Body Plan of Soft Robots

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Topics

- Why soft?
- Musculoskeletal Robot
- Continuum Robots

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Industrial Robot Arm

FANUC

YASKAWA

Kawasaki

EPSON

MITSUBISHI ELECTRIC

https://www.fanuc.co.jp/ja/product/robot/f_r_large.html https://www.yaskawa.com/products/robotics/robots-with-iec/articulated-robots https://kawasakirobotics.com/jp/ https://epson.com/industrial-robots-factory-automation https://www.mitsubishielectric.com.au/product/robots/

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State of the Art of Hard Robotics

- Trajectory planning + MPC (Model Predictive Control)?

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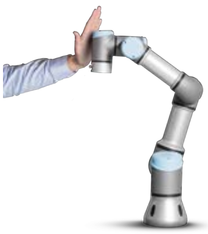
Collaborative Robot


Universal Robot, UR5


Kuka, LBR IIWA


Rethink Robotics, The Baxter & Sawyer


Kawada, Nextage


ABB, YuMi


Fanuc, CR-35iA

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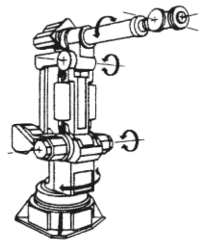
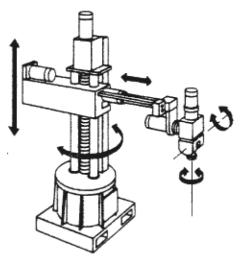
Amoeba-like Locomotion

- Limitations of rigid body mechanisms
  - 32-legged robot "Mochi" [Kujirai *et al.*, 2018]





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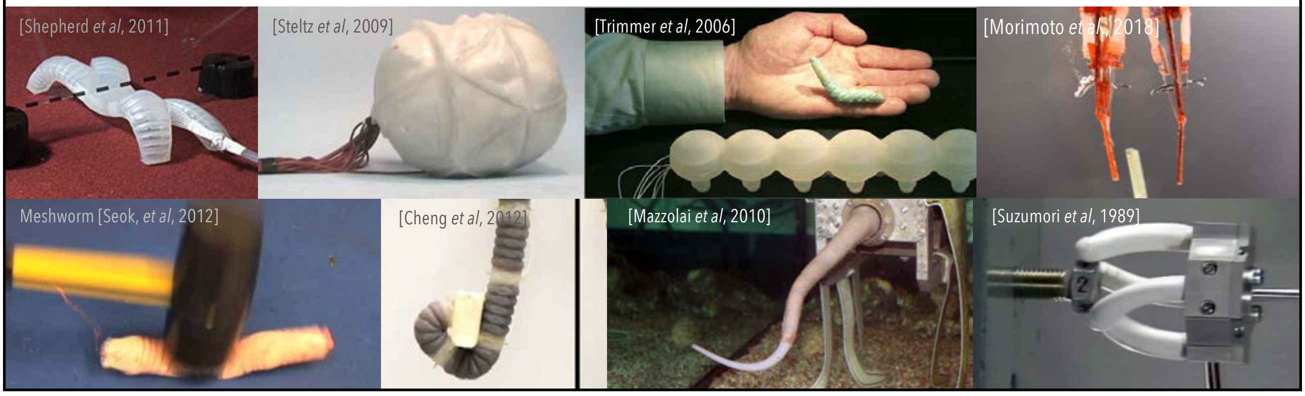
Soft Robotics

Emerging research field that focuses on the transformations in robot mechanisms and control by
leveraging the unique properties of soft materials.
(not limited to fully soft-bodied robots)



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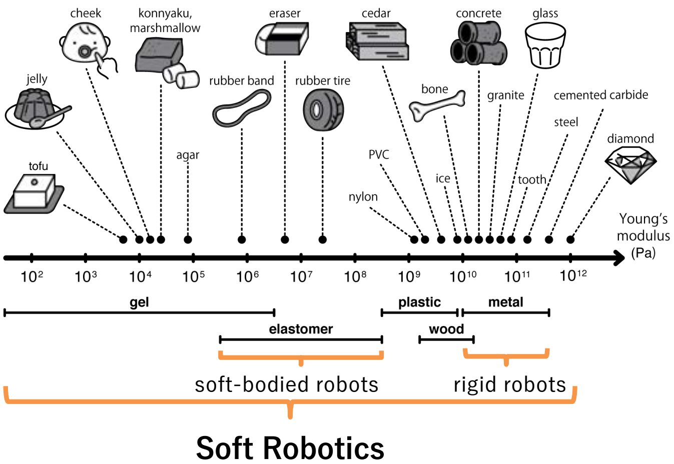
Use both "hard" and "soft"

- Right material for the right job, expanding design options
  - From metals to elastomers, from single materials to composites



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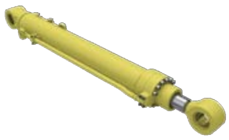
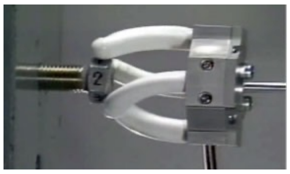
Hard vs. Soft

Classic Hard Actuators

- Assembly of rigid rigid bodies
- Output: Rotation, translation
- One of the components:
  Actuator, transmission, and effector
- Powerful, large machines

Soft Actuators

- Soft material with embedded structure
- Output: 3D Deformation, especially bending and contraction
- Actuator and body is fused
- low output force, small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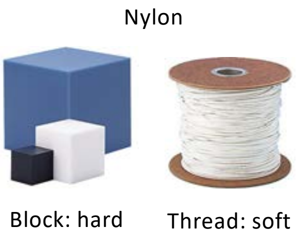
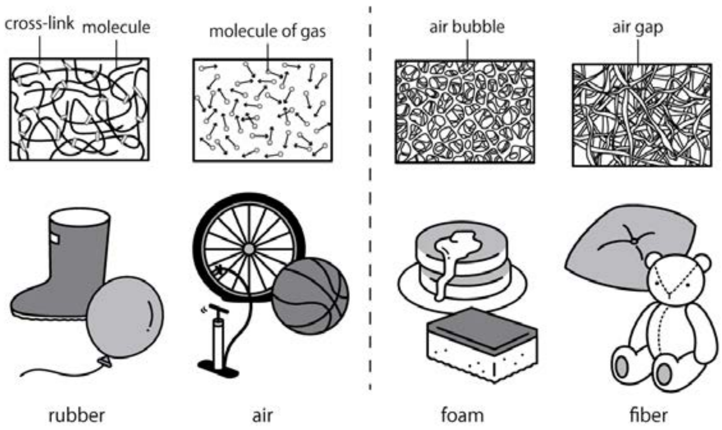
Soft Materials, Soft Structures

- Soft material: elastomer, gel, fluid (water, oil, air)
- Soft structure: thin (film, fiber), foamed





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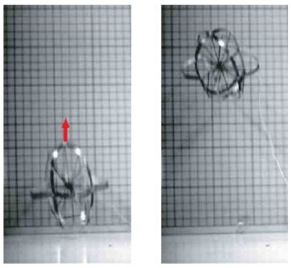
Function of Softness

- Deformation
  - Safety
  - Adaptability
  - Store and release elastic energy, entropic elasticity

Inflatable Arm
[Sanan *et al.*, 2011]

Jamming Gripper
EMPIRE



Crawling and Jumping Soft Robot
[Matsuyama, *et al.*, 2007]

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Advanced Functions

- Transformation
  - Phase-transition, jamming transition
  - Growth, self-healing
  - Biodegradable, edible
- Embodied Intelligence
  - Morphological Computation: memory, generate time series data

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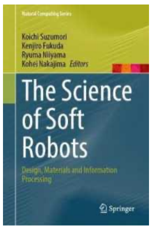
Textbook

鈴森 康一、中嶋 浩平、新山 龍馬、舛屋 賢 編著
『ソフトロボット学入門　基本構成と柔軟物体の数理』
（オーム社、2023年）



Koichi Suzumori, Kenjiro Fukuda,
Ryuma Niiyama, Kohei Nakajima Ed.
“The Science of Soft Robots”
(Springer, 2023)

