ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EPFL Biorobotics Laboratory

Investigating animal locomotion using mathematical models and biorobots

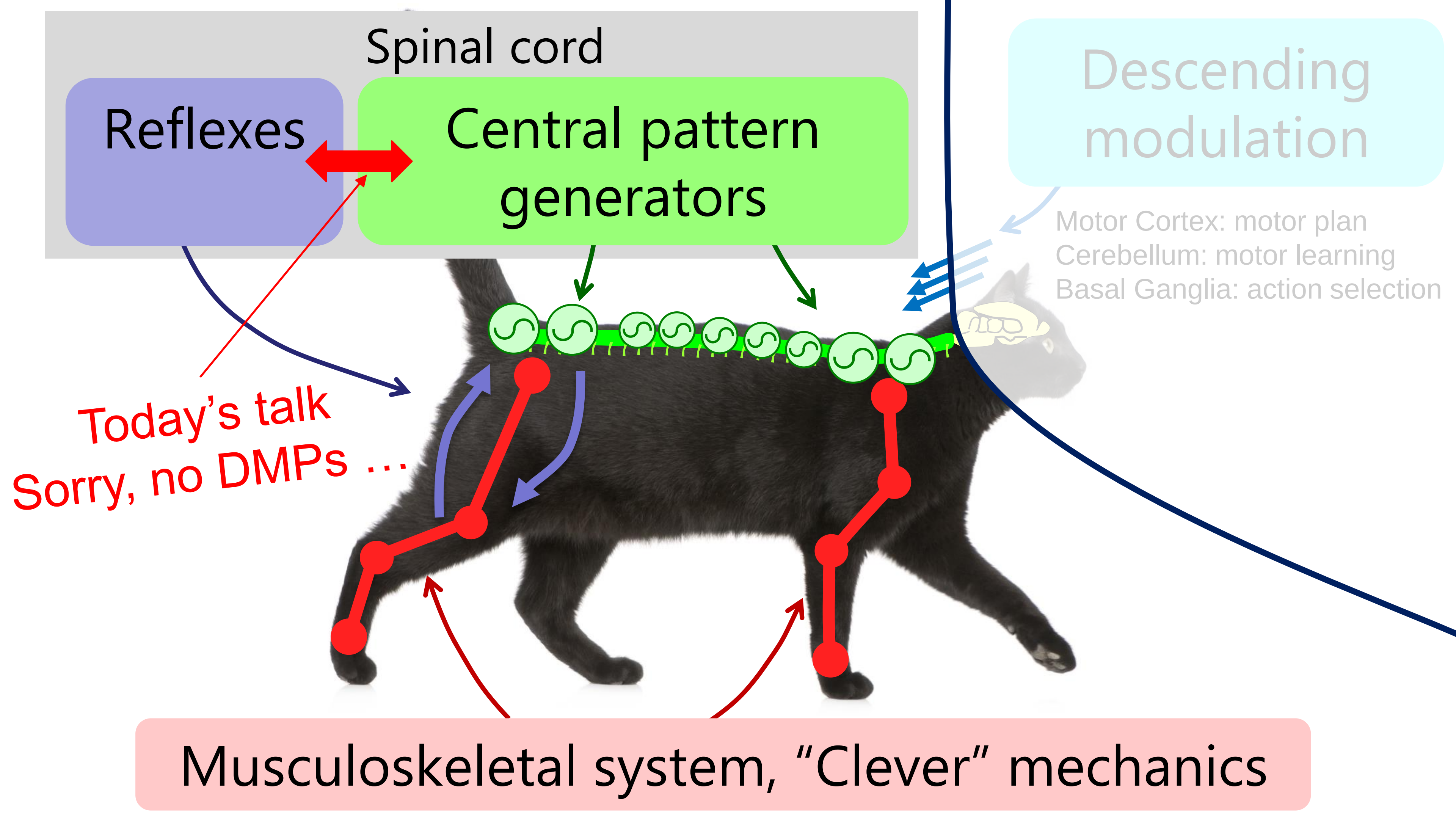
Auke Jan Ijspeert

Learning and Adaptation for Sensorimotor Control
LCCC, Lund, October 25 2018

The beauty of animal mobility

https://www.youtube.com/watch?v=CoL8Gtvxfl0

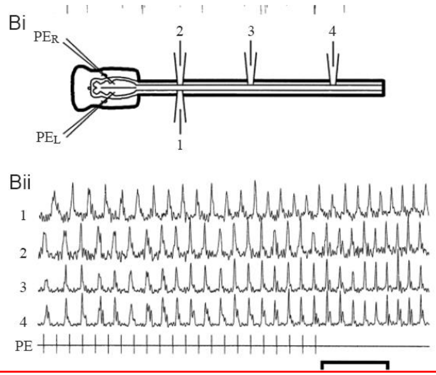
The beauty of animal mobility


Spinal cord
Reflexes
Central pattern generators
Descending modulation
Motor Cortex: motor plan
Cerebellum: motor learning
Basal Ganglia: action selection
Today's talk
Sorry, no DMPs …
Musculoskeletal system, "Clever" mechanics

Impressive features of spinal circuits

***Fictive* locomotion**

Lamprey
Salamander
Turtle
Mouse
Cat,
Monkey…



Impressive features of spinal circuits

Fictive locomotion

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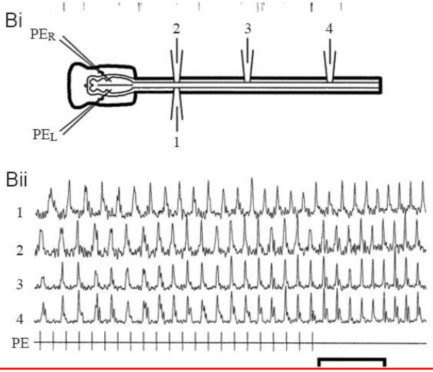
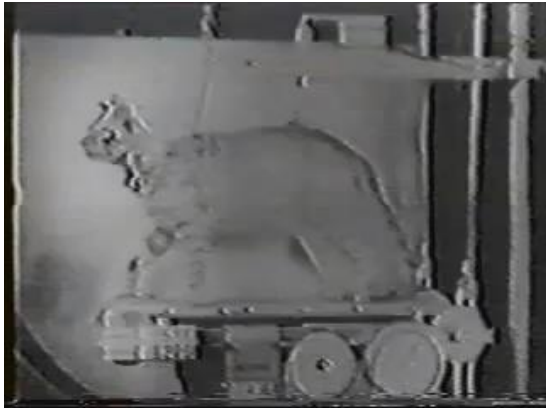


Stimulation-induced gait transitions

Cat: walk to trot to gallop
(Shik and Orlovsky 1966)
Salamander: walk to swimming
(Cabelguen et al 2003)
Bird: walk to flying
(Steeves et al 1987)

Mechanical entrainment



(Brown 1972)

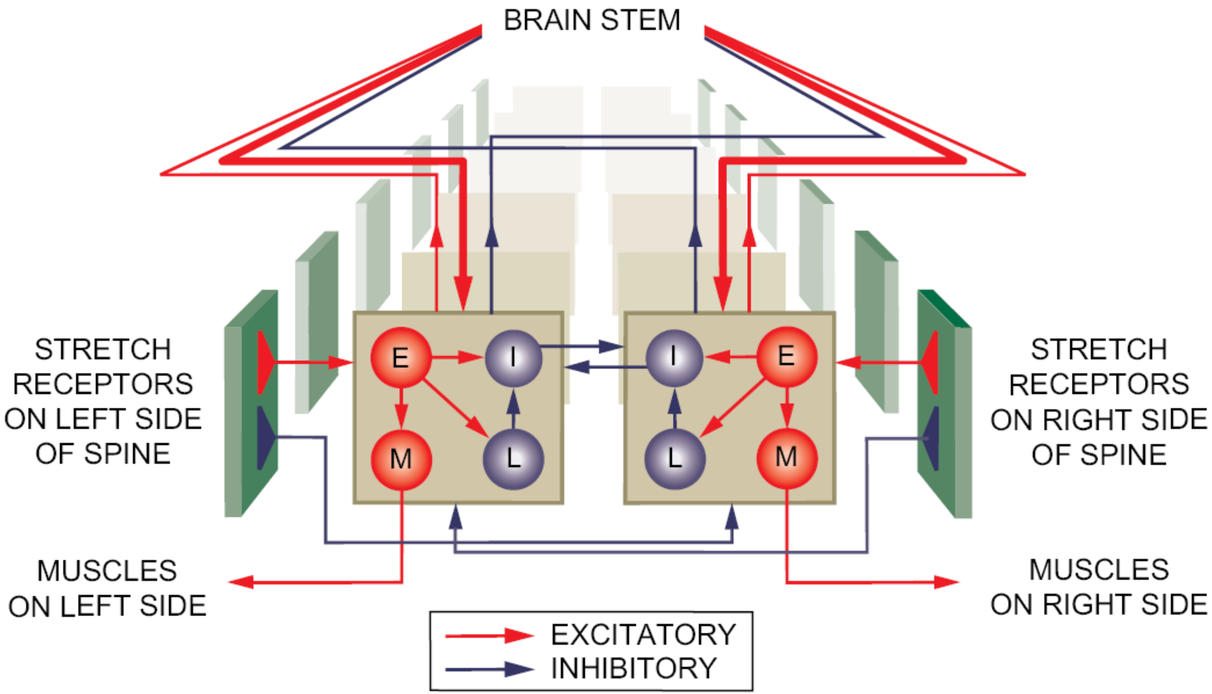
Functional animals without cortex

Cat living without cerebral cortex
(Bjursten et al 1976)

Headless chicken!!

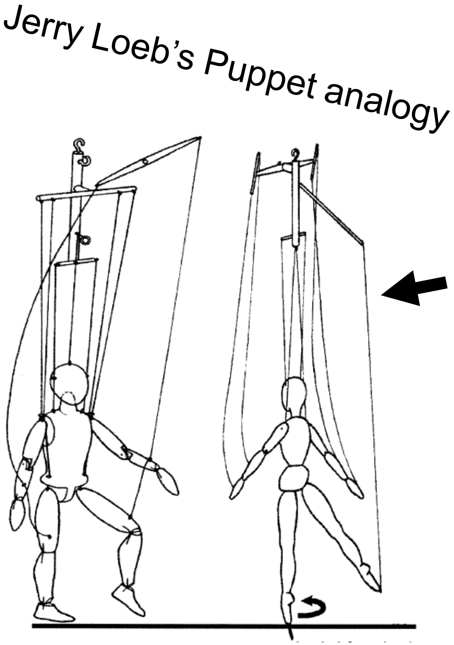
https://en.wikipedia.org/wiki/Mike_the_Headless_Chicken

