

SoRX: A Soft Pneumatic Hexapedal Robot to Traverse Rough, Steep, and Unstable Terrain

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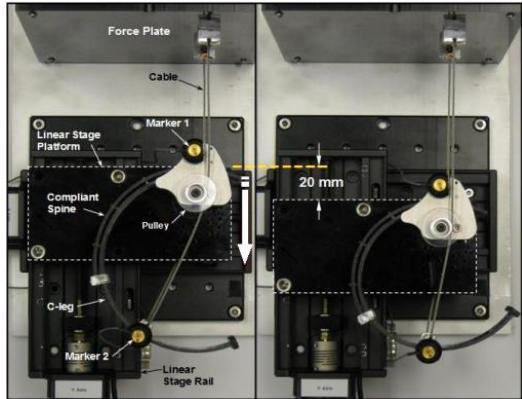
Introduction:

Springy C-leg



U. Saranli *et al.*, 2001

Tunable Device



K. C. Galloway *et al.*, 2009

Direct Drive Robots



T. Apgar *et al.*, 2018

Artificial Muscles



T. Takuma *et al.*, 2008

Studies have shown that incorporating compliant legs can significantly improve the speed and stability in varying environmental conditions^[1].

[1] J. Rummel *et al.* in IEEE ICRA, 2010

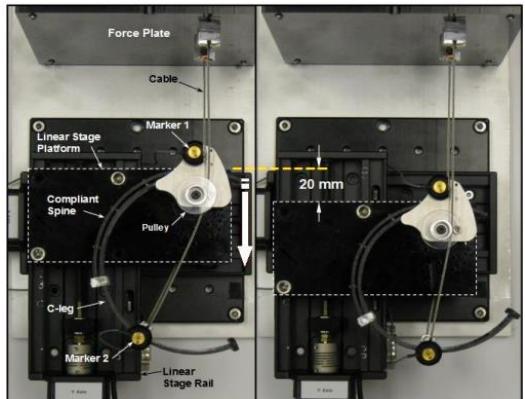
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These compliant legs come together with rigid parts



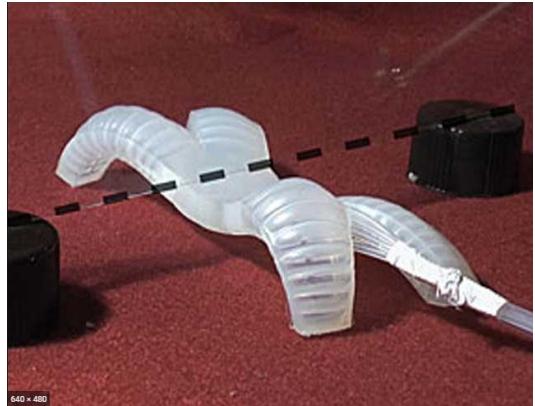
Limit the contact area along the length of legs



Reduce the ability to adapt to the environment

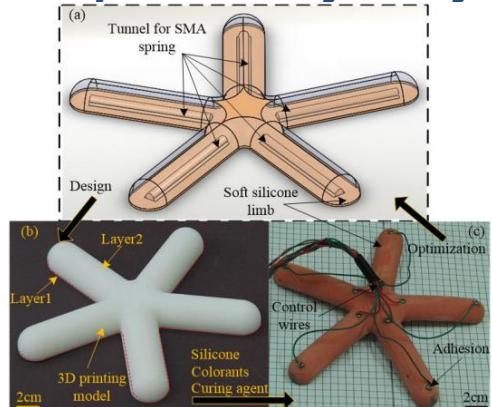
Related Work:

Soft Pneumatic Actuator



R.F. Shepherd et al., 2011

Shape Memory Alloys



S. Mao et al., 2016

3D-Printed Soft Actuator



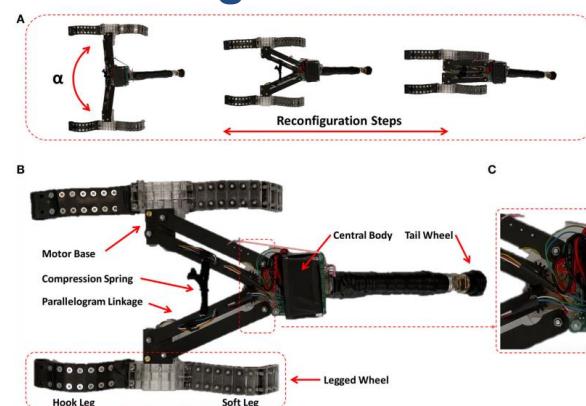
D. Drotman et al., 2017

Soft robots

Bend and squeeze to fit the shape around obstacles

Reduce the contacting stress over surroundings and the robot

Leg and Wheel



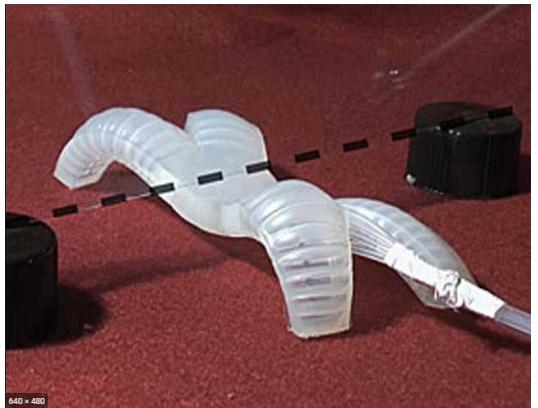
A. Sadeghi et al., 2016

Appropriate for locomotion in uneven and/or sensitive environment [1].

