ETH
Eidgenössische Technische Hochschule Zürich
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The Next Challenges in Bio-Inspired Robotics

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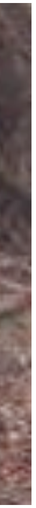
FNSNF
Swiss National Science Foundation

BIRL
Bio-Inspired Robotics Lab

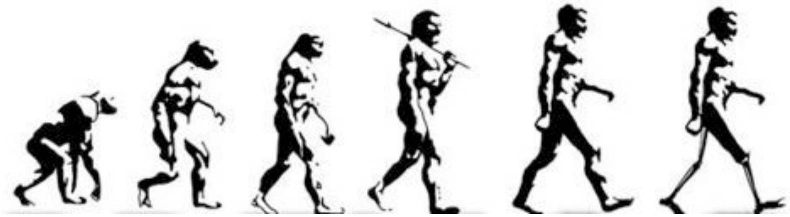

Boston Dynamics


Boston Dynamics

Robot vs. Animal



The Principle of Self-Organization



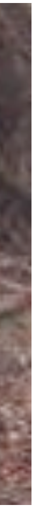
Three time perspectives

- Evolutionary
- Developmental
- Here and Now

Everything is continuously growing/adapting/changing

- Genetic components
- Musculoskeleton
- Nervous systems
- Sensory systems

Characterization of Biological Locomotion



(as compared to engineered locomotion)

- No cable attached

  Energetically autonomous!

- Many many tasks to do

  Intrinsically general purpose systems!

- Always in unstructured task-environment

  Never visit the same state again!

- No static components in the body

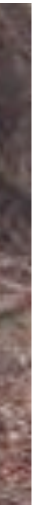
  Everything is changing over time!

- No human designers

  Everything is self-organized!

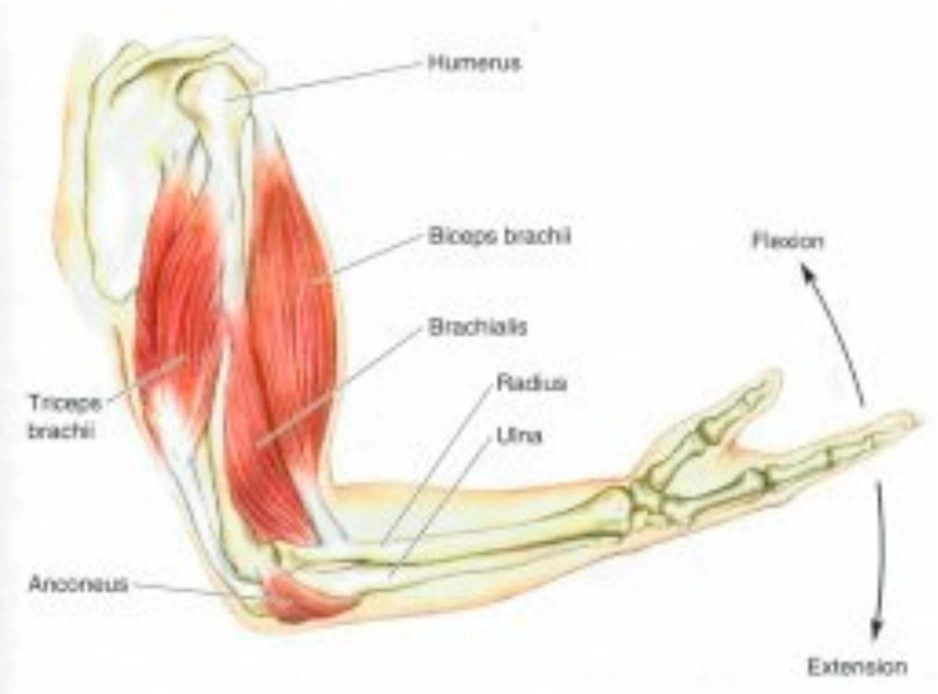
Biological Muscle

What are the Functions of Muscles?



- Generating forces
- Heat production
- Damage avoidance
- Connecting limbs
- Food?
- Attracting women (or men)!
- Etc.

Musculoskeletal Structure



Modularity

A similar component (e.g. muscle fibers) is used repeatedly

Redundancy

Many muscles (muscle groups) are controlling one joint

Diversity

Muscles are organized into any variations (e.g. cardiac-skeletal, mono-biarticular)