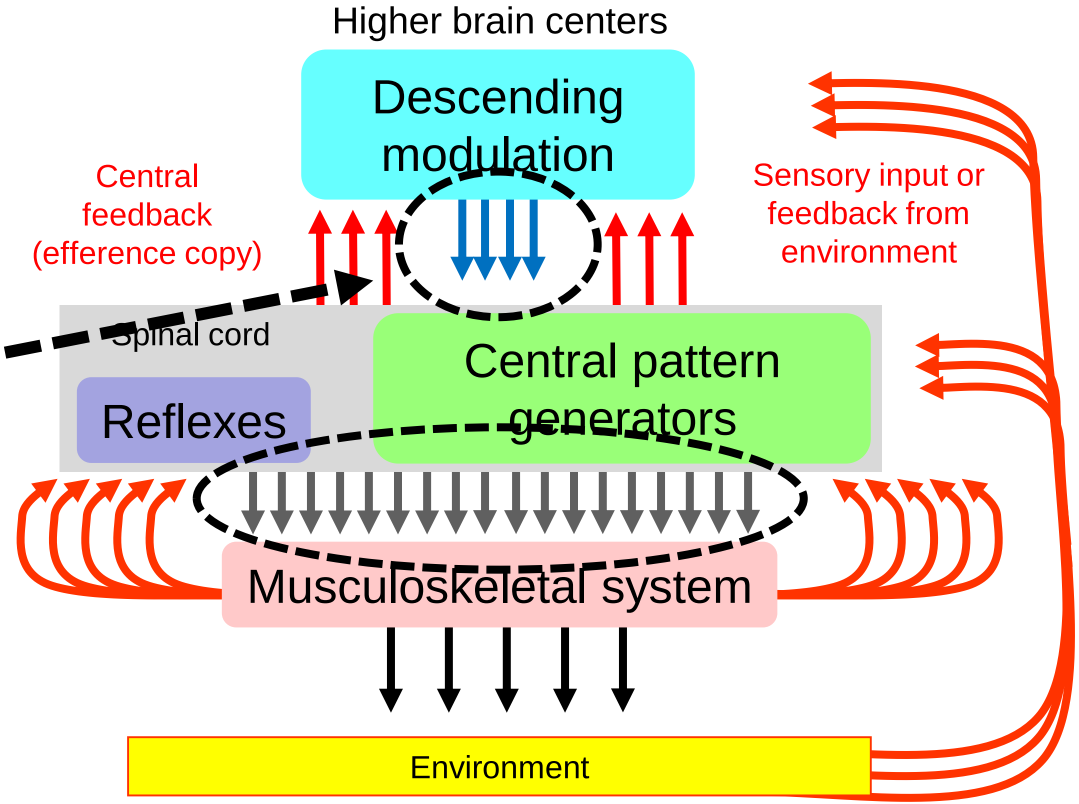
Lamprey spinal cord



Grillner, Sci. Am. 1996

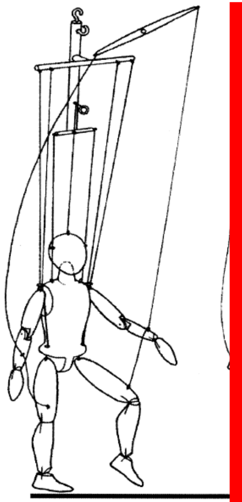
Spinal cord organization





Spinal cord organization

Jerry Loeb's Puppet analogy



Higher brain centers

Descending modulation

Central

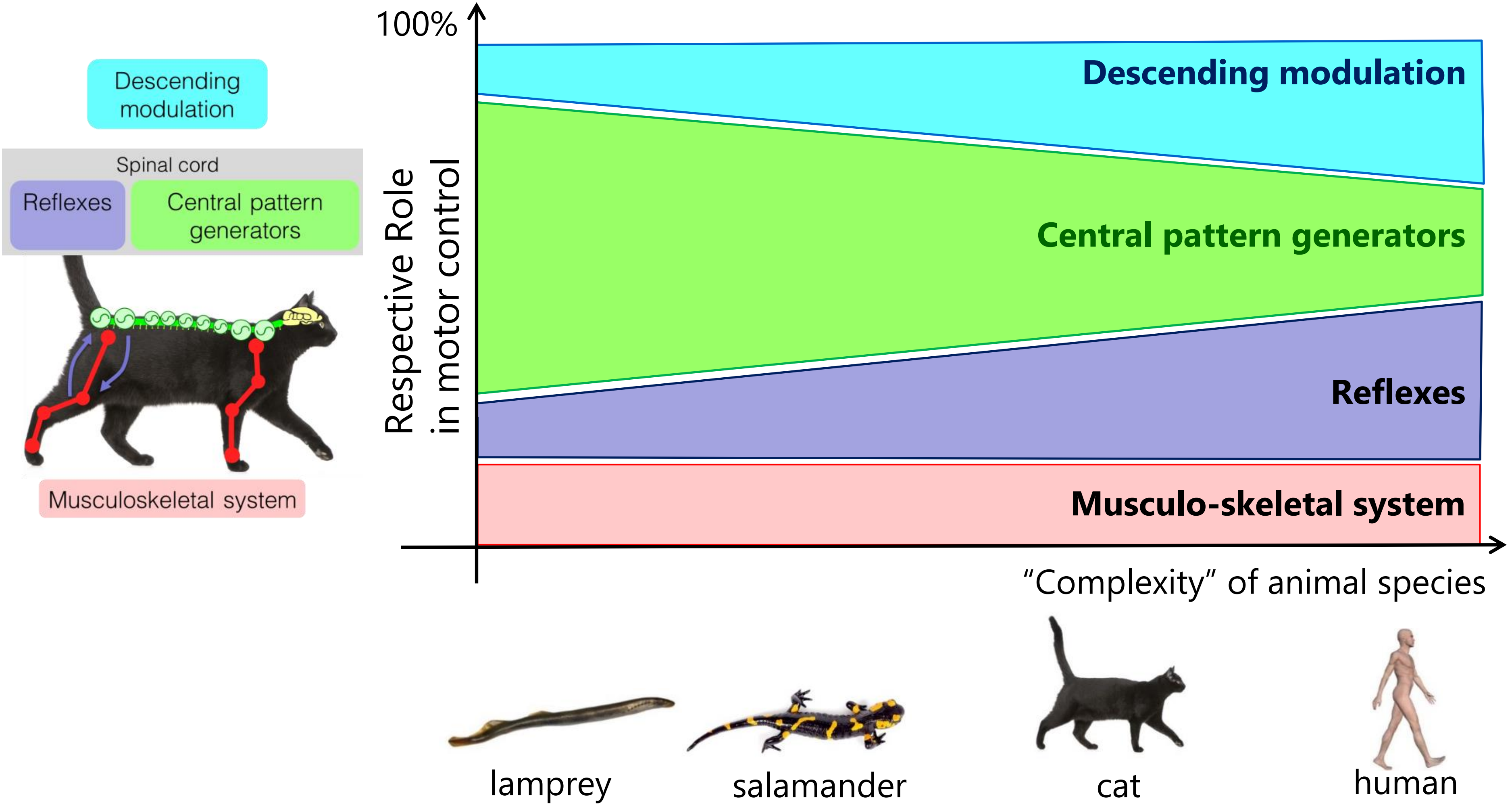
Sensory input or

The concept of CPG + reflexes is interesting for:

(1) **Low bandwidth communication** between higher centers and spinal cord

(2) **Fast feedback loops** in the spinal cord

(3) providing **motor primitives for a large range of movements**

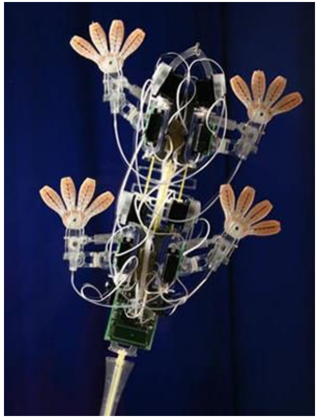


Descending modulation
Spinal cord
Reflexes
Central pattern generators
Musculoskeletal system
100%
Respective Role in motor control
Descending modulation
Central pattern generators
Reflexes
Musculo-skeletal system
"Complexity" of animal species
lamprey
salamander
cat
human

Legged biorobots

ANYmal
ETHZ, Switzerland


Aibo, SONY, Japan


StickyBot, Stanford, USA


RHex robot, USA

Asimo, Honda, Japan


BigDog,
Boston Dynamics, USA

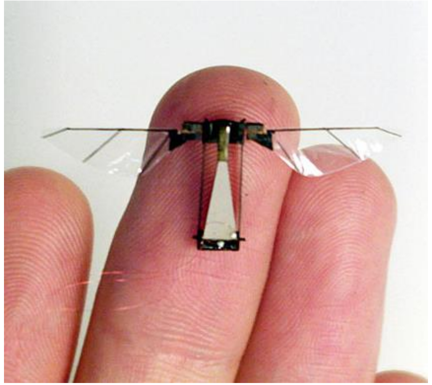
Flying biorobots

Feathered Drone, LIS, EPFL

Hummingbird, AeroVironment, USA

Ornithopter robot, U. Berkeley, USA

SmartBird, Festo, Germany



Micro aerial vehicle, Harvard Univ., USA

Swimming and crawling biorobots

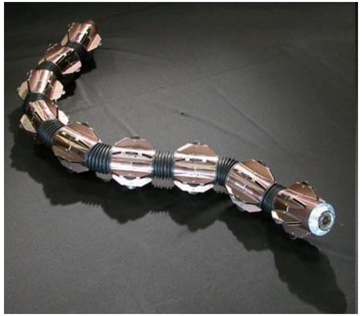
G6 Fish Robot,
University of Essex, UK

Manta Ray
EvoLogics, Germany

Lamprey robot, U. of Northeastern, USA

Lamprey robot, SSSA, Italy

Penguin robot, Festo, Germany

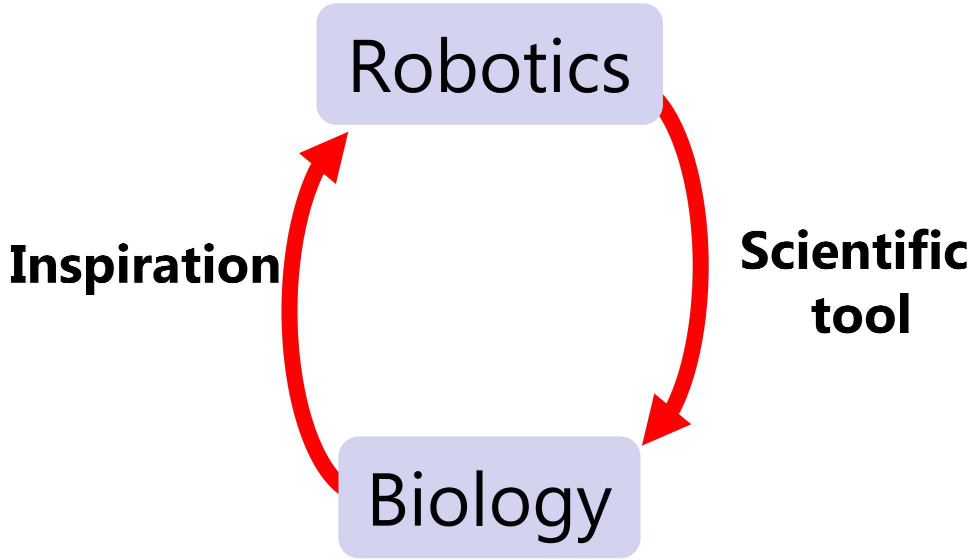


ACM robot, Tokyo Inst of Tech Japan

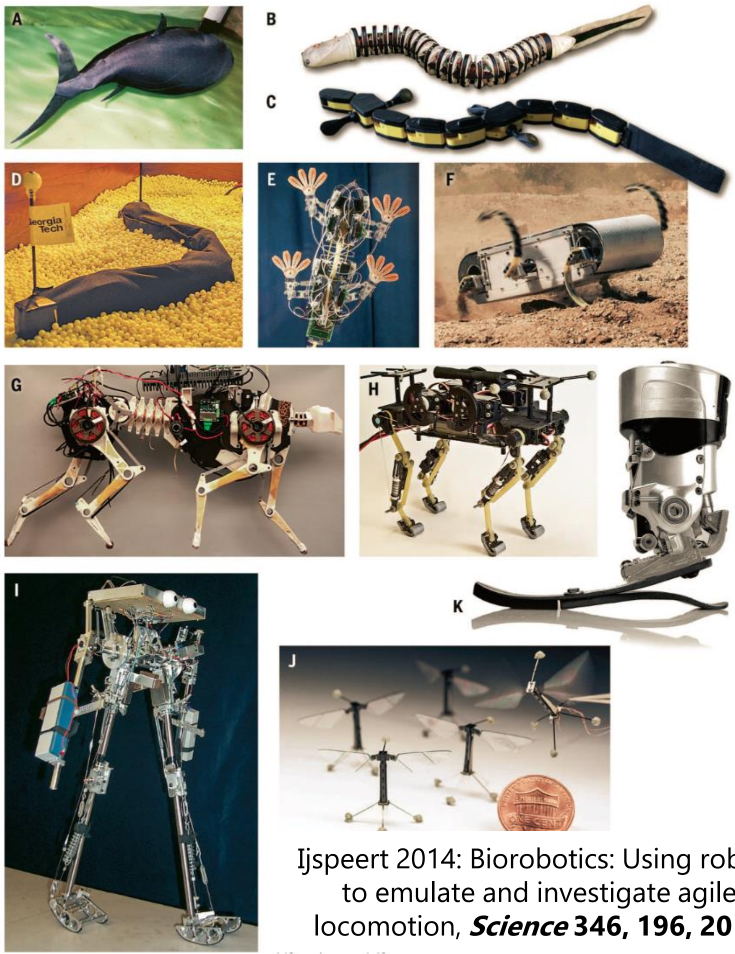
Snake Robot, CMU, USA

Biorobotics

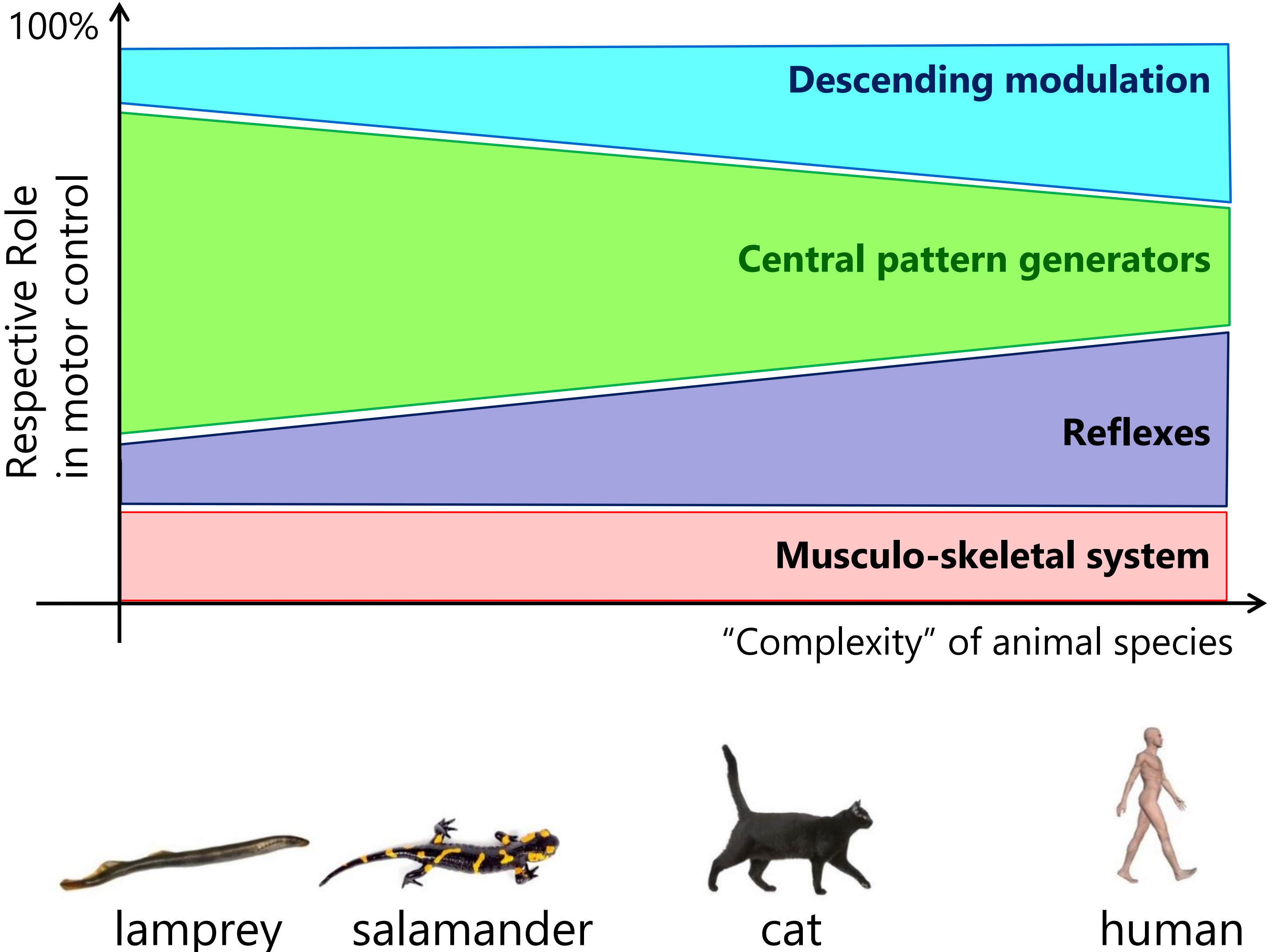
Inspection
Transport
Agriculture
Search and rescue



