

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

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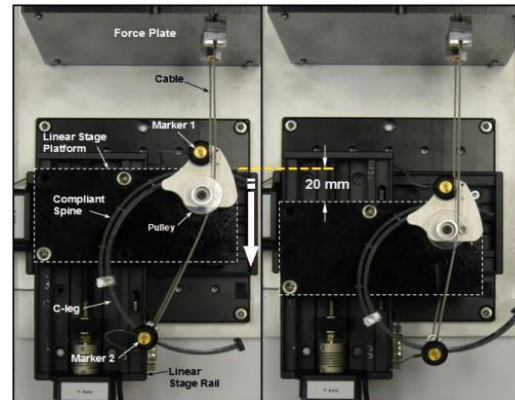
Introduction:

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

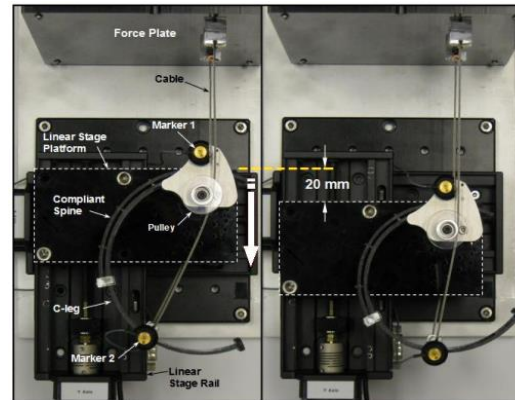
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These compliant legs come together with rigid parts



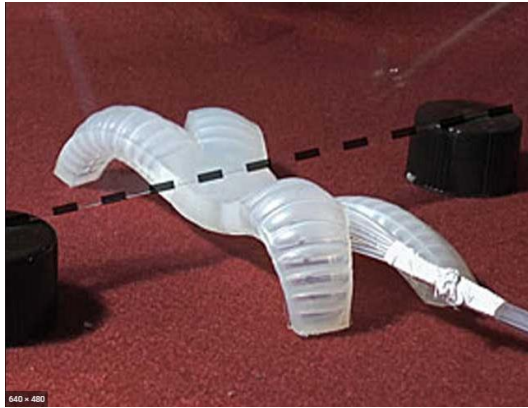
Limit the contact area along the length of legs



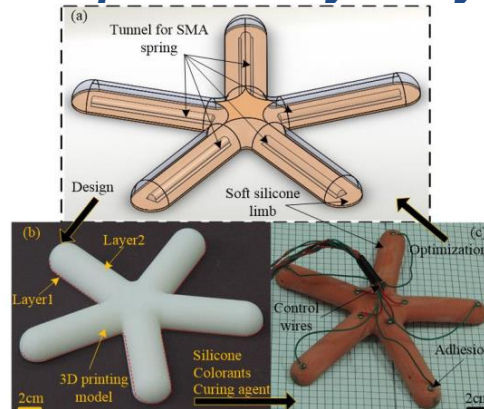
Reduce the ability to adapt to the environment

Related Work:

Soft Pneumatic Actuator

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

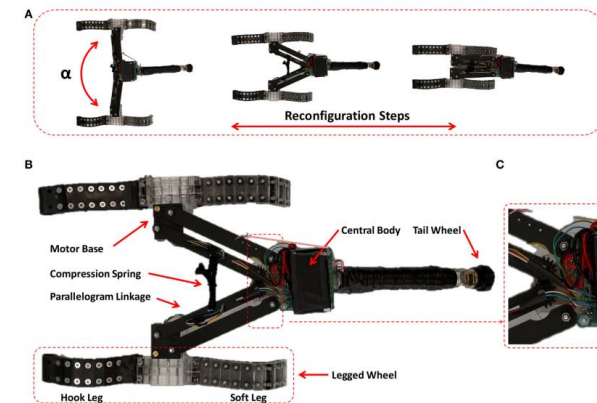
Shape Memory Alloys

S. Mao *et al.*, 2016

3D-Printed Soft Actuator

D. Drotman *et al.*, 2017

Leg and Wheel

A. Sadeghi *et al.*, 2016

Soft robots

Bend and squeeze to fit the shape around obstacles

Reduce the contacting stress over surroundings and the robot

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

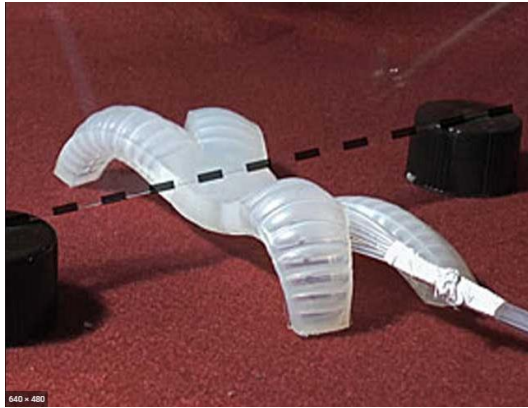
[1] E. Coevoet *et al.* in IEEE RoboSoft, 2019