Low-Level Sensory Motor Process

High Sensor Density

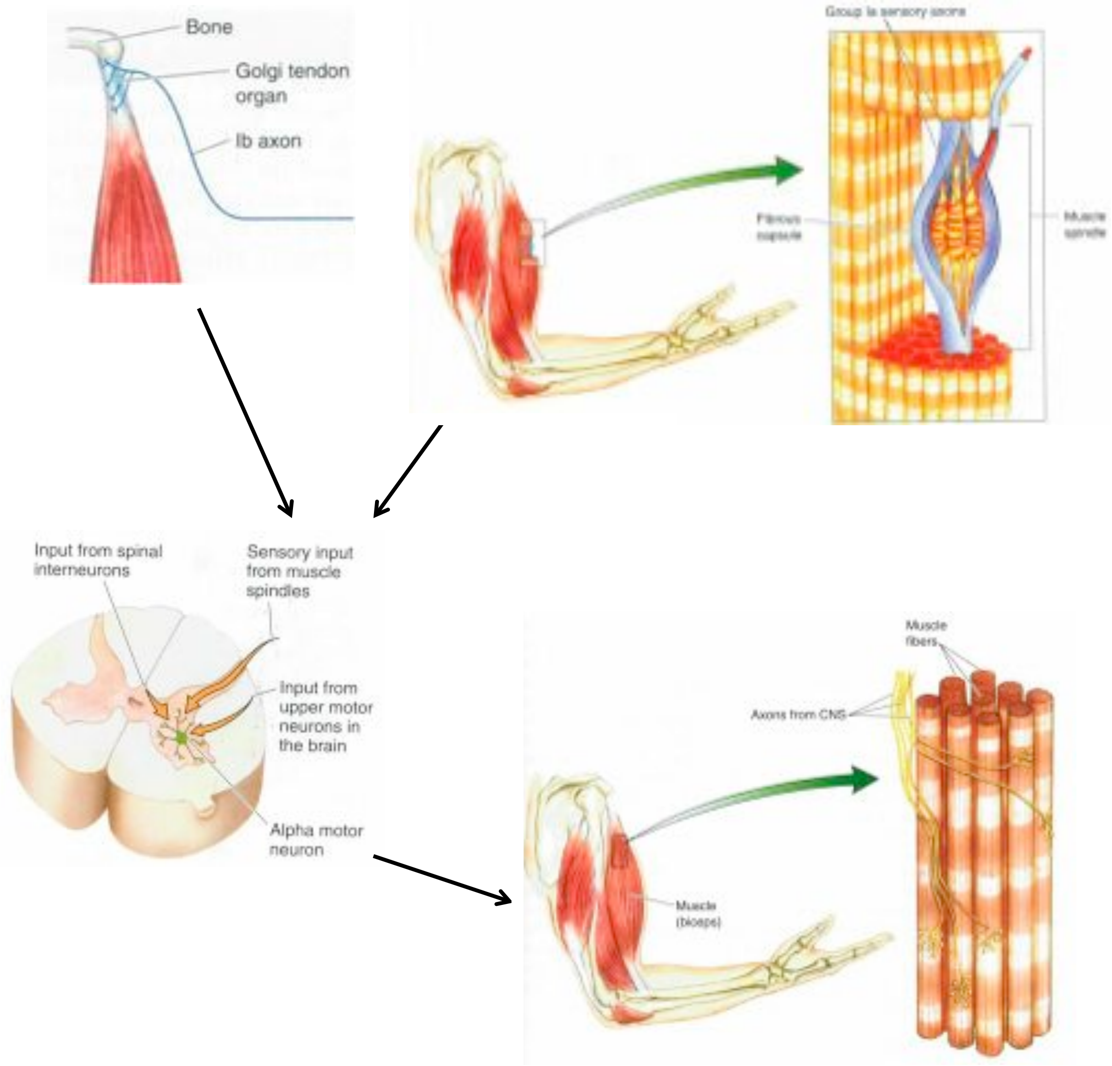
Force and length sensors are everywhere

Distributed Control

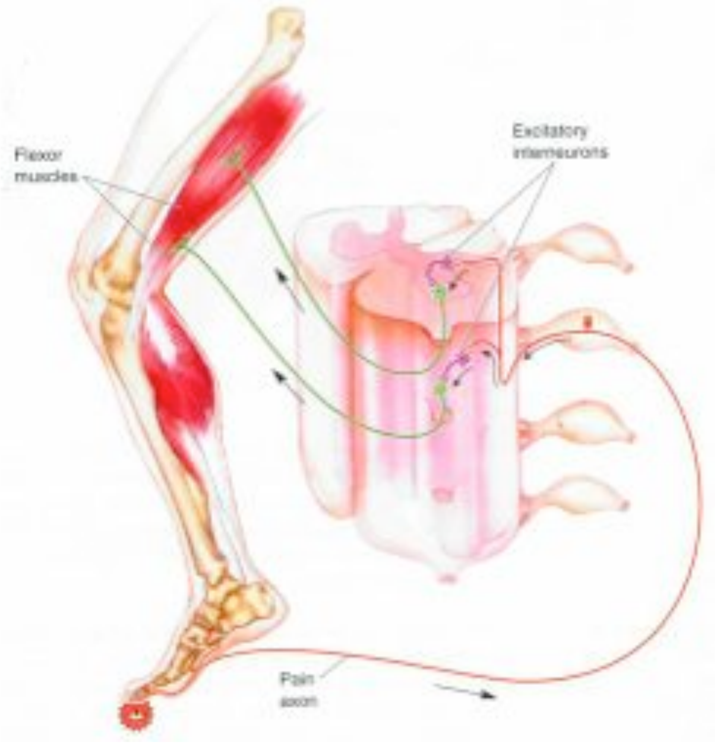
Many reflexes are in spinal cord

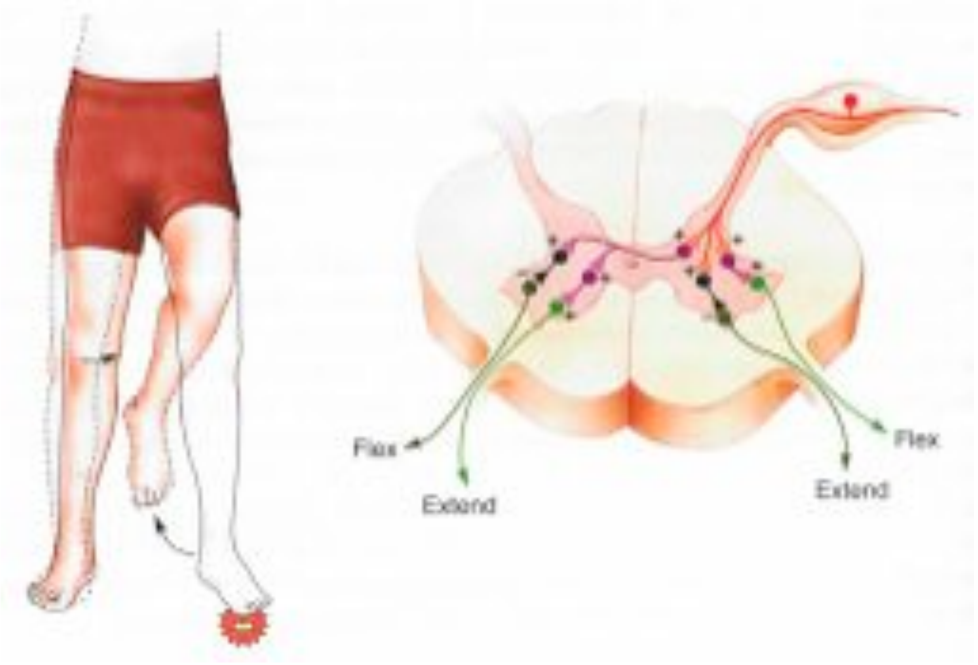
Parallel Processes

Many computational processes run in parallel



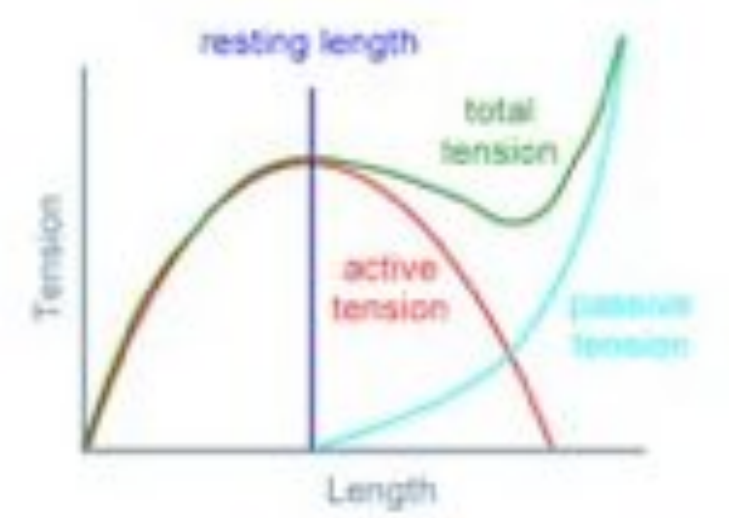
Complex Reflexes



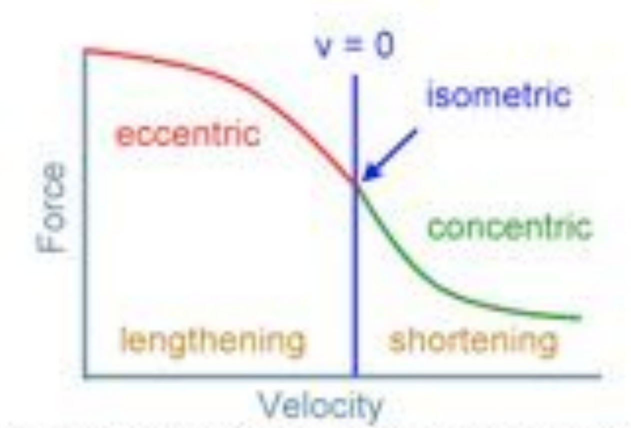


George Lauder @ Harvard

Passive and Active Dynamics



Length-Tension Curve of a Muscle



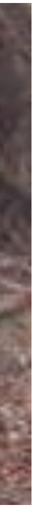
Force-Velocity Curve of a Muscle

Muscles can be:

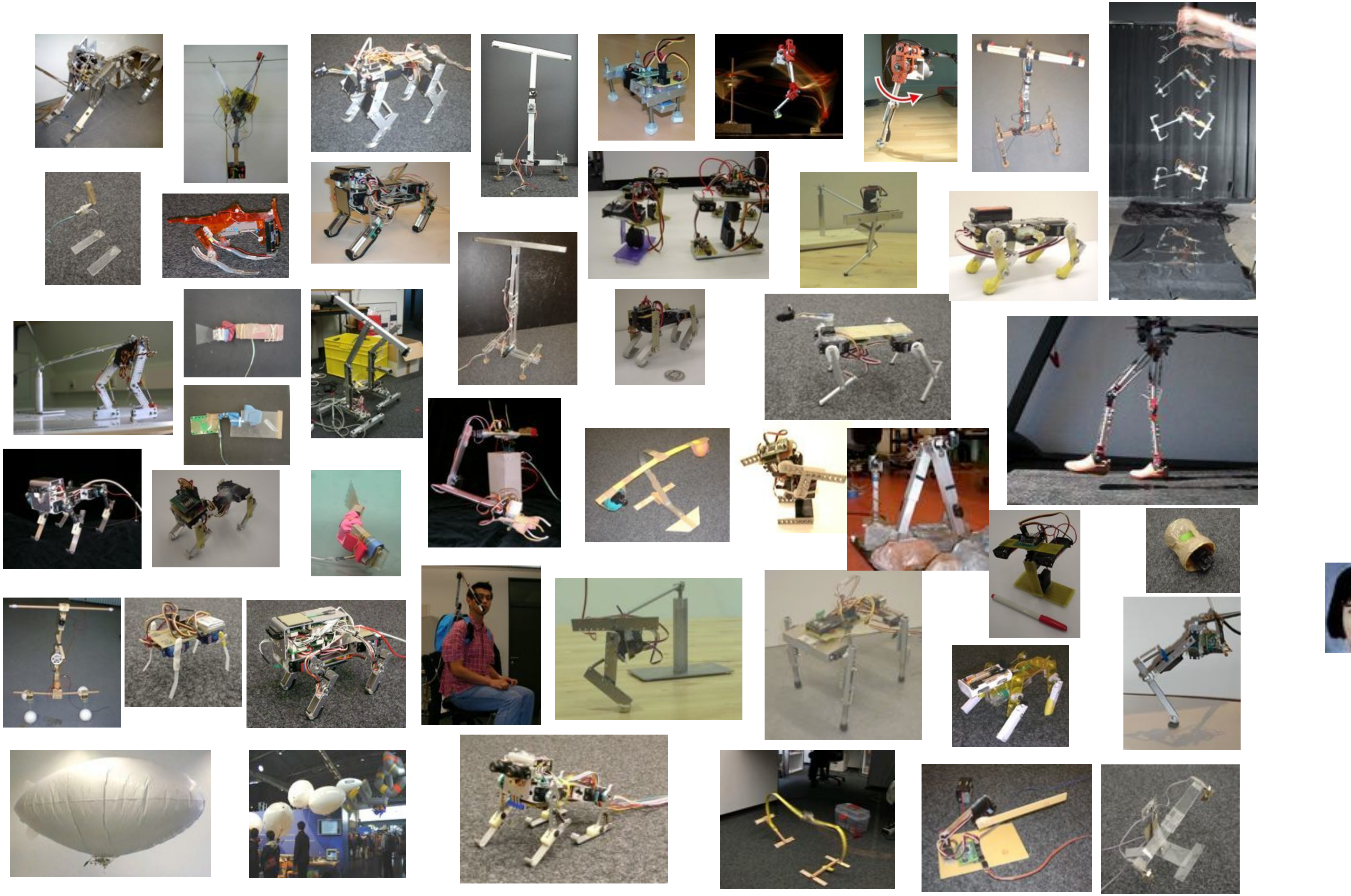
- Active force generator
- Passive nonlinear spring
- Nonlinear damper

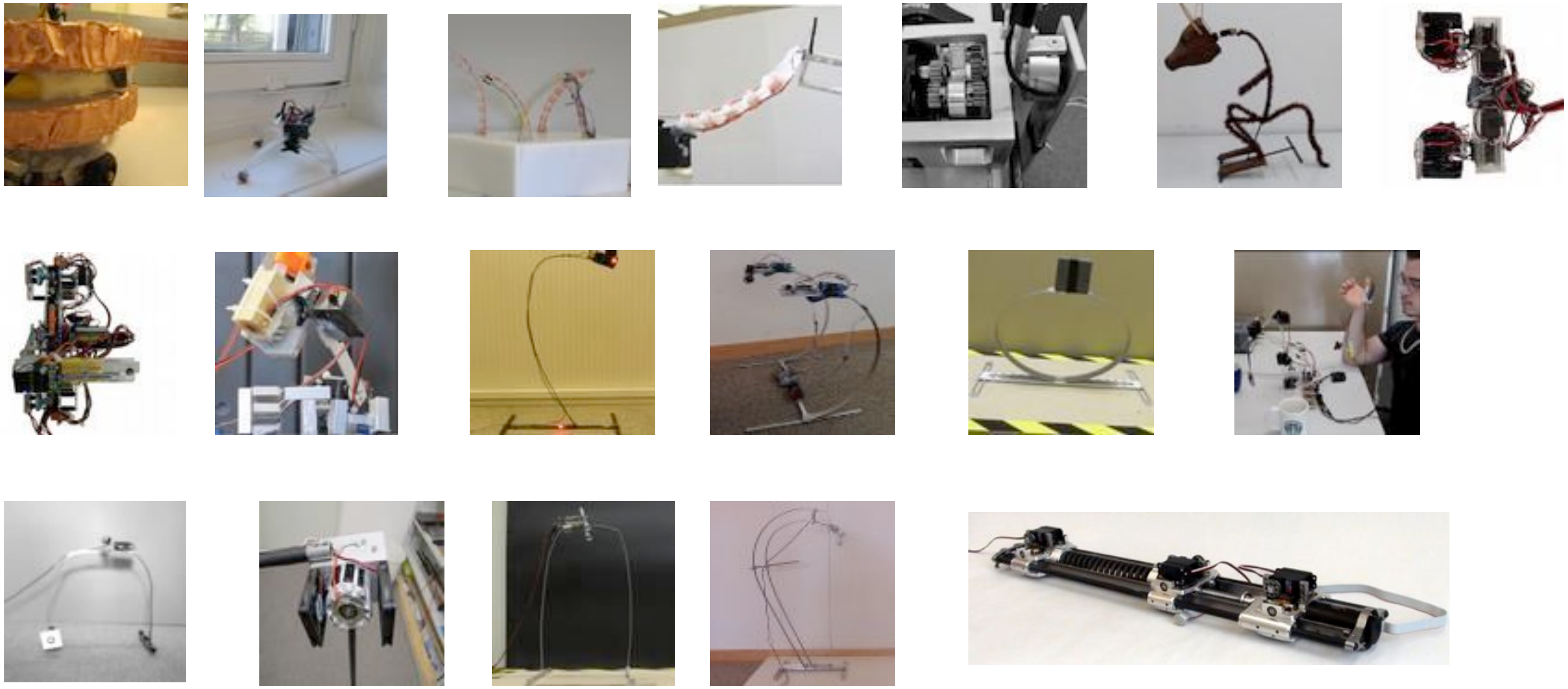
Theo Jansen, Strandbeast

Summary of Biological Muscles



-Many functions
-Modularity and repeating structures
-Many redundancies and variations
-Large diversity in the use of modules
-Many low-level sensory-motor couplings
-Not simple force generators
-Not simple springs
-Not simple dampers





More to come…

Bio-Inspired Actuation

How to Replicate Biological Muscles?