[1] E. Coevoet et al. in IEEE RoboSoft, 2019

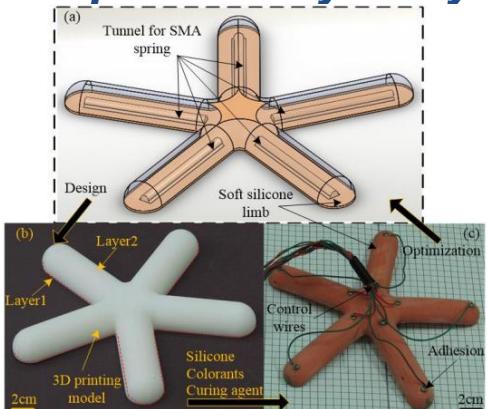
Related Work:

Soft Pneumatic Actuator



R.F. Shepherd *et al.*, 2011

Shape Memory Alloys



S. Mao *et al.*, 2016

Limits:

- one degree of freedom*
- unable to traverse rough terrain*

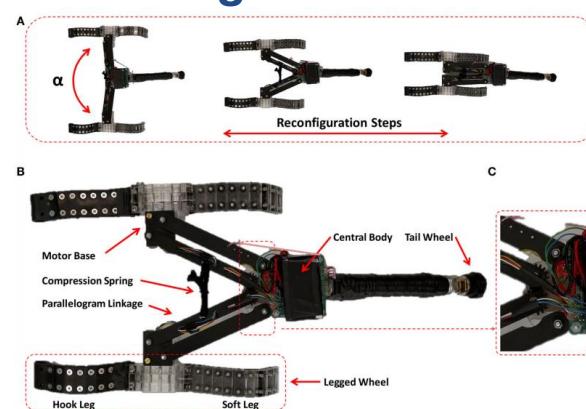
3D-Printed Soft Actuator



D. Drotman *et al.*, 2017

Limit: require multiple leg configurations for rough terrain.

Leg and Wheel



A. Sadeghi *et al.*, 2016

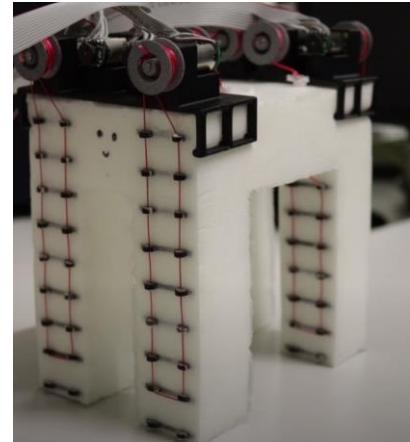
Limit: require rigid wheel for rough terrain.

Related Work:

Cable-driven Soft Legged Robots



C. Duriez *et al.*, 2016



J.M. Bern *et al.*, 2019

Limits:

- a) *no stiffness varying property*
- b) *the necessary motors may make the robot top-heavy and unstable* [1].

[1] J. M. Bern *et al.* in RSS, 2019.

Summary:

In this work, we develop:

- *A novel 2-degree-of-freedom soft pneumatic actuator with stiffness-varying property*
- *A novel Soft Robotic hexapedal robot (SoRX)*

SoRX Size:

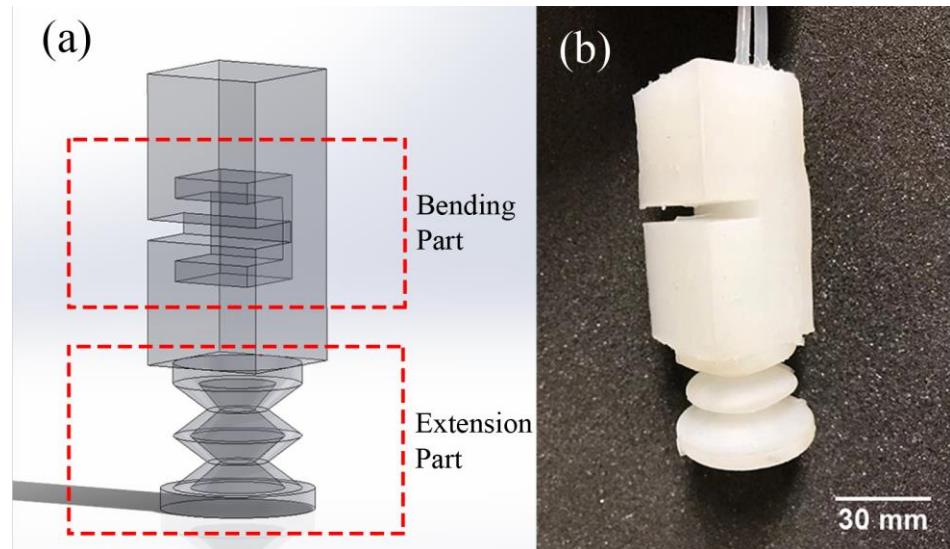
- **230 mm (L)**
- **140 mm (W)**
- **100 mm (H)**

