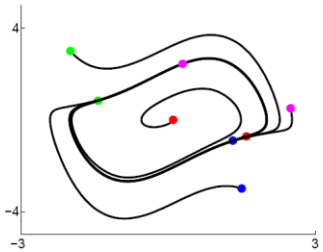
Computational Motor Control

Lecture 11:

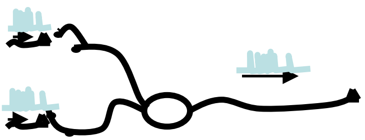
Modeling human locomotion and neuroprosthetics

Auke Jan Ijspeert

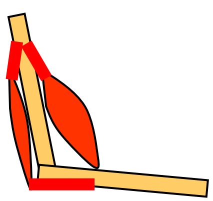
Contents of lectures



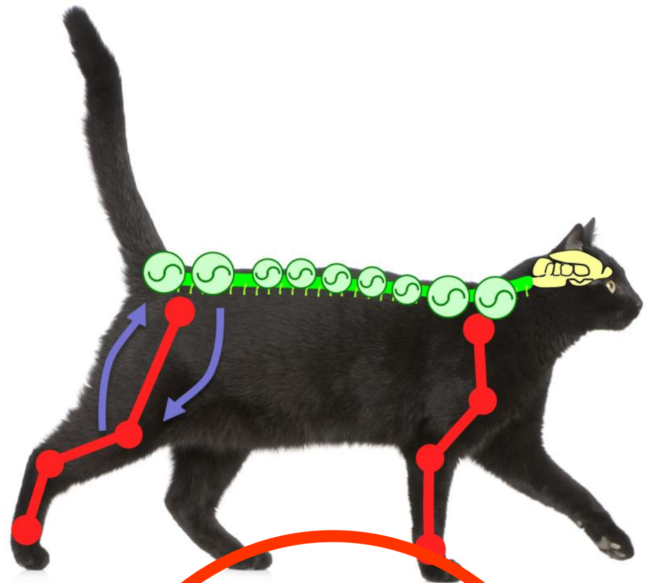
Dynamical systems

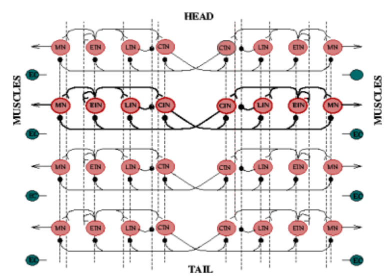


Neuron models

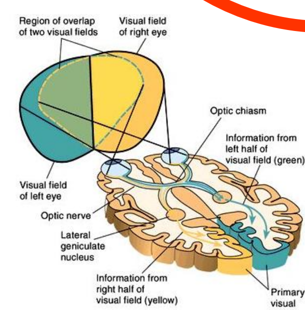


Muscle and Biomech. models

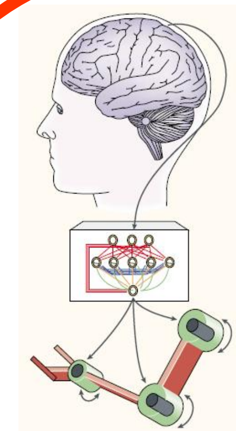




Motor system models



Visual system models



Neuroprosthetics

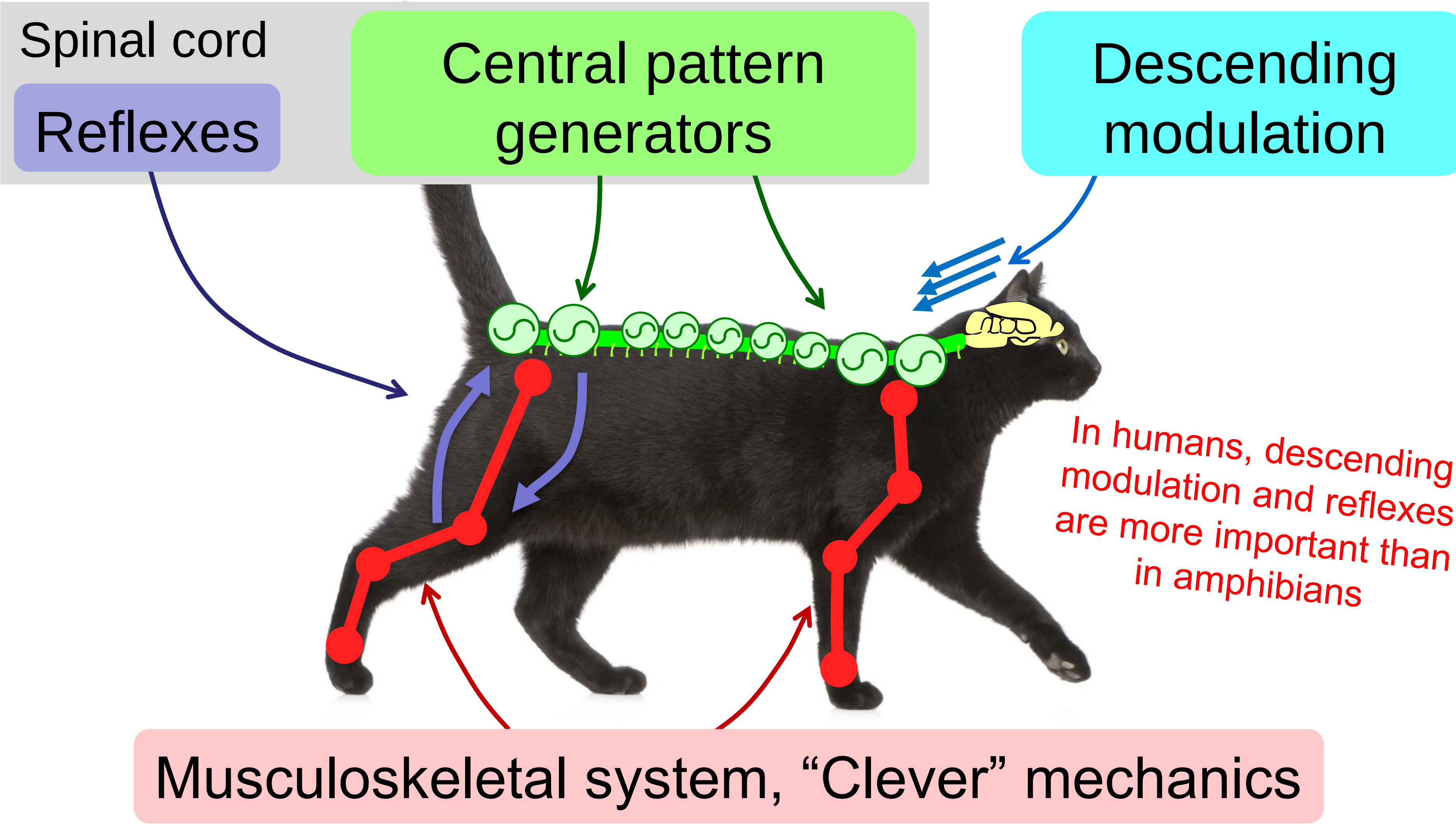
Lecture: Modeling human locomotion and neuroprosthetics