Single Author

細田 耕
『柔らかヒューマノイド』
（化学同人、2016年）

新山 龍馬
『やわらかいロボット』
（金子書房、2018年）

鈴森 康一
『いいかげんなロボット』
（化学同人、2021年）

Handbook

古川 英光、川上 勝 監修
『やわらかものづくりハンドブック』
（NTS、2022年）

日本ロボット学会編
ロボット工学ハンドブック第3版
（コロナ社、2023年2月）

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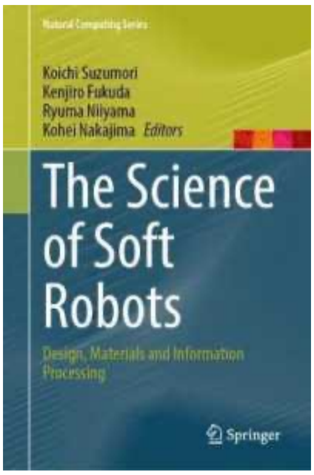
Textbook: Science of Soft Robots

1. Introduction

PART I Design of Soft Robots
2. Soft Mechanisms
3. Biological Mechanisms
4. Soft Manipulation and Locomotion

PART II Soft Materials
5. Basics of Polymer
6. Biological material
7. Flexible and Stretchable Electronics and Photonics
8. Soft actuators

PART III Autonomous Soft Robots
9. Modeling and Control of Continuum Body
10. Material Intelligence
11. Information Processing using Soft Body Dynamics



Koichi Suzumori, Kenjiro Fukuda,
Ryuma Niiyama, Kohei Nakajima Ed.
“The Science of Soft Robots”
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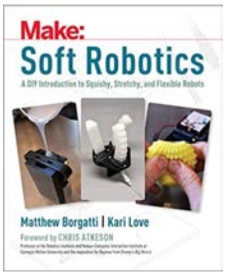
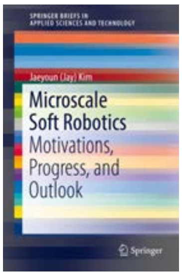
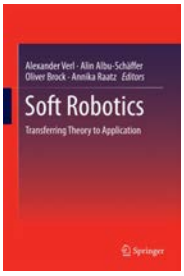


Matthew Borgatti, Kari Love
“Soft Robotics”
（Make Community, 2018）





Collection of academic papers

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ロボットアーキテクチャ

ROBOT ARCHITECTURE

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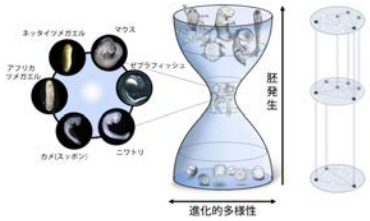
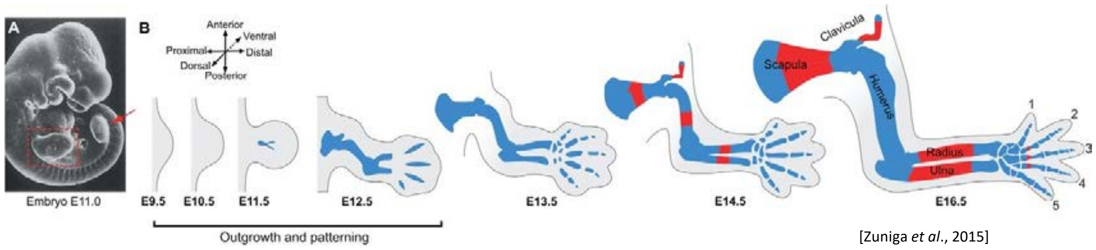
Body Plan

- Body structure and arrangement of organs in the development of multicellular organisms



[Irie., 2017]



[Zuniga *et al.*, 2015]

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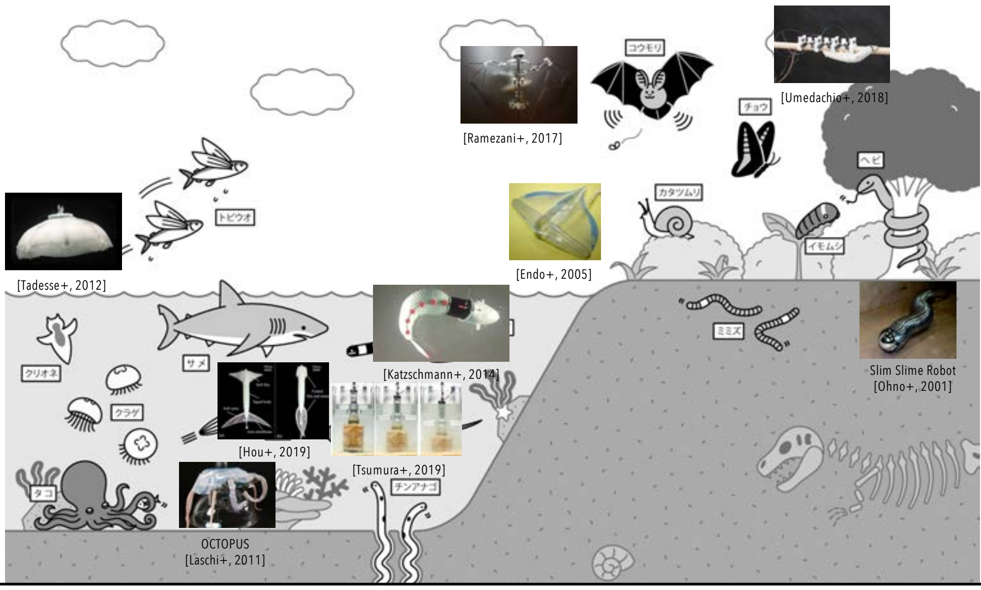
Bio-inspired Soft Robots



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Locomotion

- Terrestrial locomotion
  - Legged
  - Limbless crawling: snake, snail
  - Rolling: caterpillar
- Aerial Locomotion
  - Flapping: bee, bird
  - Gliding
- Aquatic locomotion
  - Flotage: water strider
  - Swimming : fish, eel, dolphin, salamander, penguin
    - Undulation
    - Fin
  - Jet Propulsion: squid, octopus, cuttlefish
- "Artificial" Locomotion
  - Wheel, Continuous Track
  - Jet Propulsion (gas)

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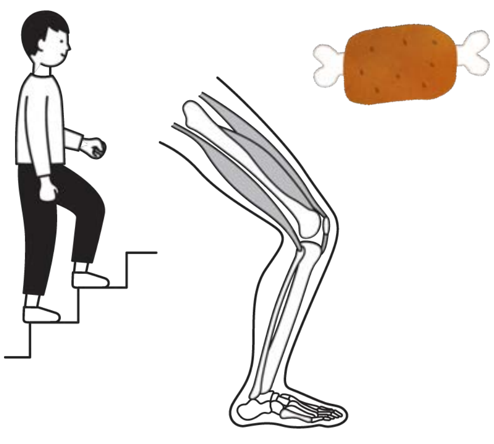
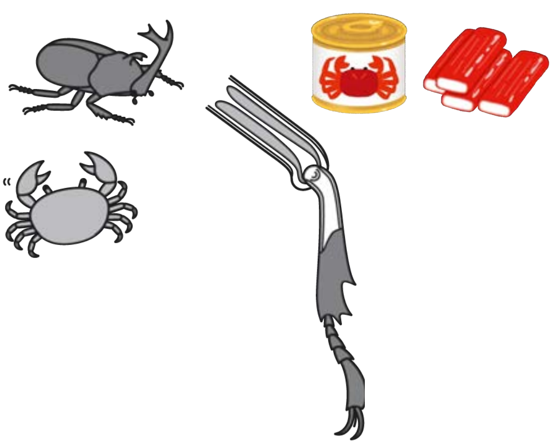
Musculoskeletal System

