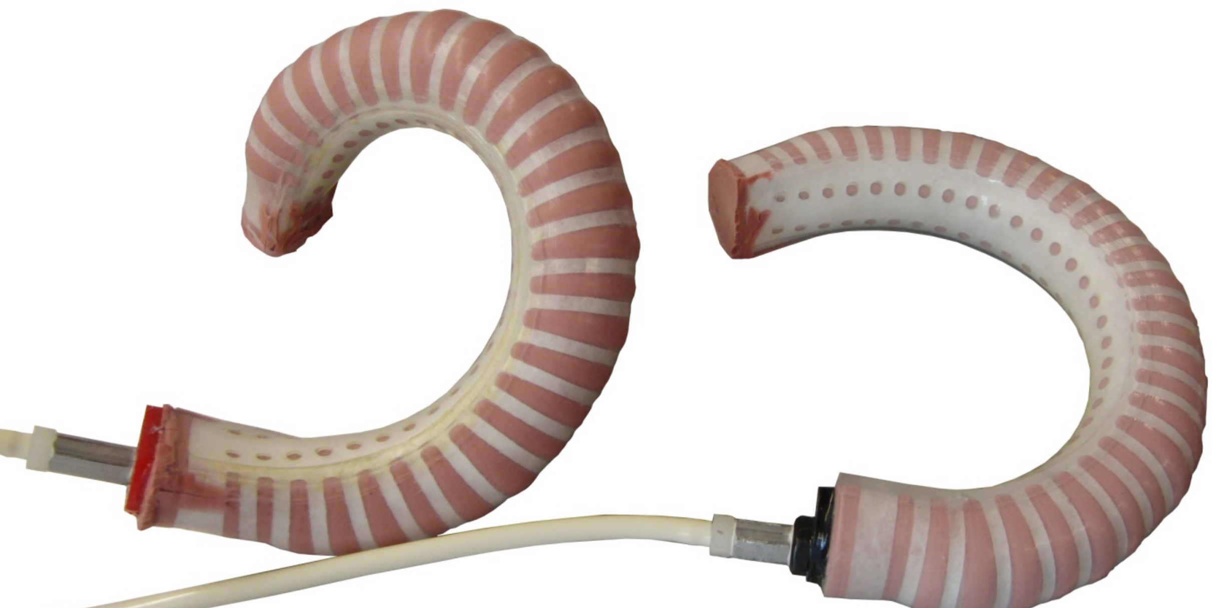
Non-woven Reinforcement Layer







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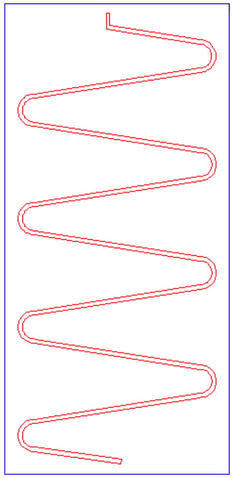
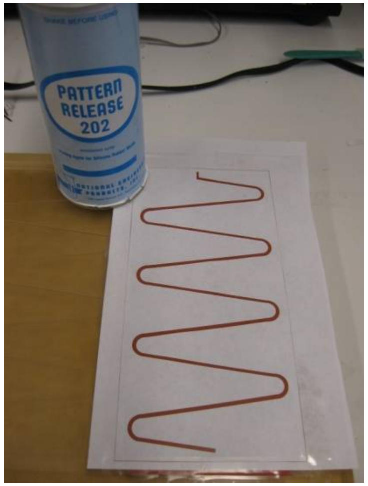
Molding Zero Thickness Channels with Pattern Release

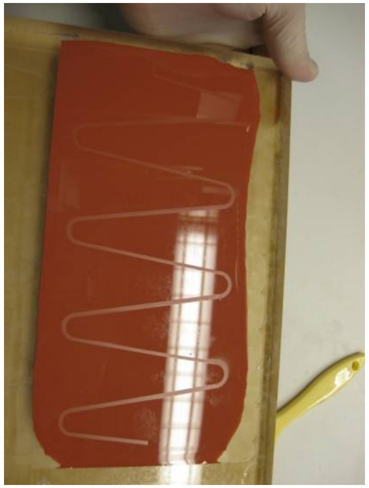
Design mask



Laser cut mask & apply pattern release



Remove mask

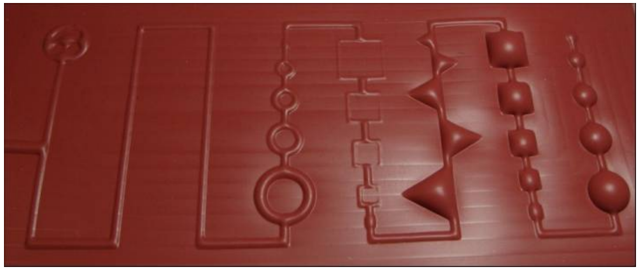


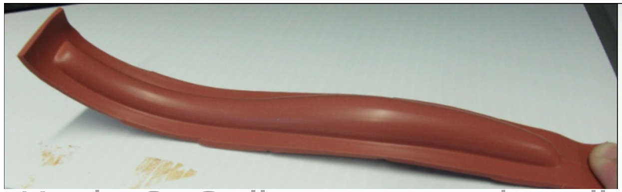
Pour second layer of silicone

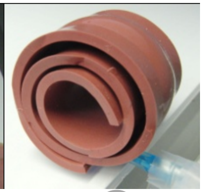
Inflate

Features

- Zero thickness air channels
- Multilayered
- Scalable
- Arbitrary 2D geometries (and in theory 3D)







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