Zhichao Liu *et al.* (ICRA 2020)

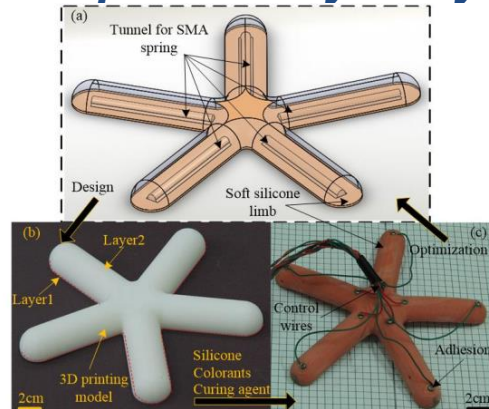
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Related Work:

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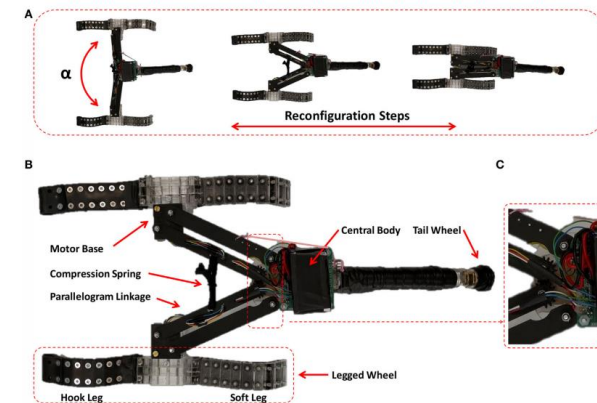
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Leg and Wheel

A. Sadeghi *et al.*, 2016

Limits:

- a. one degree of freedom
- b. unable to traverse rough terrain

Limit: require multiple leg configurations for rough terrain.

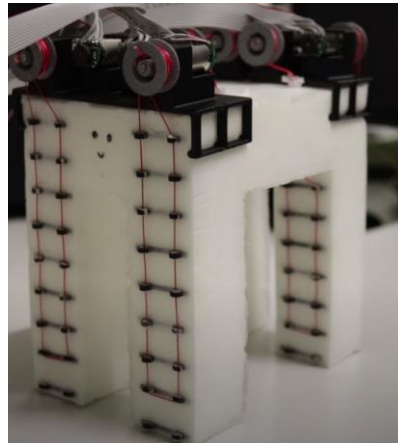
Limit: require rigid wheel for rough terrain.

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:

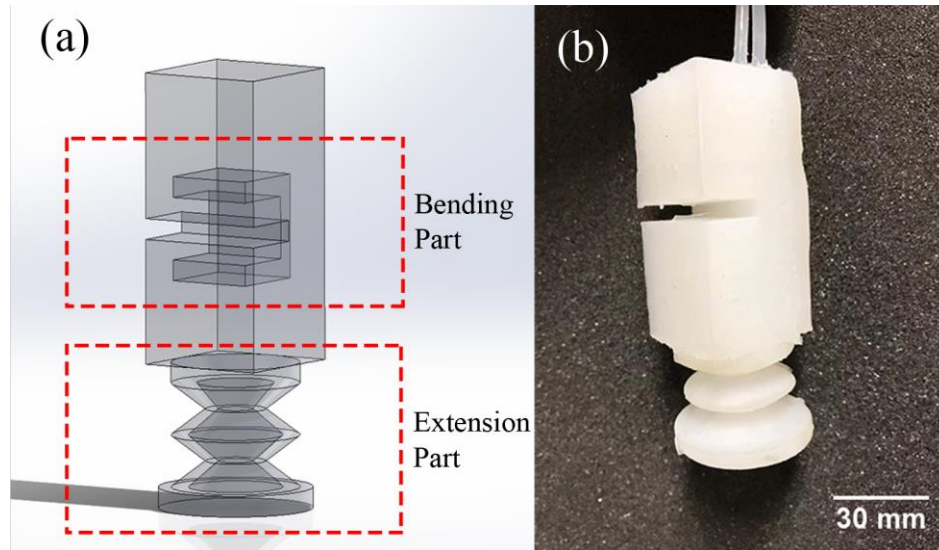
- 230 mm (L)
- 140 mm (W)
- 100 mm (H)

Weight:

- 650 g



Design and Simulation:

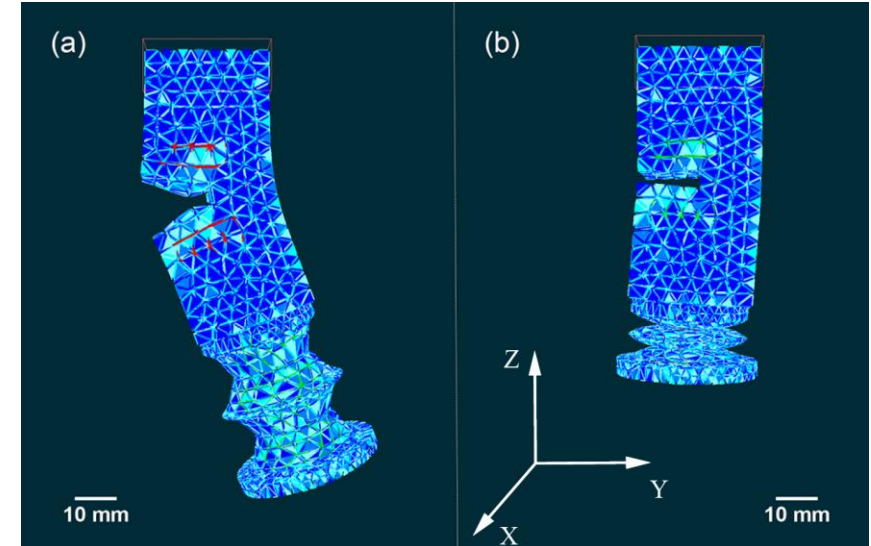


The actuator has two parts:

- 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.

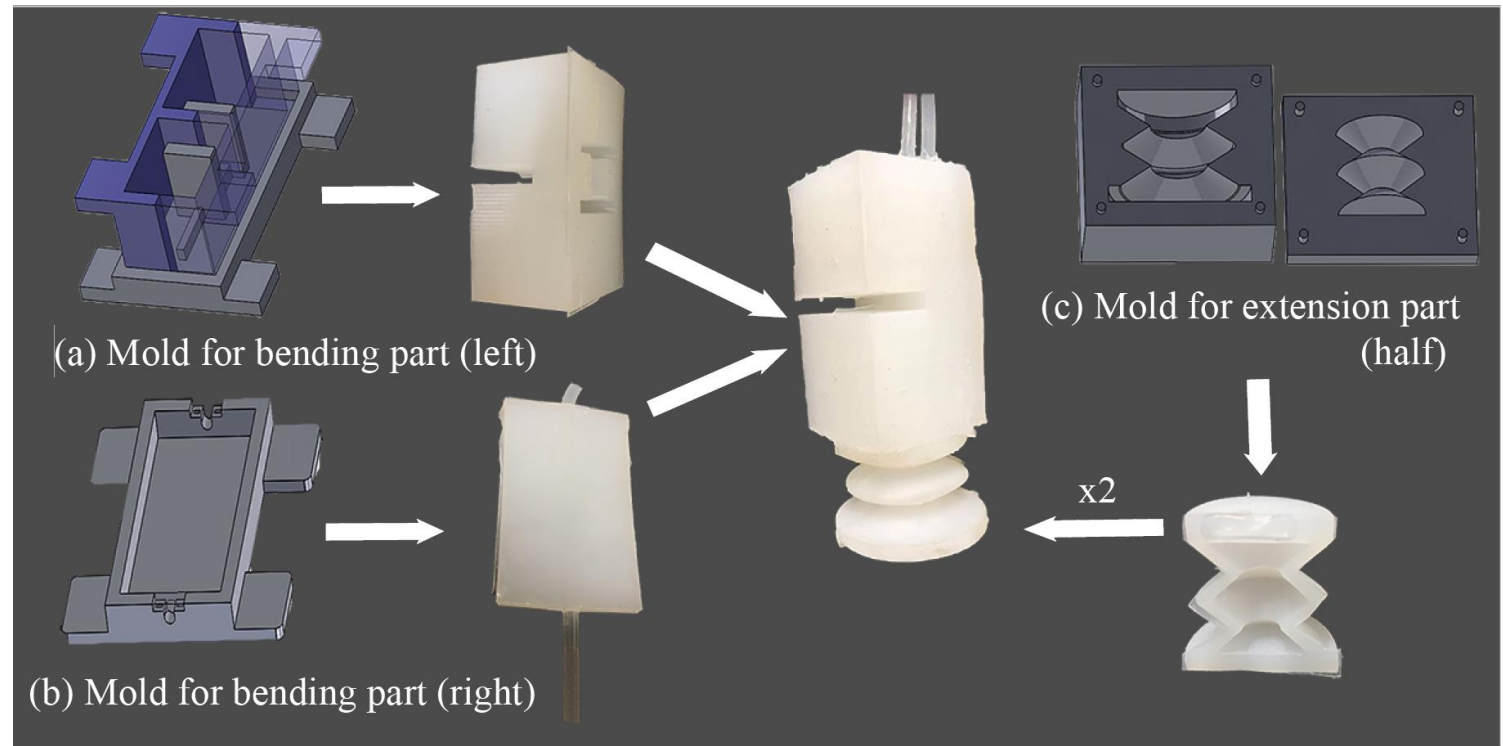
[4] E. Coevoet *et al.* in Advanced Robotics, 2017.