Endo-skeletal System 内骨格



Exo-skeletal System 外骨格



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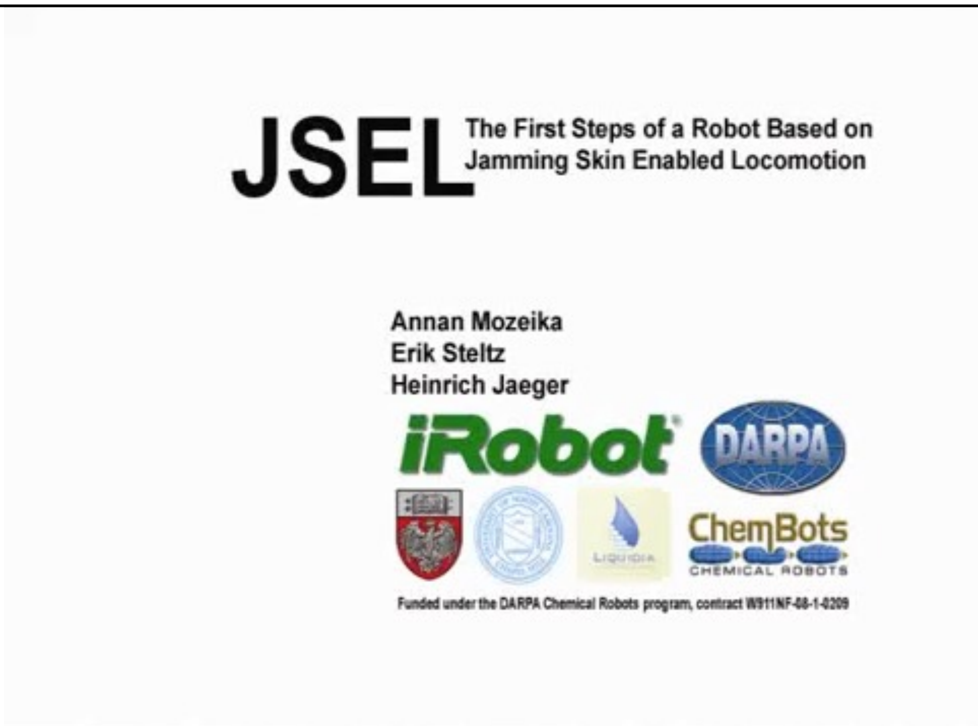

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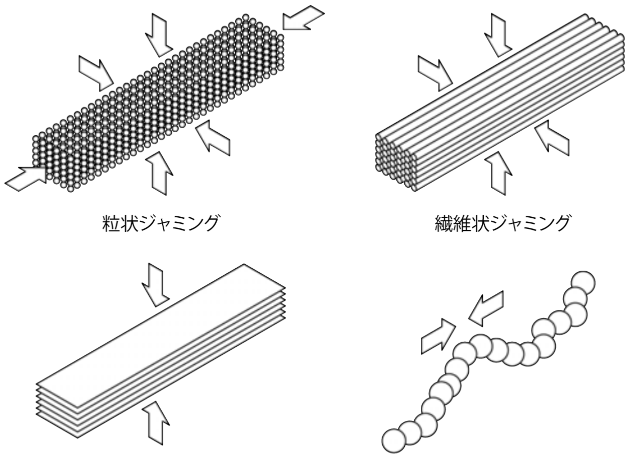
Jamming

- Granular, fiber, layer/laminar, beads



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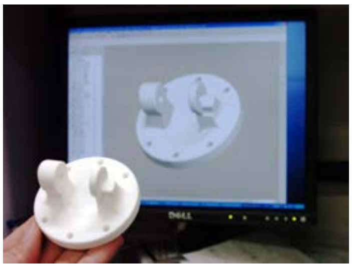
Digital Fabrication

- Making Robots with 3D Printer

Kawada Robotics, Nextage

Hack Rod by Primordial Research Project, Autodesk, and Bandito Brothers, 2016.



Stratasys Objet24

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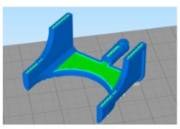
How to make a soft robot

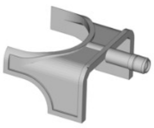
- Direct 3D printing
  Layer of light-cured resin or thermoplastic resin

- Cast molding
  Liquid soft material is poured into a mold (often 3D printed) and cured

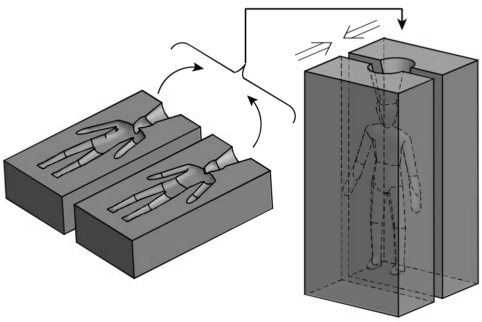


各種
スライサーソフト
ドライバソフトに入力
印刷条件の決定

3Dプリント



サポート除去
表面洗浄
UV硬化
研磨　等の後処理



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筋骨格ロボット

MUSCULOSKELETAL ROBOT

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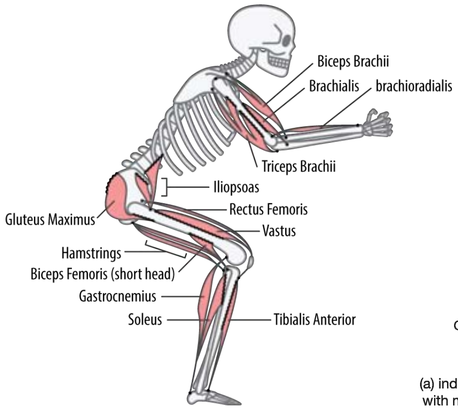
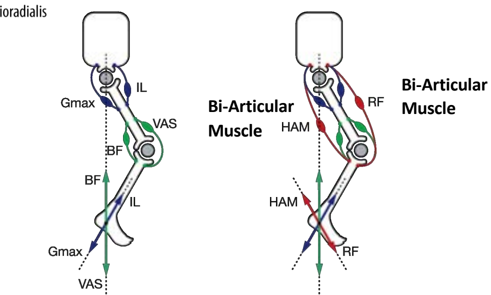
Human Musculoskeletal System

- Muscle-Tendon Complex (MTC)
  - Mono- and multi-articular muscles
  - Very difficult to emulate MTC in electric motors





(a) independently driven joints with mono-articular muscles

(b) combination of mono-articular muscles and bi-articular muscles

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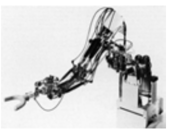
Pneumatic Artificial Muscles (PAM)

Braided-fiber

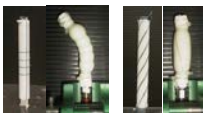

McKibben Muscle, 1957


Bridgestone-Hitach Arm
1984


Rubbertuator
[Noritsugu *et al.*, 1995]


Small-diameter PAM
[Suzumori *et al.*, 2011]

General


[Hirai *et al.*, 2001]


[Krishman, 2015]

Parallel-fiber

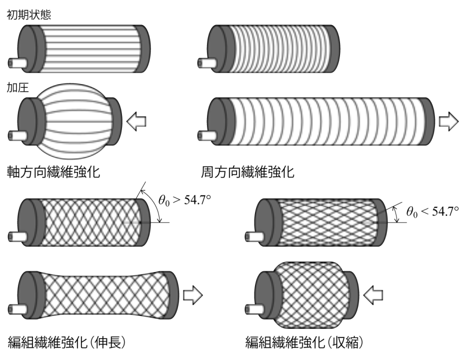

Warsaw-type, 1968


WAP-1, 1968


Pleated PAM
[Daerden *et al.*, 2001]


[Nakamura *et al.*, 2009]

Fiber-reinforced PAM Family



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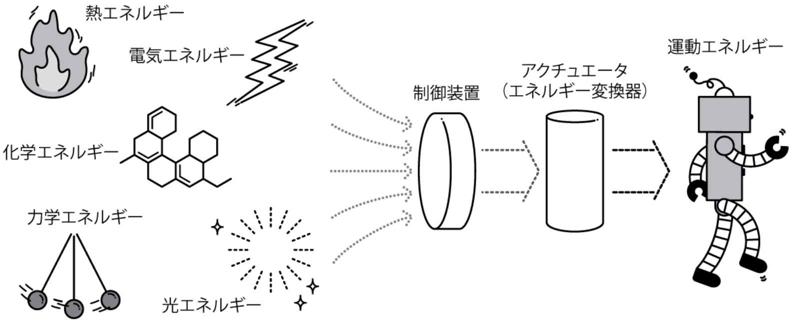
Actuator

- Actuators are Energy Converters
  - Output mechanical energy
  - The input energy can be anything
  - Controlled by information