Weight:

- **650 g**



Design and Simulation:



The actuator has two parts:

a) Bending Part

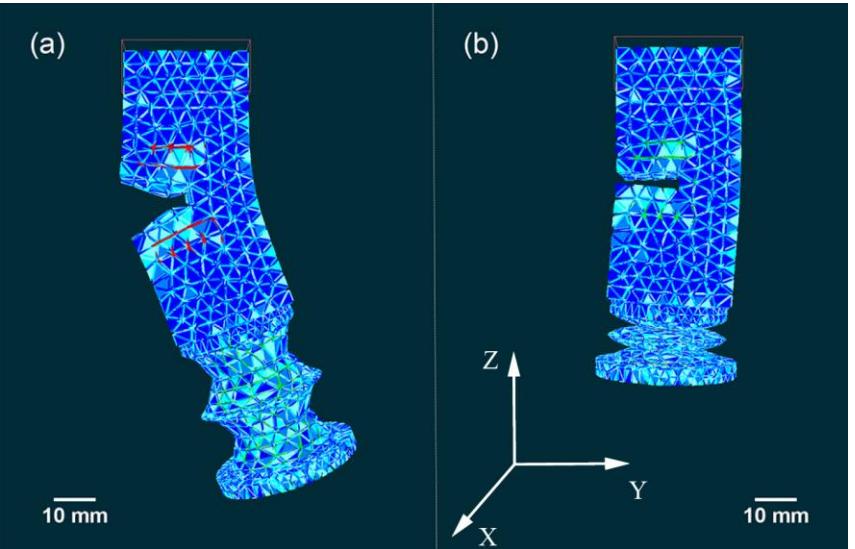
(PneuNet^[1])

b) Extension Part

(Hyper-Elastic Bellows^[2])

[1] R. F. Shepherd *et al.* in PNAS, 2011.

[2] K. M. Digumarti *et al.* in IEEE RA-L, 2017.



Simulation in SOFA^[3] with Soft Robot Plugin^[4] to guide the design.

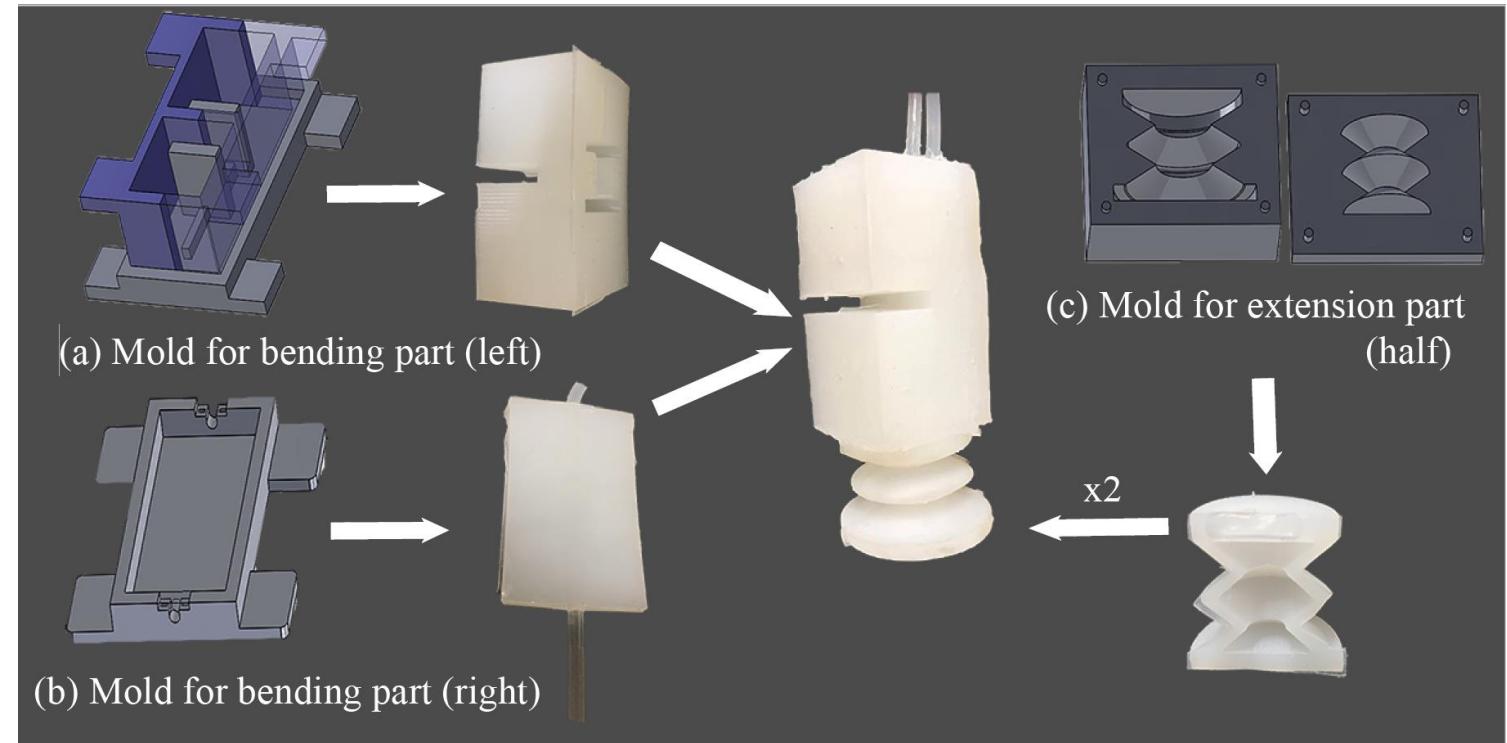
[3] J. Allard *et al.* in MMVR, 2007.