Fabrication:

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

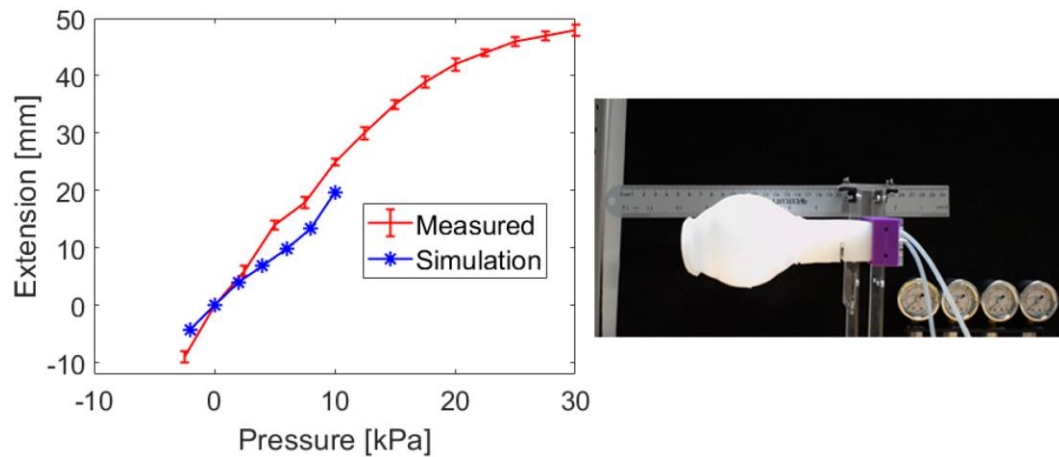
❑ **Casted Actuators:**
*Silicone elastomer
(Dragon Skin 10 FAST,
Smooth-On) and adhesive
(Sil-Poxy, Smooth-On).*

Fabrication time < 1.5 hrs



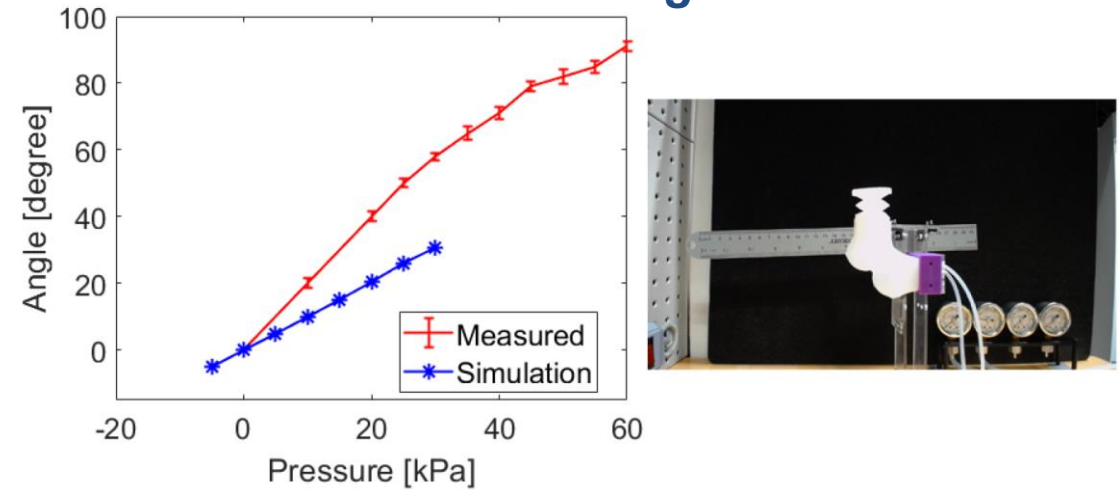
Performance:

Extension Test



The actuator can elongate by 48 mm at 30 kPa.

Bending Test



The actuator can bend 91 deg at 60 kPa.