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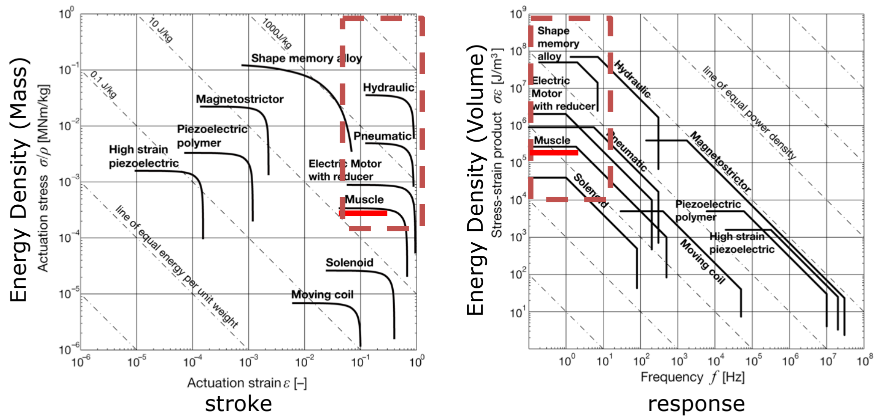
Actuator Comparison

- Challenges of Soft Acuators:
  small displacement, slow, low durability, poor availability



[Huber *et al.*, 1997] [Granosik *et al.*, 2005] [谷江, 1984] [Zupan *et al.*, 2002] [Bell *et al.*, 2005]

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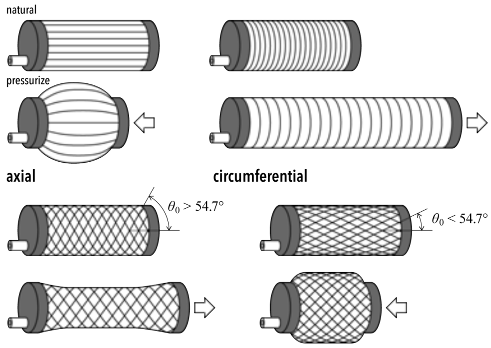
Fiber-reinforced Pneumatic Muscles



General

[Krishman, 2015]

Braided fiber

McKibben Muscle, 1957

Rubbertuator
[Noritsugu et al., 1995]

Small-diameter PAM
[Suzumori et al., 2011]

Parallel (axial) fiber

Warsaw-type, 1968

Pleated PAM
[Daerden et al., 2001]

[Nakamura et al., 2009]

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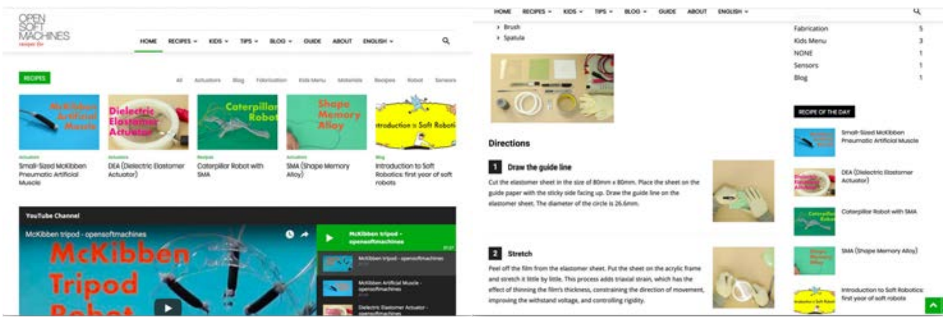
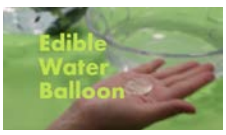
Open Soft Machines

http://opensoftmachines.com





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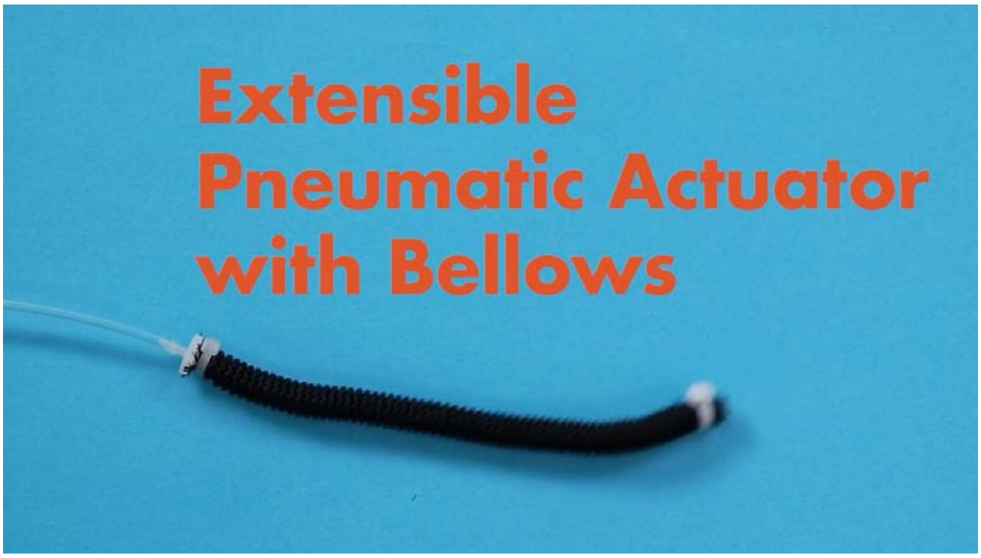

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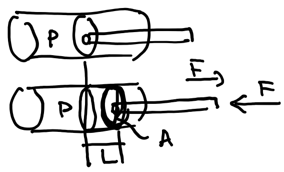
Output Work of Fluidic Actuators

仕事

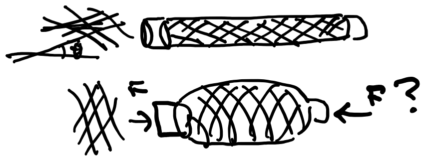
- Pneumatic Cylinders



$W_{out} = FL$

$W_{in} = PAL = PV$

- McKibben Pneumatic Artifical Muscles



$dW_{in} = dW_{out}$

$-F\,dL = P\,dV$

$\rightarrow \quad F = -P\dfrac{dV(\theta)}{dL(\theta)}$

$V = f_1(\theta)$
$L = f_2(\theta)$

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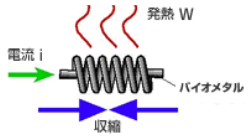
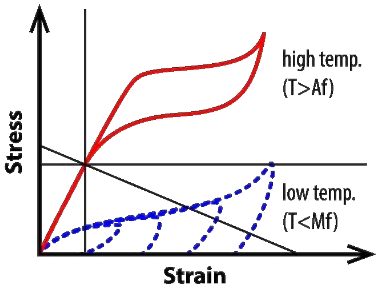
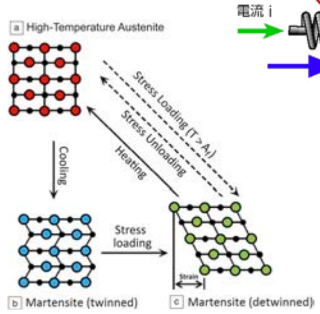
Shape Memory Alloy

- SMA
  - Ni-Ti Alloy
  - Products: Nitinol, Muscle Wires, Flexinol, and BioMetal
  - Binary, nonlinear, and hysteresis because it is based on crystalline phase transition
  - Becomes a superelastic spring when heated







[Dadbakhsh *et al.*, 2014]

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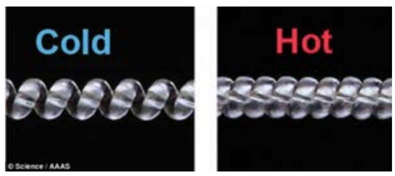
Shape Memory Polymer (SMP)

- SMP
  - Principle
    - Shape recovery by entropic elasticity when heated above the glass transition temperature Tg.
    - Shape recovery by heating above the melting point Tm, blended with a material with a low melting point.
- Crystalline polymer formed with stretching
  - Not like SMA, it works by softening
  - One-time motion: Shrink tube/film
  - Actuator: Rubber band, Twisted and Coiled Polymer (TCP)



[Haines *et al.*, 2014]