[4] E. Coevoet *et al.* in Advanced Robotics, 2017.

Fabrication:

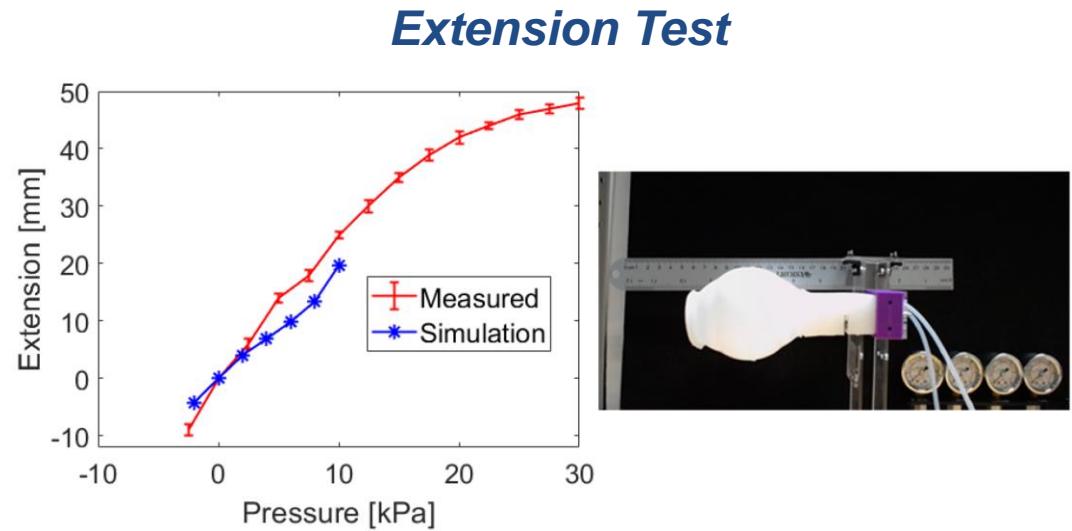
- ❑ **3D-printed Molds:**
Onyx material reinforced with carbon fiber.

- ❑ **Casted Actuators:**
Silicone elastomer (Dragon Skin 10 FAST, Smooth-On) and adhesive (Sil-Poxy, Smooth-On).

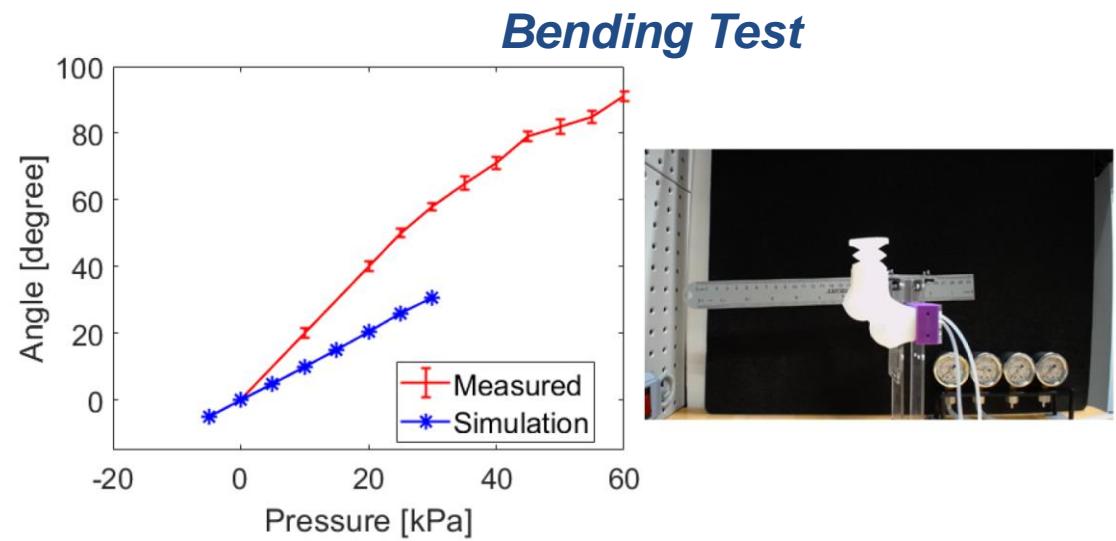


Fabrication time < 1.5 hrs

Performance:



The actuator can elongate by 48 mm at 30 kPa.