- Neuromechanical simulations of human locomotion

- Restoring mobility:
    - Prostheses
    - Orthoses
    - Spinal cord stimulation
    - Functional Electromyographic stimulation

- Restoring upper limb movements:
    - Arm/hand replacement
    - Cortical implants and population coding

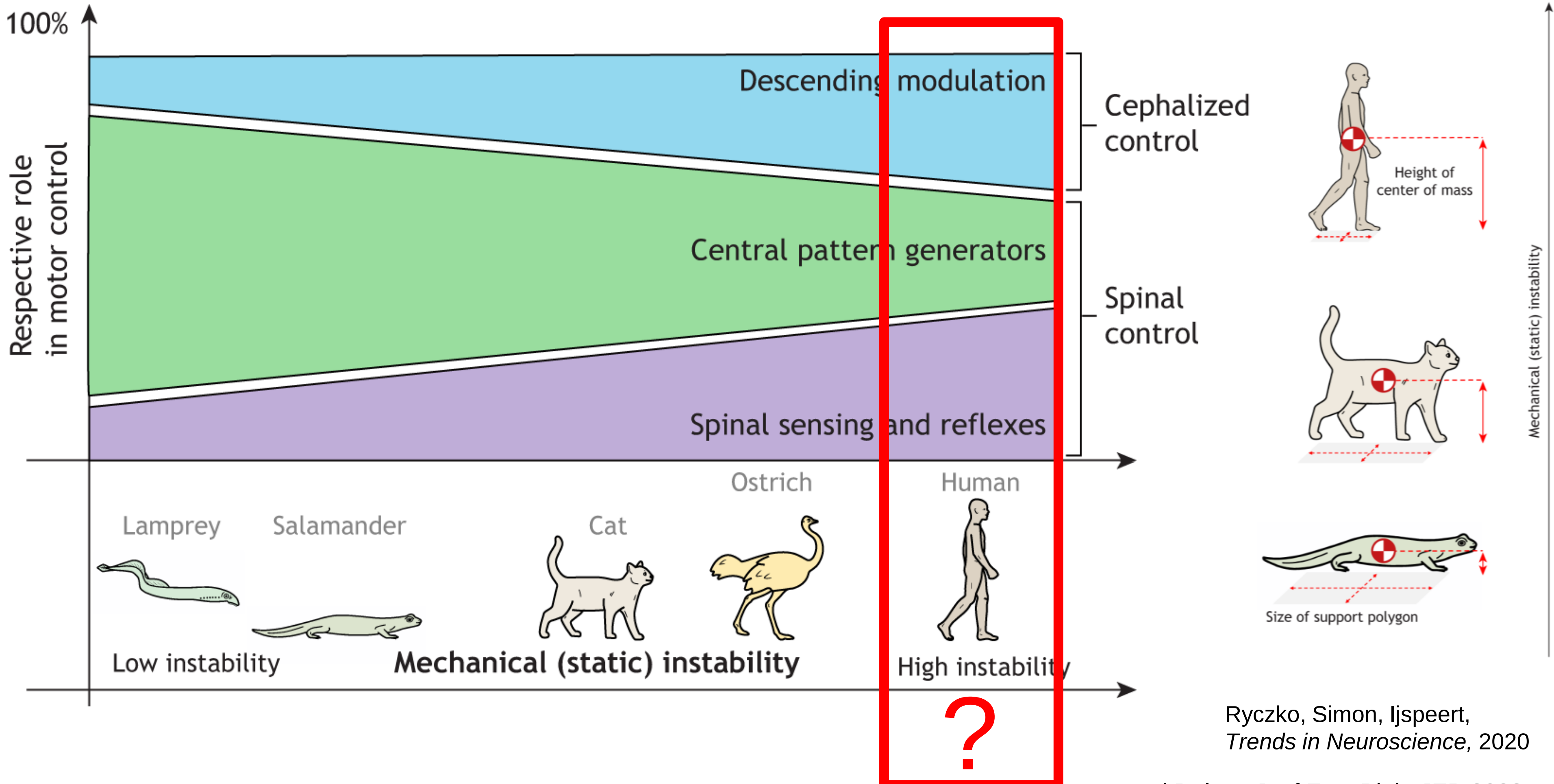
Four essential ingredients in animal motor control



Reflexes vs CPGs vs descending modulation

It looks like CPGs are fundamental in lower vertebrates, possibly less so in higher vertebrates.