Neuroscience
Biomechanics
Hydrodynamics



Ijspeert 2014: Biorobotics: Using robots to emulate and investigate agile locomotion, ***Science* 346, 196, 2014**


100%
Respective Role in motor control
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"Complexity" of animal species
lamprey
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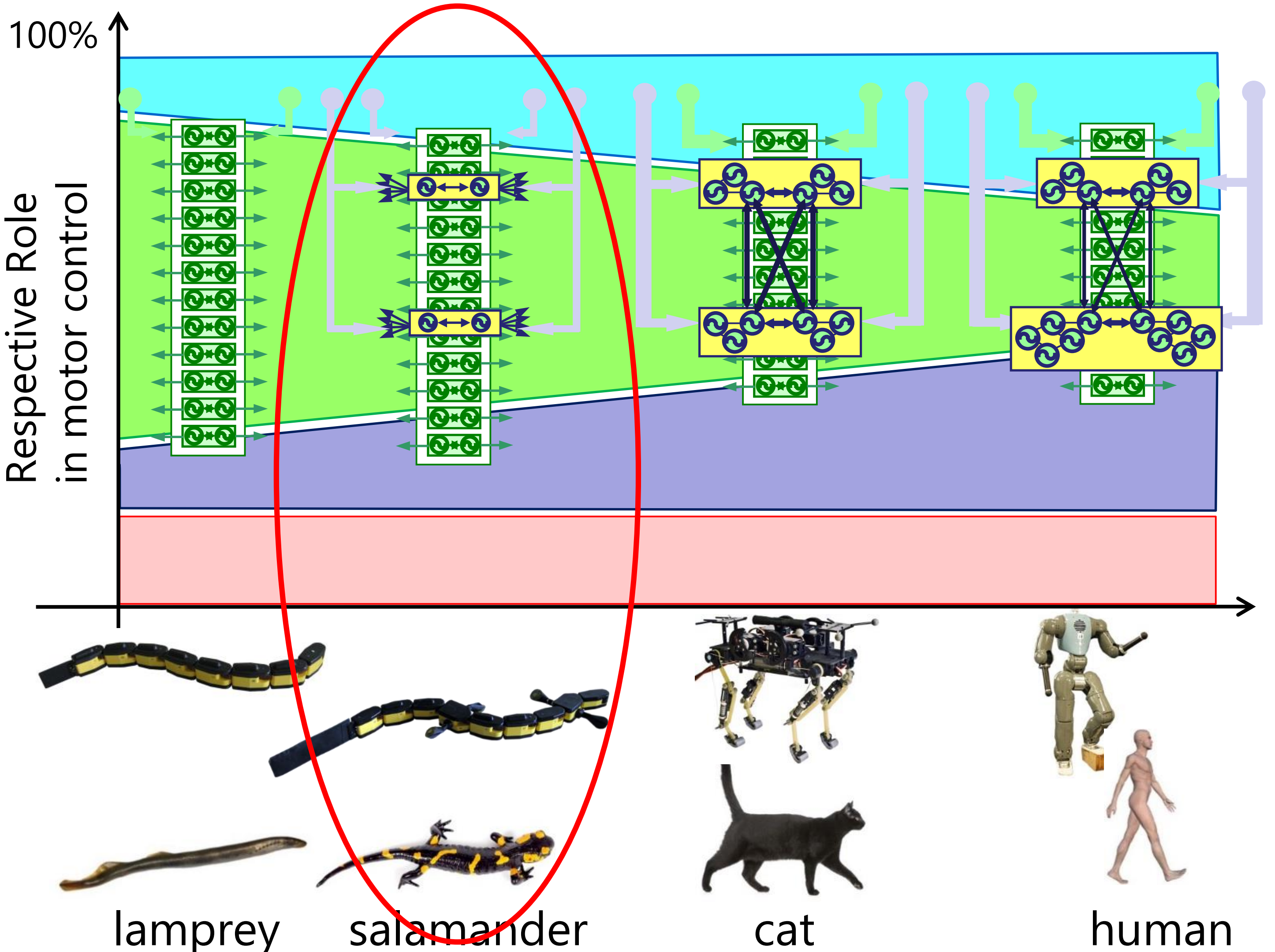
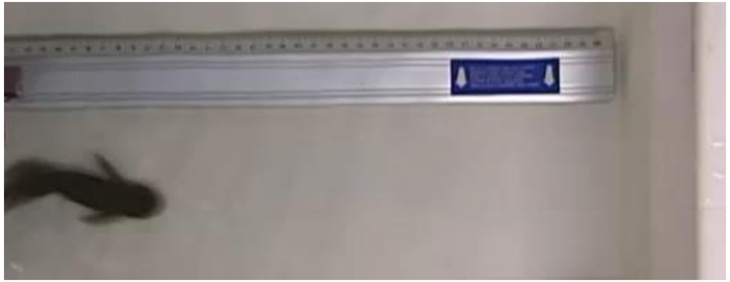
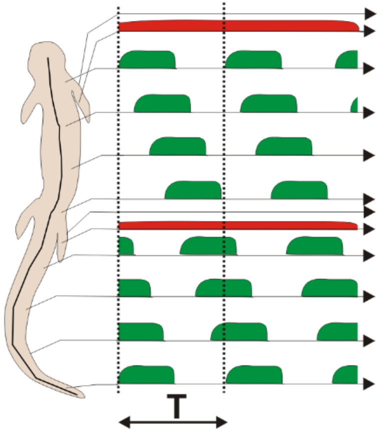
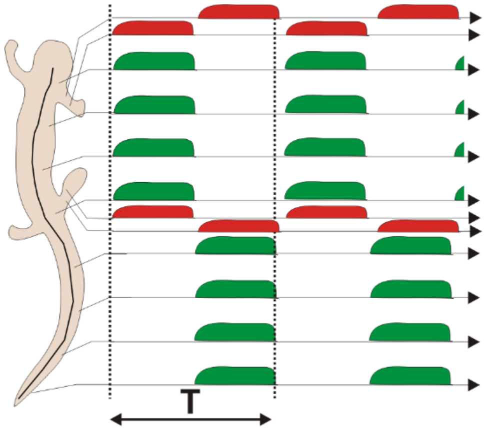

100%
Respective Role
in motor control
lamprey
salamander
cat
human

Bimodal locomotion (cartoon)





Swimming:
Traveling wave in axial muscles
Wavelength ≈ body length
Limb retractors are tonic
Short cycle durations



Walking:
Standing wave
Limb retractors/protactors are phasic
Longer cycle durations

Modeling the CPG with coupled oscillators

A segmental oscillator is modeled as an amplitude-controlled phase oscillator as used in (Cohen, Holmes and Rand 1982, Kopell, Ermentrout, and Williams 1990) :

Phase:

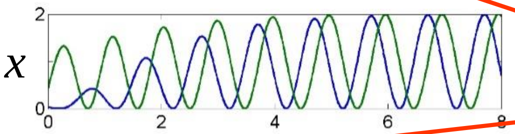
$$\dot{\theta}_i = 2\pi \nu_i + \sum_j r_j w_{ij} \sin(\theta_j - \theta_i - \phi_{ij})$$

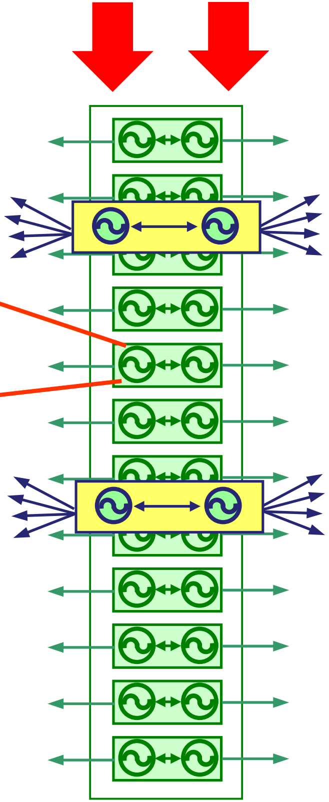
Amplitude:

$$\ddot{r}_i = a_i \left(\frac{a_i}{4} (R_i - r_i) - \dot{r}_i \right)$$

Output:

$$x_i = r_i (1 + \cos(\theta_i))$$



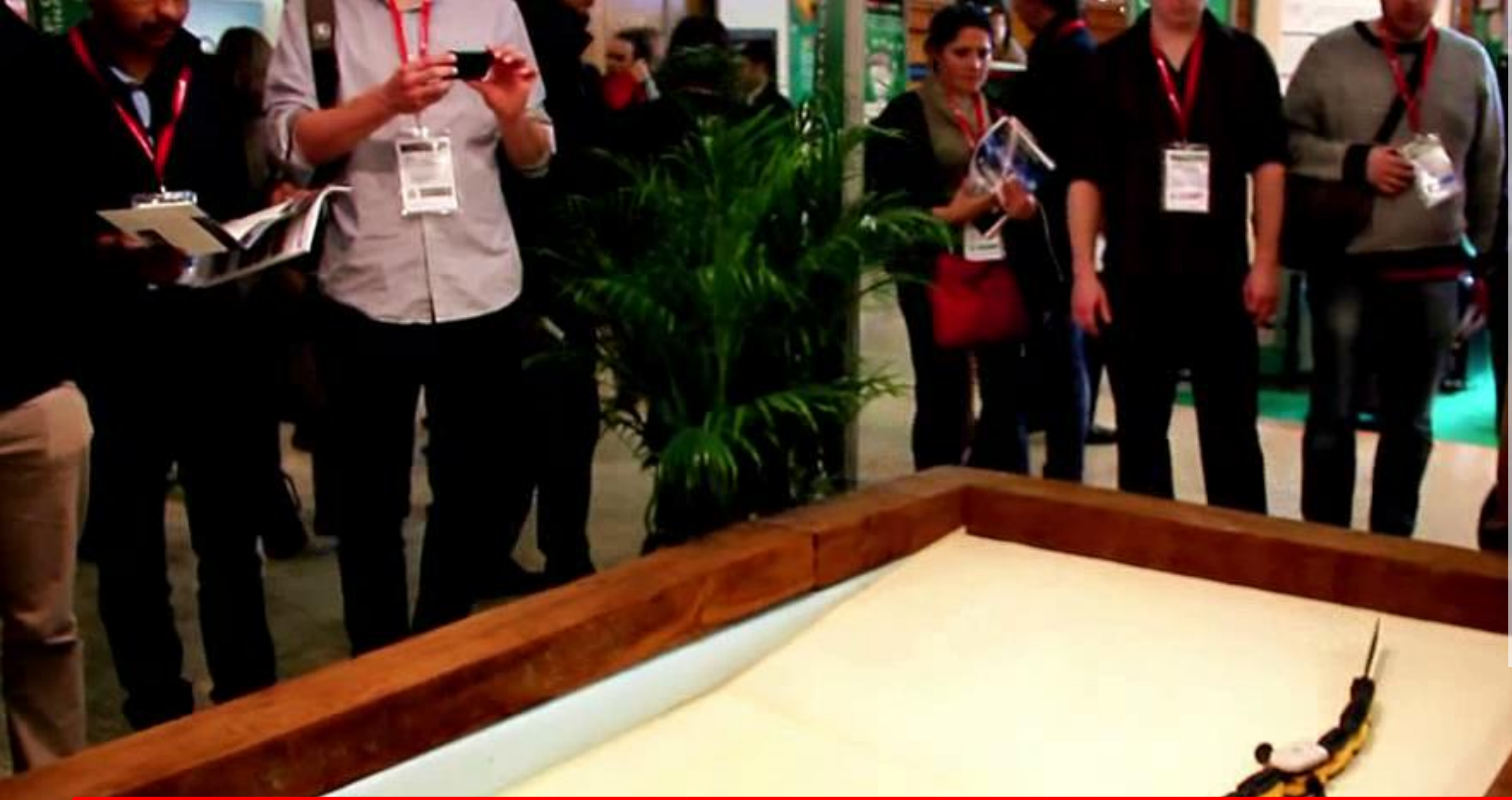


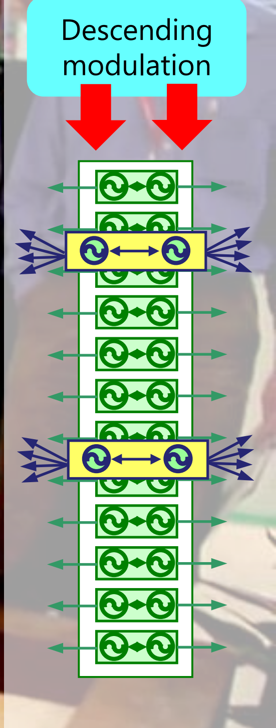
Setpoints:

$$\varphi_i = x_i - x_{N+i} \quad \textit{for the axial motors}$$

$$\varphi_i = f(\theta_i) \quad \textit{for the (rotational) limb motors}$$

[Ijspeert *et al*, *Science*, March 2007].