Performance:

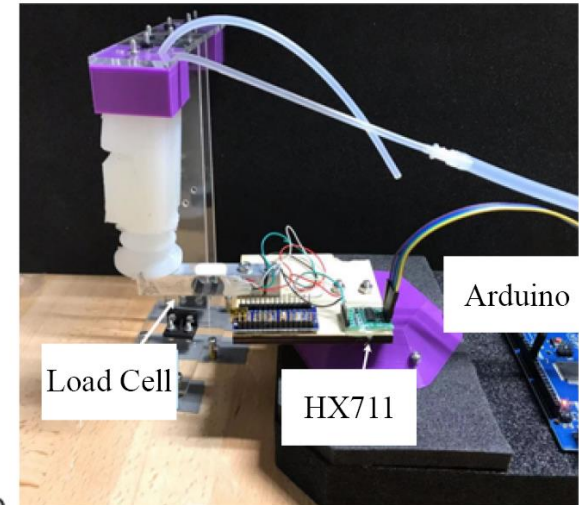
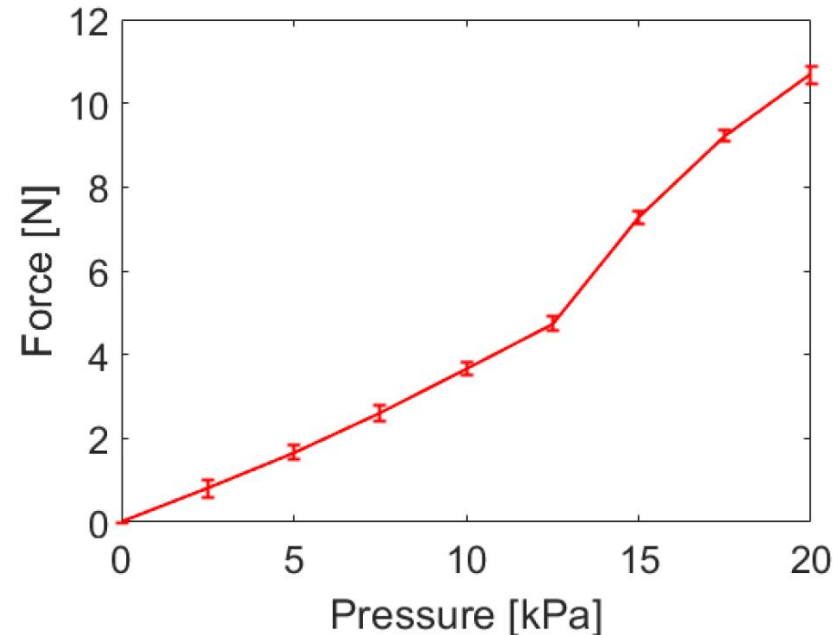
We measured the force generated by the actuator to illustrate the stiffness-varying property.

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.

Force Test

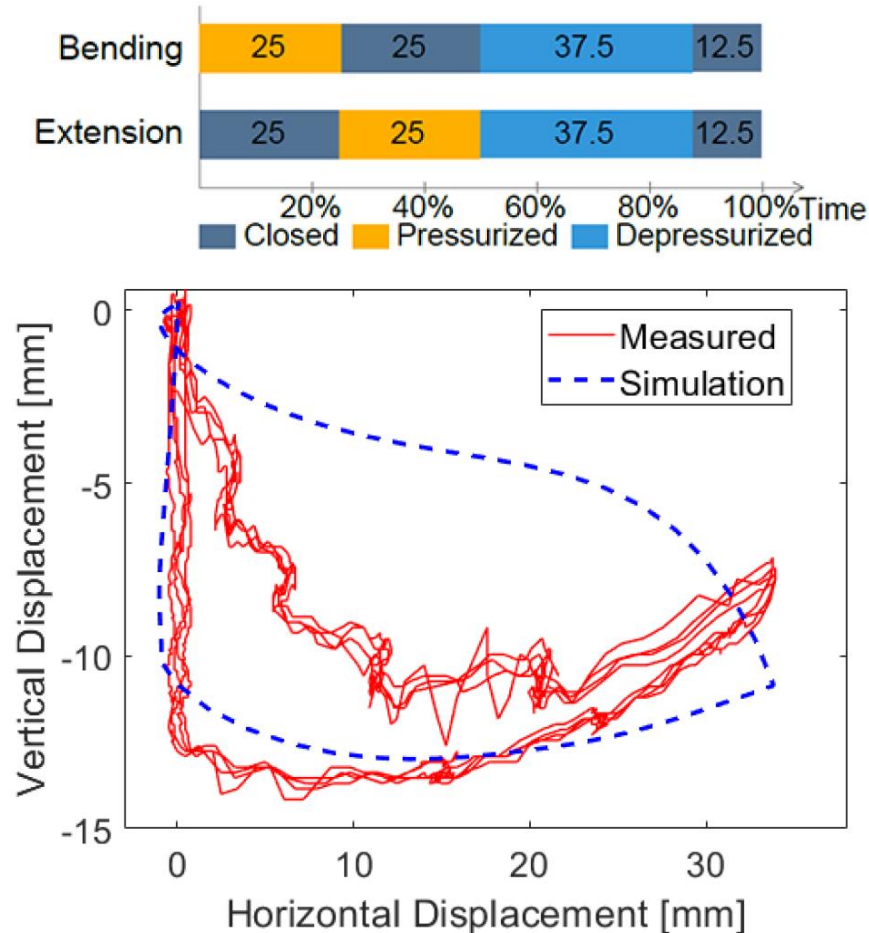


Gait Analysis:

A pressurization and depressurization sequence in air sources.



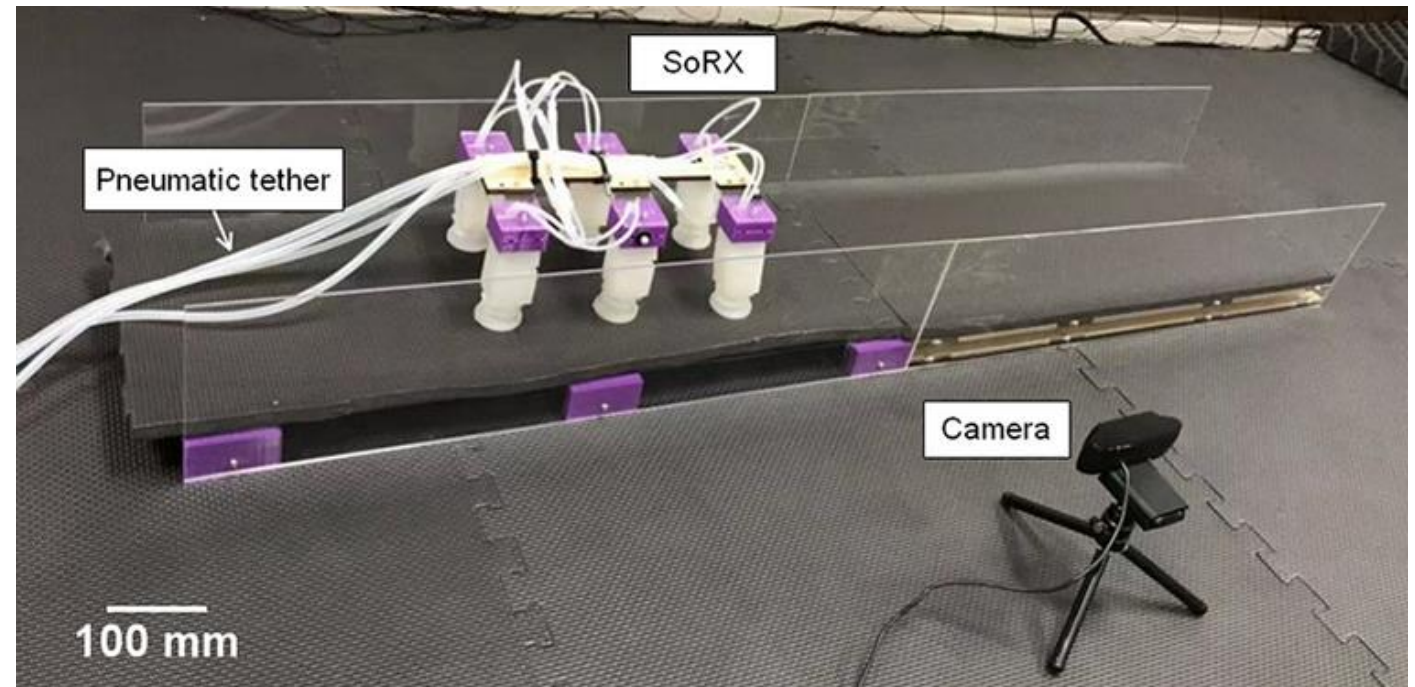
An effective cyclic control trajectory.



Experiments:

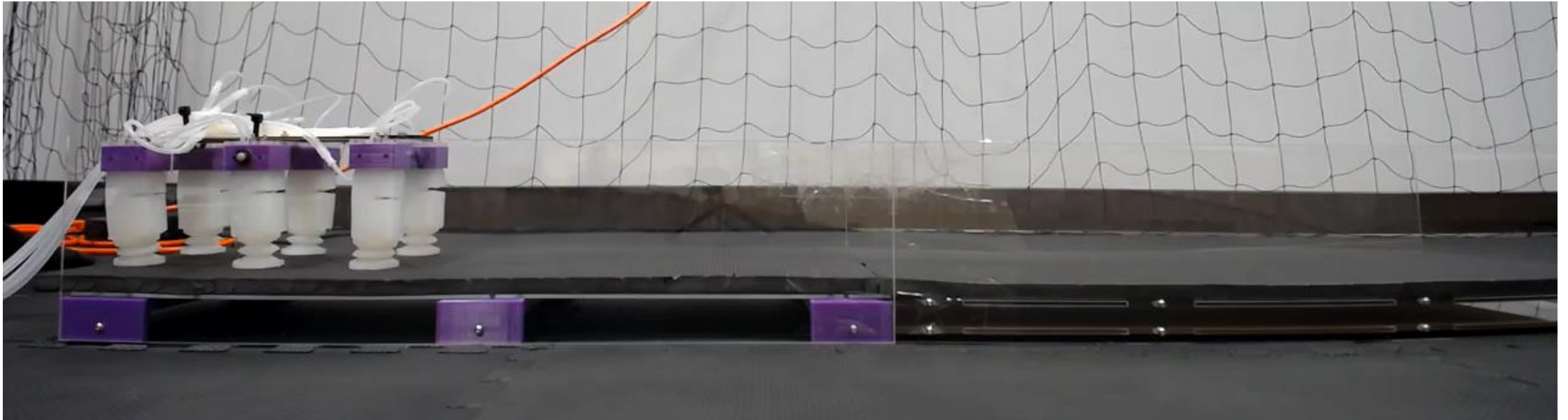
- ✓ *Running*
- ✓ *Step Climbing*
- ✓ *Traversing rough terrain*
- ✓ *Traversing steep terrain*
- ✓ *Traversing unstable terrain*

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.

Zhichao Liu *et al.* (ICRA 2020)

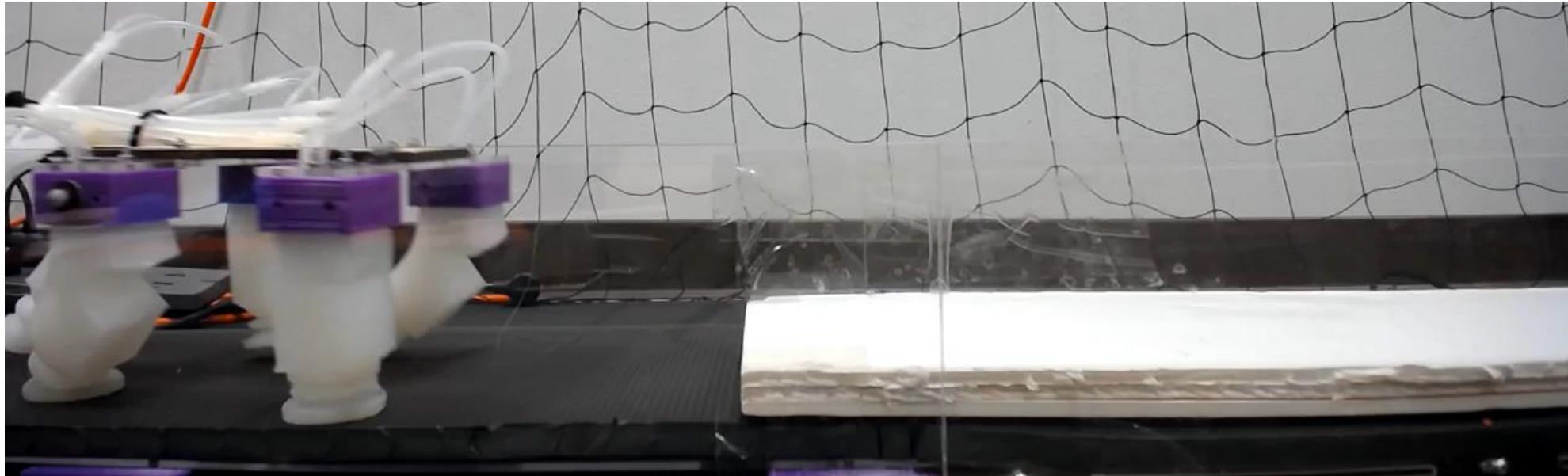
[3] R. F. Shepherd *et al.* PNAS, 2011.

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

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Step Climbing:

SoRX can overcome obstacles up to 15 mm tall passively.