Locomotion that is **mechanically instable** requires **more sensing** and **more sophisticated descending modulation** for posture control and feet placement



Ryczko, Simon, Ijspeert, *Trends in Neuroscience,* 2020

Ijspeert and Daley, J. of Exp. Biol., JEB 2023

Human locomotion circuits

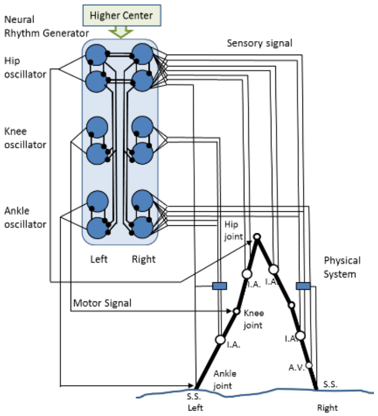
Surprisingly, the circuits underlying human locomotion are not yet well understood.

There is still a debate to which extent human locomotion depends on neural oscillators (CPGs), and there is no direct evidence of CPGs.

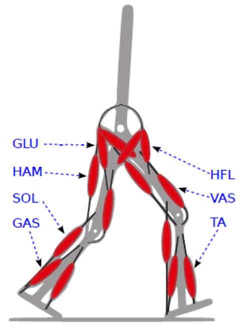
But there is **strong indirect evidence that CPGs exist in humans**. See this review paper:

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

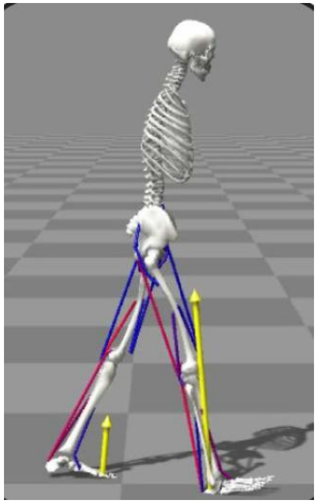


Taga 1991, 1995



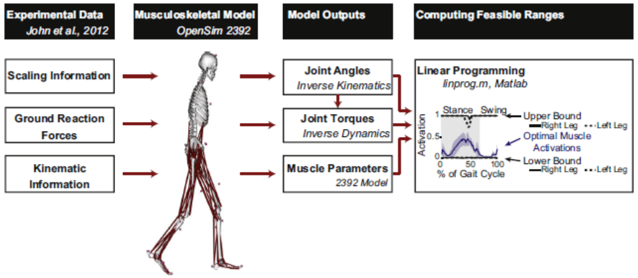
Geyer and Herr, 2010.
Song and Geyer 2015

Lee et al 2019



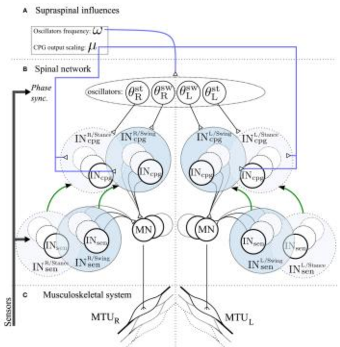
Ong et al 2019

Y. Nakamura lab
(Sreenivasa et al 2012)



L. Ting lab (Simpson et al 2015)

Falisse et al 2019



Dzeladini et al 2014

Neuromechanical models of human locomotion

References:

- Taga, G., Yamaguchi, Y., & Shimizu, H. (1991). Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biological cybernetics*, *65*(3), 147-159.
- G. Taga. A model of the neuro-musculo-skeletal system for human locomotion. I. emergence of basic gait. *Biological Cybernetics*, 73(2):97-111, 1995
- G. Taga. A model of the neuro-musculo-skeletal system for human locomotion. II Real-time adaptability under various constraints. Biological Cybernetics, 73(2):113-121, 1995
- Geyer, H., and H. Herr. 2010. "A Muscle-Reflex Model That Encodes Principles of Legged Mechanics Produces Human Walking Dynamics and Muscle Activities." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 18 (3): 263–73. https://doi.org/10.1109/TNSRE.2010.2047592.
- Song, Seungmoon, and Hartmut Geyer. 2015. "A Neural Circuitry That Emphasizes Spinal Feedback Generates Diverse Behaviours of Human Locomotion." *The Journal of Physiology* 593 (16): 3493–3511. https://doi.org/10.1113/JP270228.
- Lee, Seunghwan, Moonseok Park, Kyoungmin Lee, and Jehee Lee. 2019. "Scalable Muscle-Actuated Human Simulation and Control." *ACM Trans. Graph.* 38 (4): 73:1–73:13. https://doi.org/10.1145/3306346.3322972.
- Ong, Carmichael F., Thomas Geijtenbeek, Jennifer L. Hicks, and Scott L. Delp. 2019. "Predicting Gait Adaptations Due to Ankle Plantarflexor Muscle Weakness and Contracture Using Physics-Based Musculoskeletal Simulations." *PLOS Computational Biology* 15 (10): e1006993. https://doi.org/10.1371/journal.pcbi.1006993.
- Simpson, Cole S., M. Hongchul Sohn, Jessica L. Allen, and Lena H. Ting. 2015. "Feasible Muscle Activation Ranges Based on Inverse Dynamics Analyses of Human Walking." *Journal of Biomechanics* 48 (12): 2990–97. https://doi.org/10.1016/j.jbiomech.2015.07.037.
- Dzeladini, Florin, Jesse van den Kieboom, and Auke Ijspeert. 2014. "The Contribution of a Central Pattern Generator in a Reflex-Based Neuromuscular Model." *Frontiers in Human Neuroscience* 8. https://doi.org/10.3389/fnhum.2014.00371.