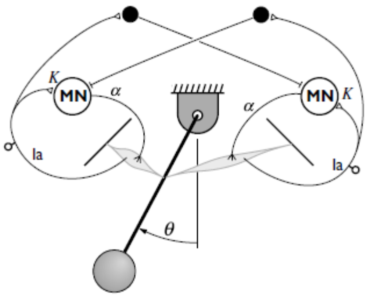


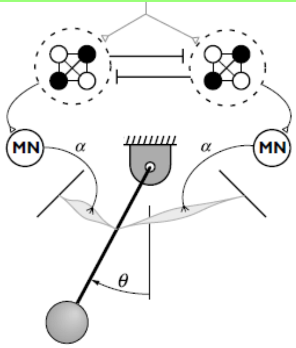


CPGs can modulate speed, heading, and type of gait under the modulation of a few drive signals

The big question

Sensory feedback vs **CPGs**





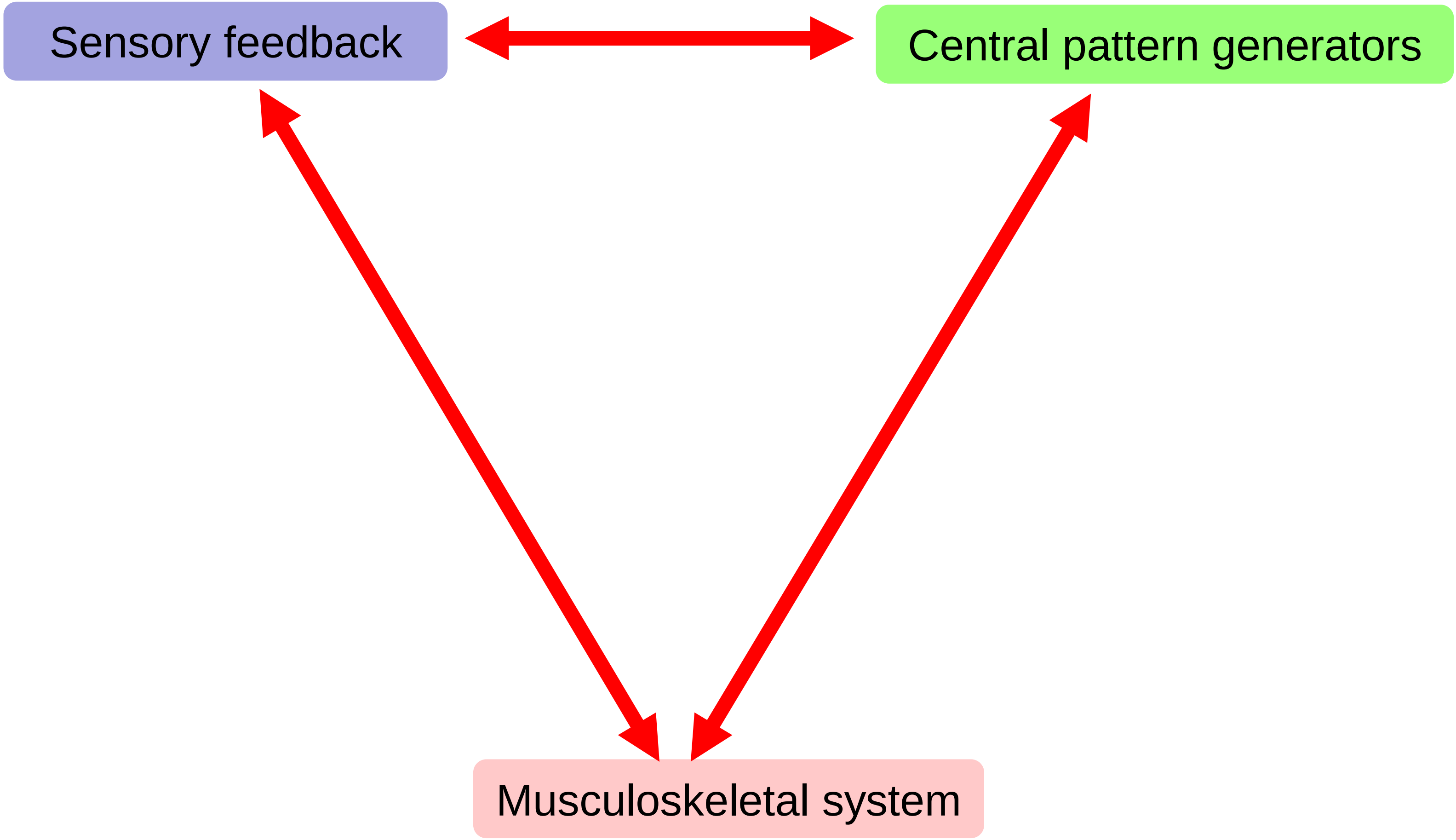
Kuo 2002,
Motor Control

Chain of reflexes — Sherrington ↔ Brown — Half centers

Peripheral control ↔ Central control

Feedback control ↔ Feedforward control

The bridge: body dynamics



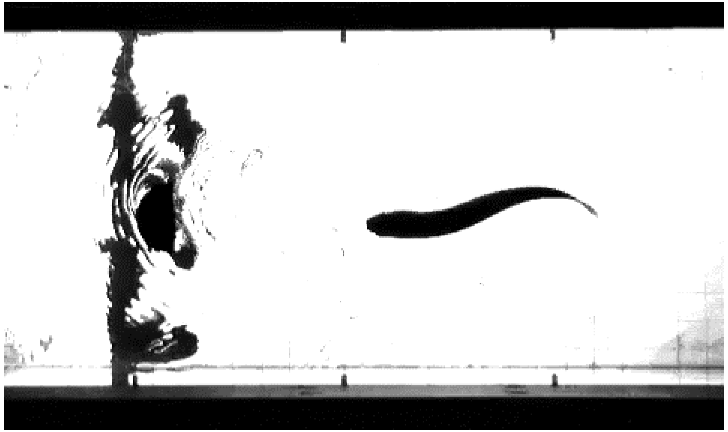
The bridge: body dynamics

Sensory feedback ⟷ Central pattern generators

Passive walker

Collins, S. H., Wisse, M., Ruina, A. (2001)
International Journal of Robotics Research,
Vol. 20, No. 2, Pages 607-615

Dead ! trout swimming



Liao, J. C. (2004).
Journal of Experimental Biology,
Vol. *207*(20), 3495-3506.
MIT tow tank, Lauder Lab Harvard
http://web.mit.edu/towtank/www/

Musculoskeletal system

Interaction of CPG and sensory feedback


L. Paez


A. Crespi


B. Bayat


K. Melo


T. Horvat


J. Arreguit O'Neil


R. Thiandiackal


Astrid Petitjean

Alumni:
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K. Karakasiliotis, R. Thandiackal

HFSP

Collaborators:


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Tohoku U.


Emily Standen
Ottawa U.

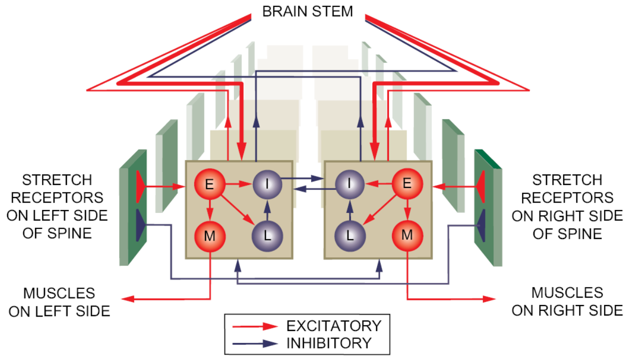

J.M. Cabelguen
U. of Bordeaux


Fred Boyer
Ecole des Mines
Nantes

Stretch receptors in the lamprey

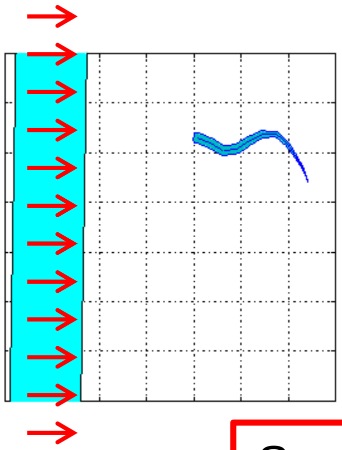
Stretch receptors within the spinal cord:

- Participate to **burst termination**.
- Help **handle perturbations**, e.g. a speed barrier.

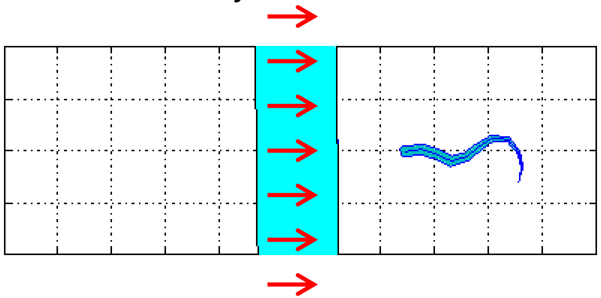


Grillner, Sci. Am. 1996

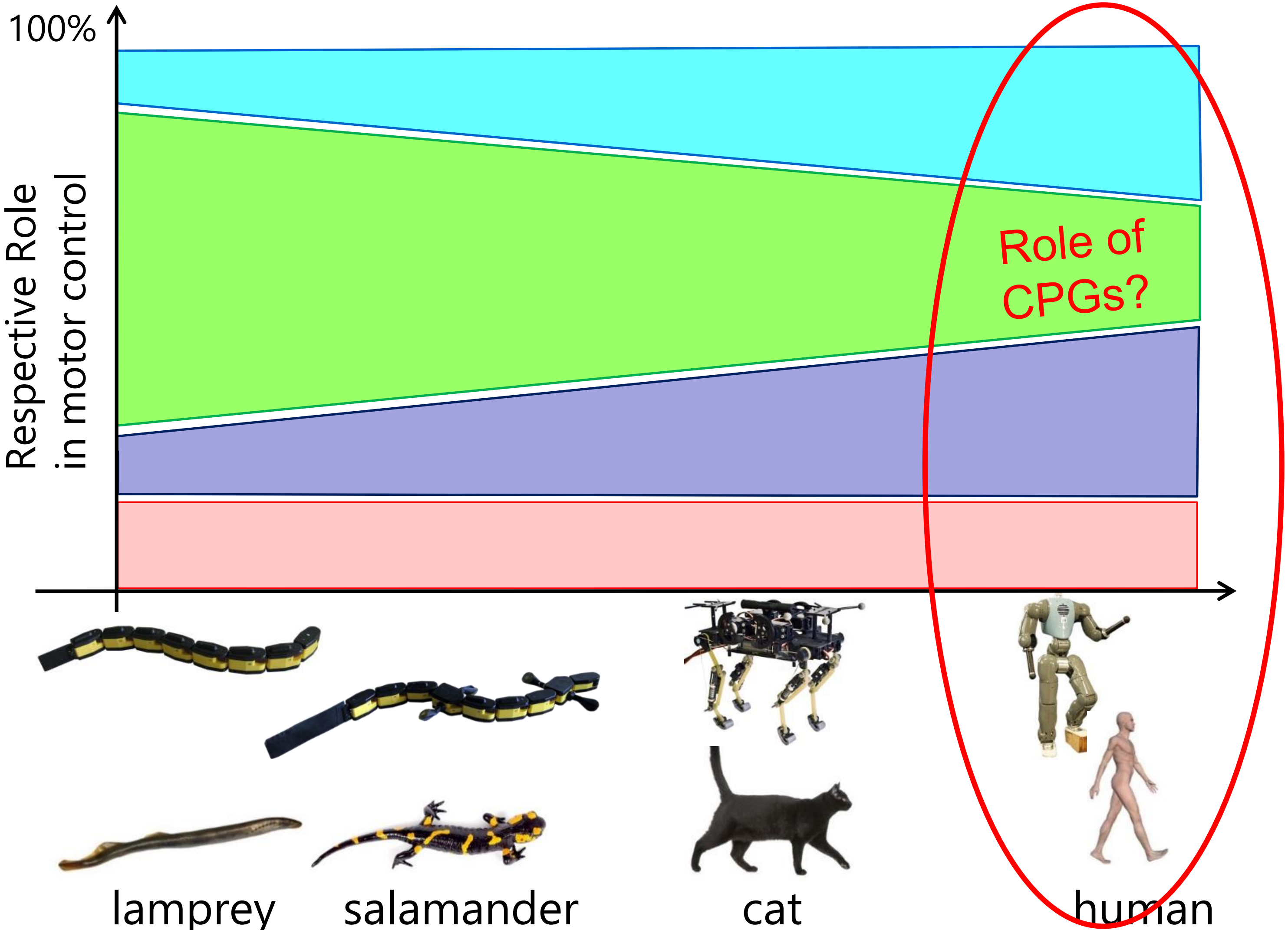
Swimming through a speed barrier
without sensory feedback (only CPG)



Swimming through a speed barrier
with sensory feedback

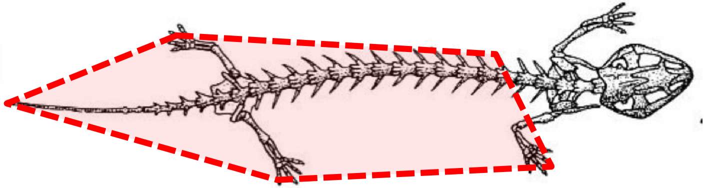


Sensory feedback helps handle perturbations

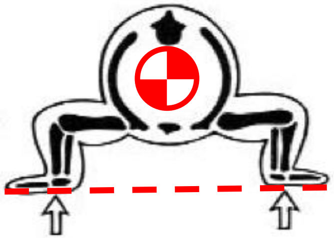

100%
Respective Role
in motor control
Role of
CPGs?
lamprey
salamander
cat
human

Key transition from amphibians to mammals

Sprawling posture



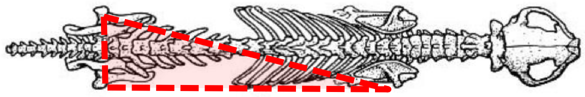
Salamander



Low center of mass

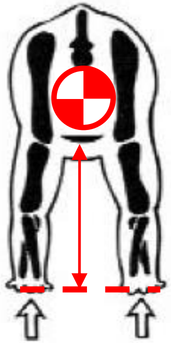
Large support polygon

Upright posture



studyblue.com

Mammal



High center of mass

Small support polygon

CPGs in humans? Most likely

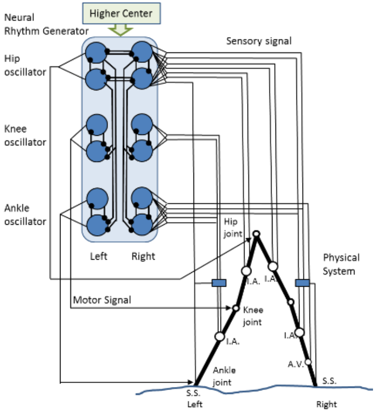
Review paper:

The Human Central Pattern Generator for Locomotion: Does It Exist and Contribute to Walking?

