ETH
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Morphological Computation toward Self-Organizing Machines

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BIRL
Bio-Inspired Robotics Lab


Boston Dynamics


Boston Dynamics

Robot vs. Animal

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!

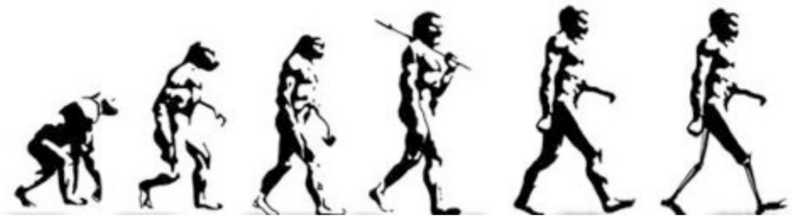
- No static components in the body

  Everything is changing over time!

- No human designers

  Everything is self-organized!

The Principle of Self-Organization

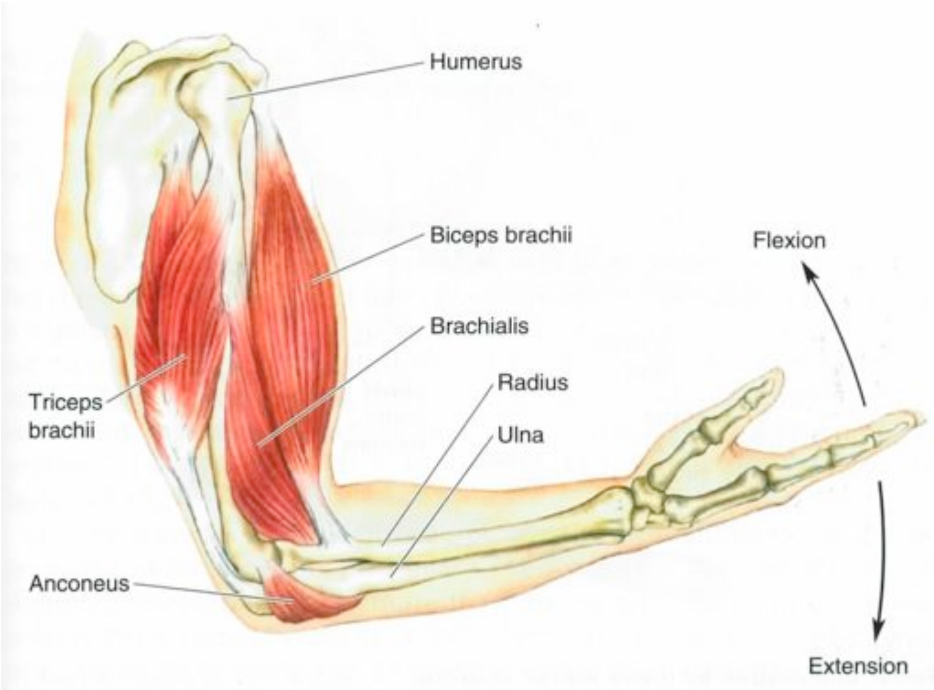


Three time perspectives
- Evolutionary
- Developmental
- Here and Now

Everything is continuously growing/adapting/changing
- Genetic components
- Musculoskeleton
- Nervous systems
- Sensory systems

George Lauder @ Harvard

Musculoskeletal Structure



Redundancy

Many muscles (muscle groups) are controlling one joint

Modularity

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

Diversity

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

Many sensors

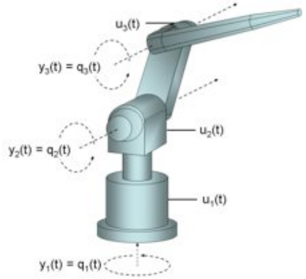
Muscle spindles and golgi-tendon organs are "everywhere"

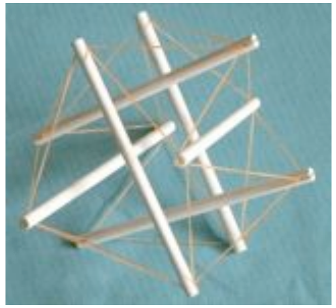
Building Bio-Inspired Robot

How to Replicate Biological Muscles?

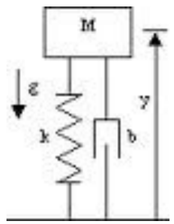
Generating forces
(Electric, hydraulic motor, etc.)

Connecting Limbs
(Joint actuation, tensegrity, etc.)





Enhancing and protecting structures
(Spring-damper-mass systems, etc.)



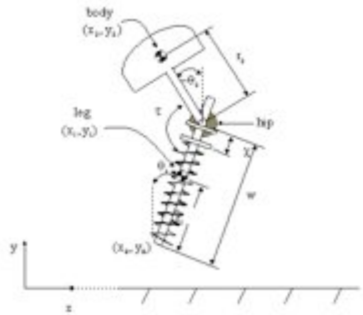


Figure 1. One-legged robot model for analysis and simulation.

Regulating motions
(Four bar mechanisms, etc.)

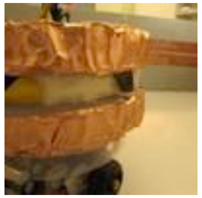
Comparing Biological and Man-Made Muscles?