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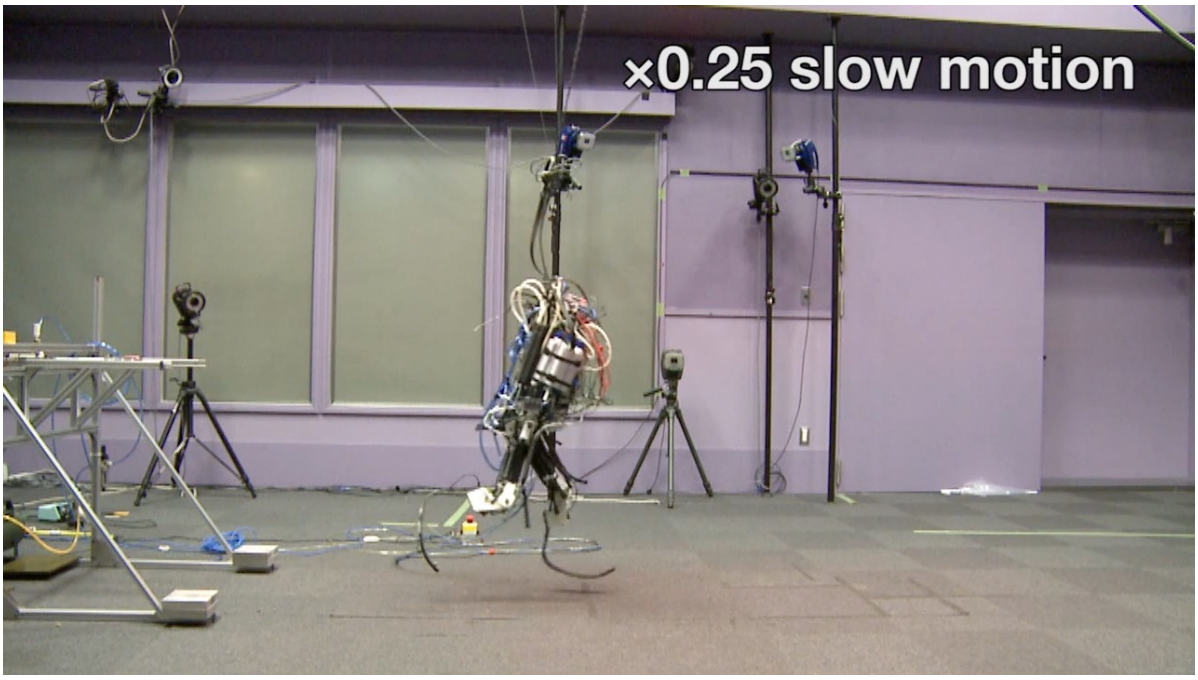

[Niiyama *et al* ., 2010]

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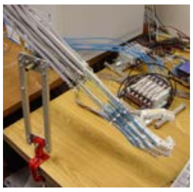
Musculoskeletal Robots

2002-2010

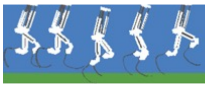

Remote handshake robot


[Niiyama et al., ICRA 2007]


[Niiyama et al ., ICRA 2009 WS]


[Niiyama et al ., 2010]
[Niiyama et al ., CLAWAR 2009]


Ars Electronica 2009


[Nishikawa et al., AMAM 2011]


[Ushigome et al ., VRMM 2010]


[Niiyama et al., 2012]
[Niiyama et al., Humanoids 2010]

2011–2013


[Nishikawa et al., 2014]
[Nishikawa et al., AMAM 2013]


[Yamada et al., IROS 2011]


[Nishikawa et al., ICRA 2016]

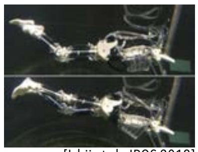

[Nishikawa et al., Humanoids 2015]

2014–present


[Fujita et al., ICISIP 2017]


[Dwindra et al., ROBIO 2018]


[Chen et al., ROBIO 2017]


[Ishii et al., IROS 2018]

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連続ロボットアーム

CONTINUUM ROBOT ARM

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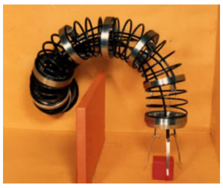
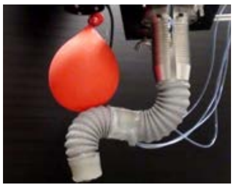
Continuum Robot Arm

- Robot arm without bones or joints, able to perform coiling and grasping, beneficial in an environment with many obstacles.
- Challenges: reaching control



Elastor [Hirose+, 1983]

OctArm [Walker+, 2006]



STIFF-FLOP [Ranzani+, 2015]

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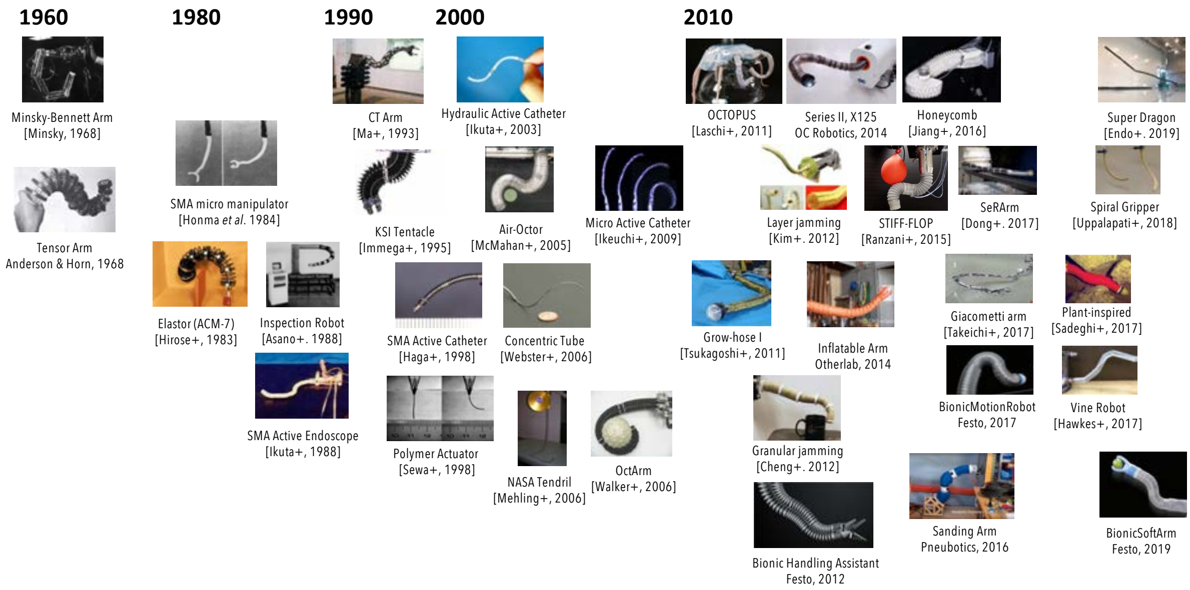
History



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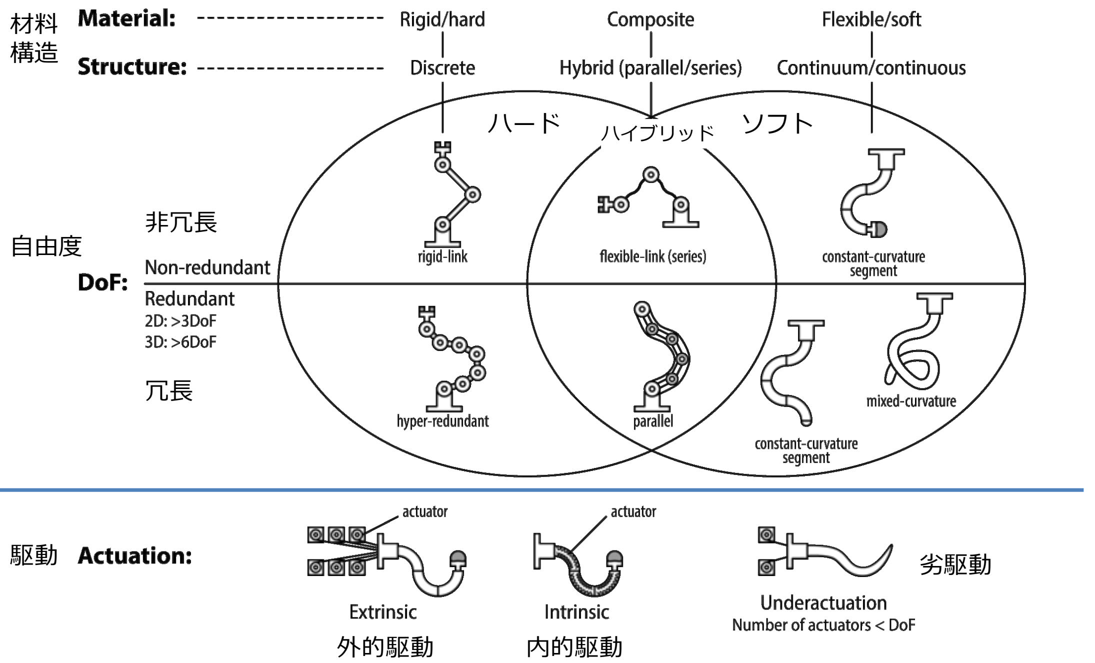