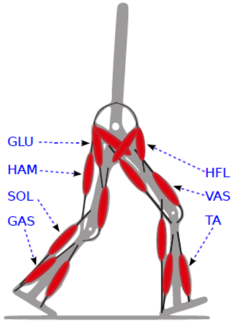
Karen Minassian, Ursula S. Hofstoetter, Florin Dzeladini, Pierre A. Guertin, and Auke Ijspeert

The Neuroscientist, 1-15, 2017

Neuromechanical models of human locomotion

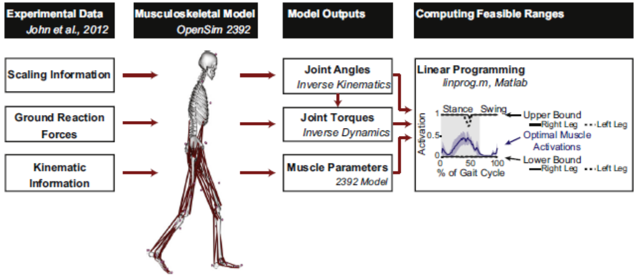


Taga 1995, 1998



Geyer and Herr, 2010.
Song and Geyer 2015

Y.Nakamura lab (Sreenivasa et al 2012)



L. Ting lab (Simpson et al 2016)

Geyer and Herr's sensory-driven model

Sensory-driven model

\+

7 muscles per leg

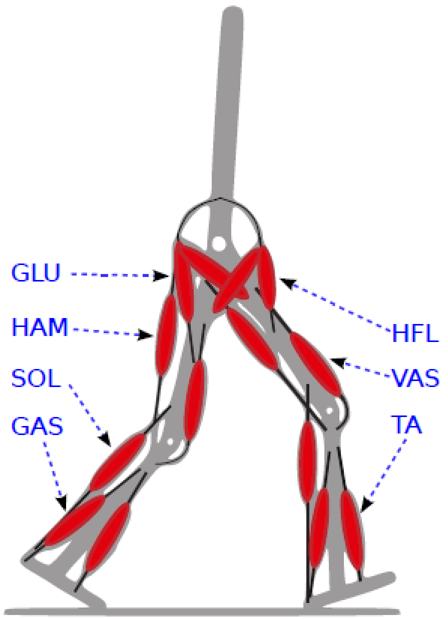
\+

Different reflexes

(positive and negative force feedback, limits of overextension, …)

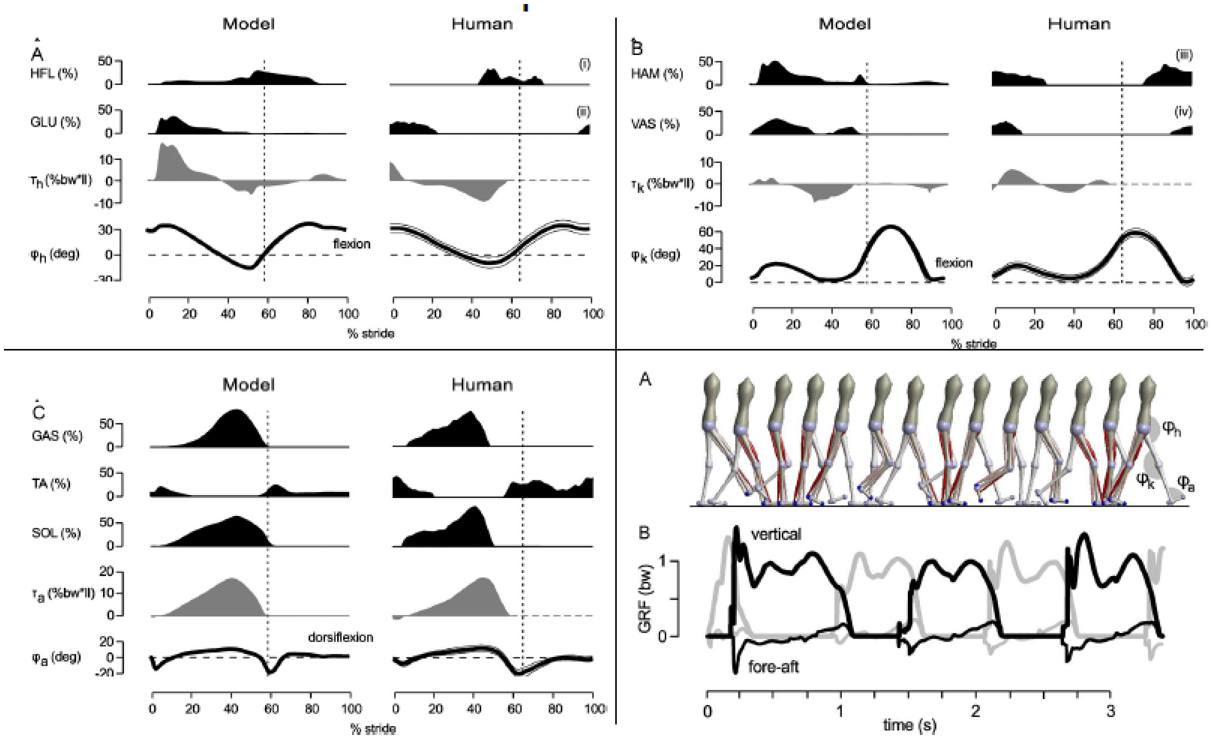
\+

Posture control (torso angle)



H Geyer, HM Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. **IEEE Trans Neural Syst Rehabil Eng** 18(3): 263-273, 2010.

Good match to human data



H Geyer, HM Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. **IEEE Trans Neural Syst Rehabil Eng** 18(3): 263-273, 2010.

Benefits of a CPG?

- Is it worth adding a CPG to the sensory-driven network?
- Yes, we think so!

Hypotheses: adding a CPG to the feedback-driven controller can

1) Improve the **control of speed**
2) Improve **robustness against sensory noise**
3) Improve **robustness against sensory failure**

This can be seen as adding a feedforward controller to a feedback controller

Florin Dzeladini

N. van der Noot

A. Wu

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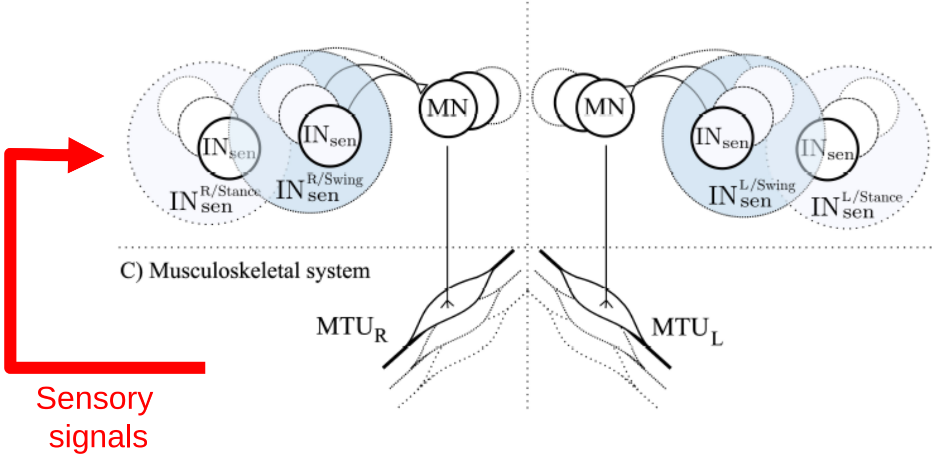
CPG construction

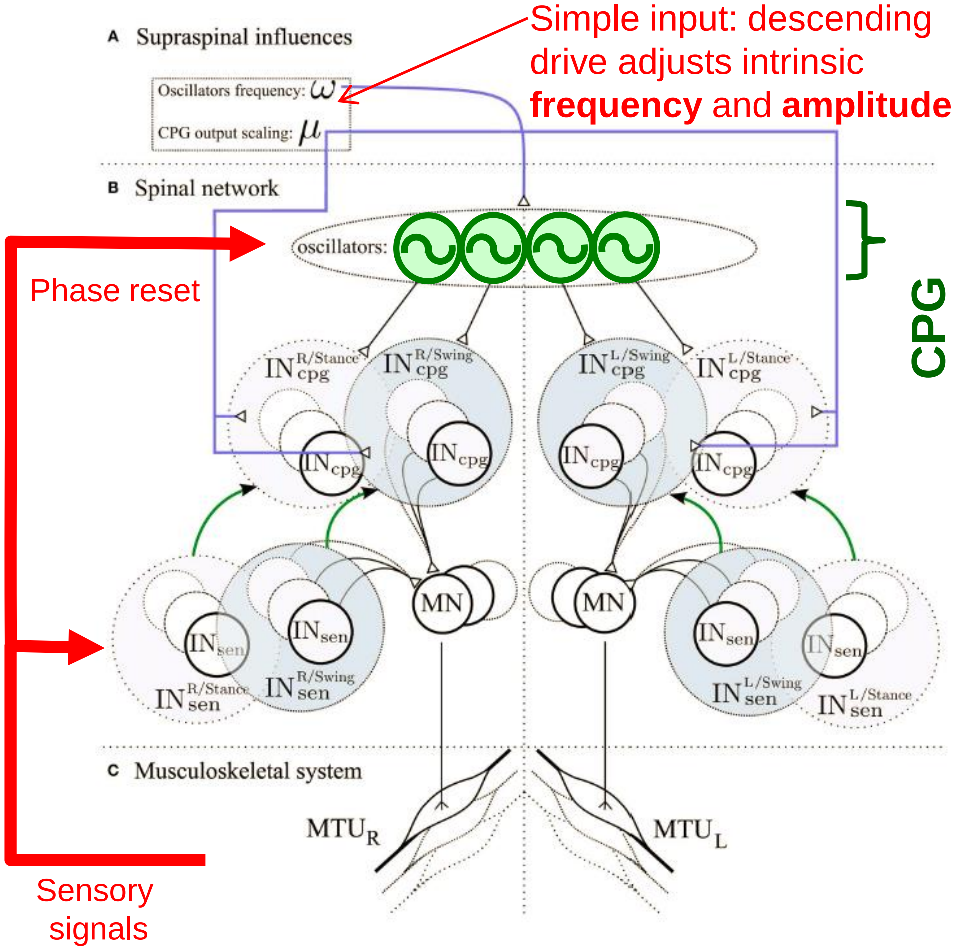
We start with the sensory-driven model:



Dzeladini et al 2014, Frontiers in Human Neuroscience

CPG construction

… and add a **CPG that replicates the control signals produced during steady-state**



Dzeladini et al 2014, Frontiers in Human Neuroscience

CPG construction

Feedback & CPG network

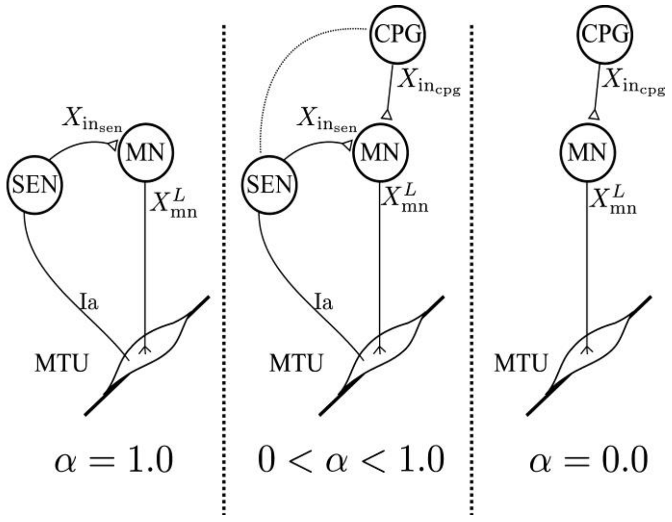
$$X_{\mathrm{mn}} = f(X_{\mathrm{in}_{\mathrm{sen}}}, X_{\mathrm{in}_{\mathrm{cpg}}}) + X^0_{\mathrm{mn}}$$

$$f(x_{\mathrm{fb}}, x_{\mathrm{ff}}) = G^s\Big(x_{\mathrm{ff}} + \alpha\big(x_{\mathrm{fb}} - x_{\mathrm{ff}}\big)\Big)$$