Generating forces

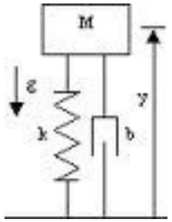
(Electric, hydraulic motor, etc.)

Connecting Limbs

(Joint actuation, tensegrity, etc.)

Enhancing and protecting structures

(Spring-damper-mass systems, etc.)



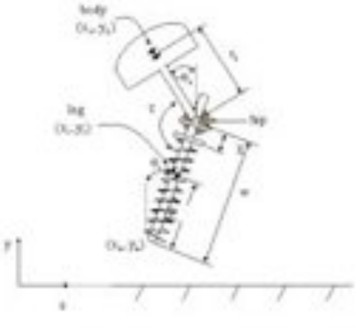


Figure 1. One-legged robot model for analysis and simulation.

Regulating motions

(Four bar mechanisms, etc.)

Comparing Biological and Man-Made Muscles?

Breaking Tension

Muscle	**100-1000 kPa**
Tendon	**100 MPa**
Steel wire	350 MPa

Power Density

Muscle	**50-200 W/kg**
Electic motors	100-200 W/kg
Car engines	400-1000 W/kg
Aircraft engines	1500-5500 W/kg
Pneumatic	10’000 W/kg
SMA	6 W/kg

Challenges of Bio-Inspired Robotics

1. Energy Efficiency
2. Self-Stability
3. Behavioral Diversity
4. Adaptive Mechanics

Energy Efficiency

Energy Efficiency & Behavioral Diversity

Robots

Animals

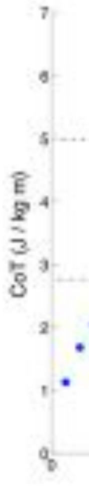
Gabrielli- von Karman Diagram

Energy Efficiency of Walking Systems

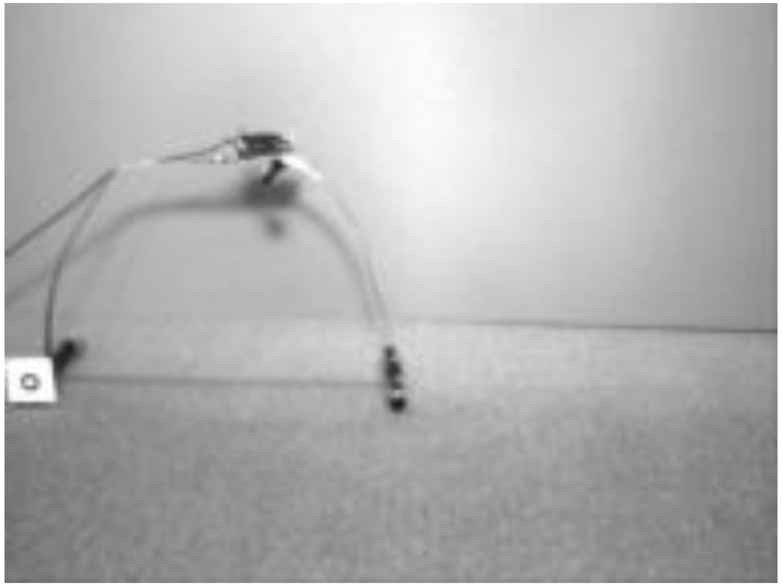
	Human	ASIMO	Cornell Biped
Energetic cost (J/Nm):	0.2	3.2	0.2
Velocity (m/s):	≈2	≈0.5	0.4

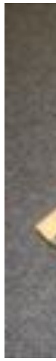
Hopping with Free Vibration of Curved Beam

Reis and Iida, 2011



Locomotion with Curved Beams





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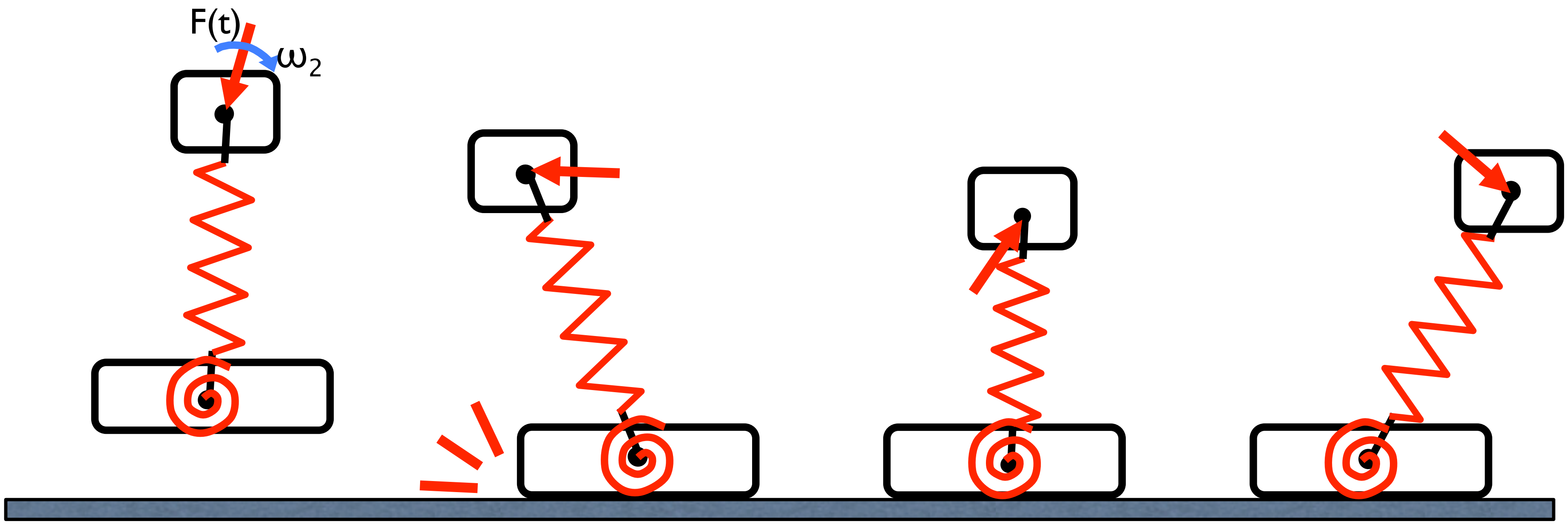
Physics and Economy of Hopping

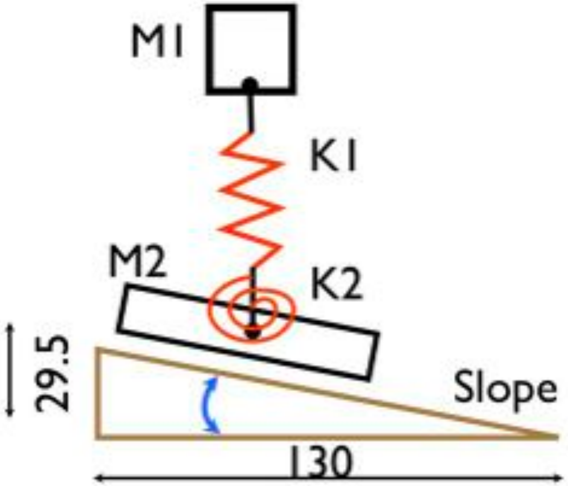


Cost of Transport = Cost of actuation

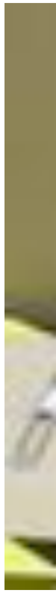
+ Cost of mechanical impact

+ Cost of mechanical damping

Passive Hopping with a Curved Beam



M1 = 4.5 Kg
M2 = 0.25 Kg
K1 =~ 4.2 KN/m
K2 =~ 135 Nm/rad
Speed = 0.55 m/sec
Slope =~ 0.118 radians
CoT =~ 0.22

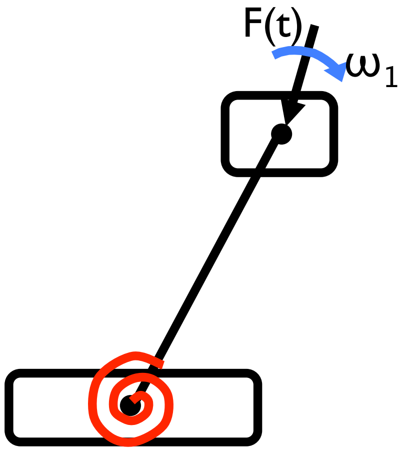


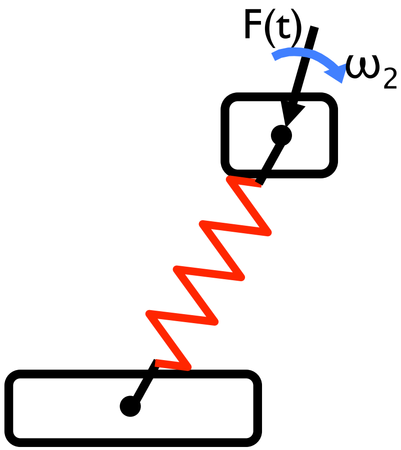
Gunura, K., Reis, M., Iida, F. (in preparation).