The actuator can bend 91 deg at 60 kPa.

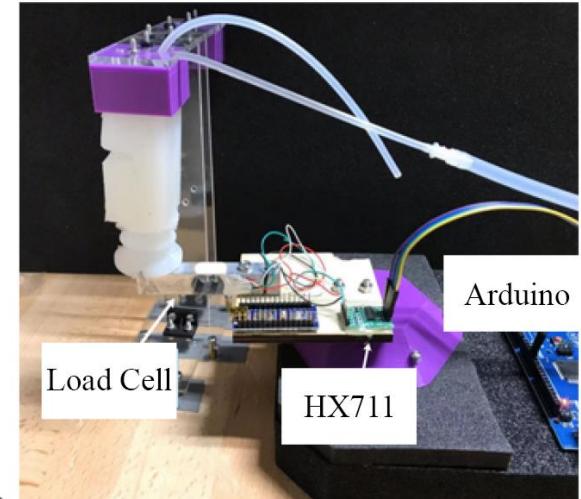
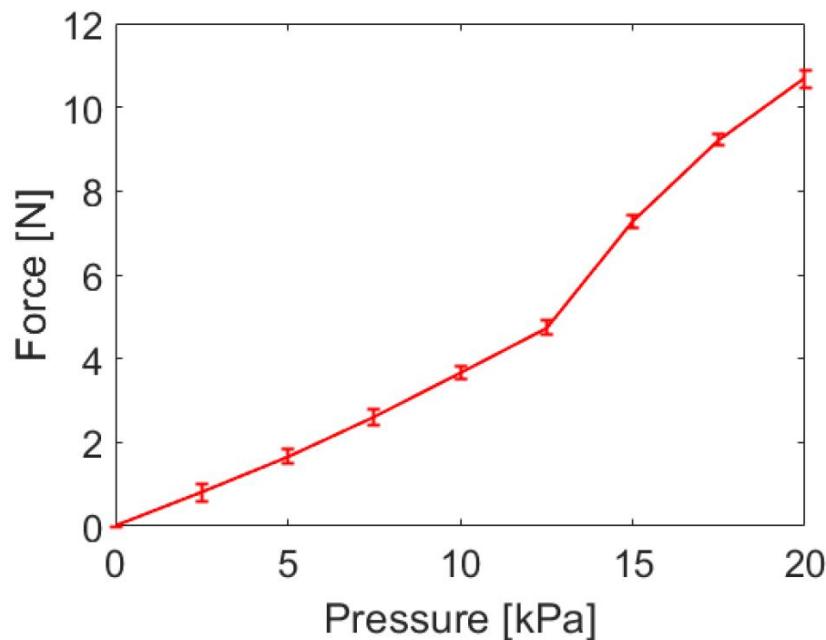
Performance:

We measured the force generated by the actuator to illustrate the stiffness-varying property.

The actuator can apply 10.67 N at 20 kPa.



The robot can lift a maximum weight of 3.26 kg with an alternating tripod gait.