$\alpha = 0$ → pure feedforward

$\alpha = 1$ → pure feedback

Similarly to Kuo 2002, Motor Control



pure feedback

pure feedforward

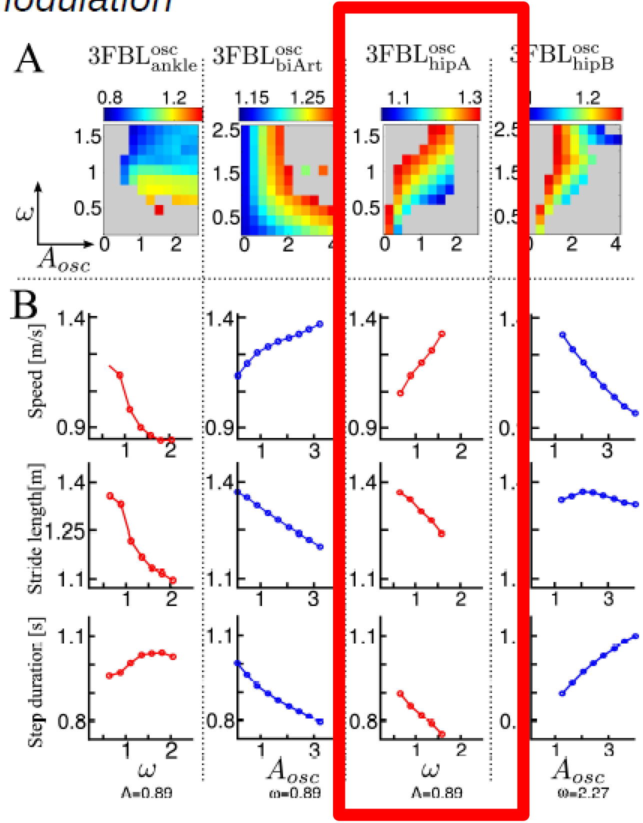
Dzeladini et al 2014, Frontiers in Human Neuroscience

Results: speed modulation

- Simple model of supraspinal influences
  Feedforward frequency and amplitude modulation

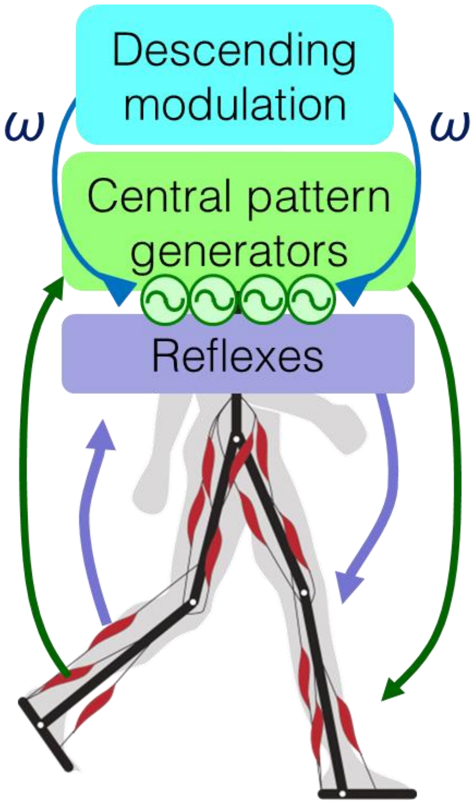
Nice control of speed by adding oscillators to the hips

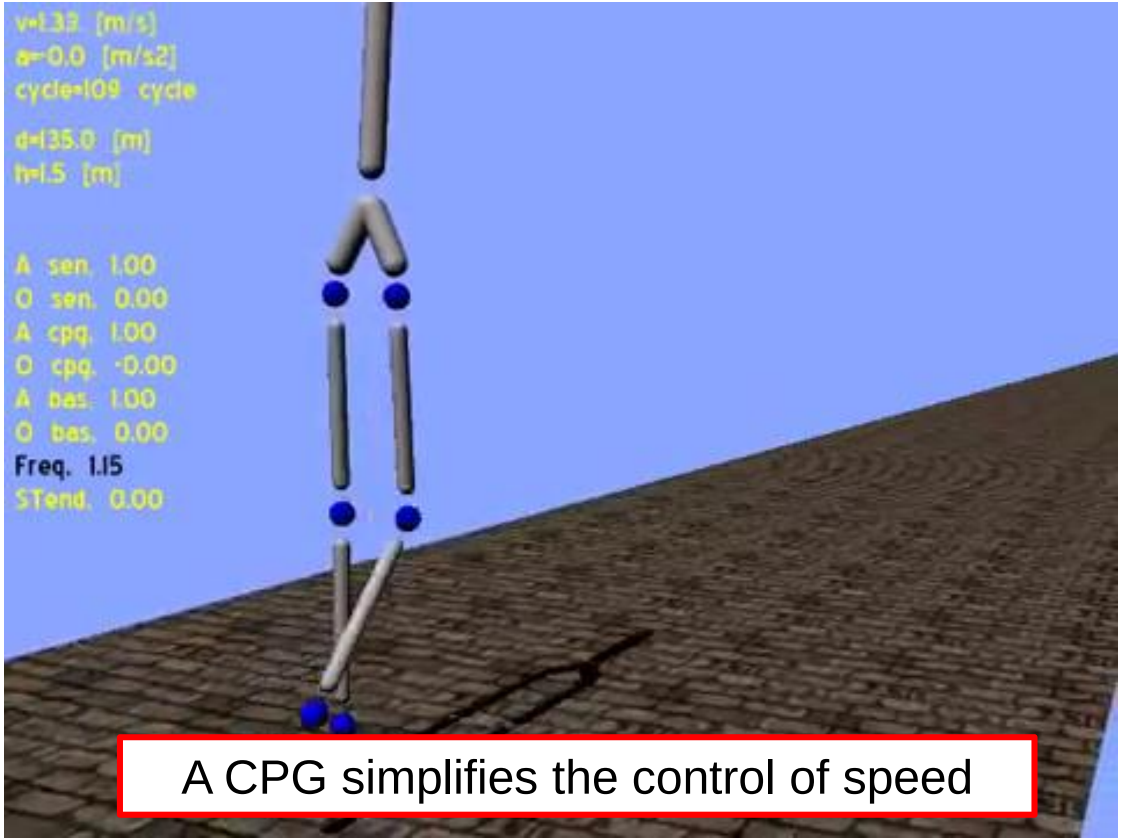
- *Tested on different models*
  - *Feedforward added on ankle pathways*
  - *Feedfoward added on biArt pathways*
  - *Feedforward on pathways acting on all hip muscles*
  - *Feedforward on pathways acting on two over four hip muscles*



Dzeladini et al 2014, Frontiers in Human Neuroscience

Neuromechanical model





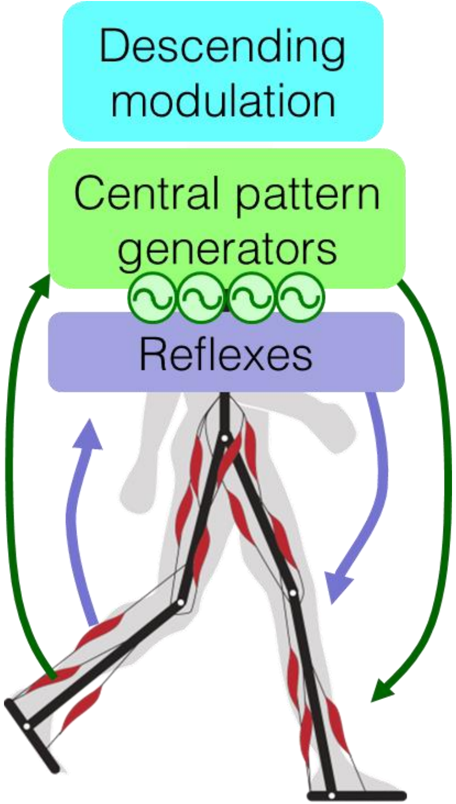
Dzeladini et al, The contribution of a central pattern generator in a reflex-based neuromuscular model, **Frontiers in Human Neuroscience**, Vol 8, 371, 2014

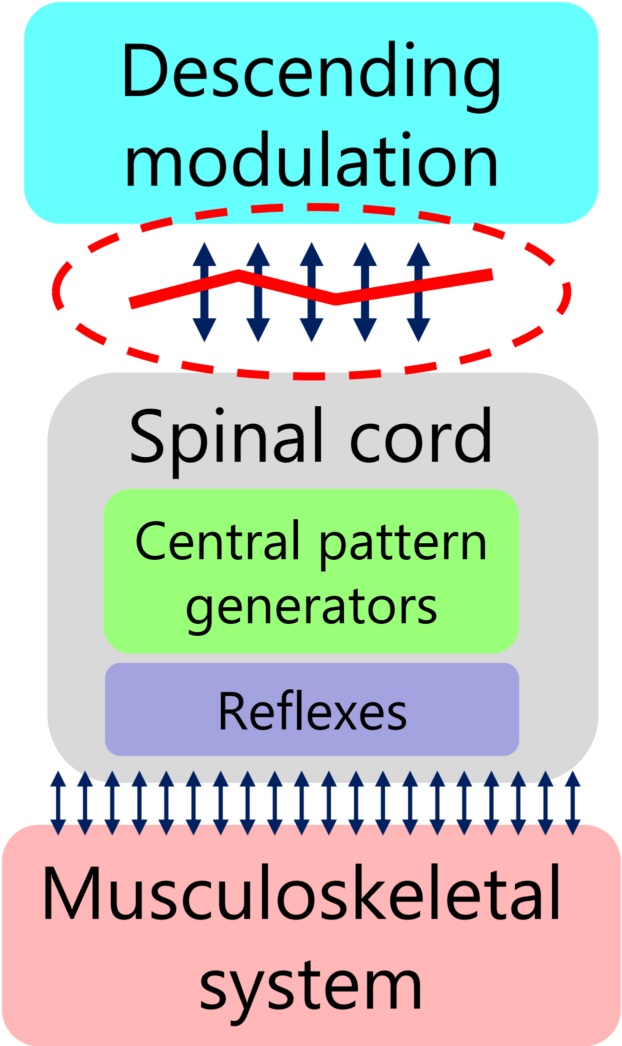
Using a similar model as a robot controller

Nicolas Van der Noot

Renaud Ronsse

Van Der Noot et al, The International Journal of Robotics Research, 2018


Descending modulation
Central pattern generators
Reflexes


Descending modulation
Spinal cord
Central pattern generators
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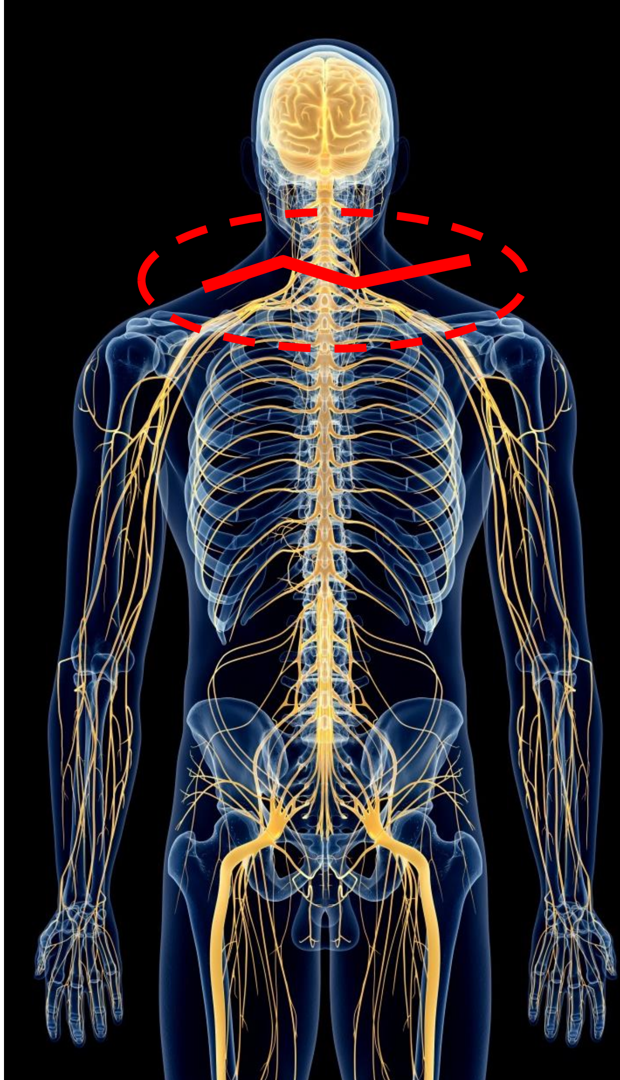
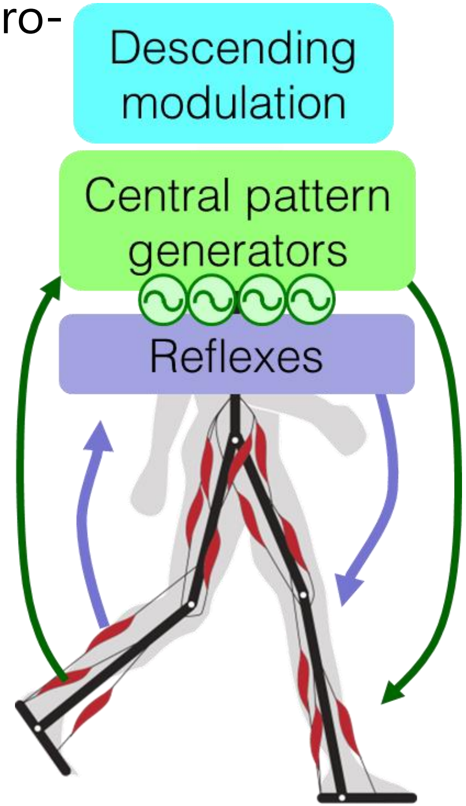
Musculoskeletal system