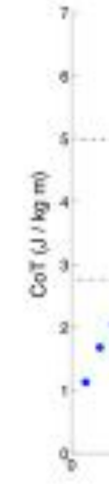
Free Vibration of a Curved Beam

ω_θ=7.9rad/s

ω_r=31.4rad/s

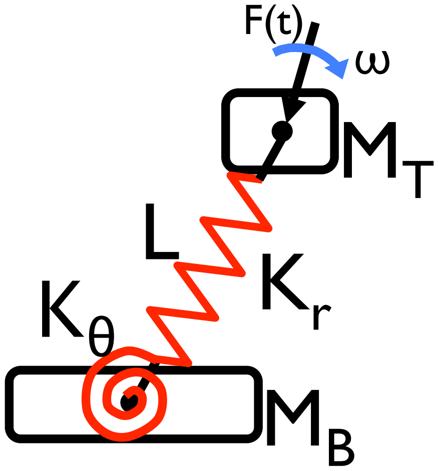






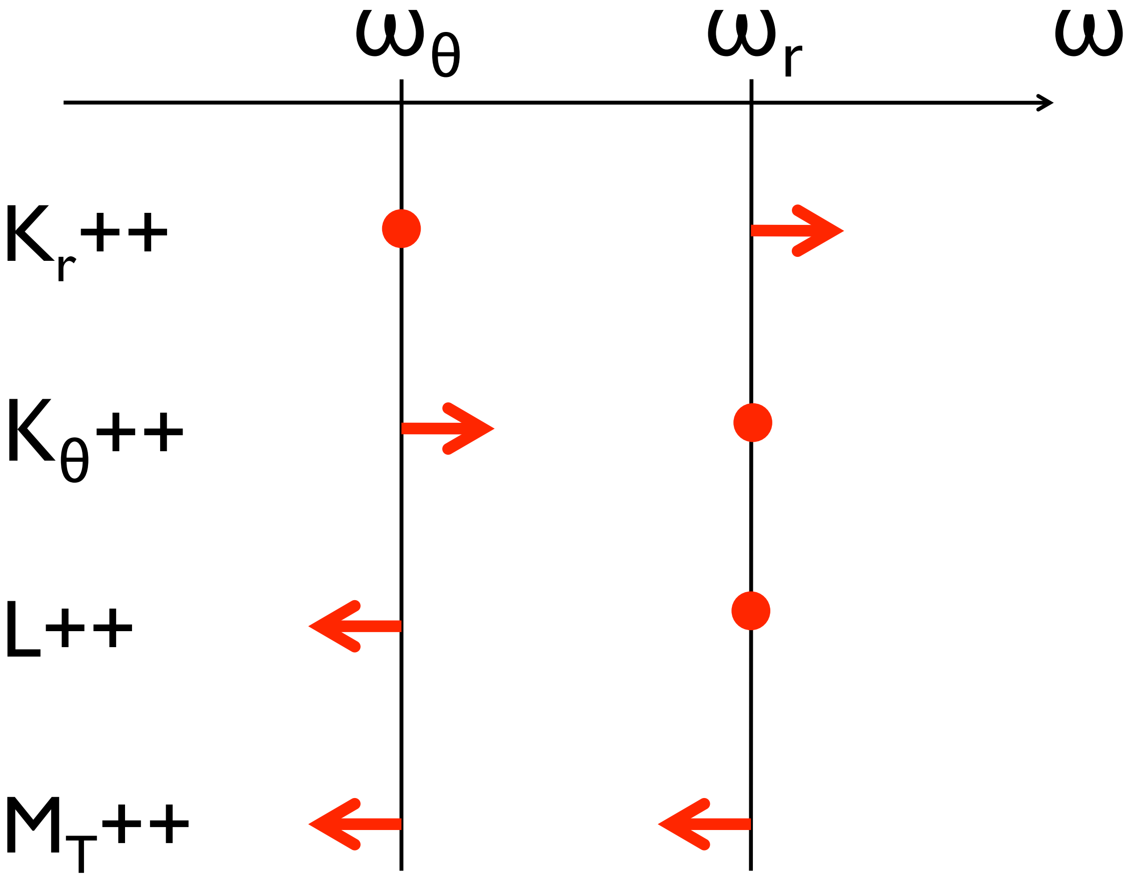
Reis

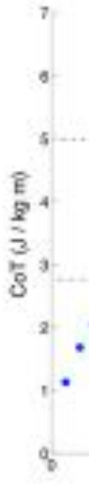
Design of Mechanical Dynamics



$$\omega_\theta = \sqrt{\frac{K_\theta}{I_\theta}} = \frac{1}{L}\sqrt{\frac{K_\theta}{M_T}}$$

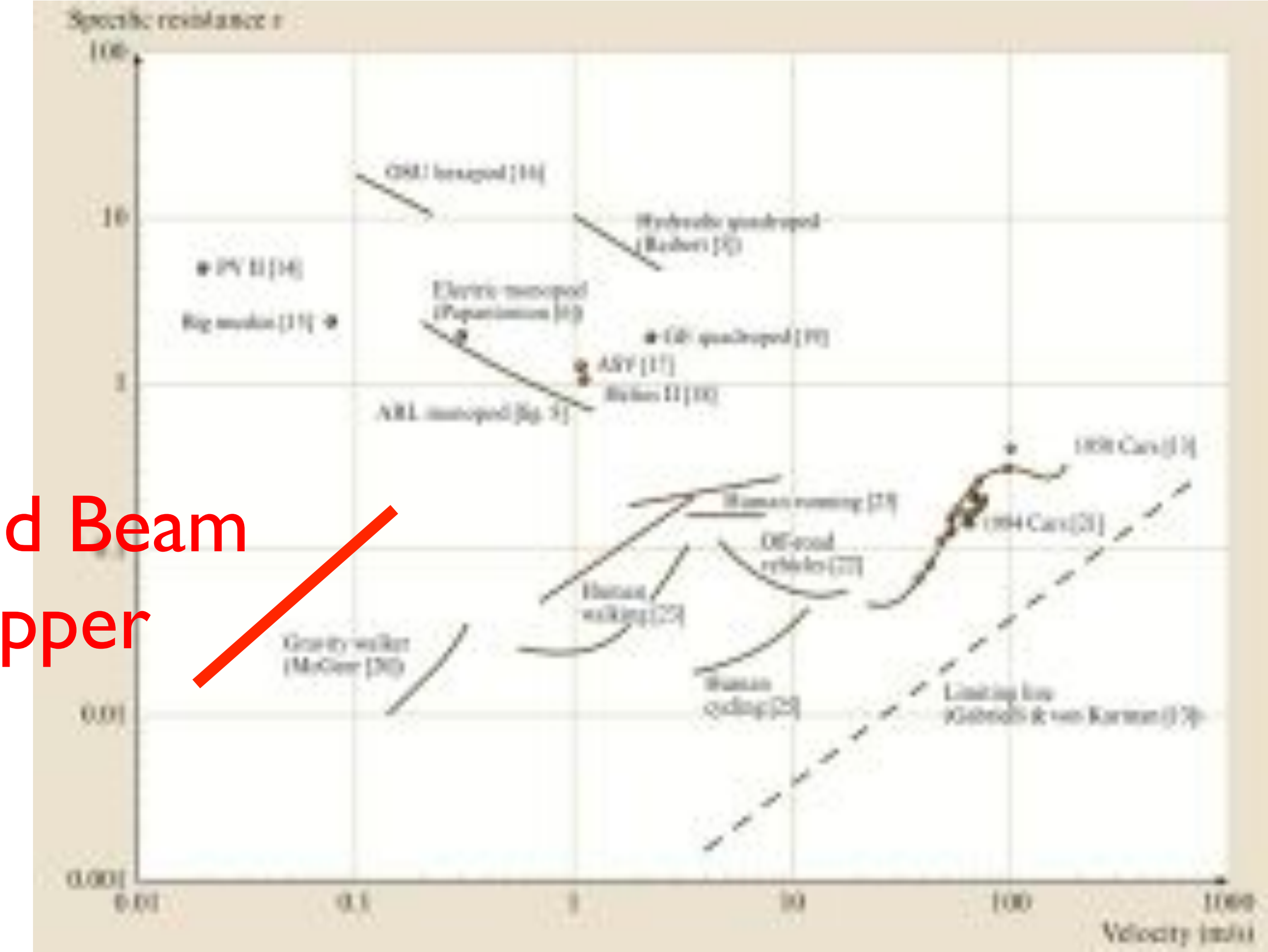
$$\omega_r = \sqrt{\frac{K_r}{M_T}}$$





Reis

Locomotion Efficiency with Free Vibration



Curved Beam
Hopper

Gabrielli- von Karman Diagram

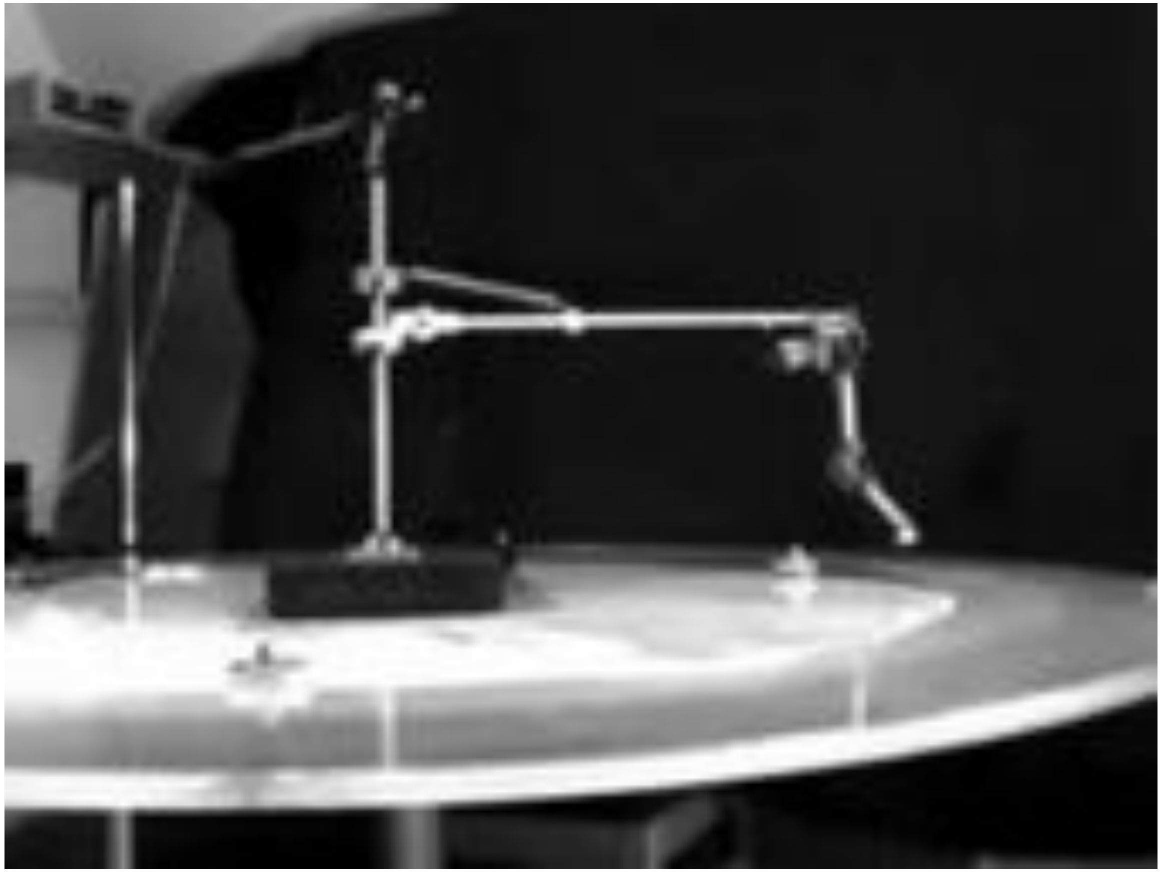
Take-Home Message 1

For energy efficient motion control,

- do not rely on actuation
- exploit passive dynamics
- collision with small mass
- store energy in springs

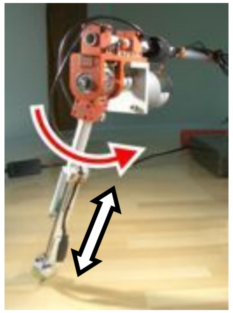
Self-Stability

Simple Hopping Robot



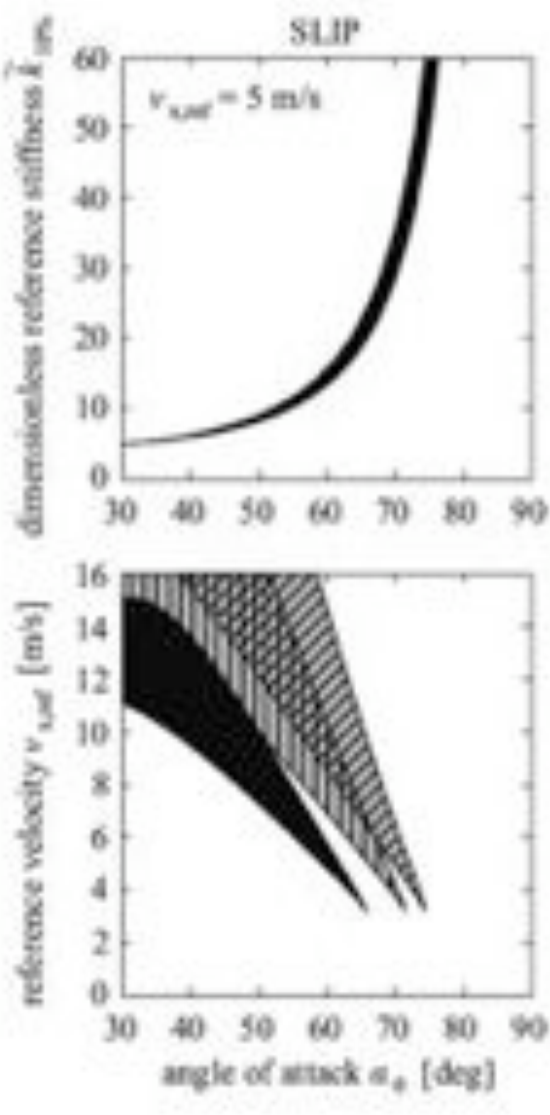
Bio-Leg I (University of Jena)
Rummel, J., Iida, F., Seyfarth, A. (2008) *ICRA2008*, 367-372.