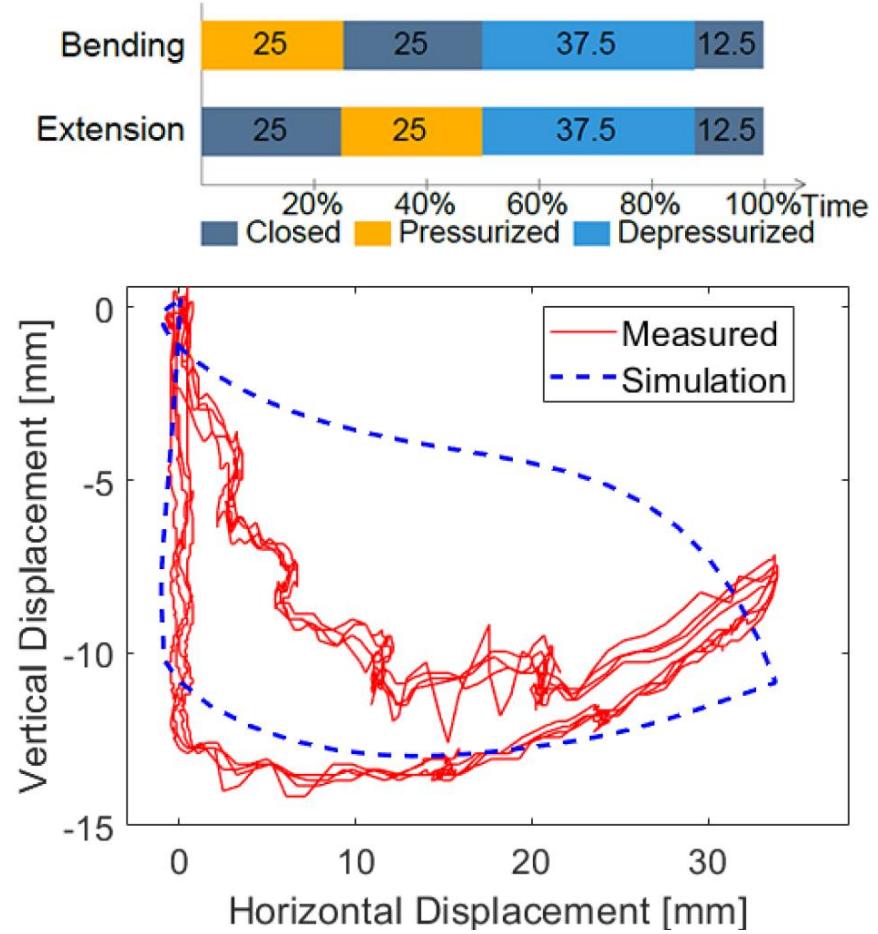


Gait Analysis:

A pressurization and depressurization sequence in air sources.



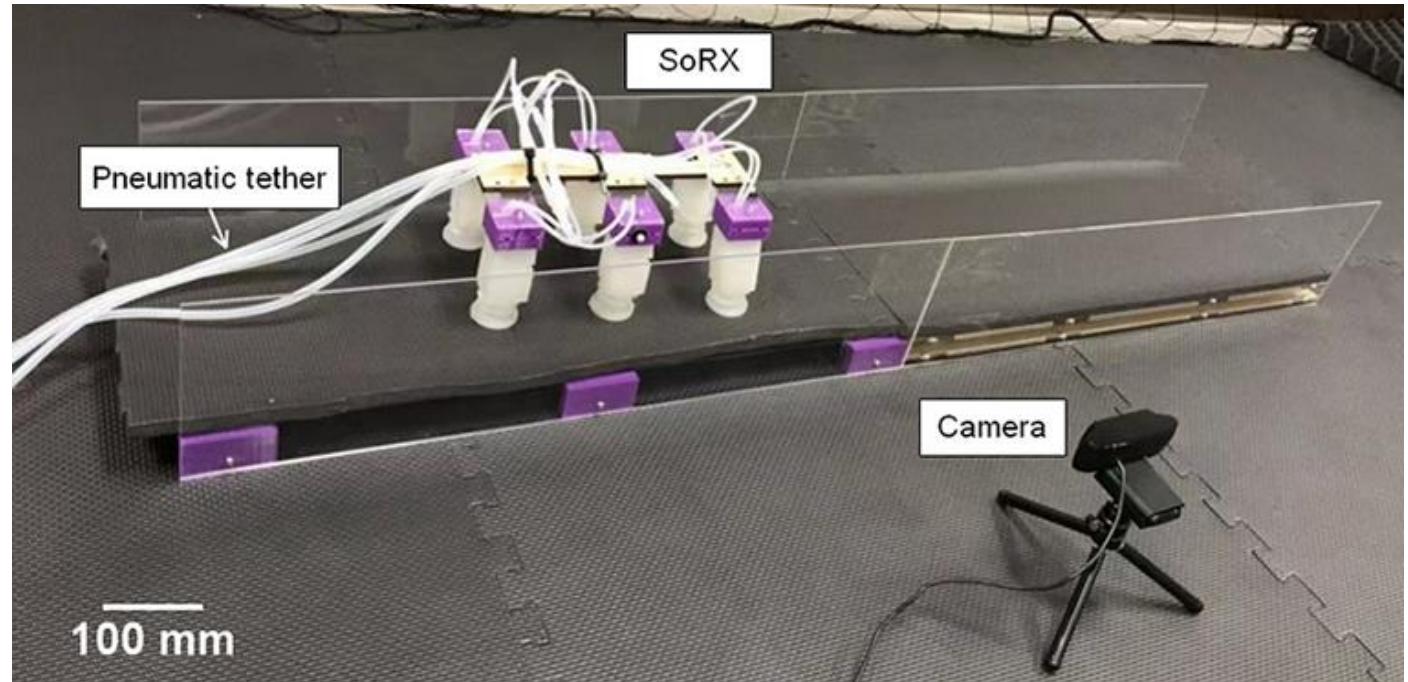
An effective cyclic control trajectory.



Experiments:

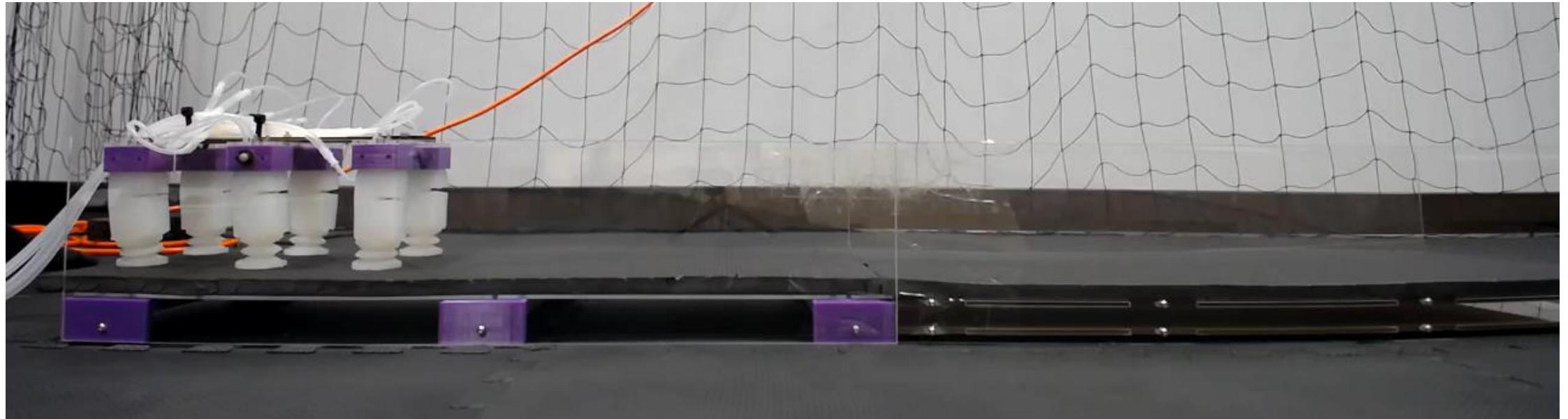
- ✓ **Running**
- ✓ **Step Climbing**
- ✓ **Traversing rough terrain**
- ✓ **Traversing steep terrain**
- ✓ **Traversing unstable terrain**

Experimental Setup



Running:

Top speed of 0.44 body lengths per second (BL/s), or 101 mm/s on flat ground.



Running:

Speeds for Soft Robots

Robots	Speed [BL/s]	Speed [mm/s]
SoRX	0.44	101.0
Quadrupedal ^[1]	0.14	20.0
Puppy ^[2]	0.12	15.6
Multigait ^[3]	0.05	6.7
Five-limb ^[4]	0.003	0.43

SoRX is the fastest soft pneumatic legged robot to date.

[1] D. Drotman *et al.* in IEEE ICRA, 2017.

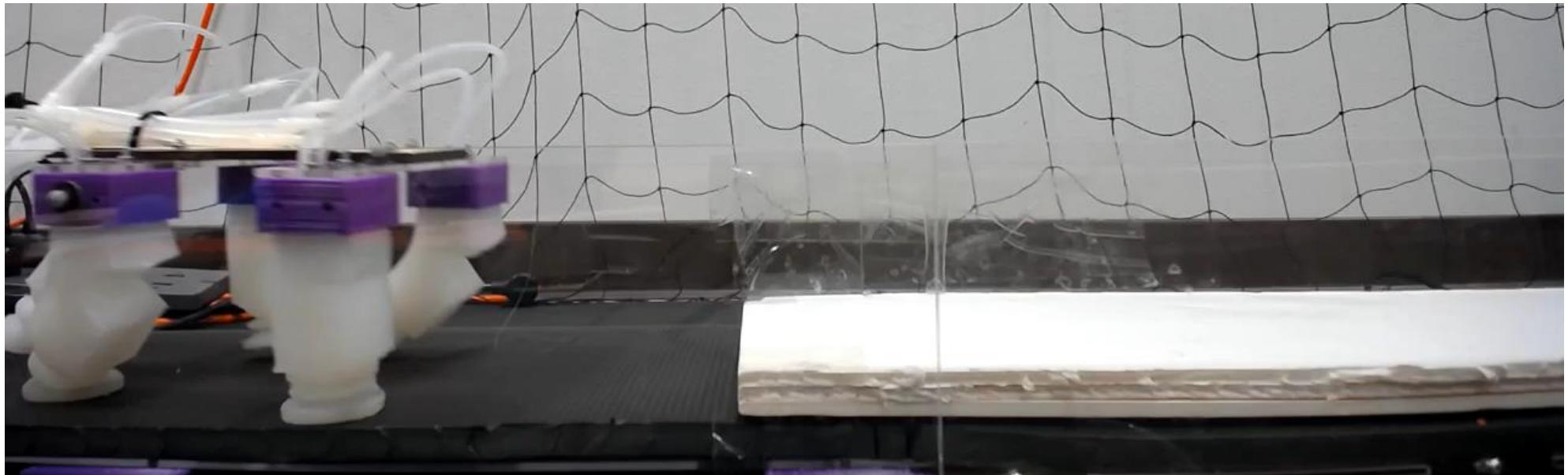
[2] J. M. Bern *et al.* in RSS, 2019.

[3] R. F. Shepherd *et al.* PNAS, 2011.

[4] S. Mao *et al.* IEEE/RSJ IROS, 2016.

Step Climbing:

SoRX can overcome obstacles up to 15 mm tall passively.