Geyer and Herr's sensory-driven model

Sensory-driven model

+

7 muscles per leg

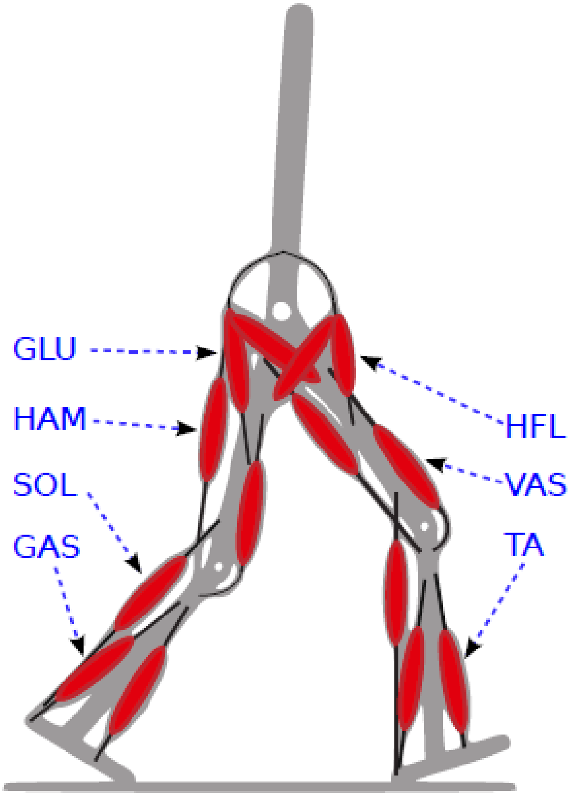
+

Different reflexes

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

+

Posture control (torso angle)

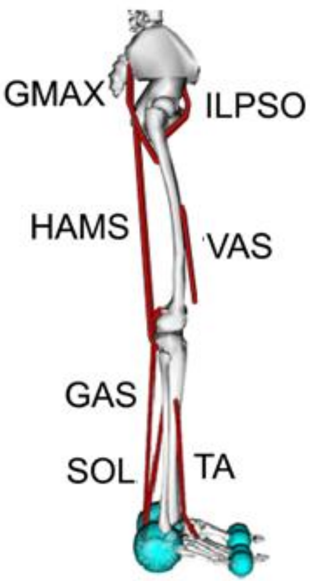


H Geyer, HM Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. **IEEE Trans Neural Syst Rehabil Eng** 18(3): 263-273, 2010.

Geyer and Herr 2010

The model is based on a series of **phase-dependent reflexes** and **tonic feedforward signals** that are activated at specific moments during the whole cycle.

ES: early stance, **MS**: mid-stance, **PS**: pre-swing **S**: swing, **LP**: landing preparation



	Stance			*Swing*	
	ES	*MS*	*PS*	*S*	*LP*
GMAX	PD		C	F+	
HAMS	PD			F+	
ILPSO	PD		C	L+ , PD	
				L−(HAMS)	
VAS	F+, C				
GAS	F+				
SOL	F+				
TA	L+				
	F-(SOL)				