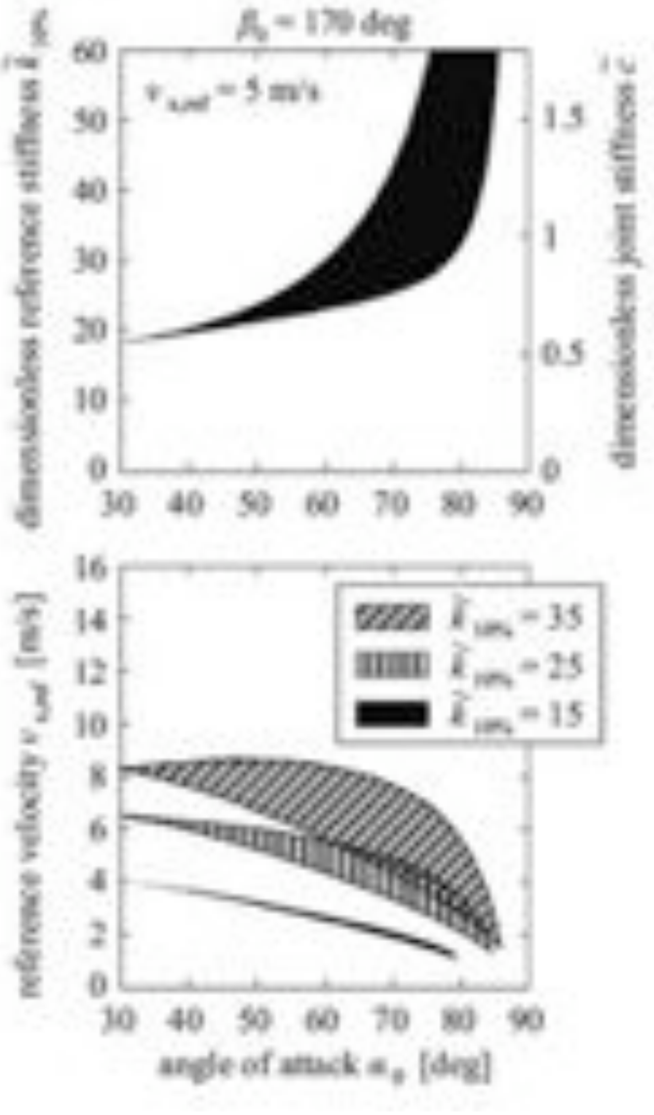
Design Principle of Hopping Robot



Stability

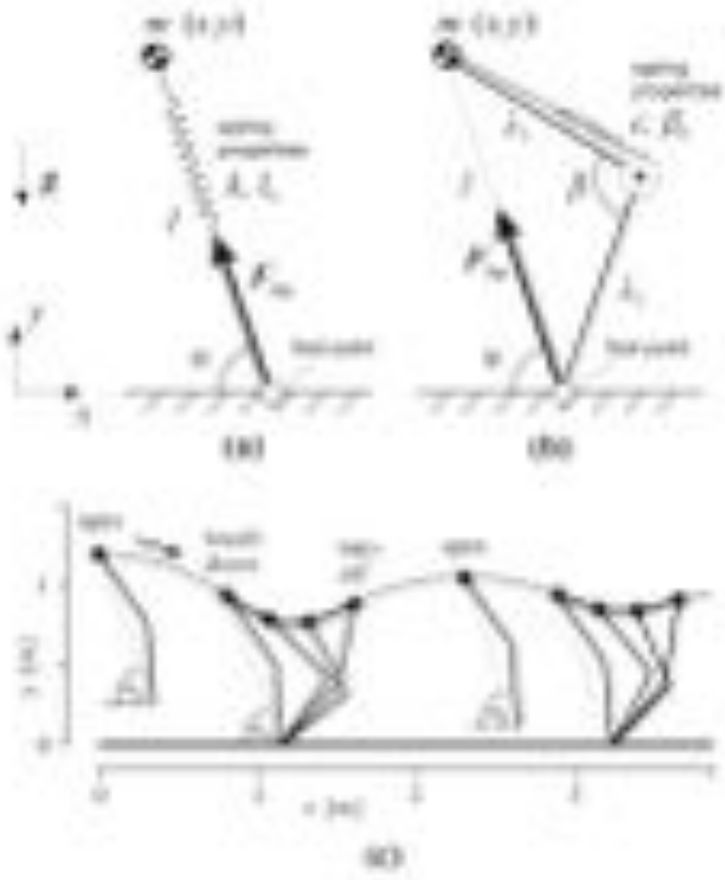
Fwd Speed





Rummel, J. and Seyfarth, A. (2009).

Rummel-Seyfarth Model



Introduce a nonlinear spring in the SLIP model

Spring torque:

$$\tau(\Delta\beta) = c\Delta\beta$$

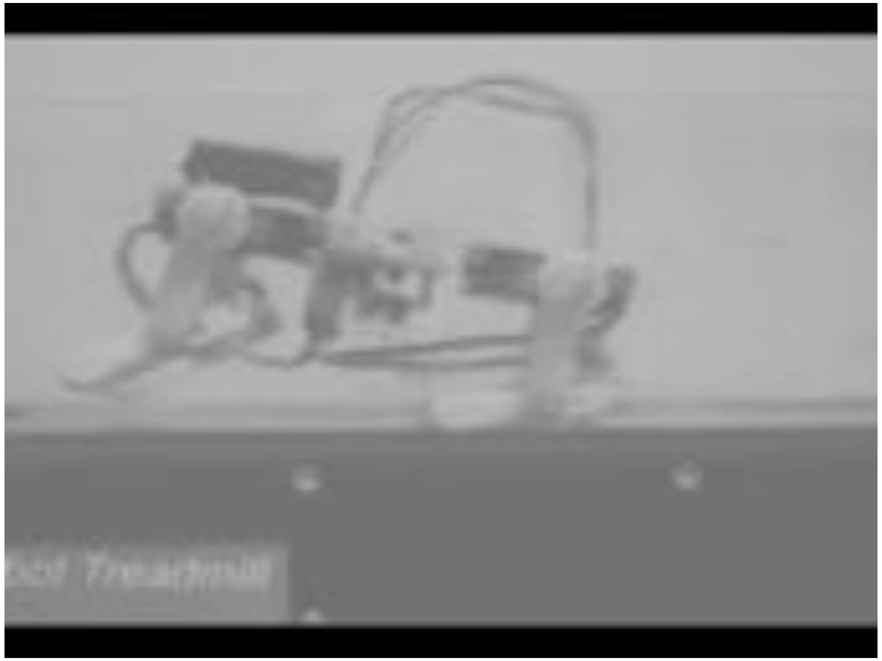
Natural length:

$$l_0(\beta_0) = \sqrt{\lambda_1^2 + \lambda_2^2 - 2\lambda_1\lambda_2\cos(\beta_0)}$$

Spring force:

$$F_{\text{leg}}(\tau) = \frac{l}{\lambda_1\,\lambda_2}\,\frac{\tau}{\sin\beta}$$

Quadruped Running

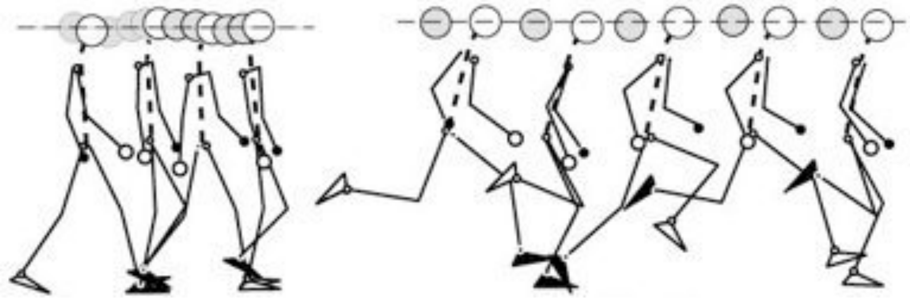


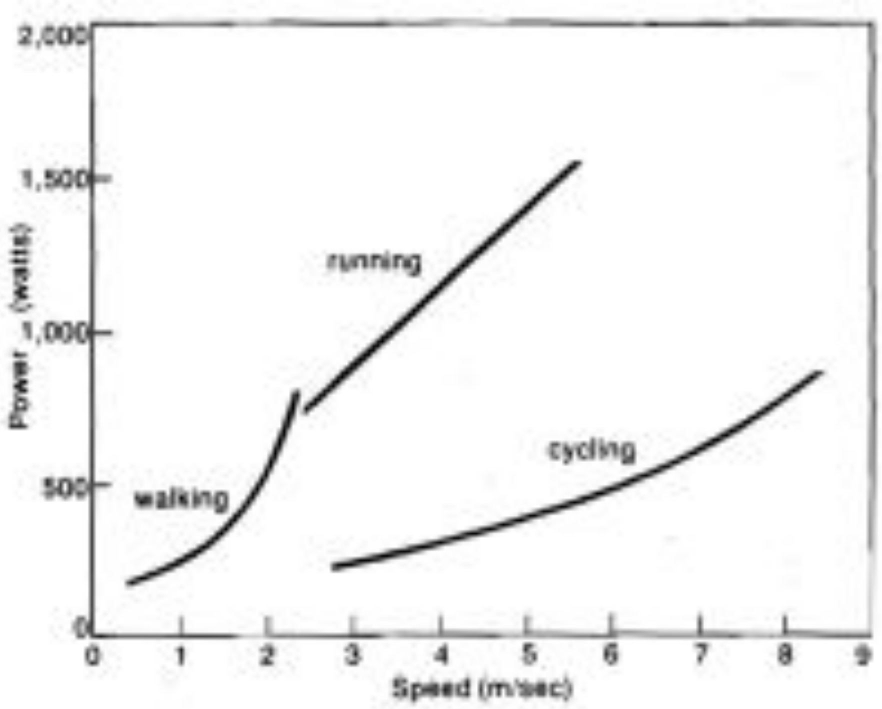
Running Dog Robot Puppy: Iida, F., Pfeifer, R. (2006)

Robotics and Autonomous Systems, Vol. 54 (8), 631-640.