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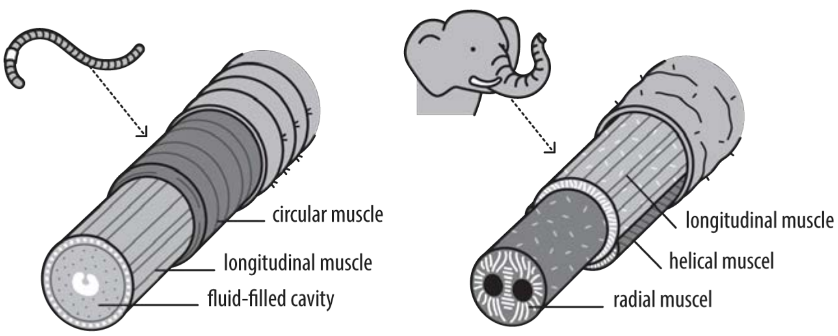
Soft Skeletal Sytem

- Hydrostatic Skeleton
  液体包骨格
  - Fluid-filled bladder surrounded by muscles
- Muscular Hydrostat
  筋肉包骨格
  - Muscle-filled hydrostatic skeleton



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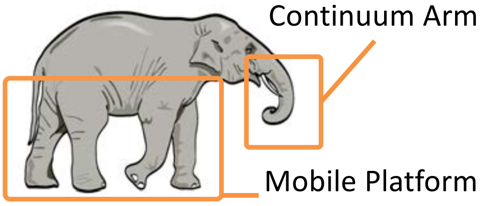
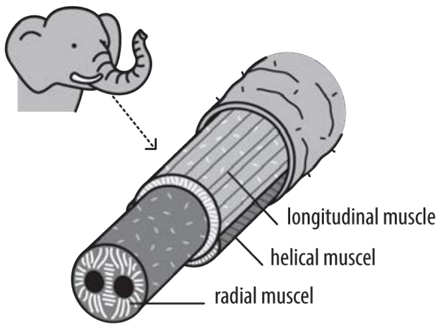
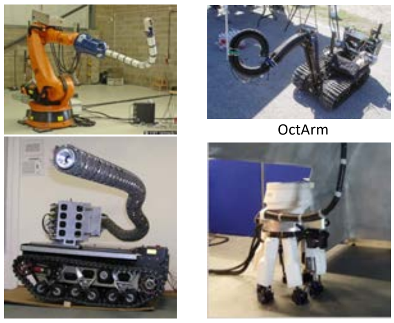
Elephant's Trunk

- Muscular Hydrostat
  筋肉包骨格
  - Muscle-filled hydrostatic skeleton







OctArm

OC Robotics

MiRoR Project

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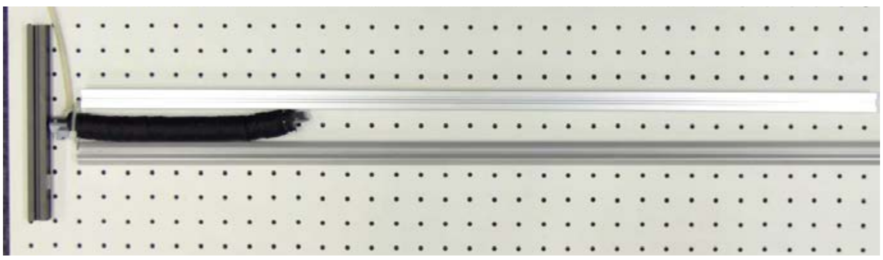
Extensible Soft Actuator

- EPAB (Extensible Pneumatic Actuator with Bellows)
  [Yukisawa *et al.*, ROBIO2017]



Related Works

McKibben PAM (α > 54.73°) | Hydro Muscle [Sridar+, 2016] | Elastomeric Origami [Martinez+, 2012] | Shell-reinforced SPA [Agarwal+, 2016] | Inverse PAM [Hawkes+, 2016] | Pneumatic Reel Actuator [Hammond+, 2017] | Continuum arm [Ansari+, 2017]

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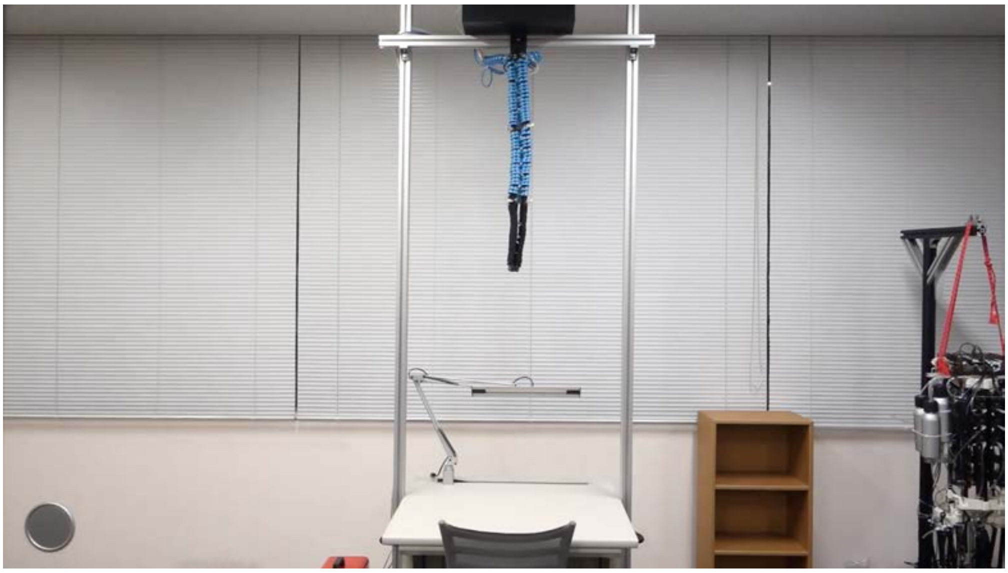
Ceiling Continuum Arm

[Yukisawa *et al.*, ROBIO 2017]
[Yukisawa *et al.*, RoboSoft 2018]



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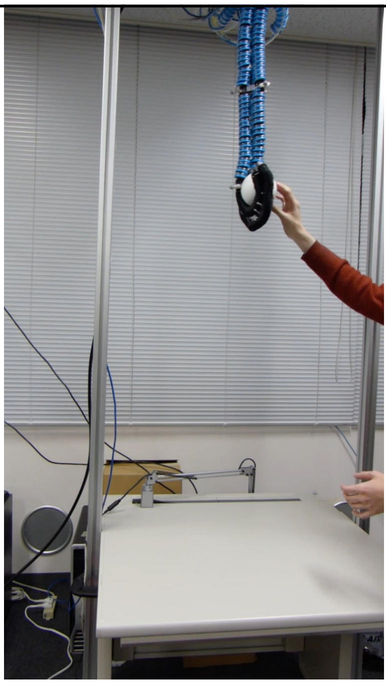
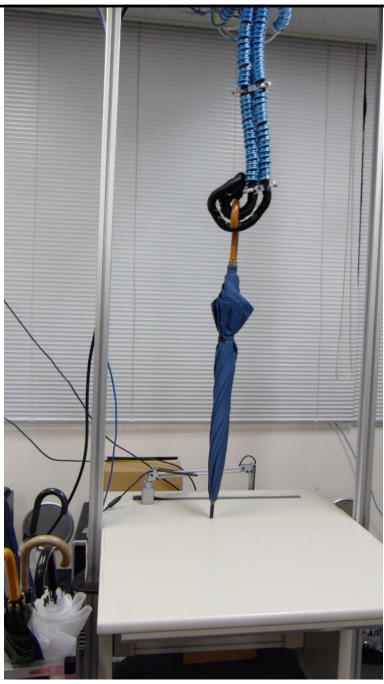