PD: proportional-derivative control based on the pelvis tilt angle

C: constant (feedforward) signal

F: Force feedback

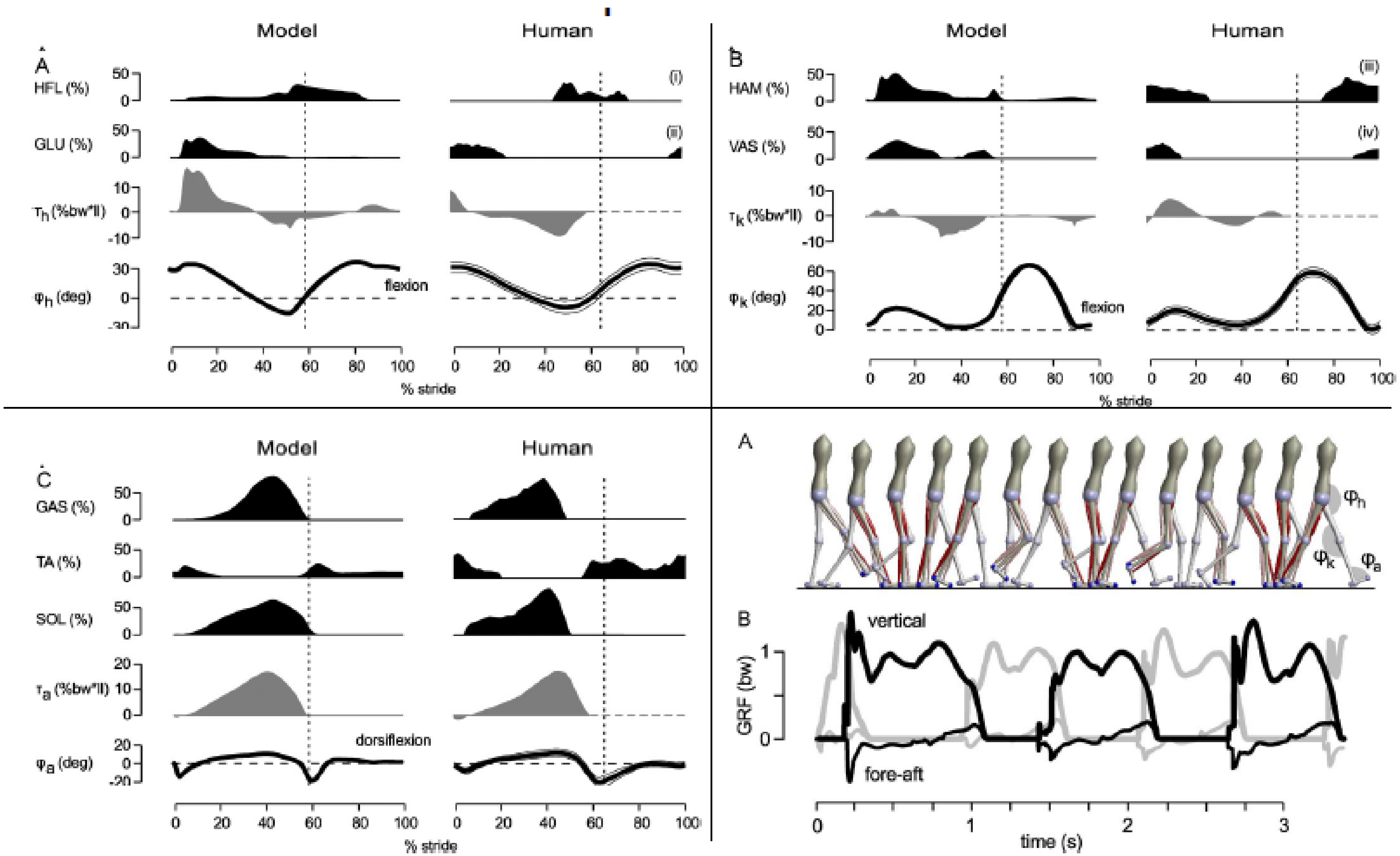
L: Length feedback

+/-: Positive/negative feedback

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

The model properly replicates human joint kinematics, EMG signals and ground reaction forces.



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?

- Since the sensory-driven controller is producing human-like gait features, it worth adding a CPG to the sensory-driven network?
- Yes, we think so!

Florin Dzeladini

N. van der Noot

A. Wu

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**
4) Reduce **transient times.**

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

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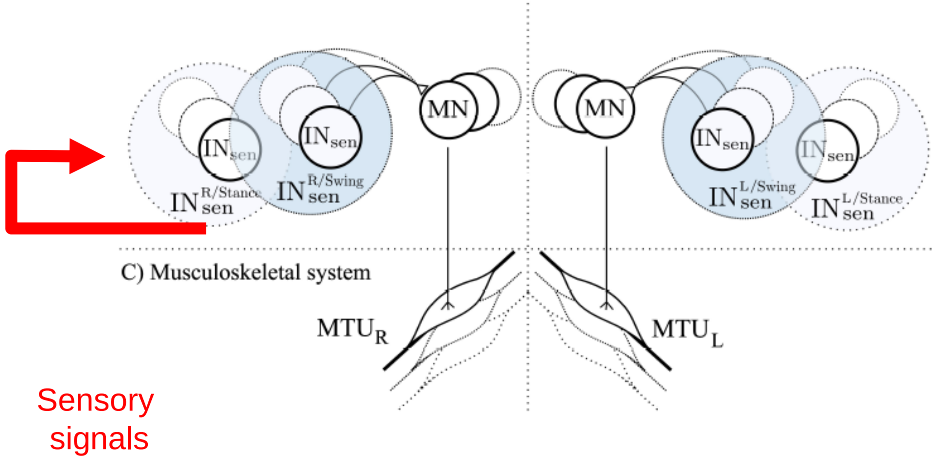
Dzeladini et al, The contribution of a central pattern generator in a reflex-based neuromuscular model, ***Frontiers in Human Neuroscience***, Vol 8, 371, 2014