Behavioral Diversity

Adaptivity and Gait Patterns





(Margaria, 1938)

Righ

Lef

Biological systems use different <u>control mechanisms</u> for different purposes.

Behavior Diversity of Biped Robot

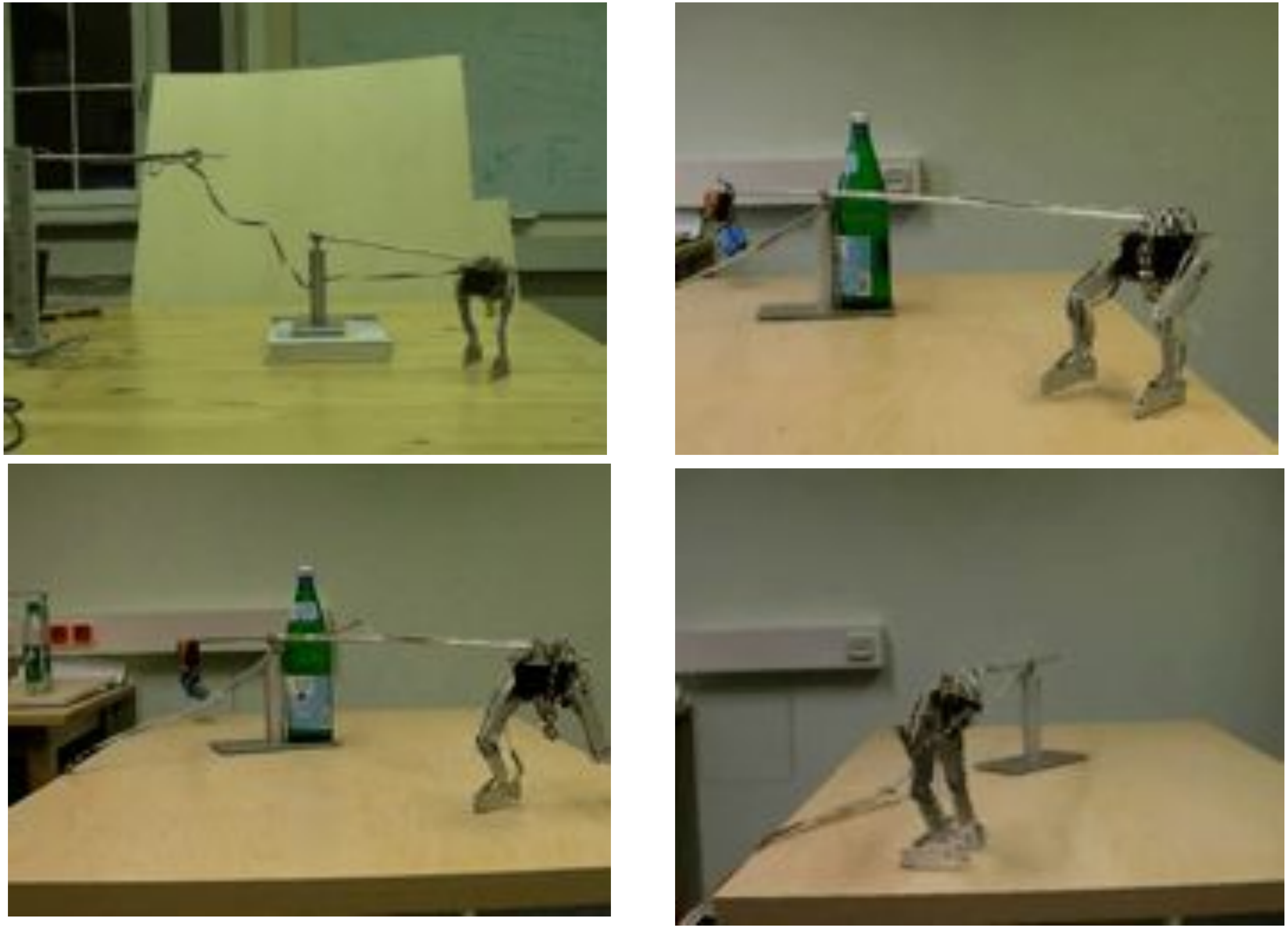
Jena Walker (Locomotion Lab, Univ. Jena)

Iida, J., Rummel, J., Seyfarth, A. (2008) *J. Biomechanics,* 41 (3), 656-667.

Righ

Left

Behavior Diversity of Biped Robot



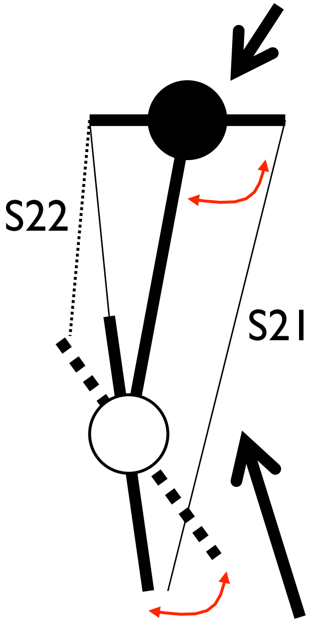
Iida, J., Rummel, J., Seyfarth, A. (2008) *J. Biomechanics,* 41 (3), 656-667.

Bipedal Walking and Running using Biarticular Springs

Jena Walker (Locomotion Lab, Univ. Jena)

Motor Control:

$$P_1 = A\ \sin(\omega\ t) + B$$
$$P_2 = A\ \sin(\omega\ t + \pi) + B$$



Tension Spring:

$$Fsp_{ij} = \begin{cases} K_{ij}(x_{ij} - N_{ij}) - D_{ij}\dot{x}_{ij} : & \mathrm{x} \geq 0 \\ 0 : & \mathrm{x} < 0 \end{cases}$$

Iida, J., Rummel, J., Seyfarth, A. (2008) *J. Biomechanics,* 41 (3), 656-667.

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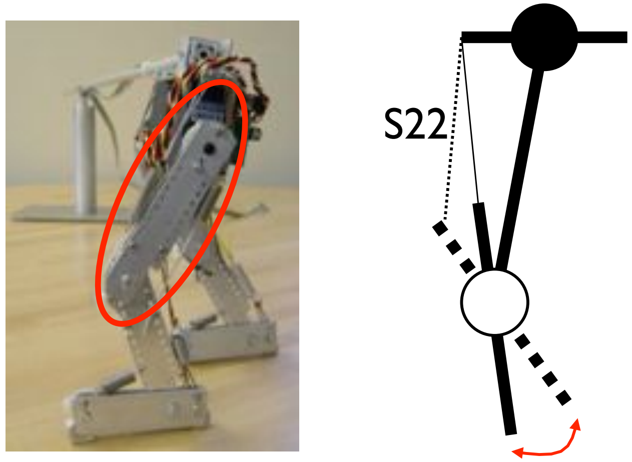

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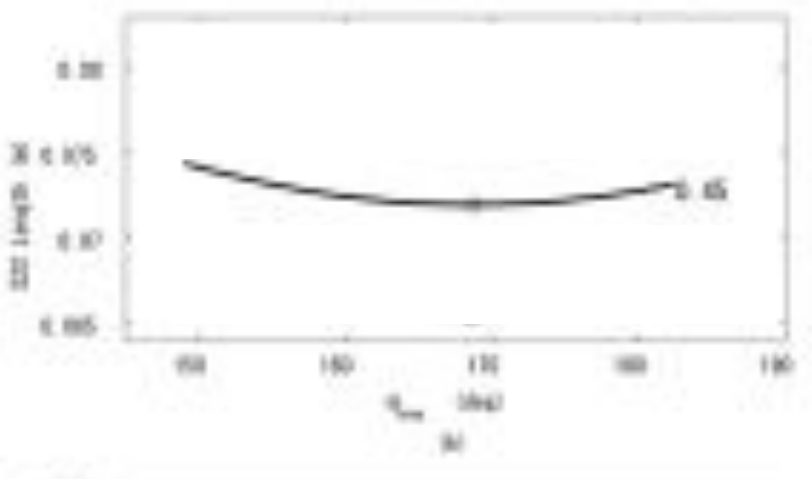

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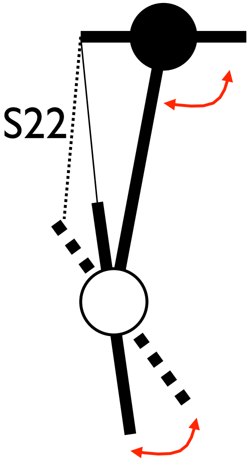

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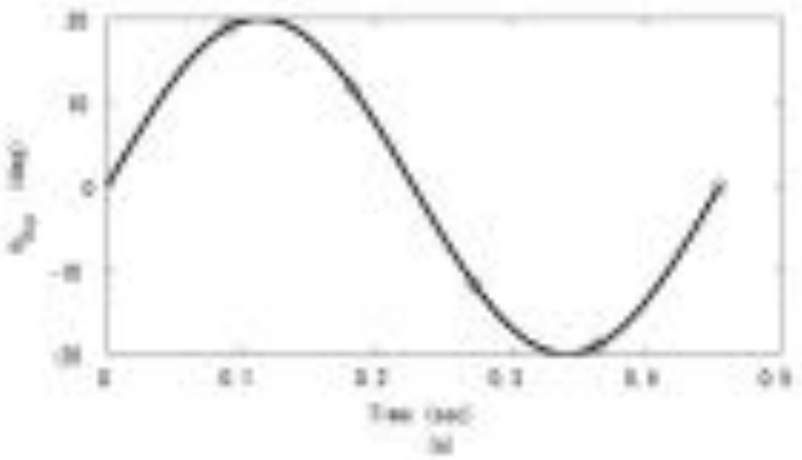

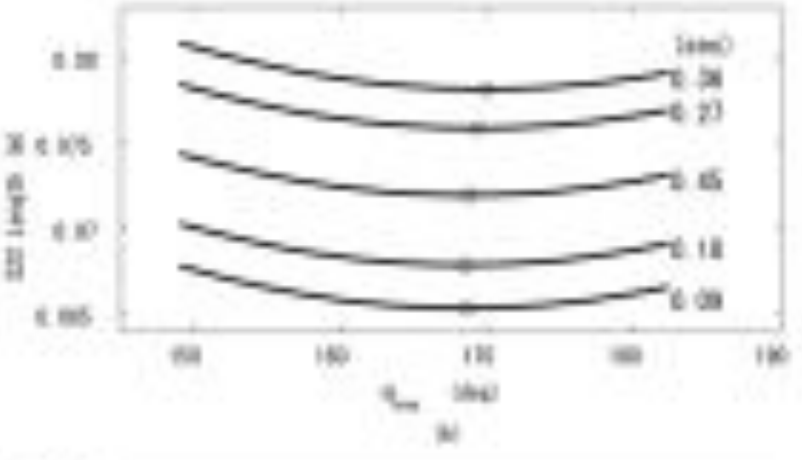

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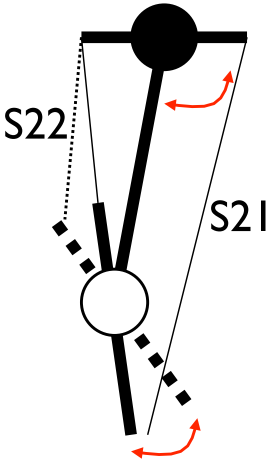