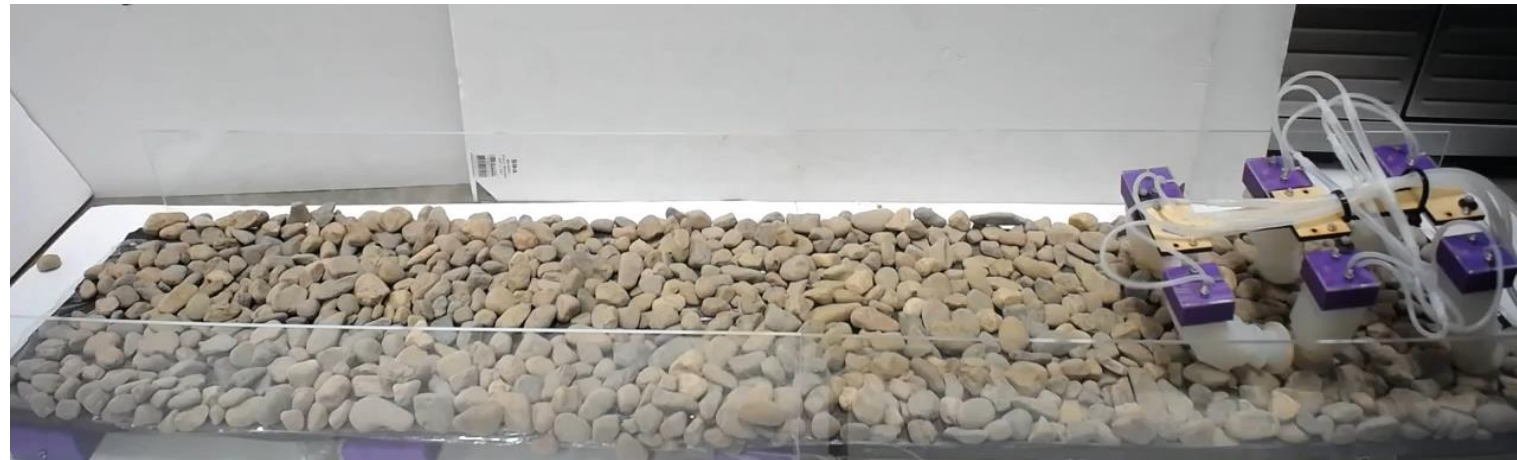


Rough Terrain:



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

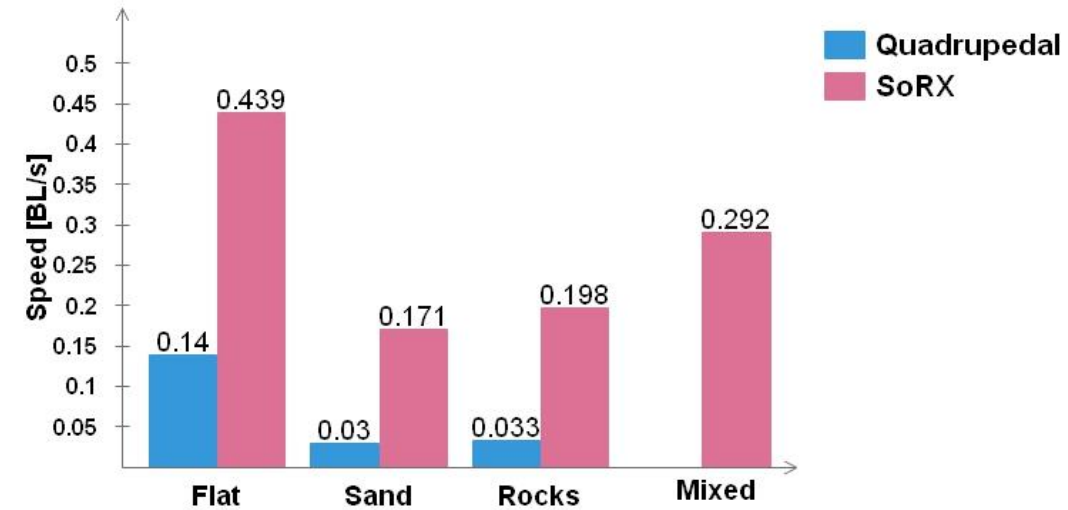
*0.198 body lengths per second (BL/s)
for rocky terrain*



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***

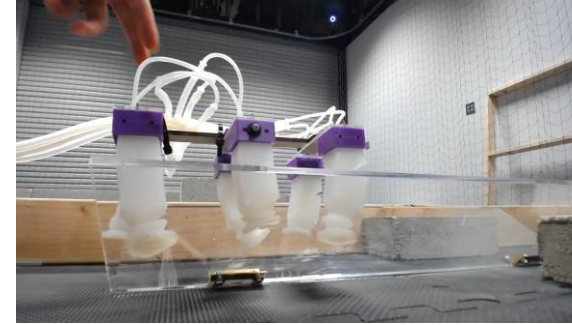
[1] D. Drotman *et al.* in IEEE ICRA, 2017.

Steep and Unstable Terrain:

A slope of 10 deg.



A 15-deg inclined groove.



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



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

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Thank you!