CPG construction

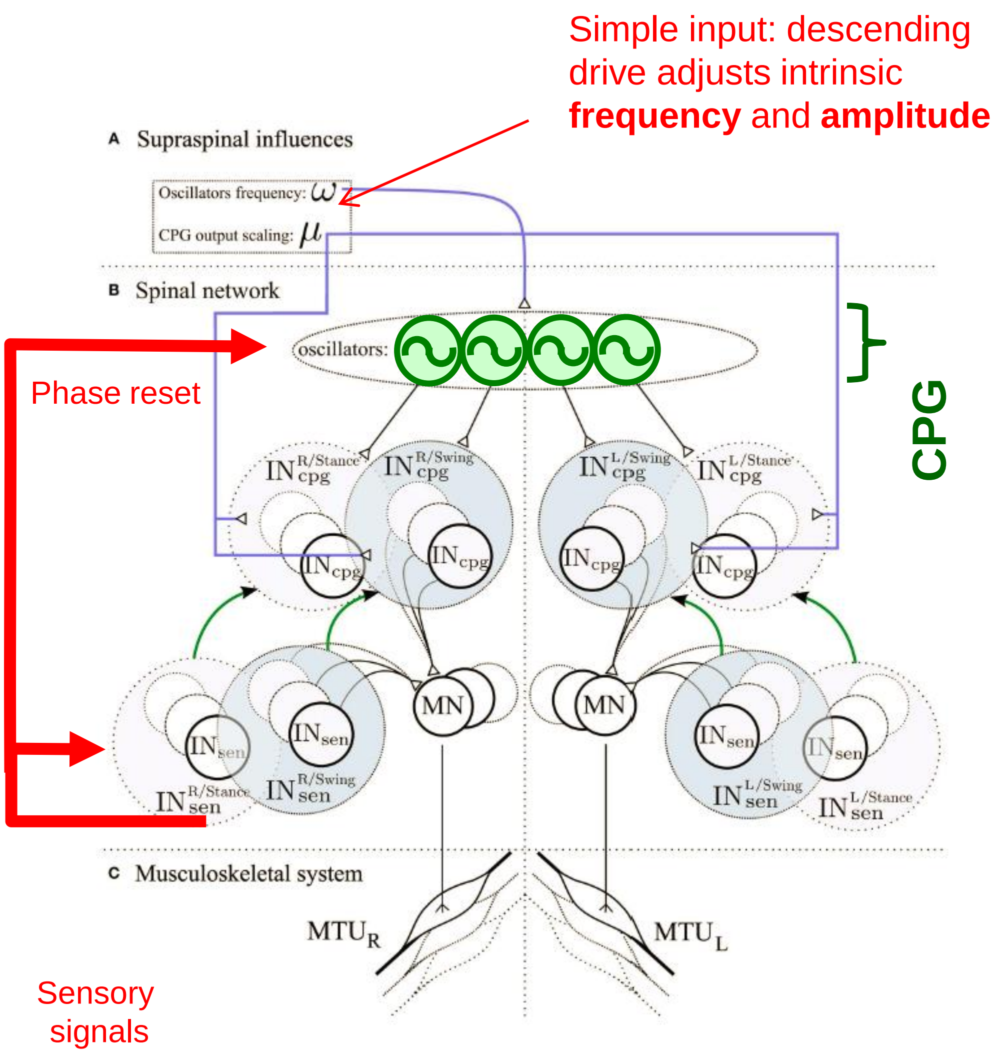
We start with the sensory-driven model:



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

CPG construction

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



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

CPG construction

For every joint, we tested what is the best mix of feedback and feedforward control signals

Feedback & CPG network

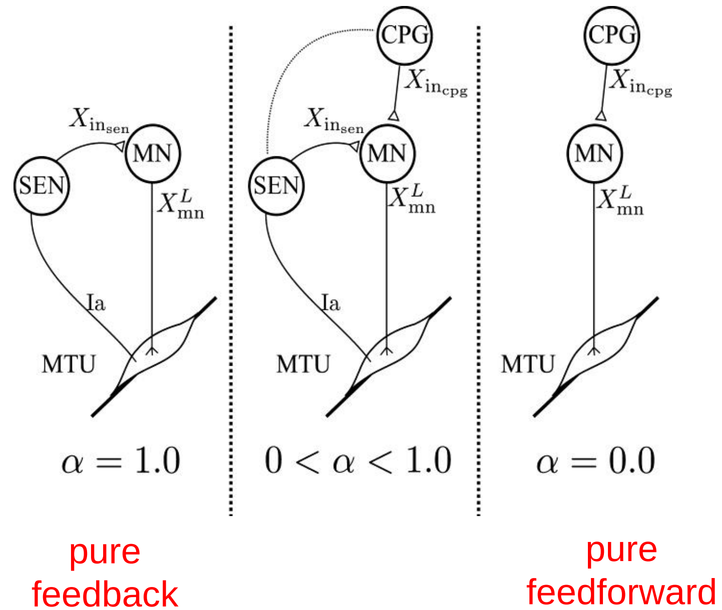
$$X_{\mathrm{mn}} = f\left(X_{\mathrm{in}_{\mathrm{sen}}}, X_{\mathrm{in}_{\mathrm{cpg}}}\right) + X^0_{\mathrm{mn}}$$