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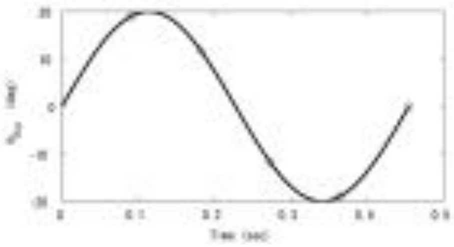
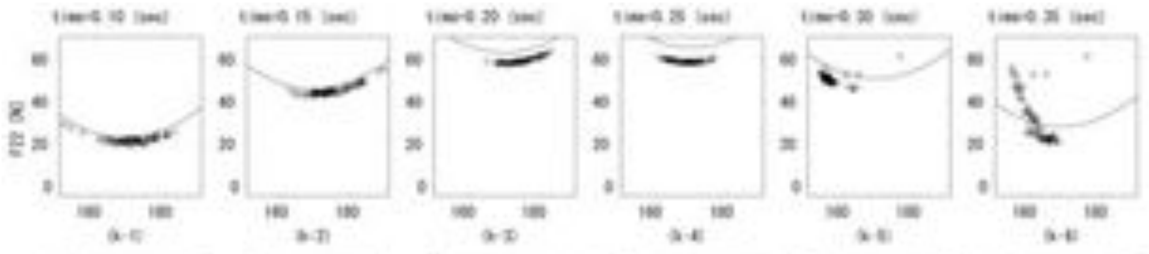
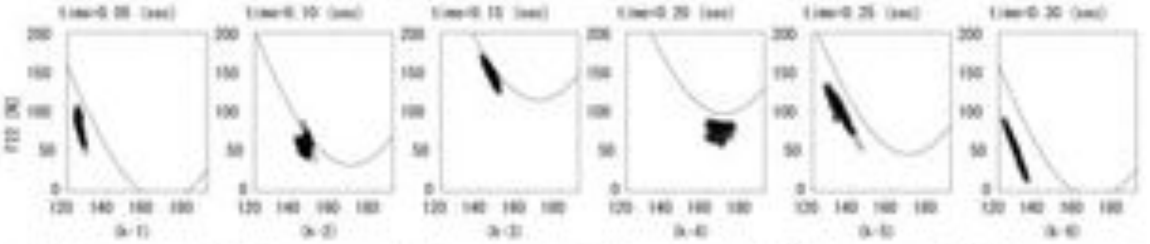




Walking

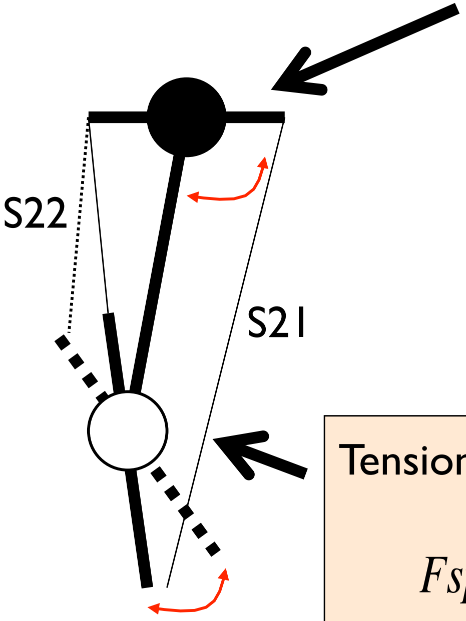


Running

Iida, J., Rummel, J., Seyfarth, A. (2008) *J. Biomechanics,* 41 (3), 656-667.

Behavior Diversity of Biped Robot

Jena Walker (Locomotion Lab, Univ. Jena)



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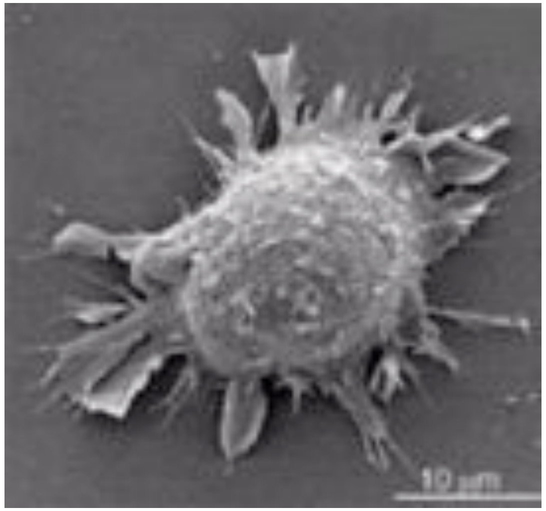
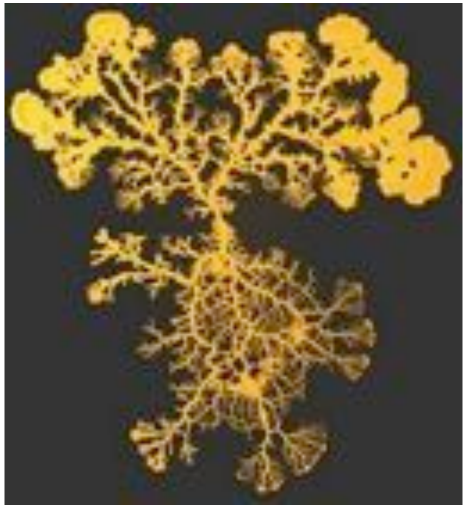
- Motors trigger basic oscillation
- Knees and ankles are passive
- "Biarticular springs" provide complex dynamics

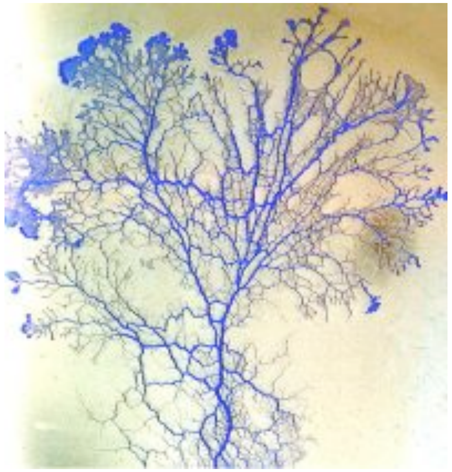
Iida, J., Rummel, J., Seyfarth, A. (2008) *J. Biomechanics,* 41 (3), 656-667.