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







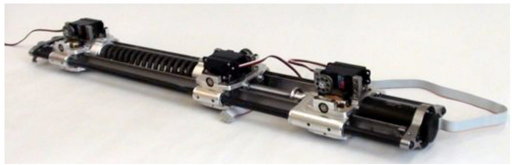










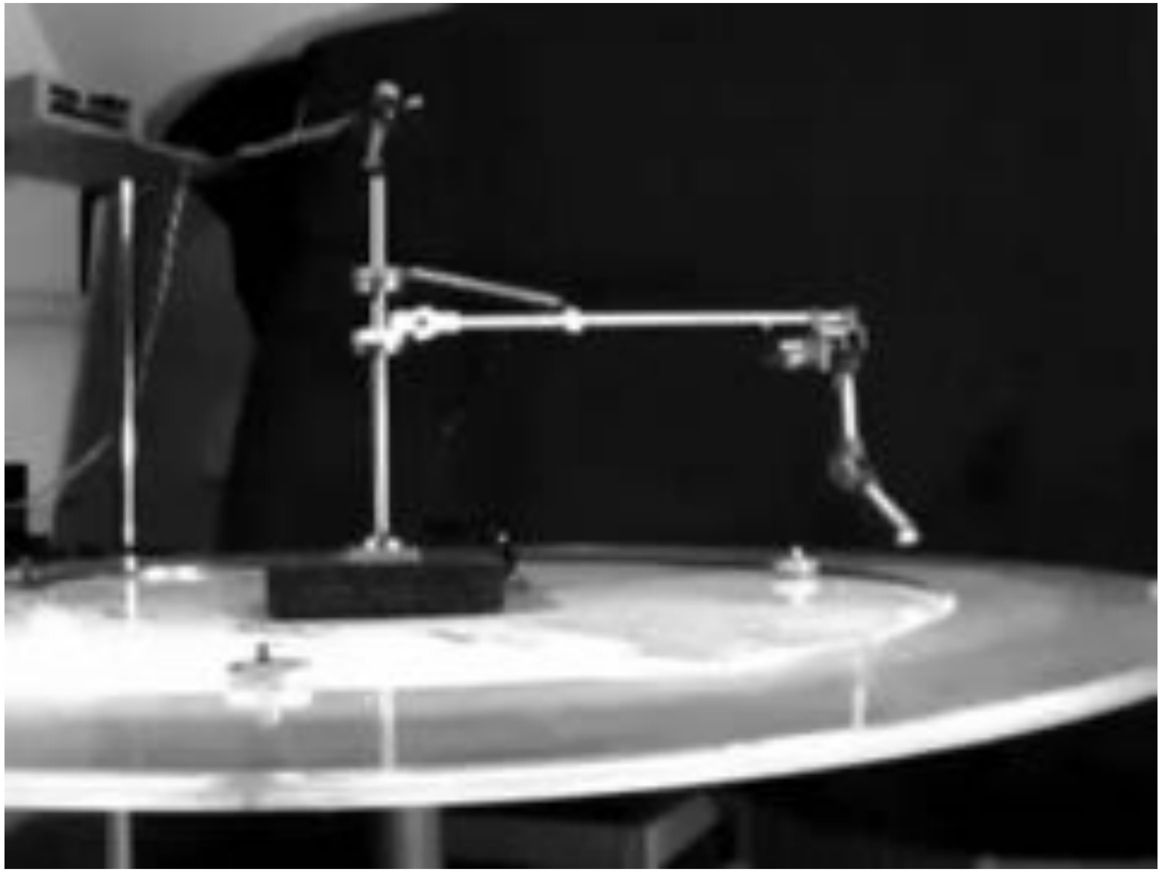

More to come…

Case Studies of Bio-Inspired Robotics

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

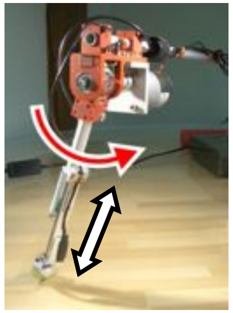
Self-Stability

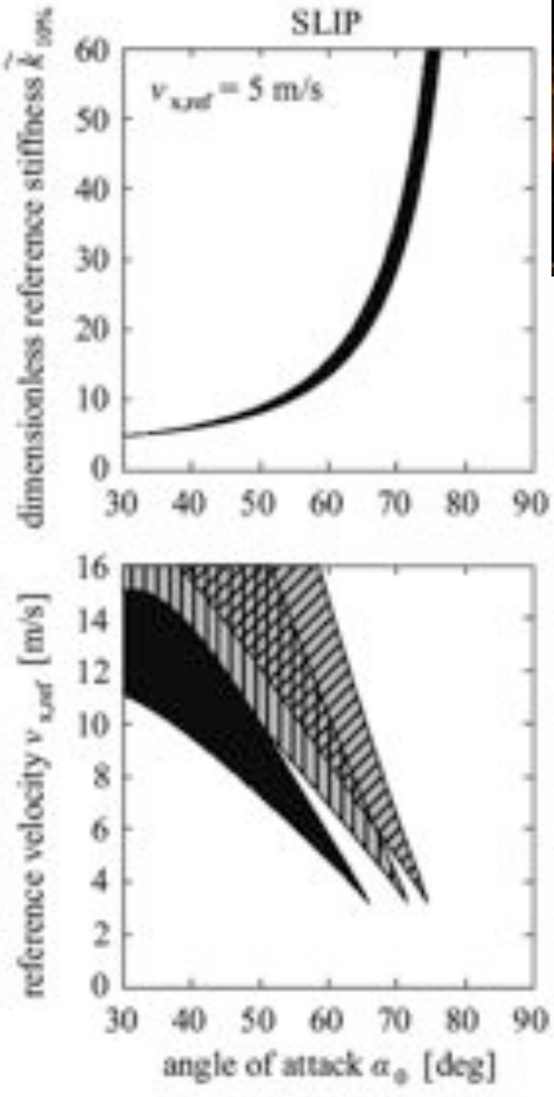
Simple Hopping Robot

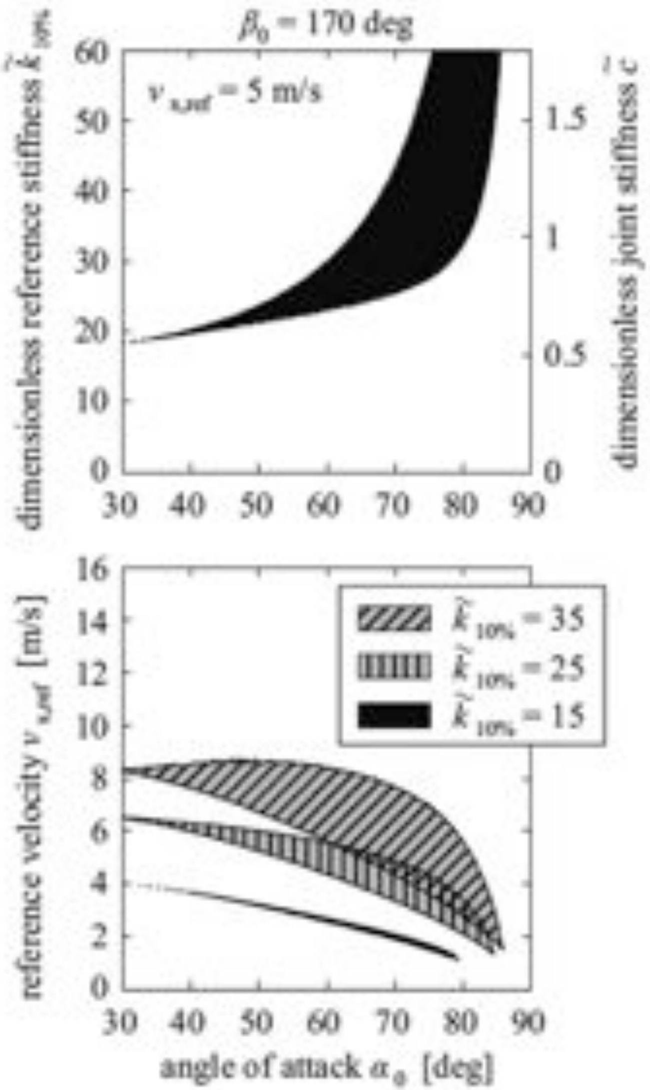


Bio-Leg I (University of Jena)
Rummel, J., Iida, F., Seyfarth, A. (2008) *ICRA2008*, 367-372.

Design Principle of Hopping Robot





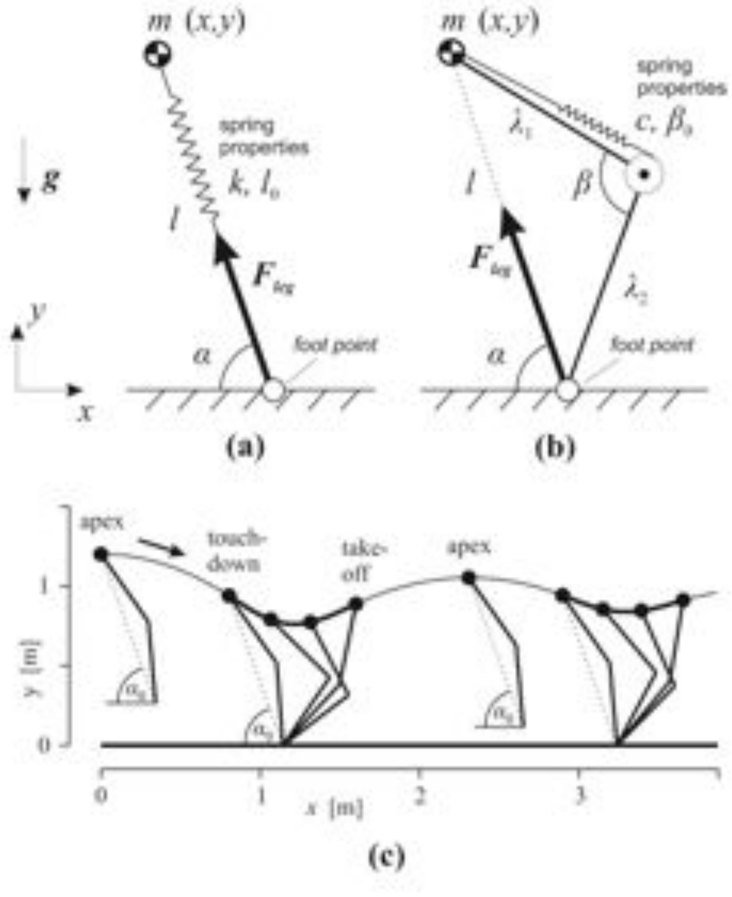


Stability

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:

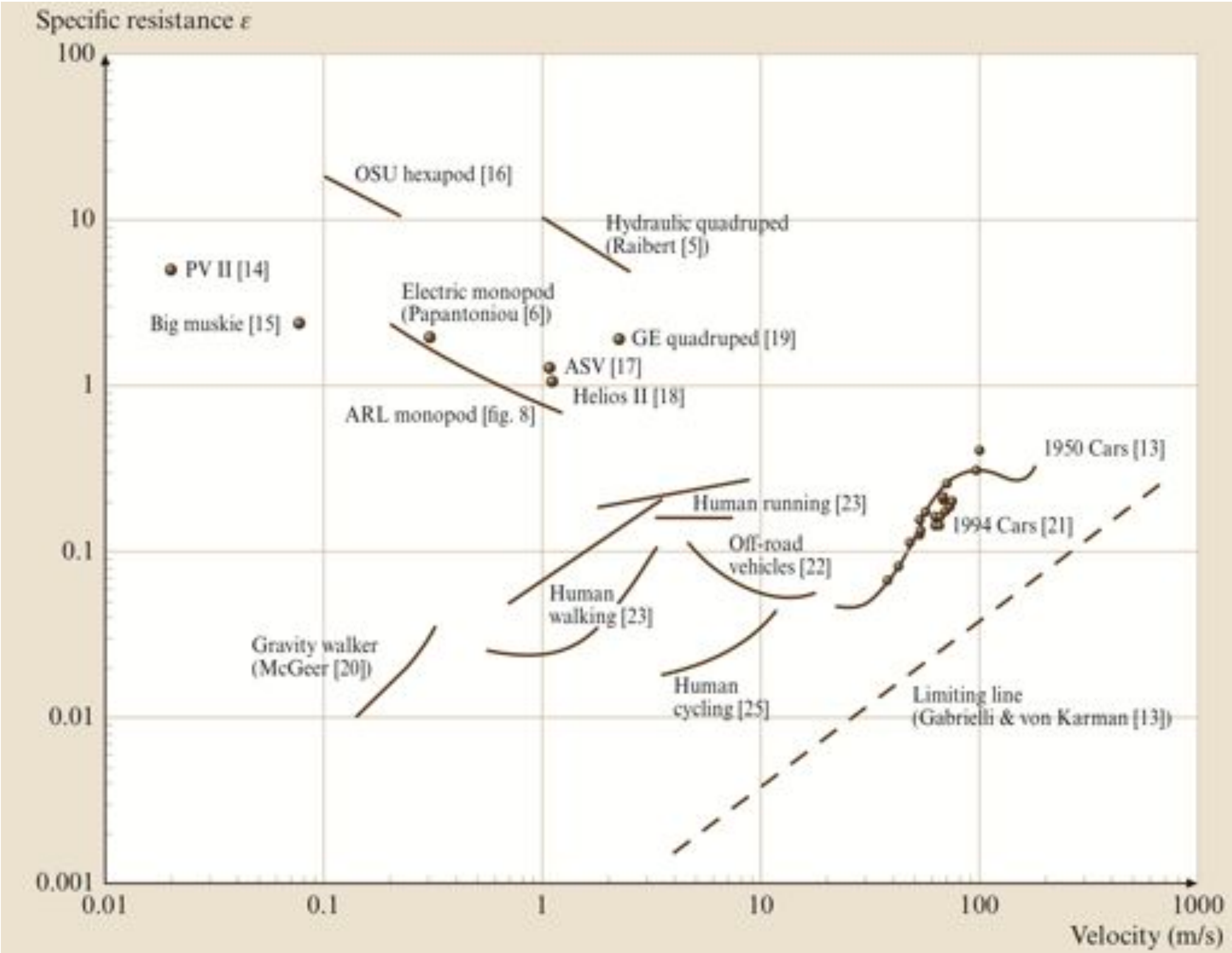
$$l_0(\beta_0) = \sqrt{\lambda_1^2 + \lambda_2^2 - 2\lambda_1\lambda_2\cos(\beta_0)}$$

Spring force:

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

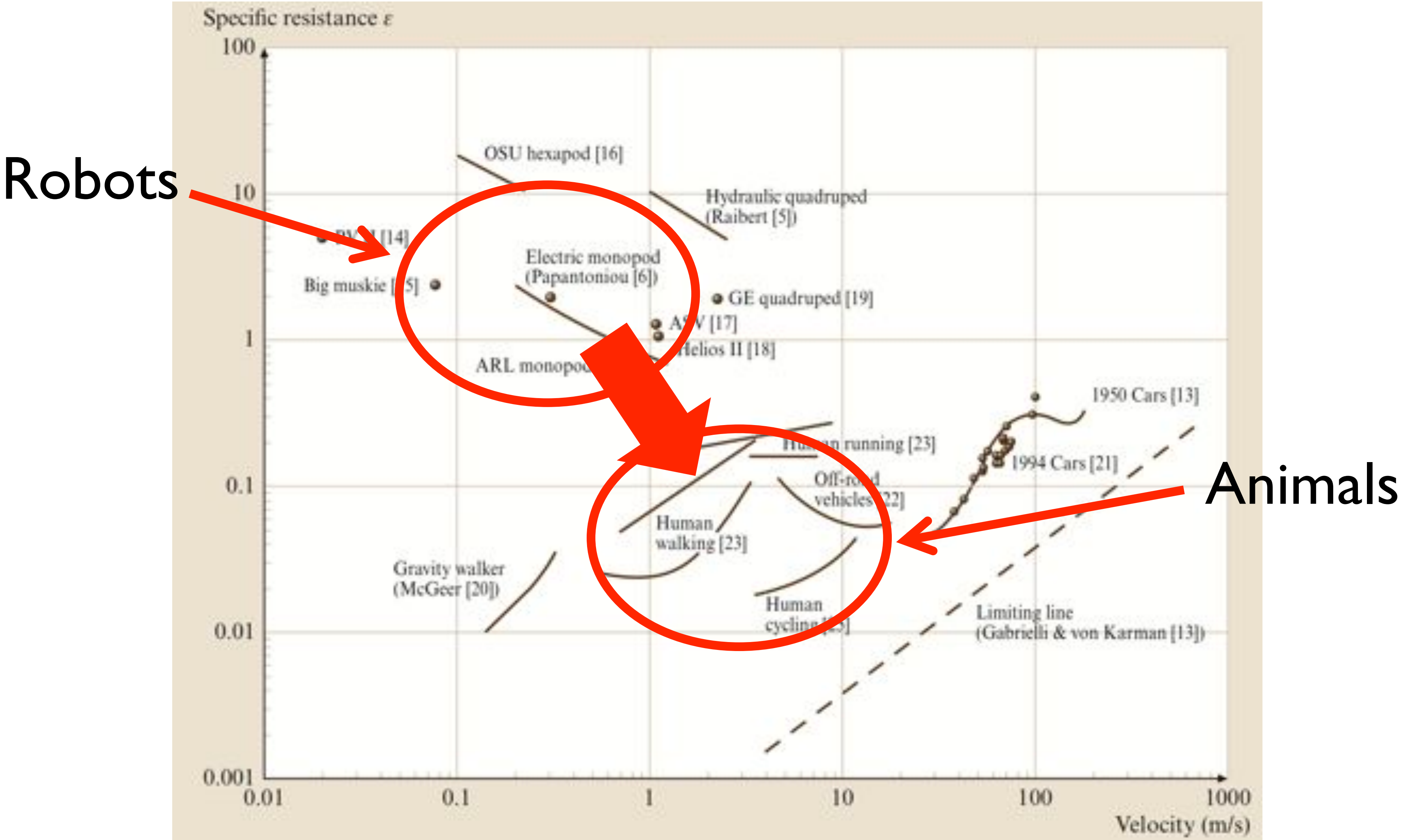
Energy Efficiency

Energy Efficiency & Behavioral Diversity



Gabrielli- von Karman Diagram

Energy Efficiency & Behavioral Diversity



Gabrielli- von Karman Diagram

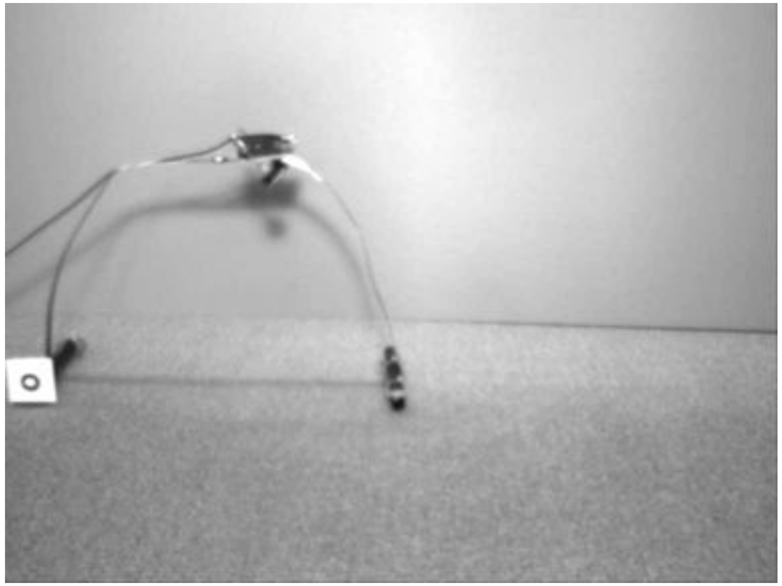
Energy Efficiency of Walking Systems

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

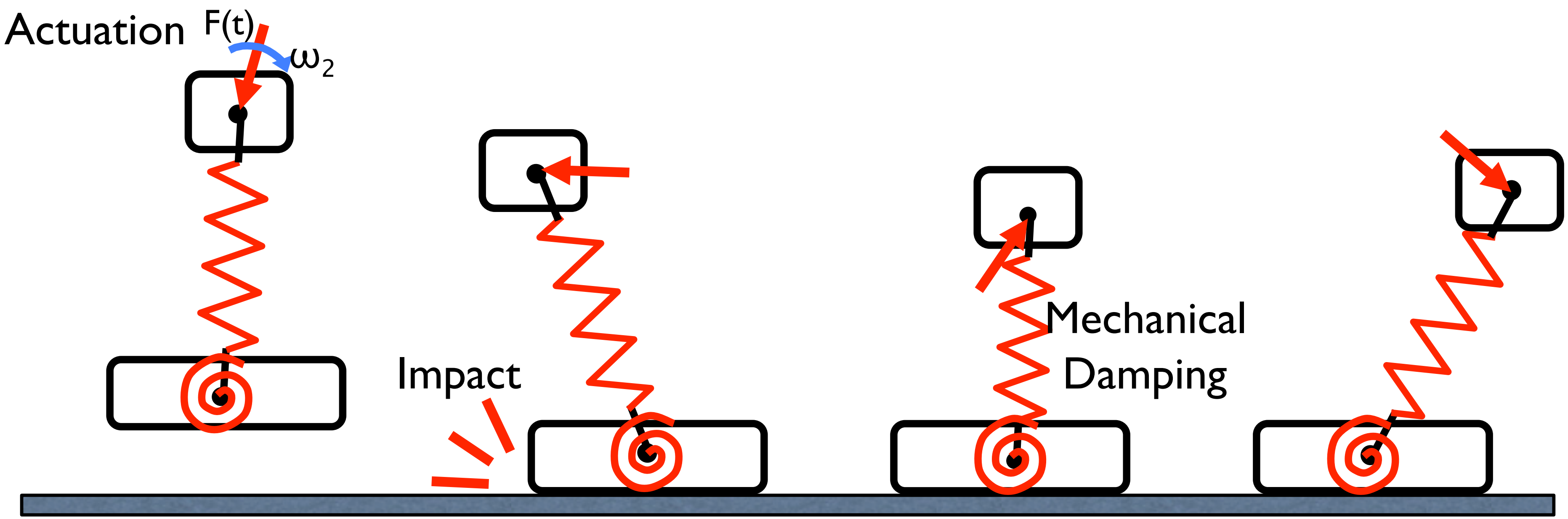
Hopping with Free Vibration of Curved Beam

Reis and Iida, 2011

Locomotion with Curved Beams



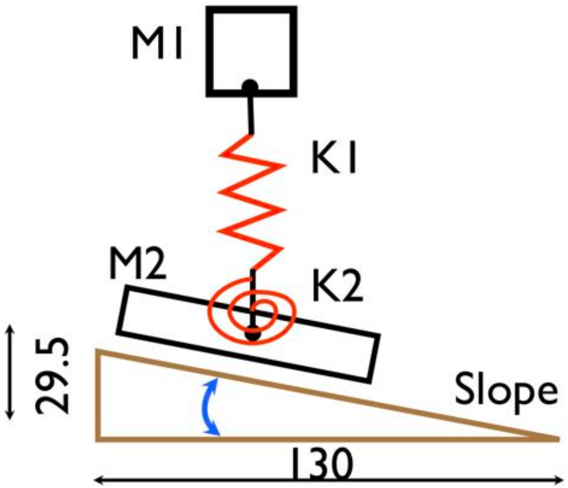
Physics and Economy of Hopping



Cost of Transport = Cost of actuation
+ Cost of mechanical impact
+ Cost of mechanical damping

Free vibration can reduce all three of these!

Passive Hopping with a Curved Beam

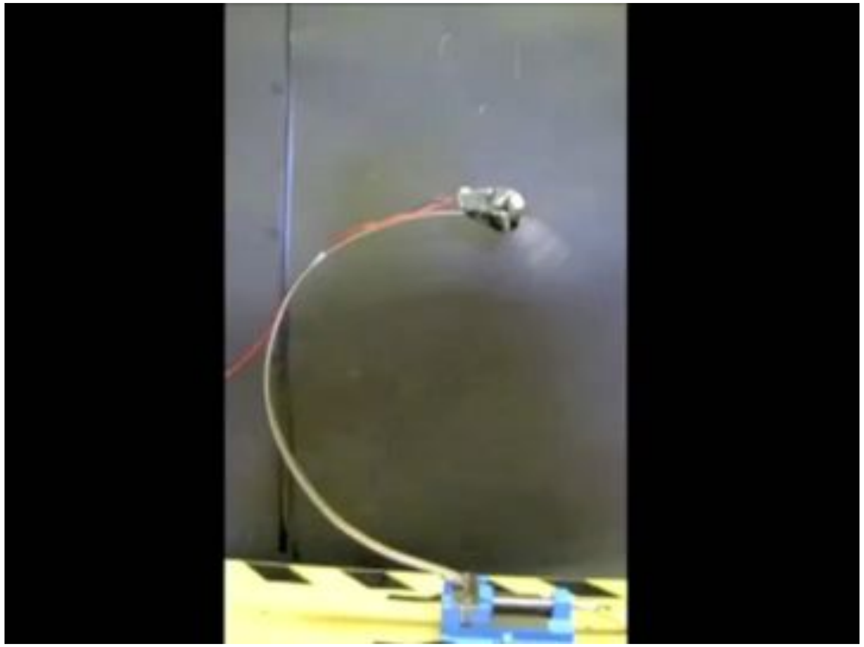


M1 = 4.5 Kg
M2 = 0.25 Kg
K1 =~ 4.2 KN/m
K2 =~ 135 Nm/rad
Speed = 0.55 m/sec
Slope =~ 0.118 radians

CoT =~ 0.22

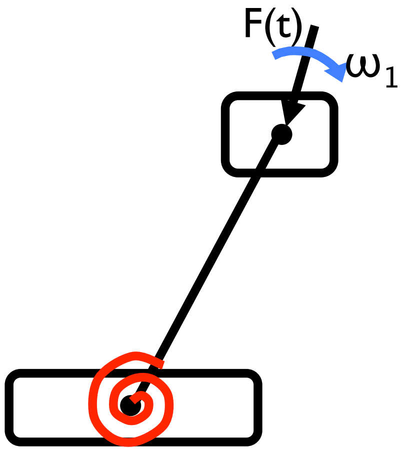
Gunura, K., Reis, M., Iida, F. (in preparation).