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

$\alpha = 0$ → pure feedforward

$\alpha = 1$ → pure feedback

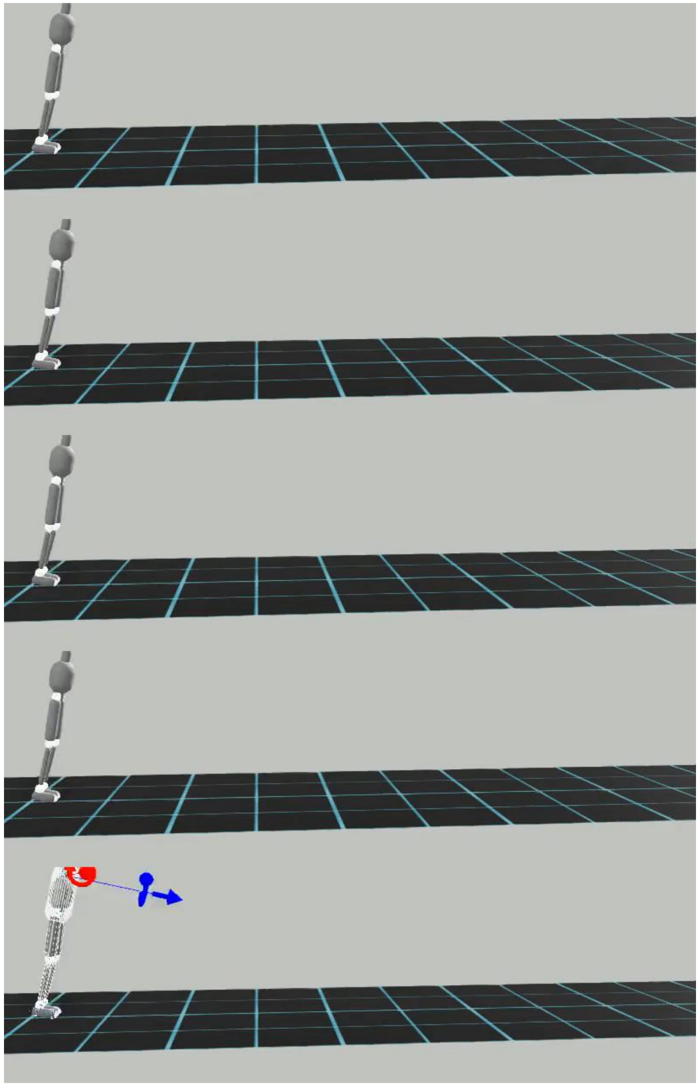
Similarly to Kuo 2002, Motor Control



We found that **adding CPG signals to the hip muscles** has the best effect on modulating the speed.

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

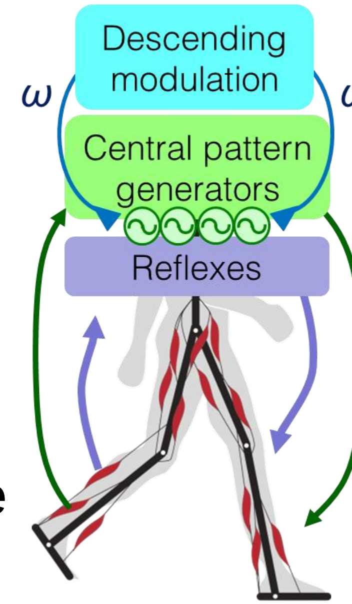
Optimization of parameters



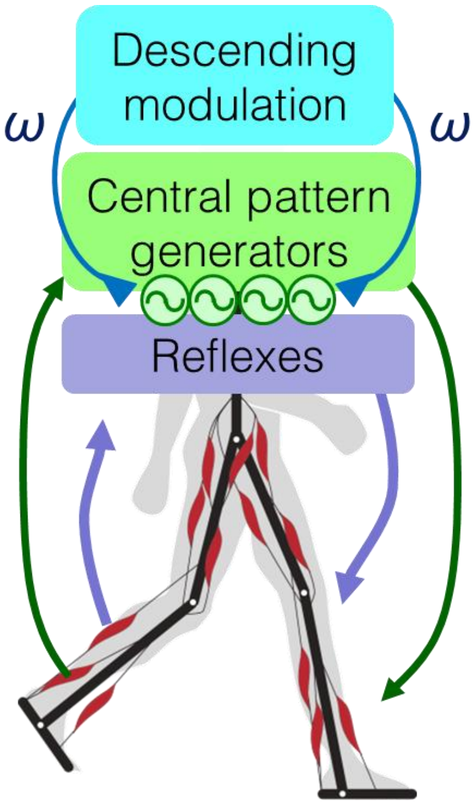
Optimizer:
Particle Swarm optimization

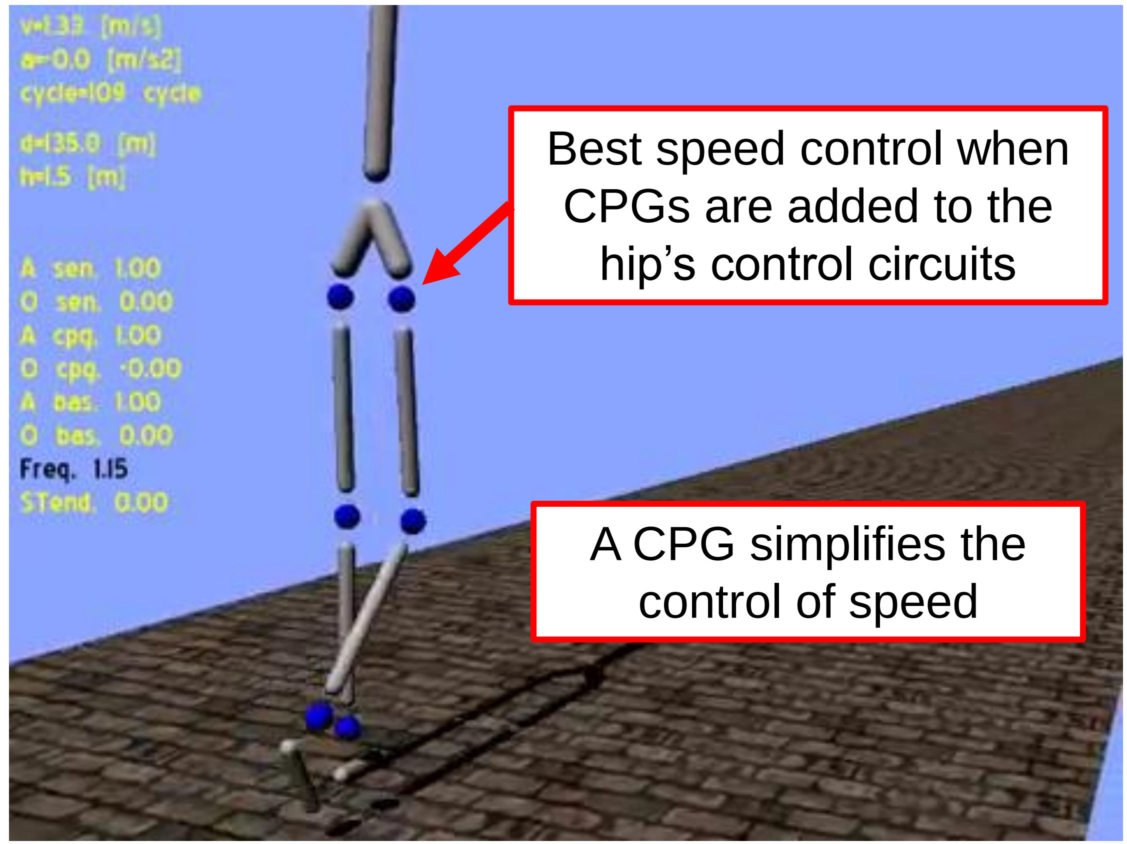
Open parameters (25):
Reflex gains and thresholds