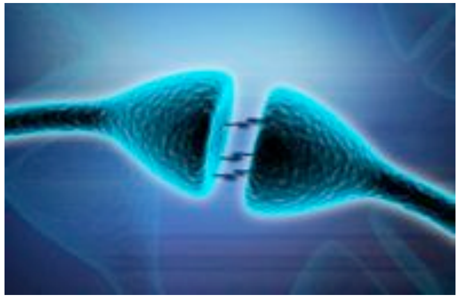
Adaptive Mechanics

Morphing and Adhesion

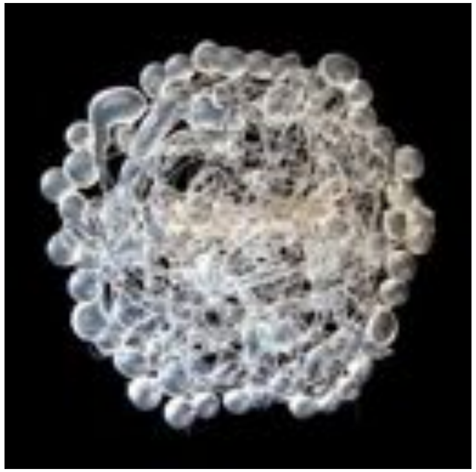


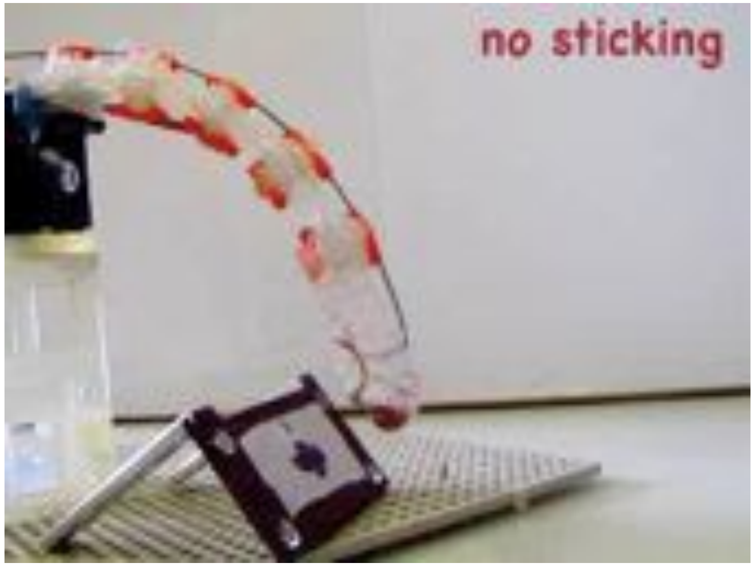


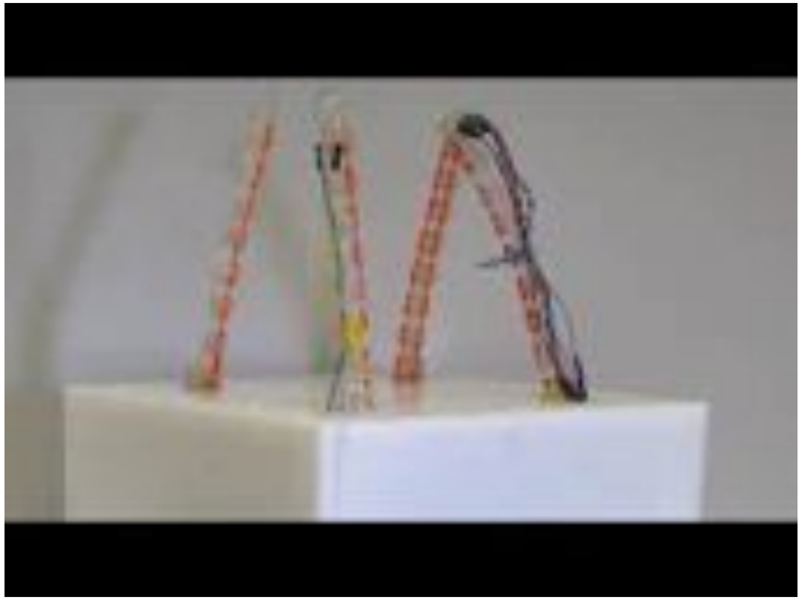




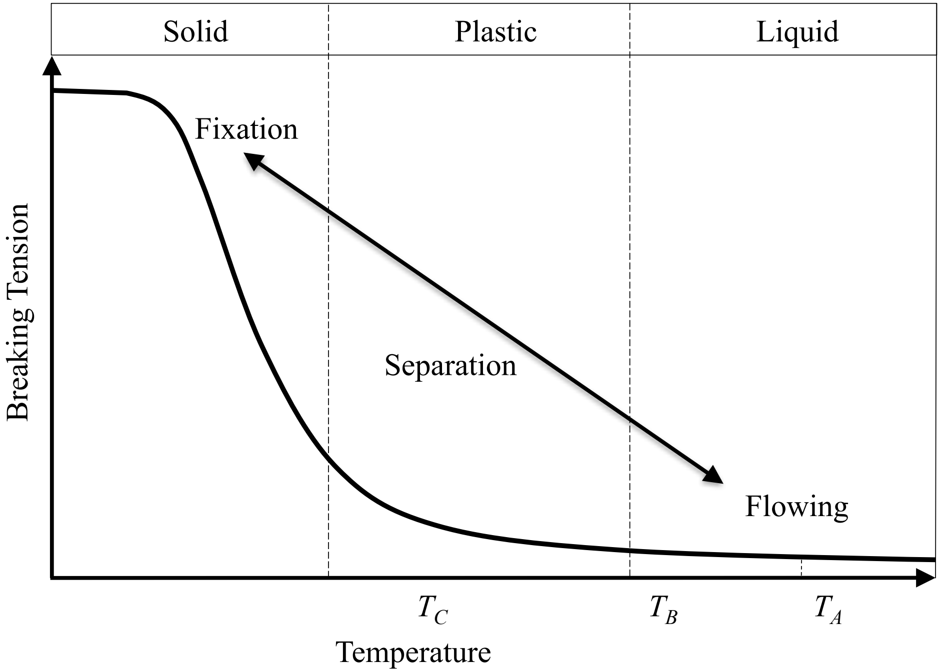
Robots Made of Hot Melt Adhesives




no sticking



Thermoplastic Polymer



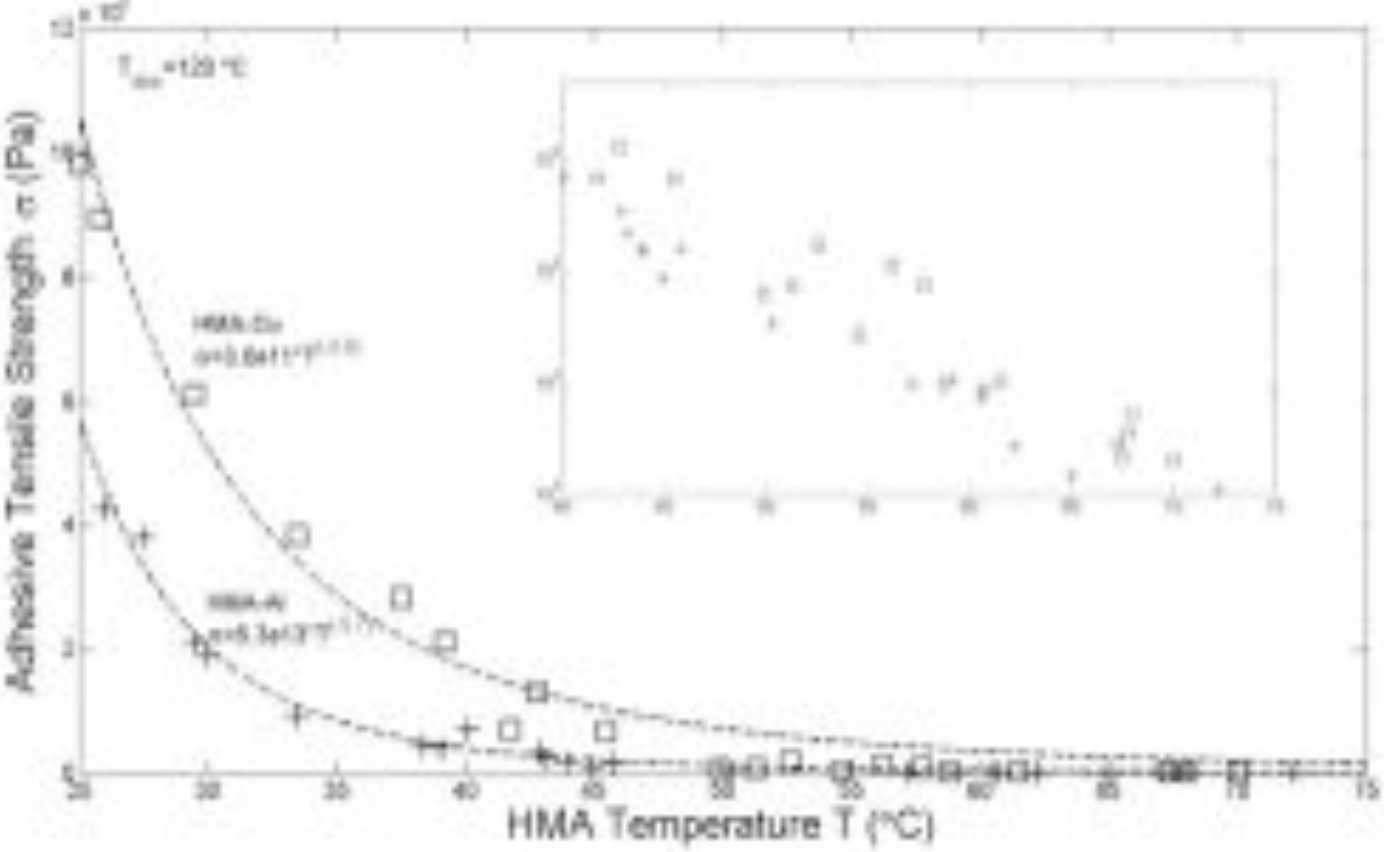
-Three distinctive phases: solid, plastic, and liquid

-Repeatedly transform between them

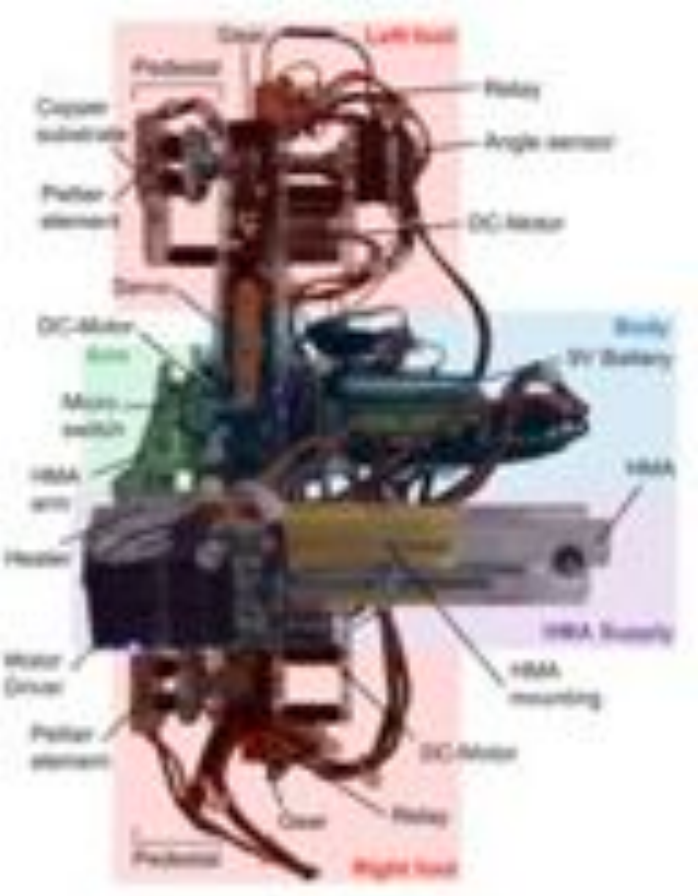
-Adhesive in liquid

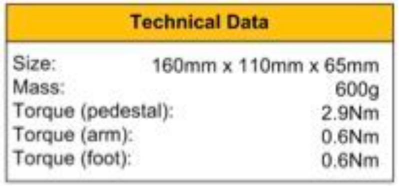
-Large tensile strength in solid

Thermoplastic-Adhesion Property



Climbing Robot Experiment



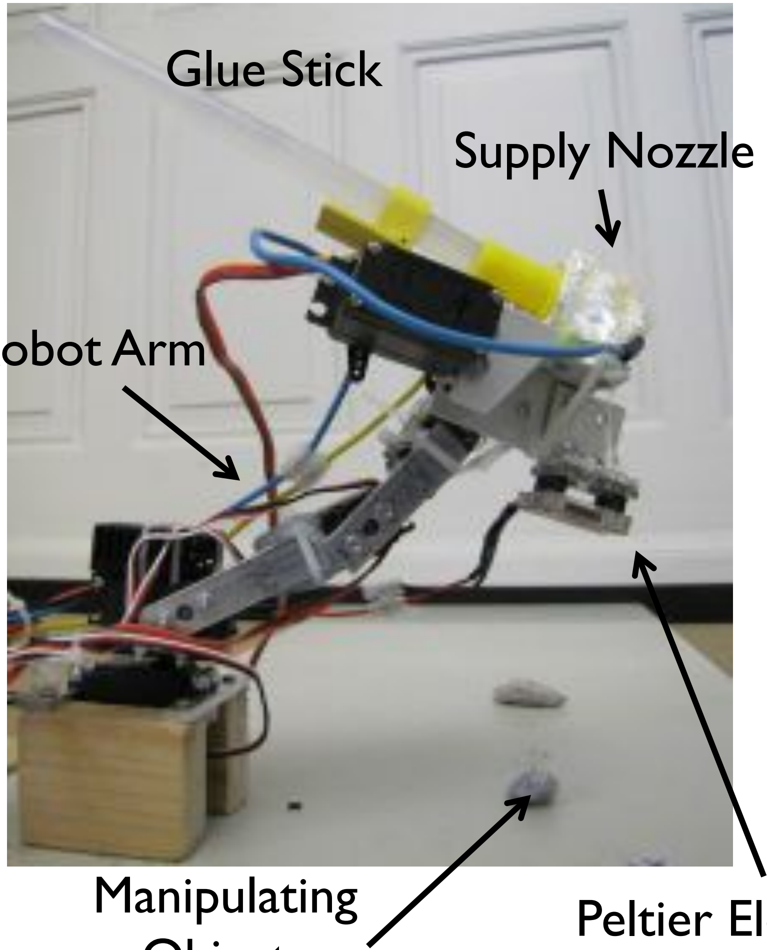


Technical Data	
Size:	160mm x 110mm x 65mm
Mass:	600g
Torque (pedestal):	2.9Nm
Torque (arm):	0.6Nm
Torque (foot):	0.6Nm

Maximum adhesion strength up to 150N/cm^2

Osswald, M. and Iida, F. (2011).

Pick and Place Experiment



Glue Stick

Supply Nozzle

Robot Arm

Manipulating Objects

Peltier Element

Wang, L. and Iida, F. (in preparation).

Summary

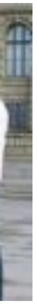
Self-organization of real-world robots is the challenge of bio-inspired robotics research

Self-organization provides solutions to deal with unstructured task-environments, e.g.

- energy efficiency,
- self-stability,
- behavioral diversity,
- adaptive mechanics

which will hopefully lead to autonomous robot development and evolution!

Collaborators & Acknowledgement



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Exploration of Mechanical Intelligence

Thank You!

Thank you!

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