Throwing a ball



Pulling out an umbrella

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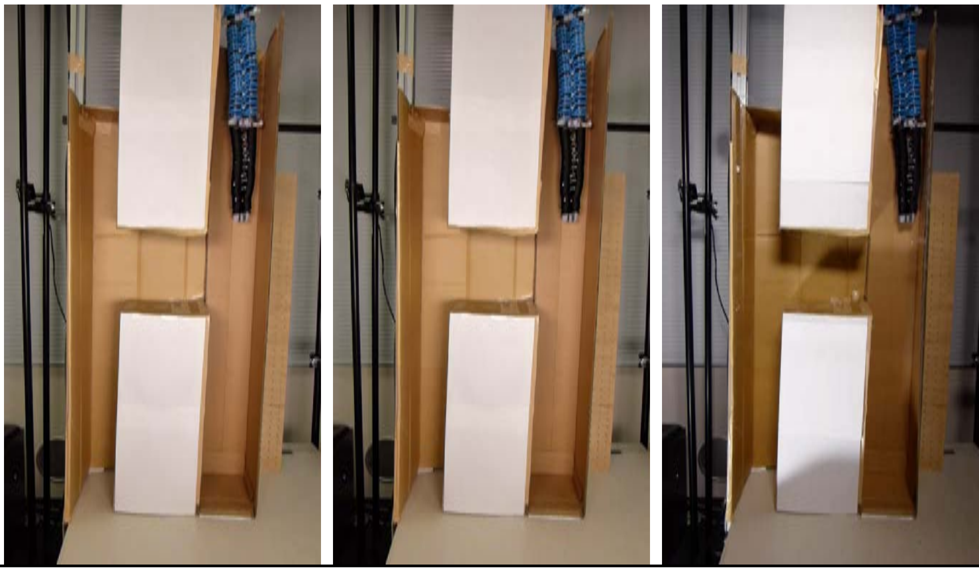
Maze Tasks (feedforward control)



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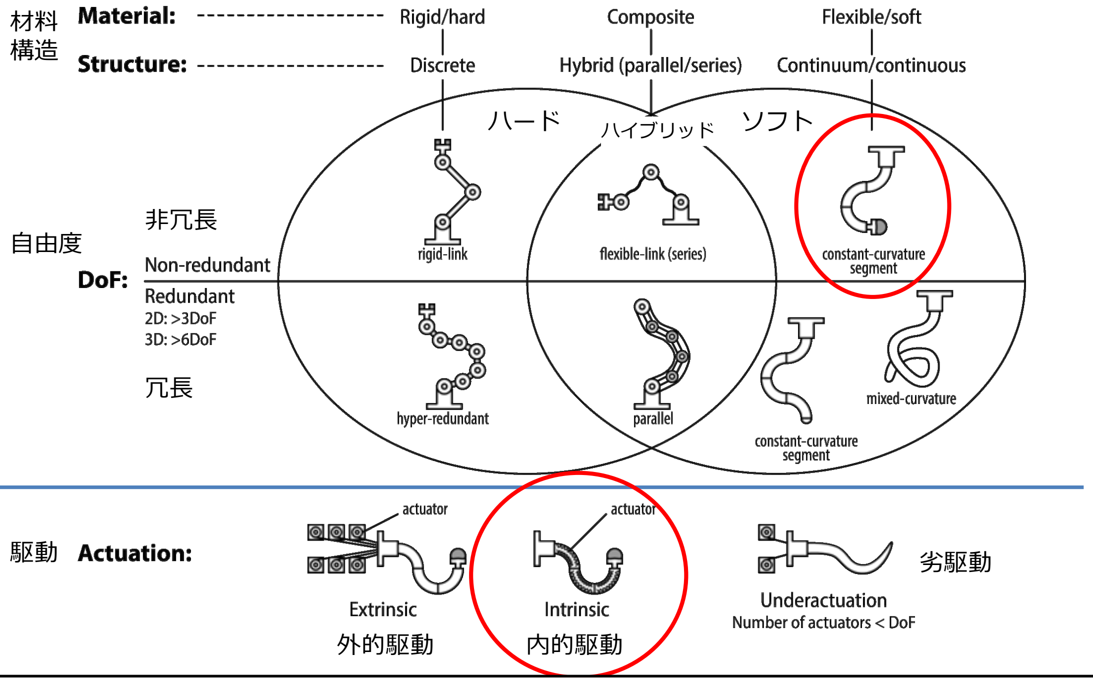

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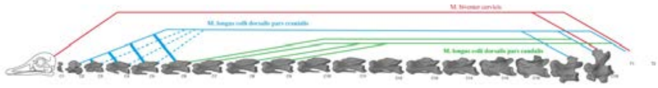
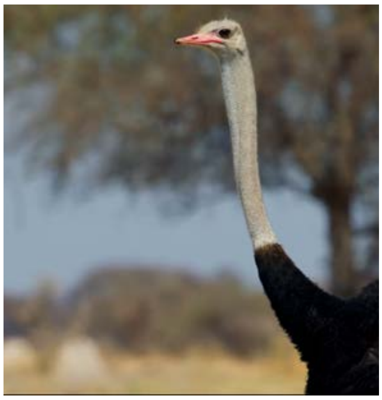
Hybrid RobOstrich Manipulator

[Manome *et al.*, 2024]





https://www.youtube.com/watch?v=KL6ZmgbG-z8

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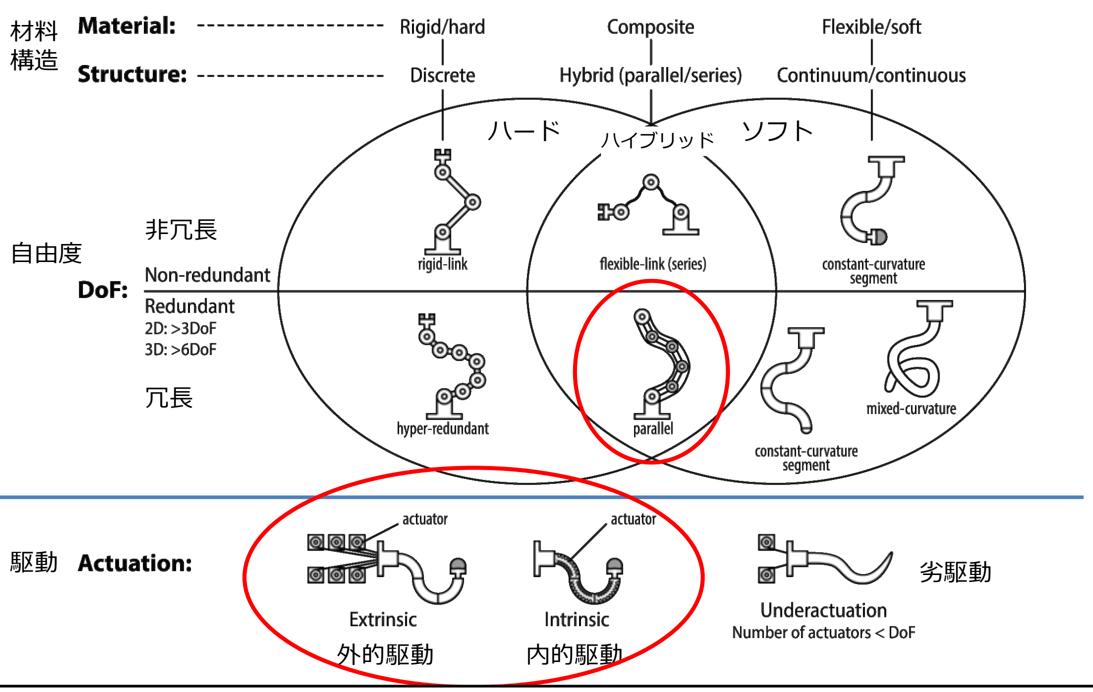

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インフレータブルロボット

INFLATABLE ROBOTS

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Inflatables


Rubber balloon


Swim ring


Inflatable castle


Hot air balloon

Foil balloon


Inflatable boat


Wacky waving tube


Inflatable dome

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Inflatable Robots

Robots using a membrane structure supported by internal pressure.
Large, lightweight, and can be folded by deflating.