Controllers for exoskeletons

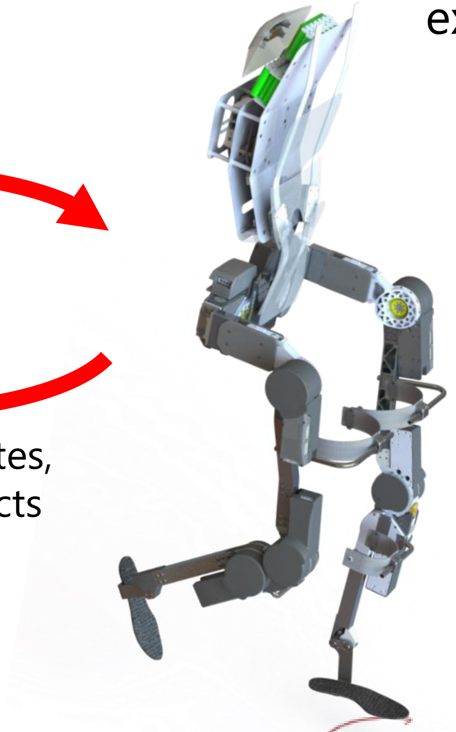
Simulated neuro-mechanical controller



Torques

Joint angle states, Ground contacts

Wearable exoskeleton



Coordinator:
H. Van der Kooij

Symbitron project:
U. Twente, TU Delft, Imperial College, Santa Lucia Fondation, Össur, EPFL

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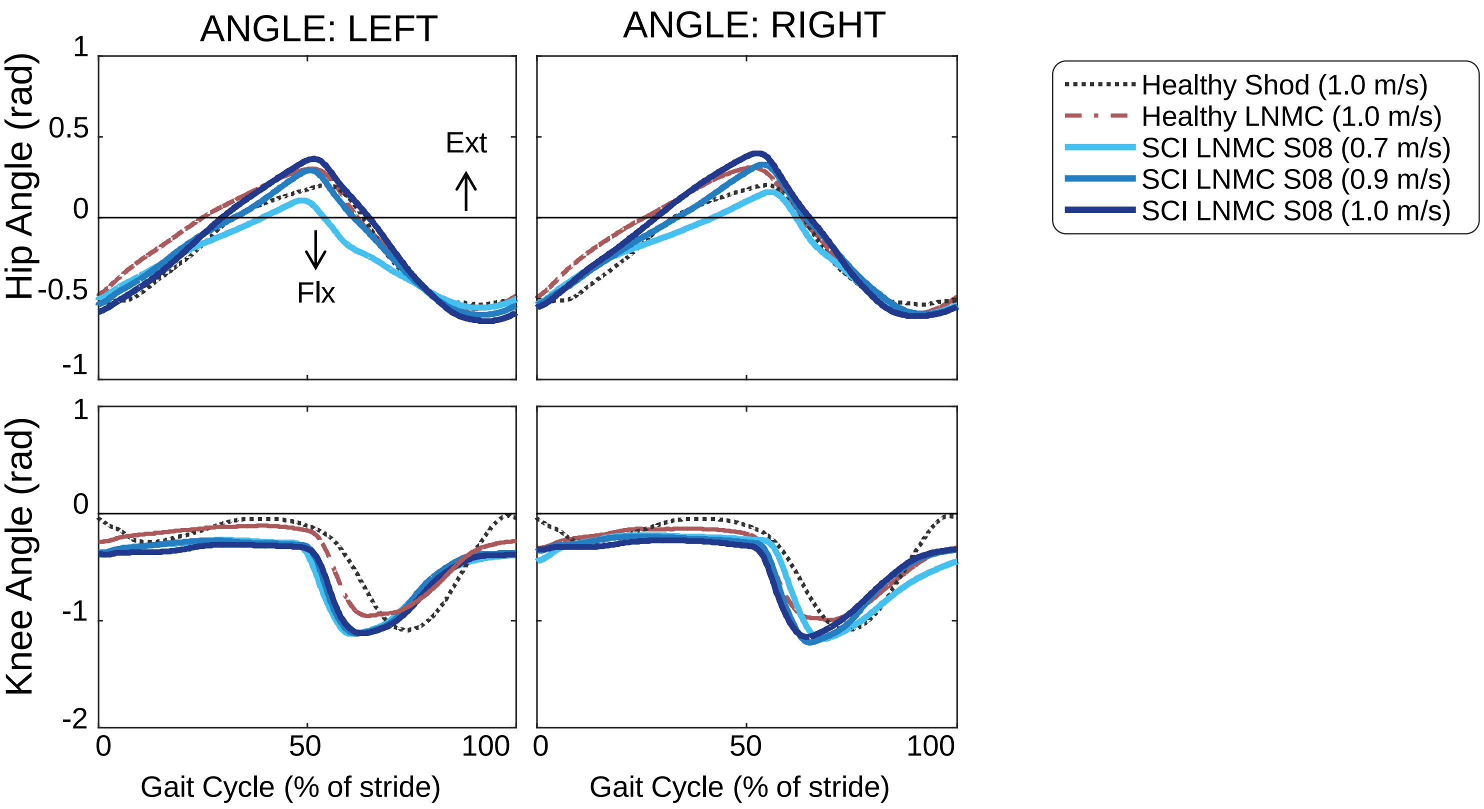
Similar joint angles as healthy locomotion (but without a reference trajectory!)



Push perturbations

Symbitron project:
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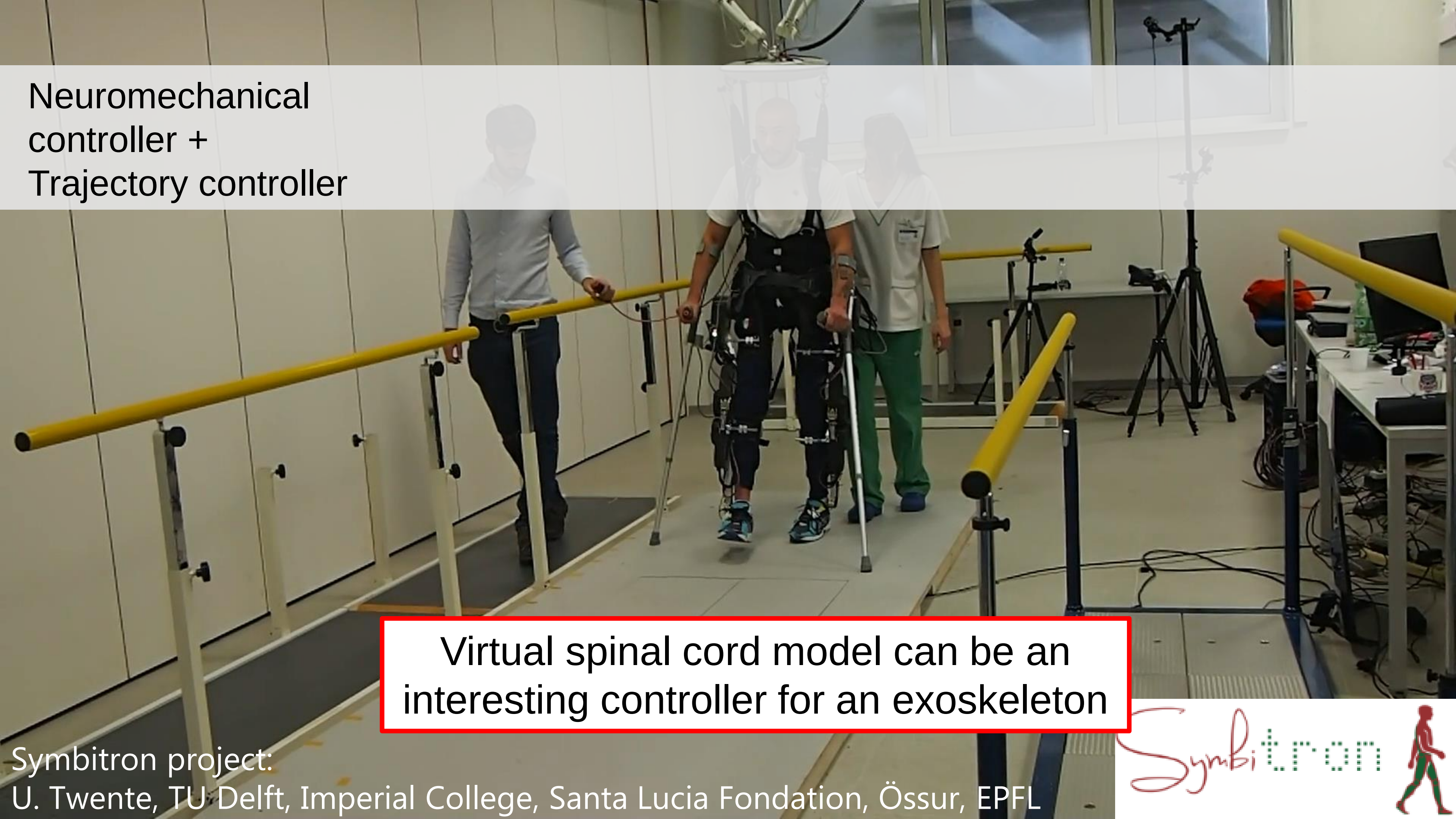
Symbitron

Neuromechanical
controller +
Trajectory controller



Virtual spinal cord model can be an interesting controller for an exoskeleton

Symbitron project:
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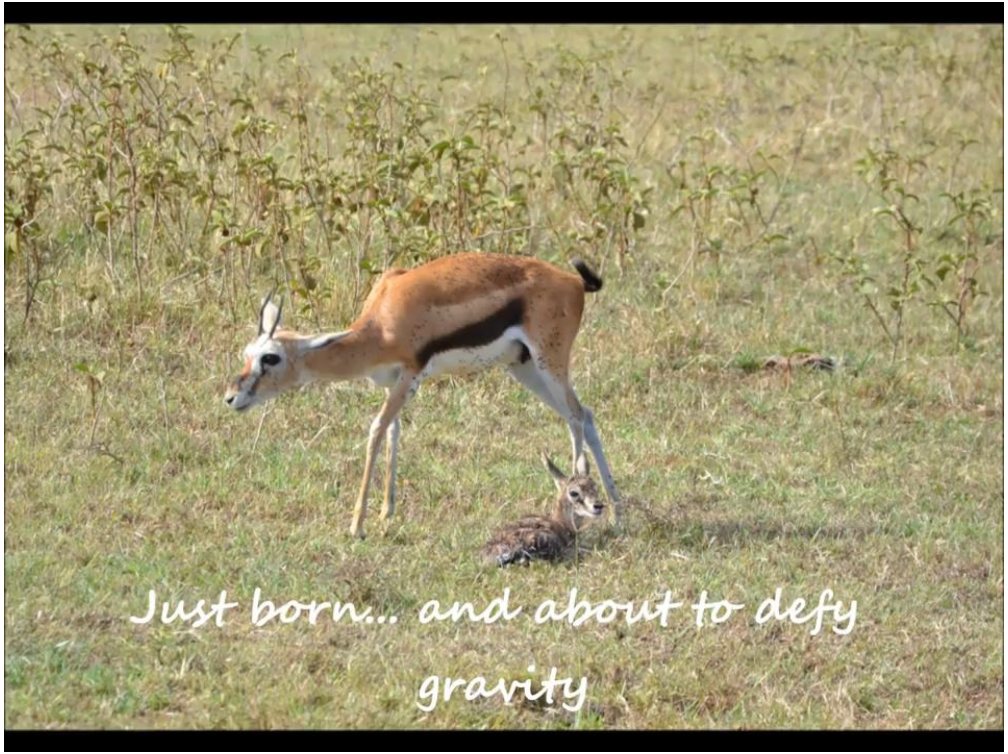
What about learning?

What about learning?

Gazelles learn to walk **<u>in hours</u>**



https://www.youtube.com/watch?v=9jOdy0kDqv4

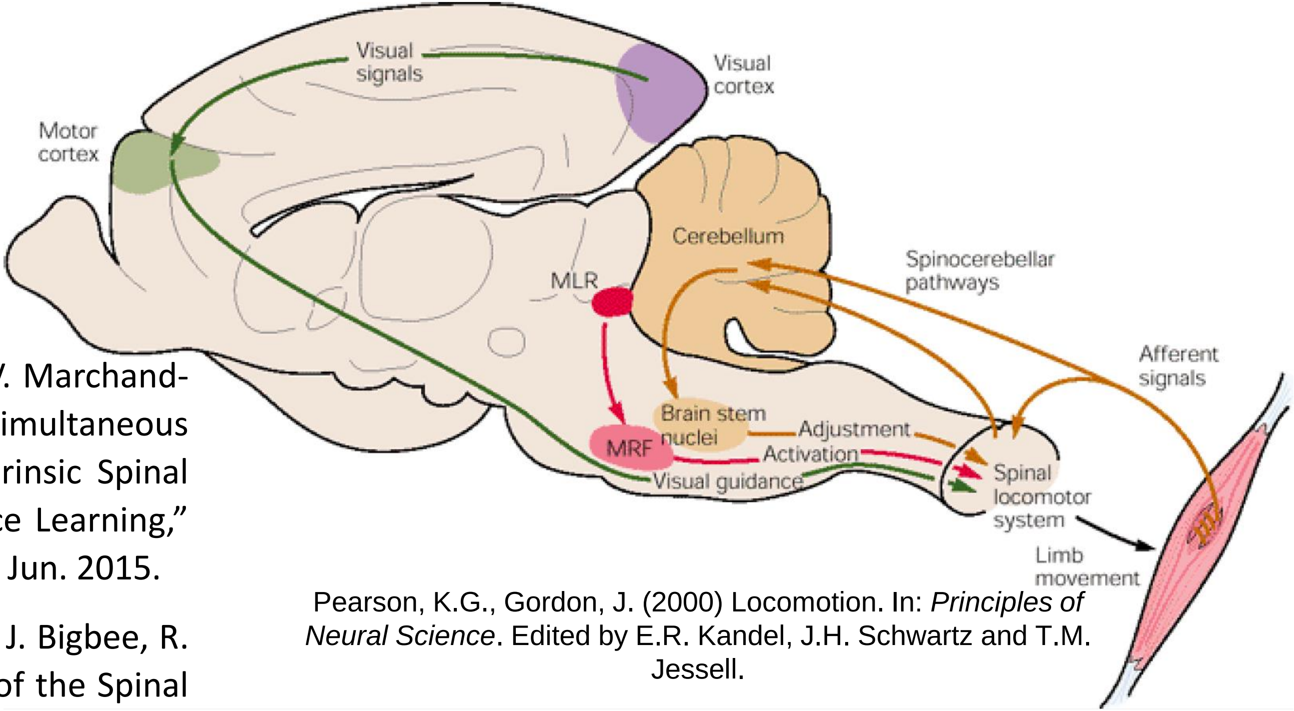
Big difference between mammals

Humans learn to locomote **in months**

What about learning?