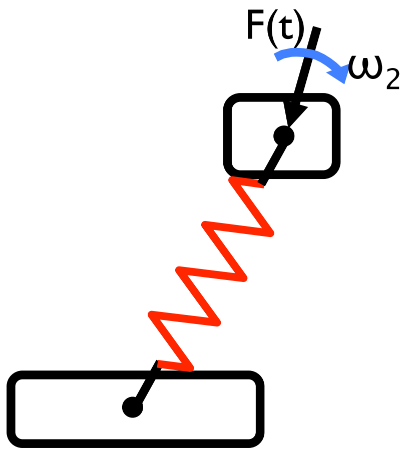
Free Vibration of a Curved Beam



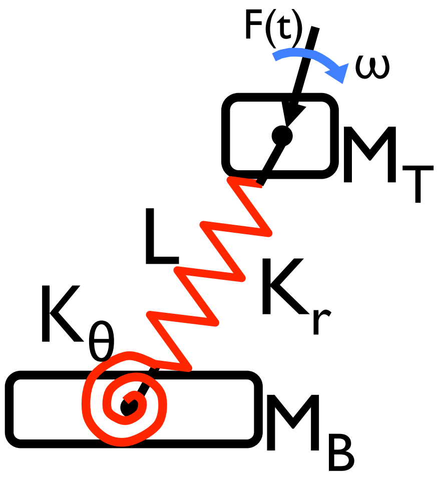
ω_θ=7.9rad/s

ω_r=31.4rad/s



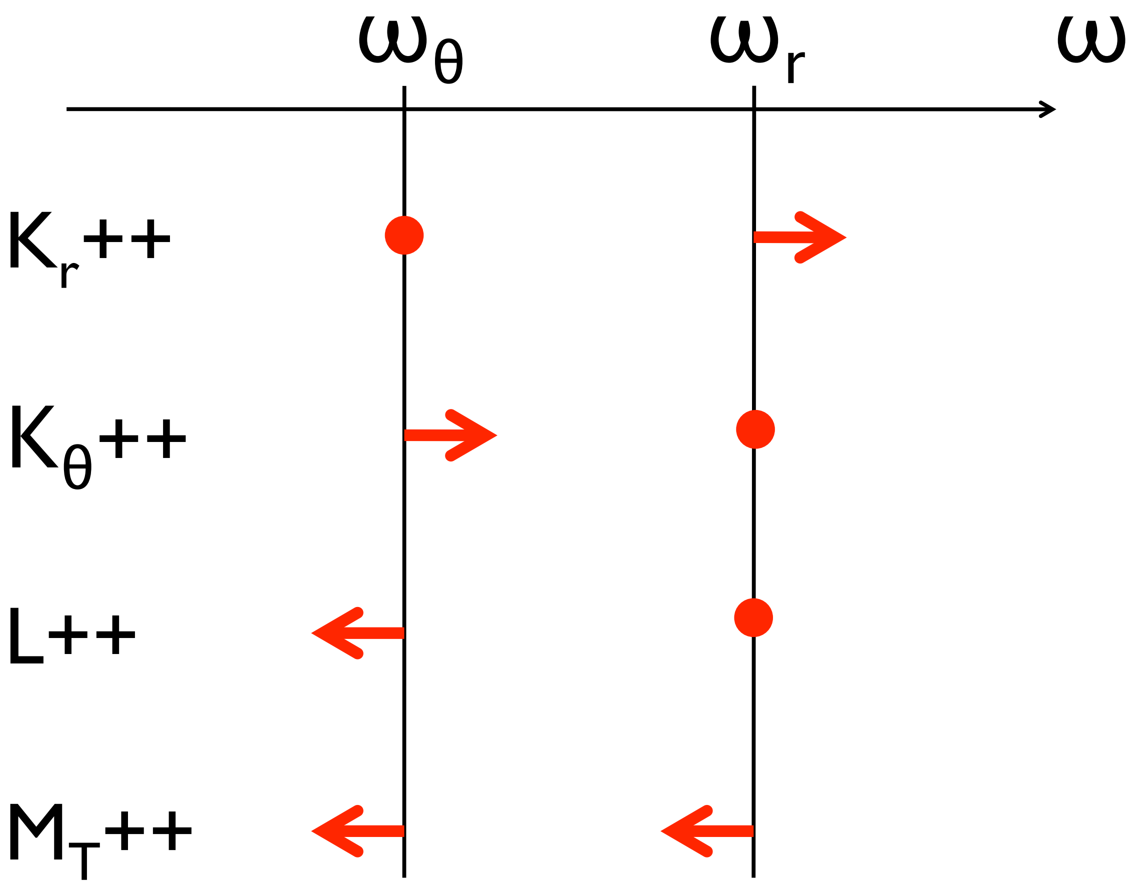


Design of Mechanical Dynamics

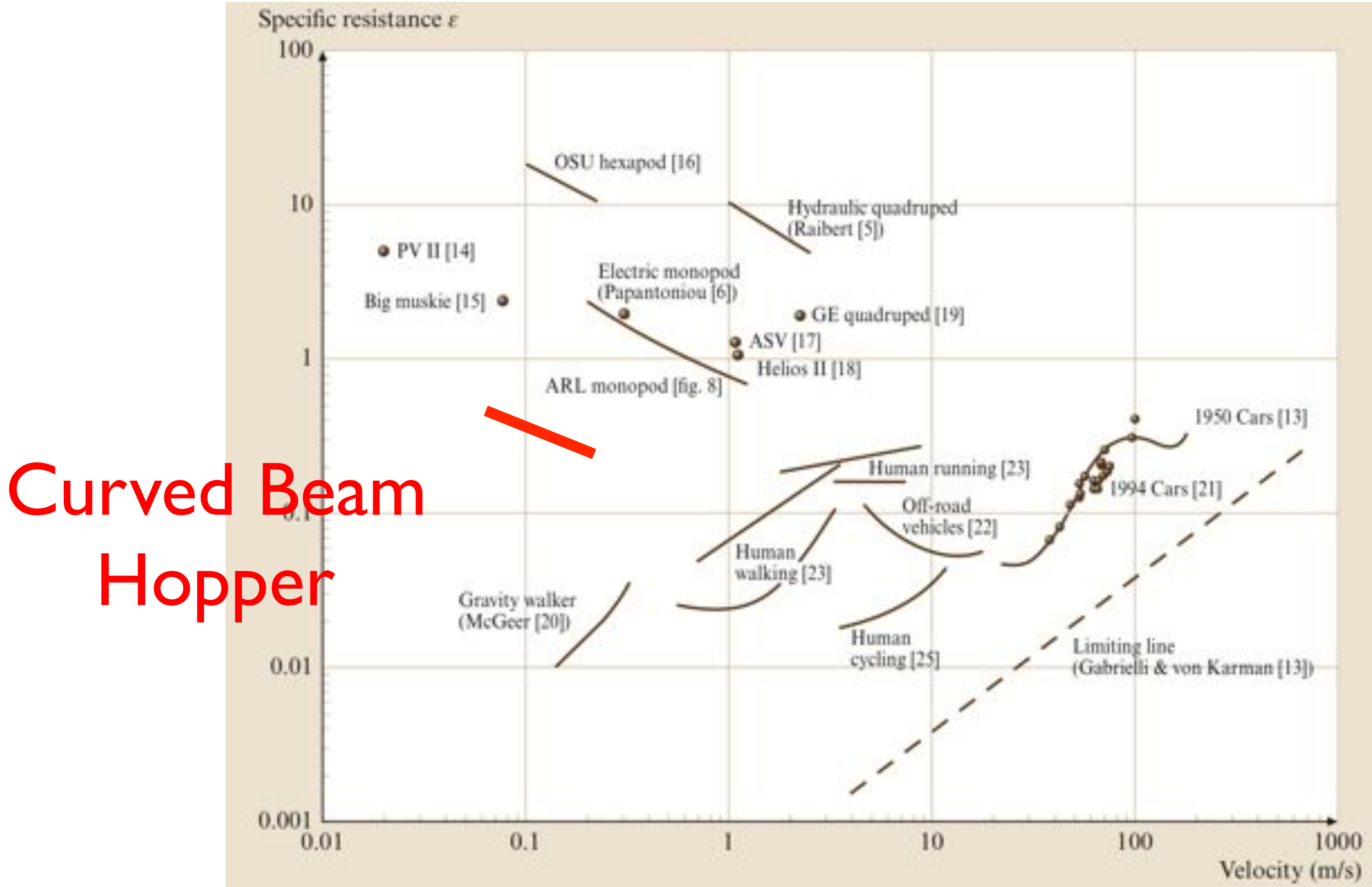


$$\omega_\theta = \sqrt{\frac{K_\theta}{I_\theta}} = \frac{1}{L}\sqrt{\frac{K_\theta}{M_T}}$$