Inflatable robot arm, Otherlab, 2011


Inflatable arm [Sanan, *et al.*, 2011]


Inflatable arm, iRobot, 2012


Vine-inspired robot [Hawkes+, 2017]

Baymax, Disney, 2014


Soft upper body [Alspach+, 2015]


King Louie, Pneubotics [Best+, 2015]


Isoperimetric soft robot [Usevitch+, 2020]

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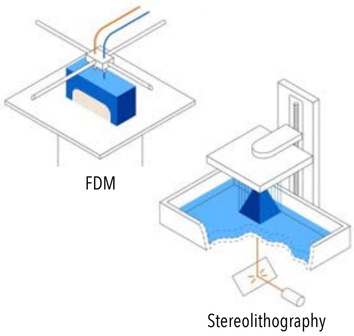
Why membrane-based robots?

- Fabrication Challenges of 3D Soft Robots
- Start from 2D: compact, affordable, ease of production

Raise the dimension from 2D to 3D

Layering: 3D Printing



Folding: Origami Robots


Origami Robot [Felton *et al.* 2014]

Blowing: Inflatable Robots

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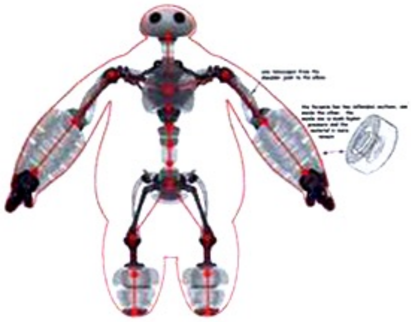
Baymax from “Big Hero 6”



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WPI-CMU team
Atlas robot with inflatable suit

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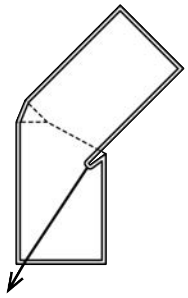
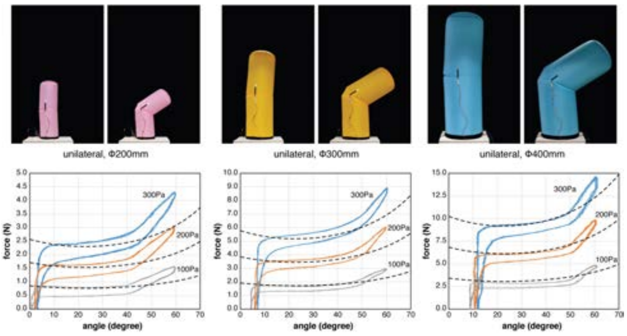
Inflatable Joint



- Blower-powered Soft Inflatable Joints [Seong *et al.*, RoboSoft 2019]
  - Active control of the internal pressure
  - Driven by tendon wires pulled by linear actuators
  - Theoretical models for both unilateral and bilateral joints



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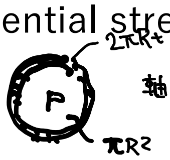
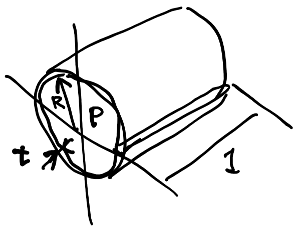
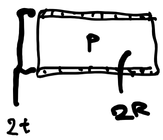
Theory of thin-walled cylinder

- Axial stress and circumferential stress
  - Area under pressure



軸応力 $\sigma_a = \frac{P\pi R^2}{2\pi R t} = P\frac{R}{2t}$





円周応力 $\sigma_c = \frac{P2t}{2t} = P\frac{R}{t}$

$\sigma_a : \sigma_c = 1 : 2$

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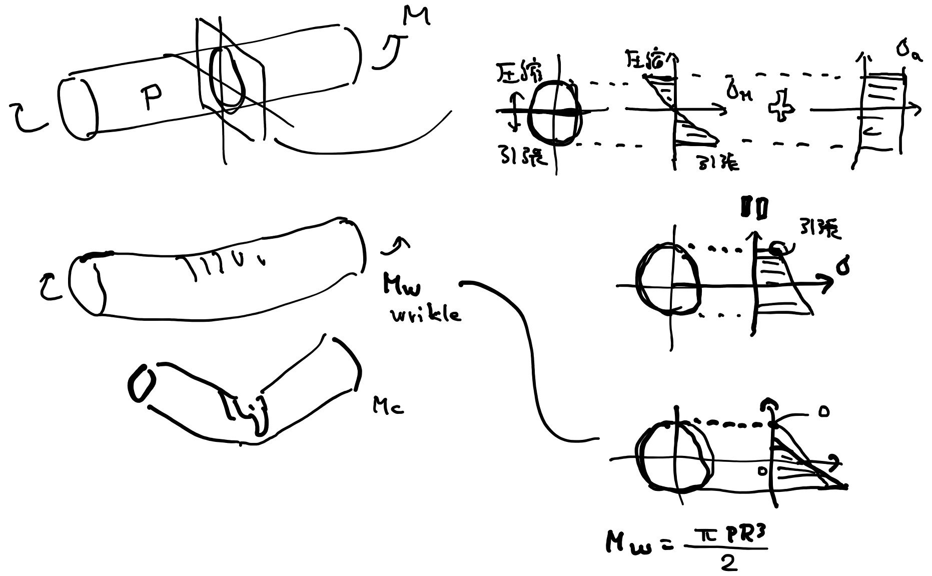
Inflatable beams subjected to bending



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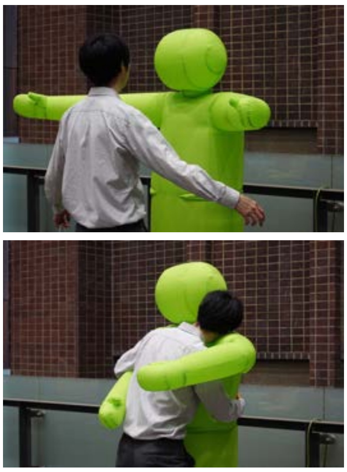
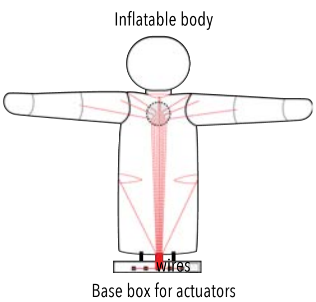
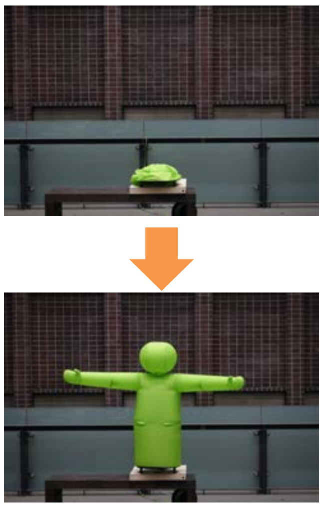
pHRI (physical human-robot interaction)

- Inflatable Humanoid Robot, 6 DoF







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Physical Human–Robot Interaction

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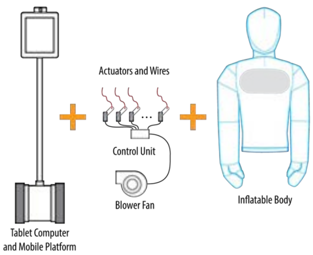
Avatar Application



[Niiyama *et al.*, IJAT 2023]

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Summary

- Softness expands the possibilities of robotics
  - Deformation and transfromation
  - Continuum Body
- Soft Body Plan
  - Musculoskeletal System
  - Continuum Arm
  - Inflatable

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Assignment

- ソフトロボットに関する査読付き原著論文を1つ読み、提案されているロボットの形状、素材、アクチュエータ、センサ等を1枚の手描きのスケッチで図解してください。また、数百ワードで論文の背景、目的、方法、結果をまとめてください。
  取り上げた論文の書誌情報（著者、タイトル、ジャーナル名と巻・号、または国際会議名とページ番号、発表年）をアクセスできるDOI等のリンクを明記すること。
- Read one peer-reviewed original paper on soft robotics and create a single hand-drawn sketch that illustrates the proposed robot’s shape, materials, actuators, sensors, and other key components. In addition, write a few hundred words summarizing the paper’s background, objective, methods, and results.
  Clearly cite the paper you chose, including full bibliographic information—authors, title, journal name with volume and number or conference name with page numbers, and year—and provide an accessible link.
- 締め切り：2週間後

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