Learning/adaptation takes place at multiple levels

- Motor cortex
- Cerebellum
- Brainstem
- Spinal cord



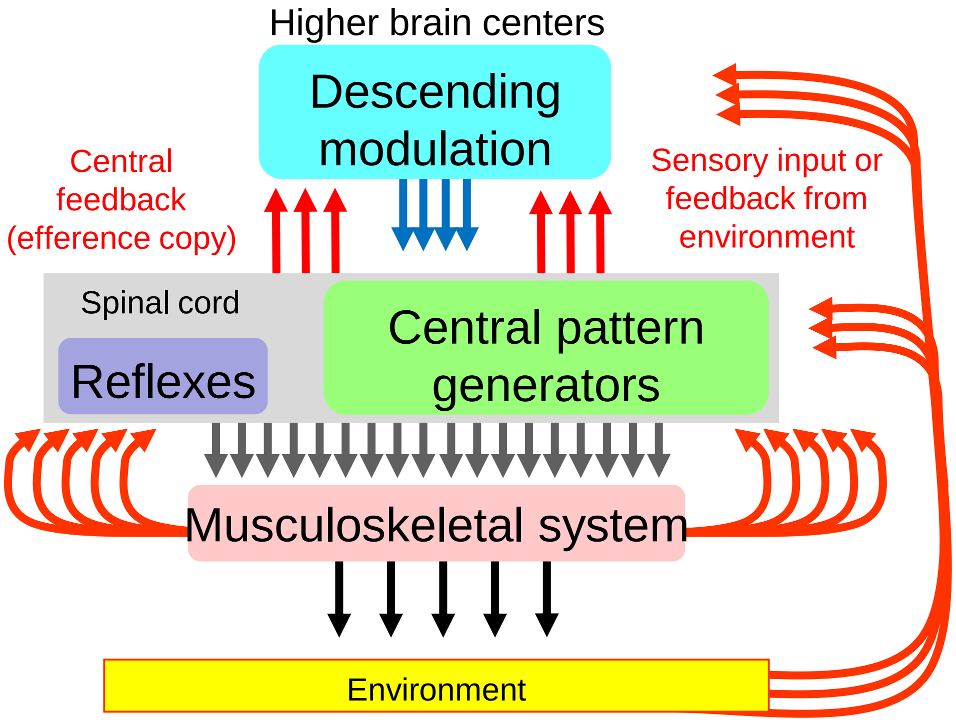
Pearson, K.G., Gordon, J. (2000) Locomotion. In: *Principles of Neural Science*. Edited by E.R. Kandel, J.H. Schwartz and T.M. Jessell.

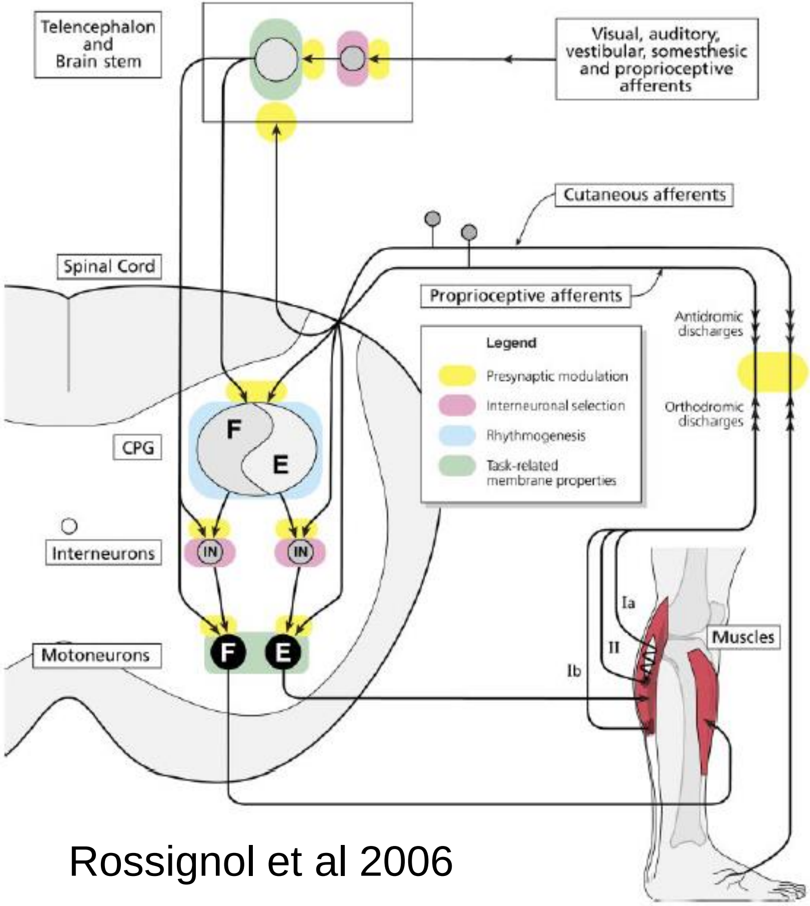
S. Vahdat, O. Lungu, J. Cohen-Adad, V. Marchand-Pauvert, H. Benali, and J. Doyon, “Simultaneous Brain–Cervical Cord fMRI Reveals Intrinsic Spinal Cord Plasticity during Motor Sequence Learning,” *PLOS Biol.*, vol. 13, no. 6, p. e1002186, Jun. 2015.

V. R. Edgerton, N. J. K. Tillakaratne, A. J. Bigbee, R. D. de Leon, and R. R. Roy, “Plasticity of the Spinal Neural Circuitry After Injury,” *Annu. Rev. Neurosci.*, vol. 27, no. 1, pp. 145–167, 2004.

Learning is simplified with the right neuromechanics

Spinal dynamics: an opportunity and a challenge for motor learning and motor planning





Rossignol et al 2006

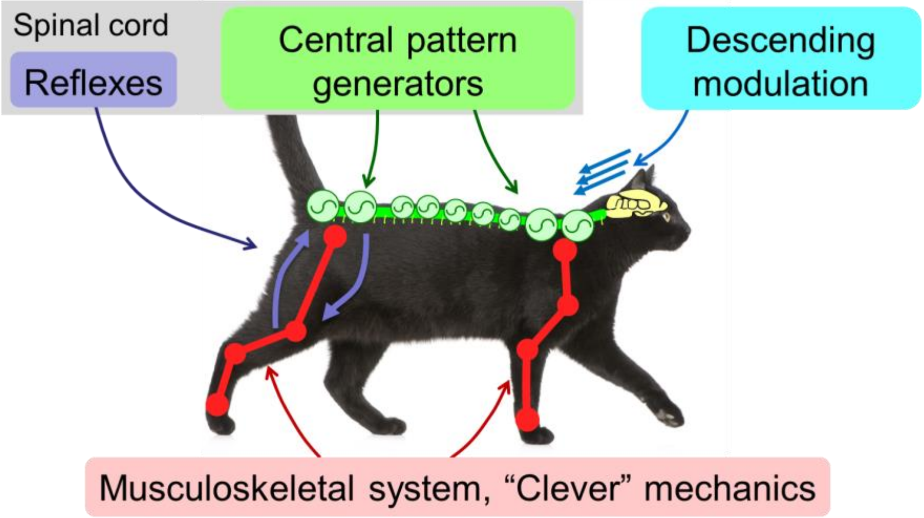
Take-home messages

The spinal cord offers sophisticated control circuits for locomotion

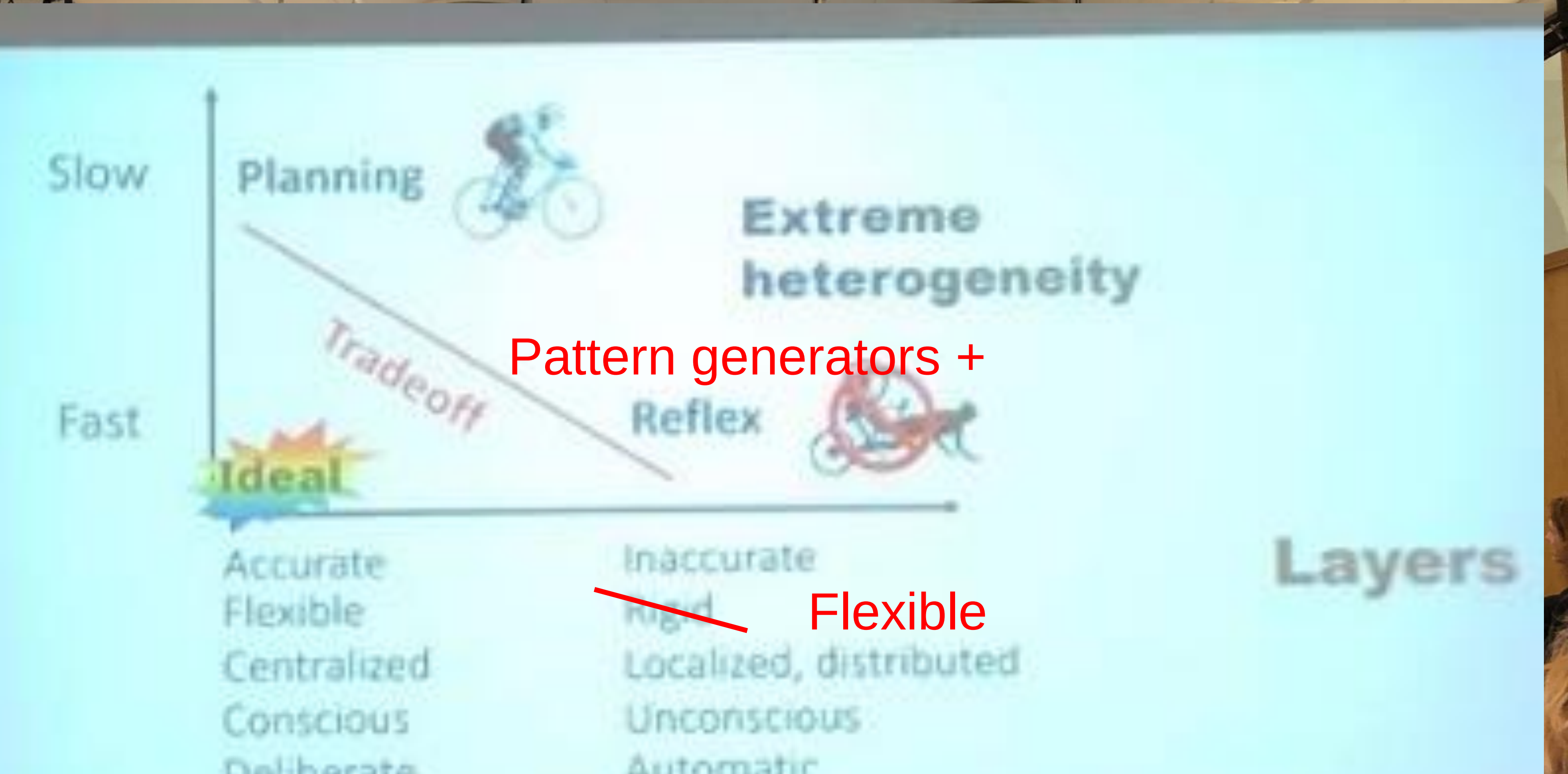
CPGs and sensory feedback are good friends!
They provide **redundant control mechanisms**

Their respective roles **have probably changed during evolution**

Good compromise: **distributed oscillators that are synchronized by sensory feedback** (in addition to <u>weak</u> central coupling)



Take-home messages



Pattern generators +

Flexible

People at BIOROB, EPFL


A. Ijspeert


A. Crespi


B. Bayat


K. Melo


S. Lipfert


A. Wu


H. Ra

Open postdoc position!

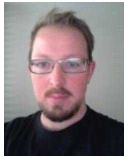

R. Baud


T. Horvat


J. Lanini


F. Dzeladini


J. Arreguit O'Neil


P. Eckert


L. Paez


S. Ramalingasetty


S. Faraji


M. Caban


S. Hauser


M. Mutlu


F. Longchamp


A. Guignard


S. Fiaux

ALUMNI

O. Michel, M. Asadpour, J. Buchli, L. Righetti, Y. Bourquin, P.A. Mudry, M. Taric, S. Dégallier, M. Porez, , R.Ronsse , A. Gams, R. Moeckel, K. Karakasiliotis, S. Pouya, A. Sproewitz, J. Knuesel, A. Bicanski, Y. morel, J.v.d. Kieboom, D. Renjewski, T. Petric, L. Colasanto, S.Bonardi, M. Ajallooeian, M. Vespignani, N. van der Noot, A. Tuleu. P. Müllhaupt, R. Thandiackal

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SEVENTH FRAMEWORK PROGRAMME

HFSP

FNSNF

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Crocodile and lizard like robots for filming wildlife (BBC Spy in the Wild)