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



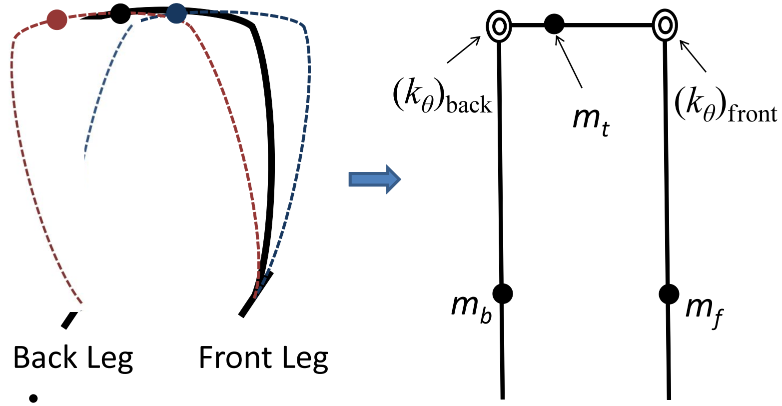
Locomotion Efficiency with Free Vibration



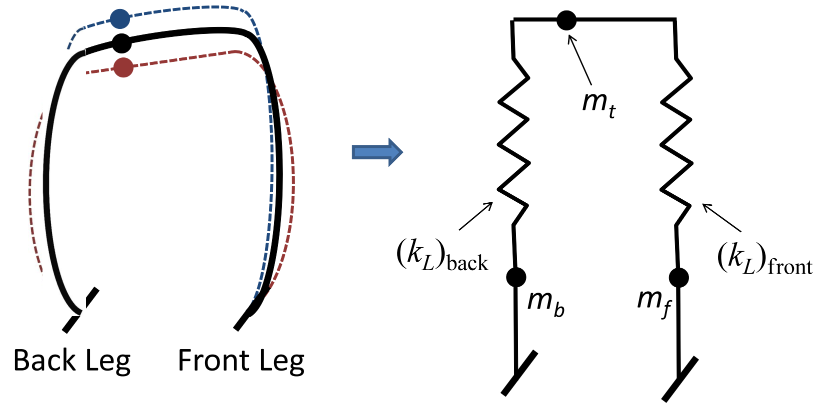
Gabrielli- von Karman Diagram

Behavioral Diversity?

Walking



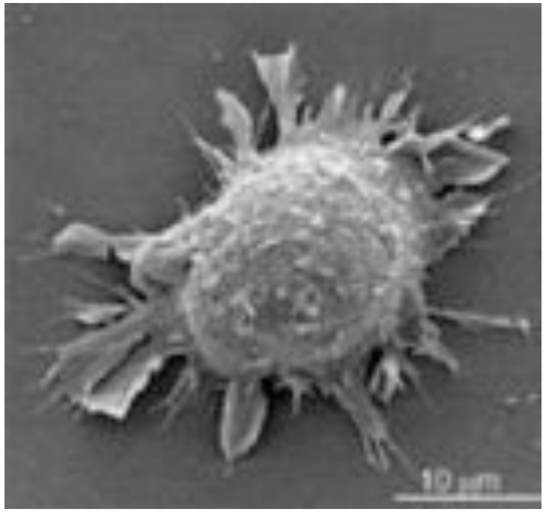
Hopping

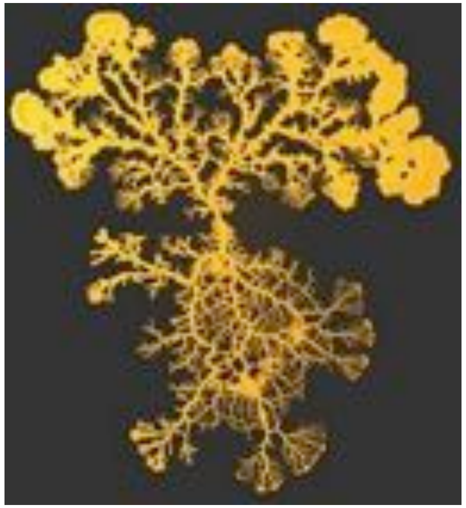


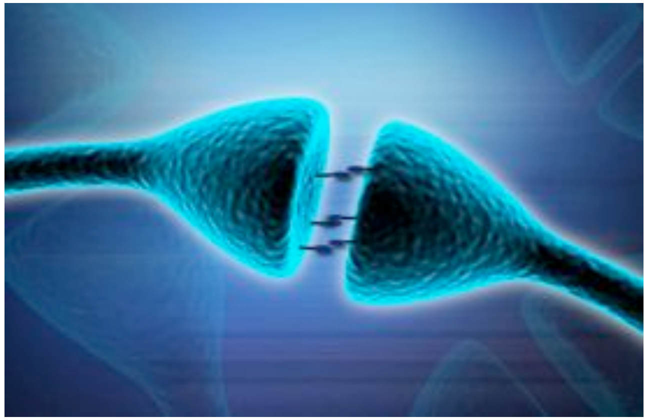
More details in the poster by M. Reis!

Adaptive Mechanics

Morphing and Adhesion





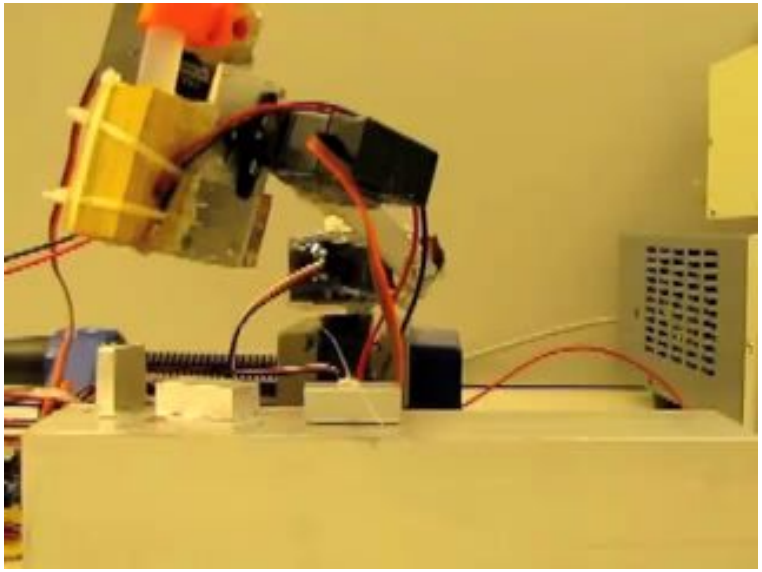
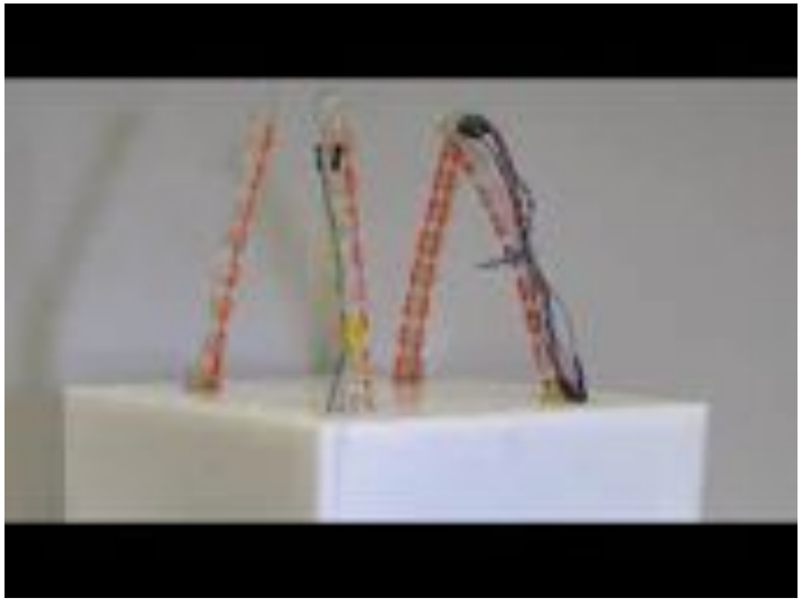