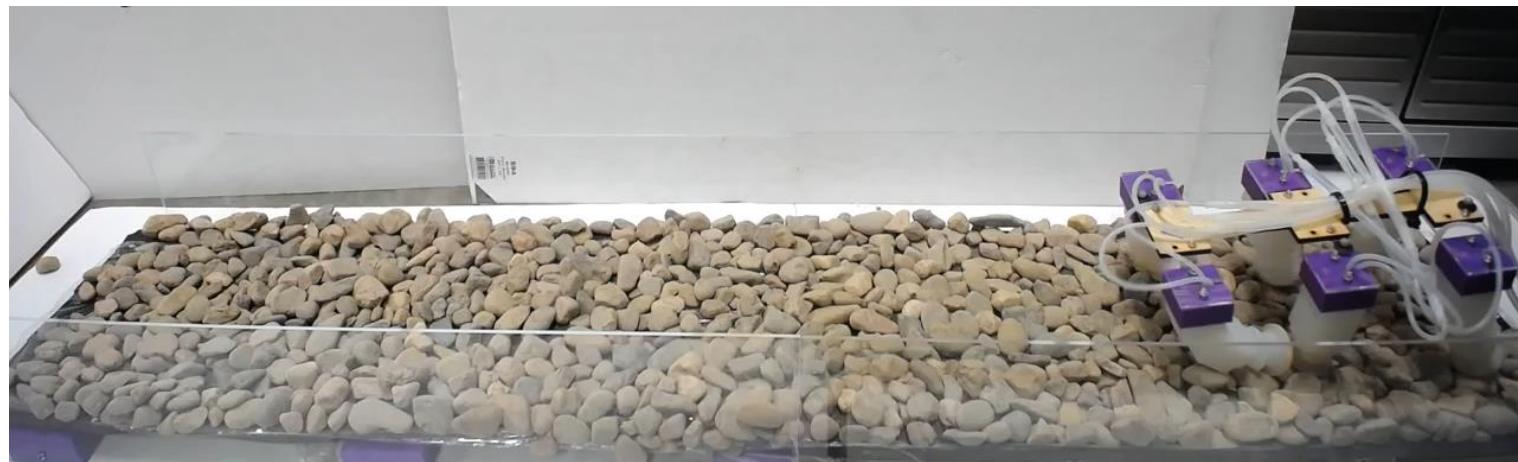


Rough Terrain:



*0.171 body lengths per second (BL/s)
for sandy terrain*

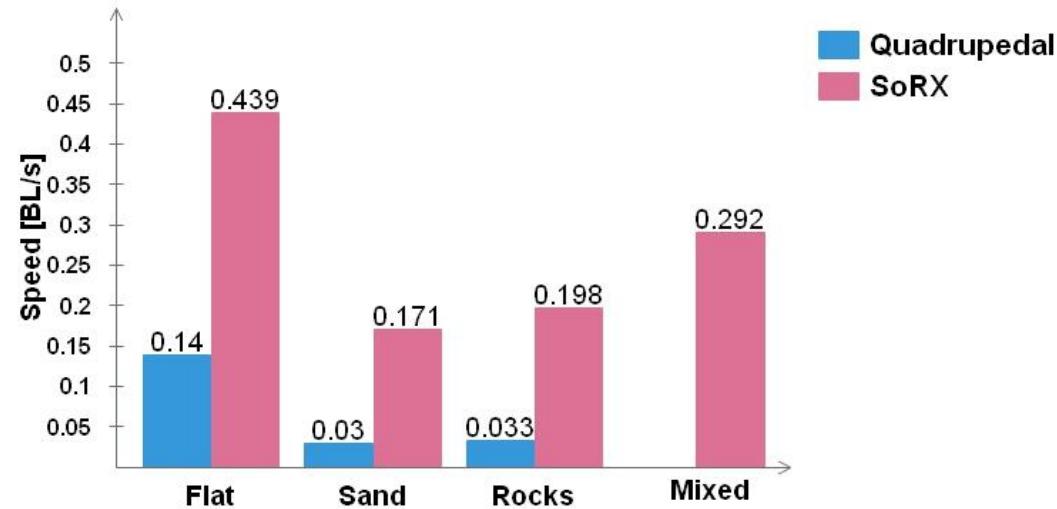
*0.198 body lengths per second (BL/s)
for rocky terrain*



Transitioning Mixed Terrain:



***0.292 body lengths per second (BL/s)
for a mixed terrain with the same gait pattern.***



Terrain traversal speeds for Quadrupedal^[1] and SoRX

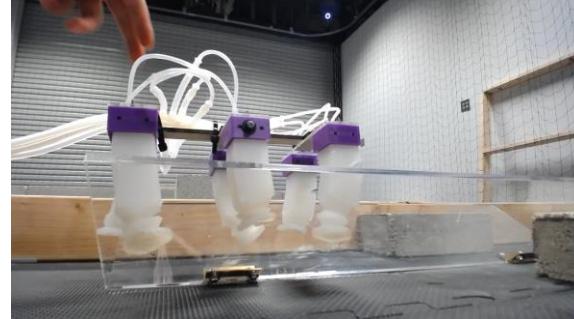
[1] D. Drotman et al. in IEEE ICRA, 2017.

Steep and Unstable Terrain:

A slope of 10 deg.



SoRX is the first soft pneumatic legged robot to climb a slope.



A 15-deg inclined groove.



An unstable platform vibrating with a speed of approximately 200 mm/s.

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Thank you!