Robots Made of Hot Melt Adhesives

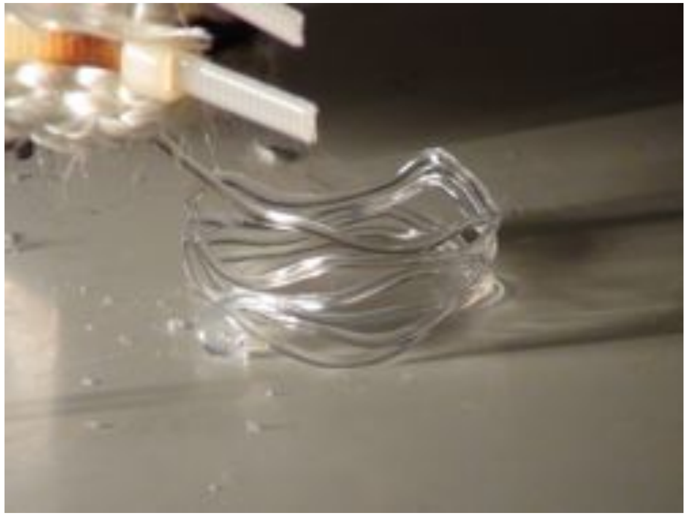


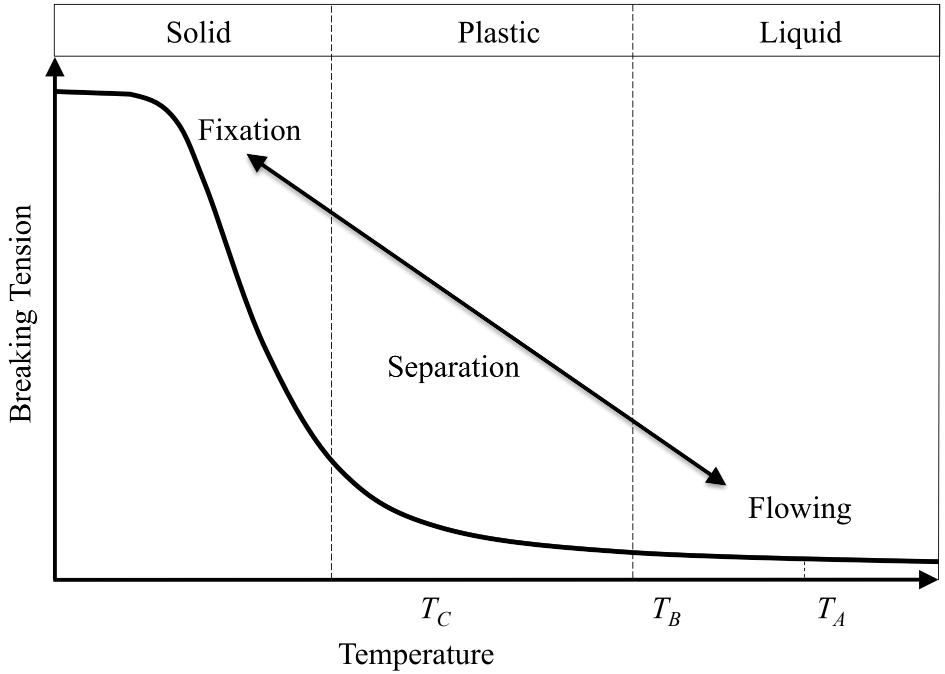





Thermoplastic Polymer

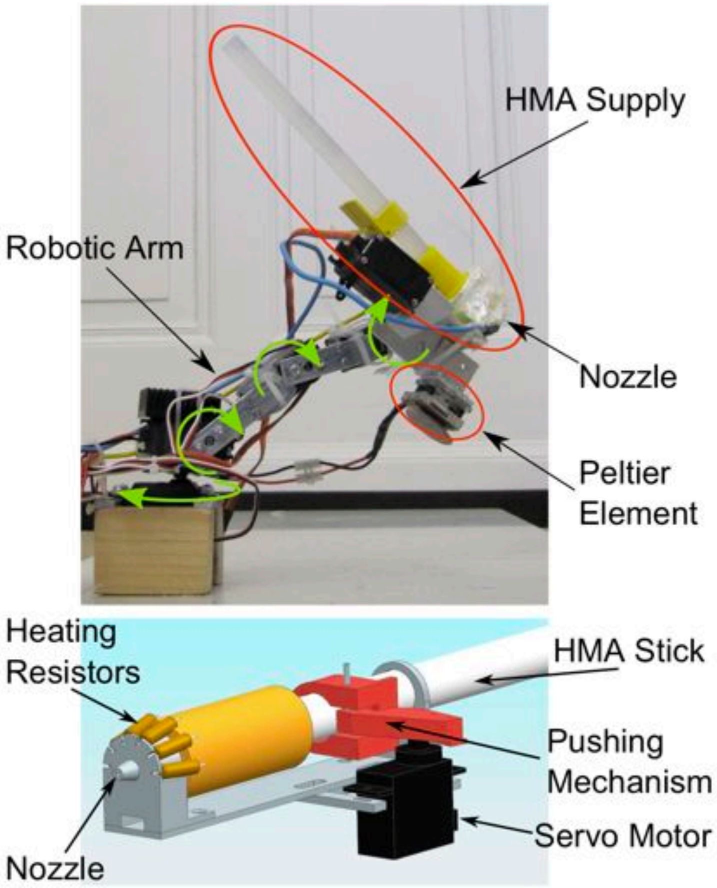


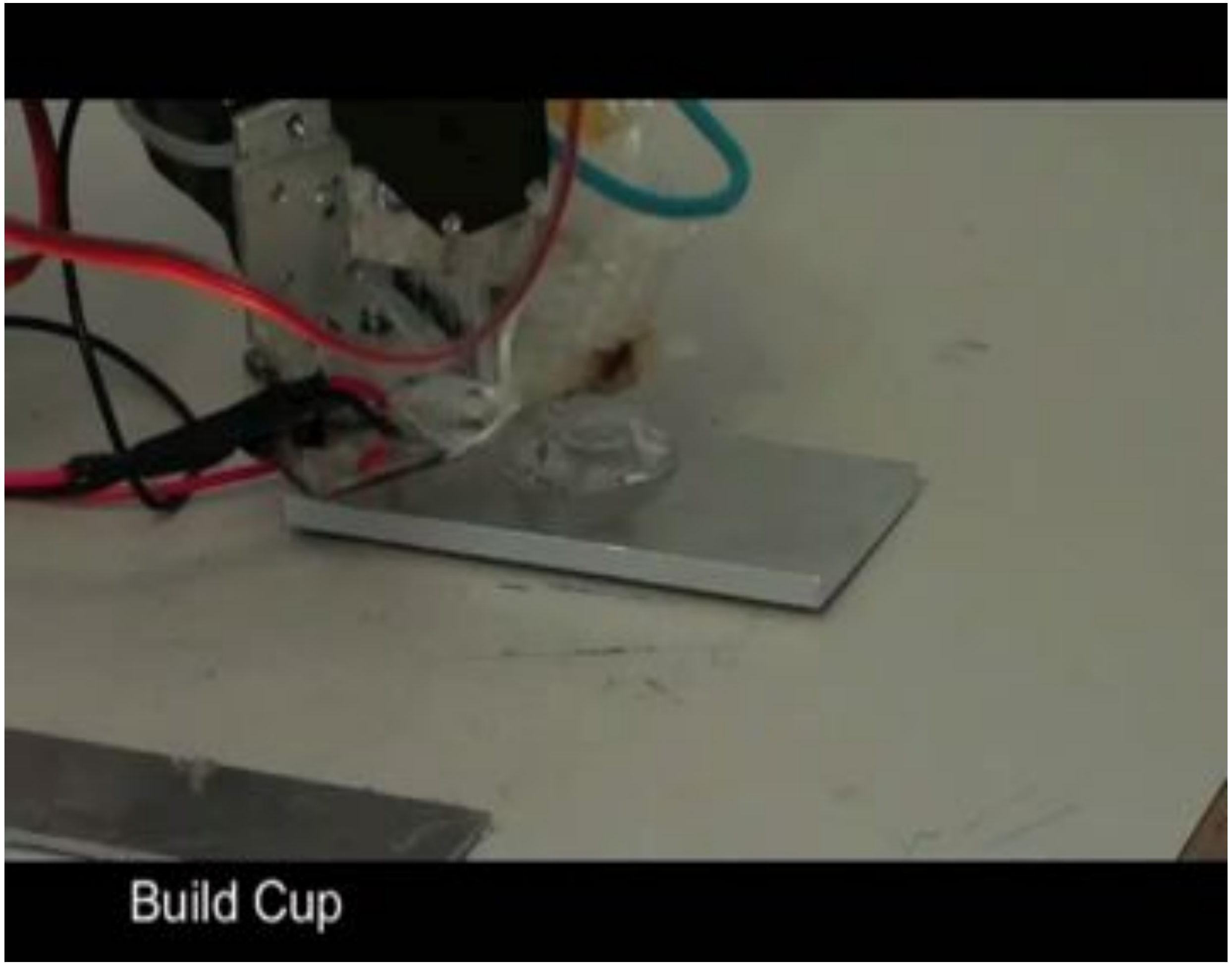


- -Three distinctive phases: solid, plastic, and liquid
- -Repeatedly transform between them
- -Adhesive in liquid
- -Large tensile strength in solid


no sticking

Autonomous Robot Body Extension



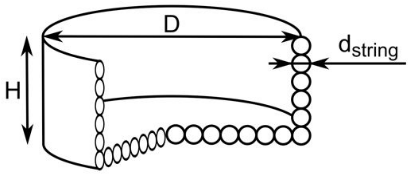


Brodbeck, L., Wang, L. and Iida, F. (in preparation).

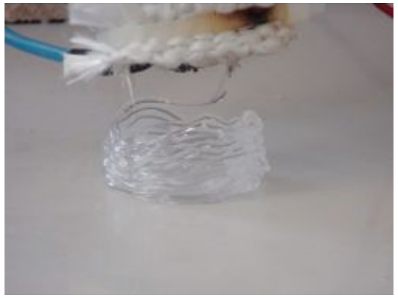
Autonomous Robot Body Extension

Task Identification

Autonomous Design

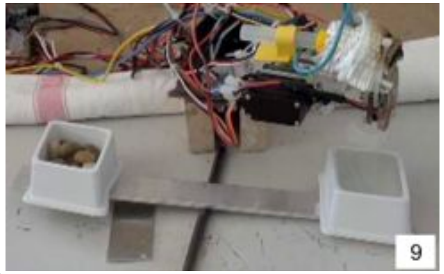


Autonomous Construction



Autonomous Assembly

Autonomous Operation



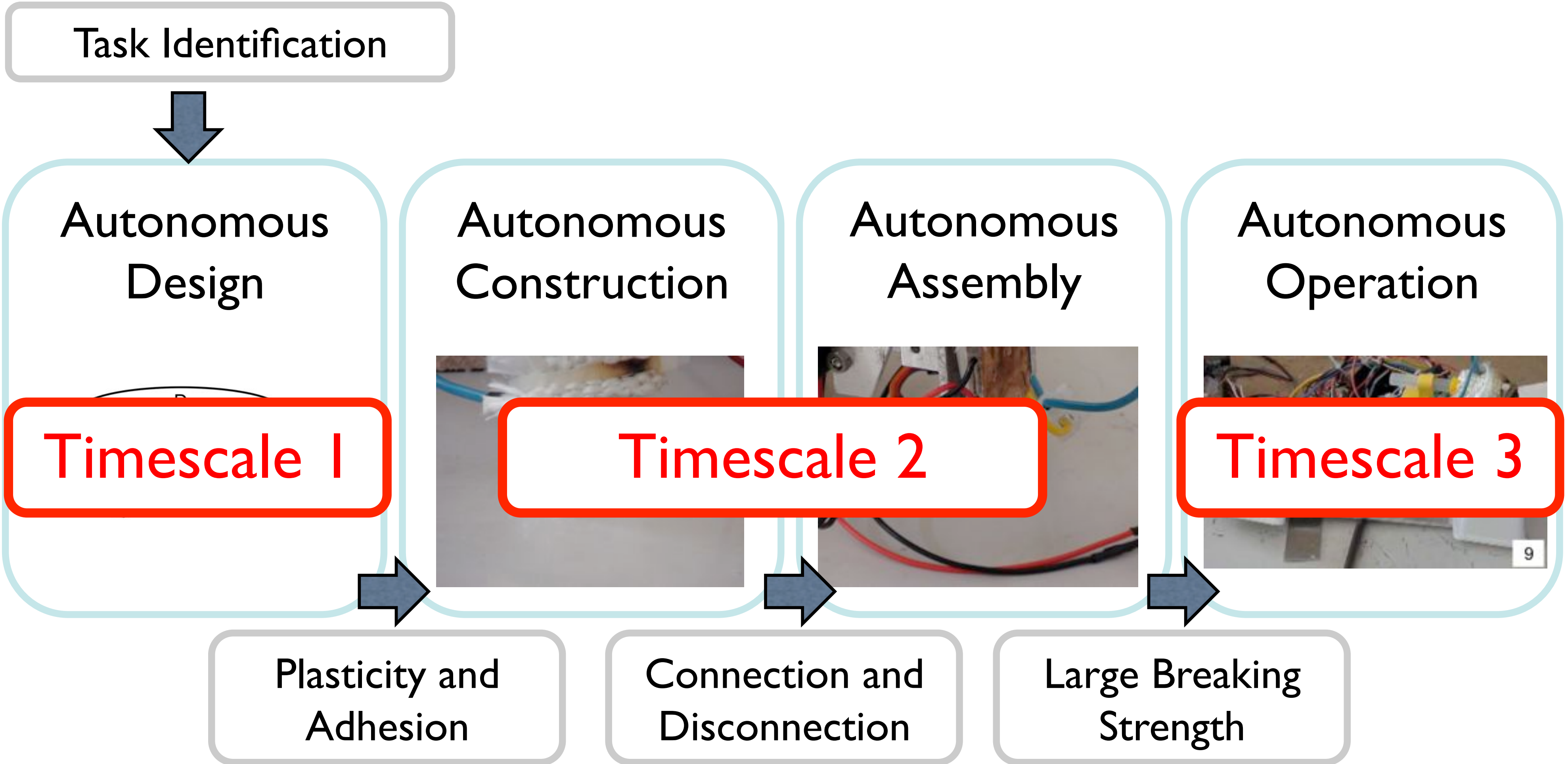
Plasticity and Adhesion

Connection and Disconnection

Large Breaking Strength

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

Autonomous Robot Body Extension



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

Conclusions

Morphological computation gives us many ideas for self-organization ***in the real world***.

Challenges:

How can self-organization processes be ***physically meaningful***?

- Self-stability in motion control
- Energy-efficient (and rapid) motion control

How can we ***scale up*** real-world self-organization processes?

- Material, material, material, and material!
- Self-organization in different timescales

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For publications, video, pictures:

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