Fitness function (staged evol.):
1) Reach a minimum distance
2) Reach a **desired speed**
3) Limit knee over extension
4) **Minimize energy**



Speed control





Best speed control when CPGs are added to the hip's control circuits

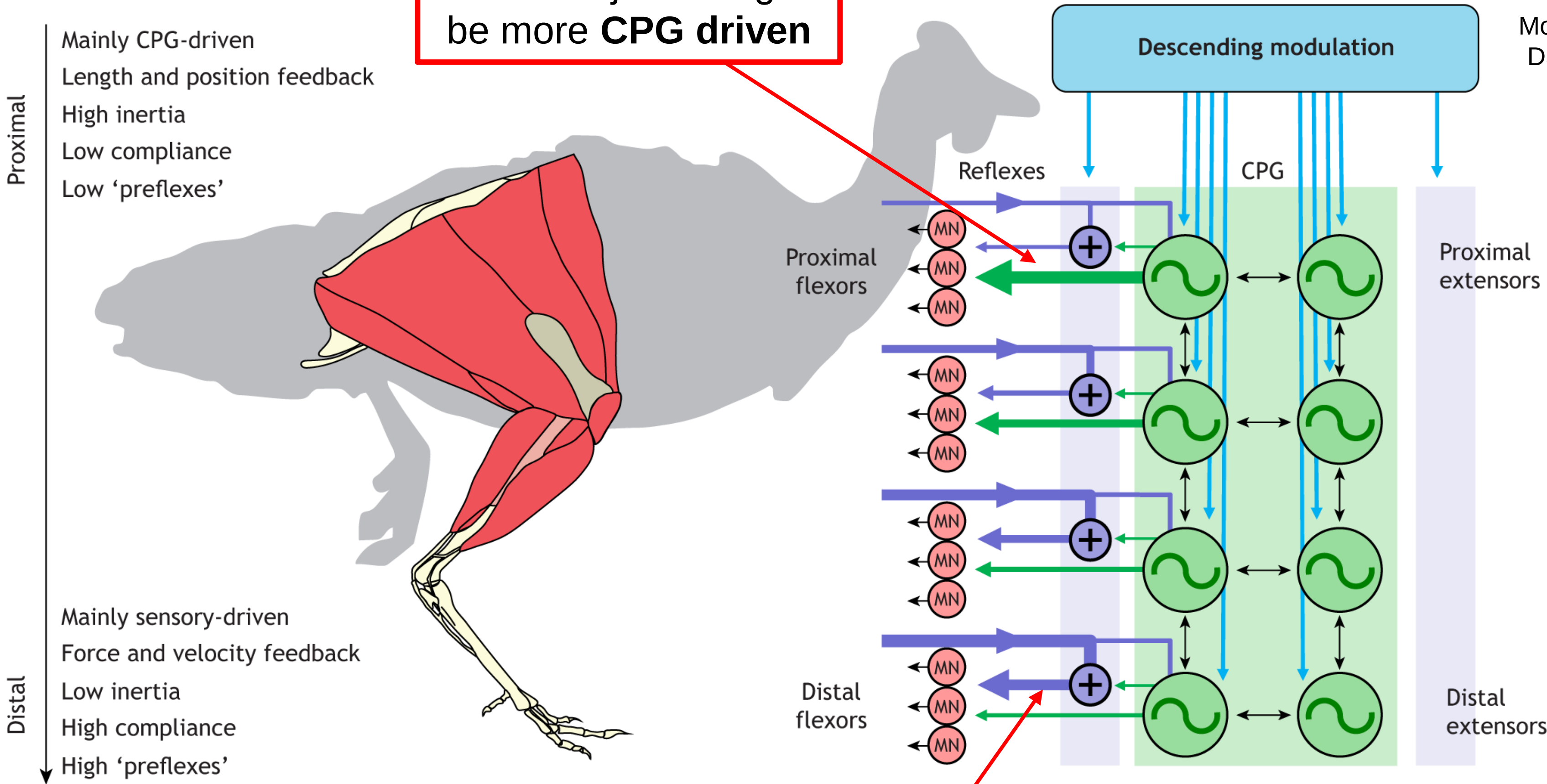
A CPG simplifies the control of speed

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

A proximal-distal gradient?

Monica Daley

Proximal joints might be more **CPG driven**



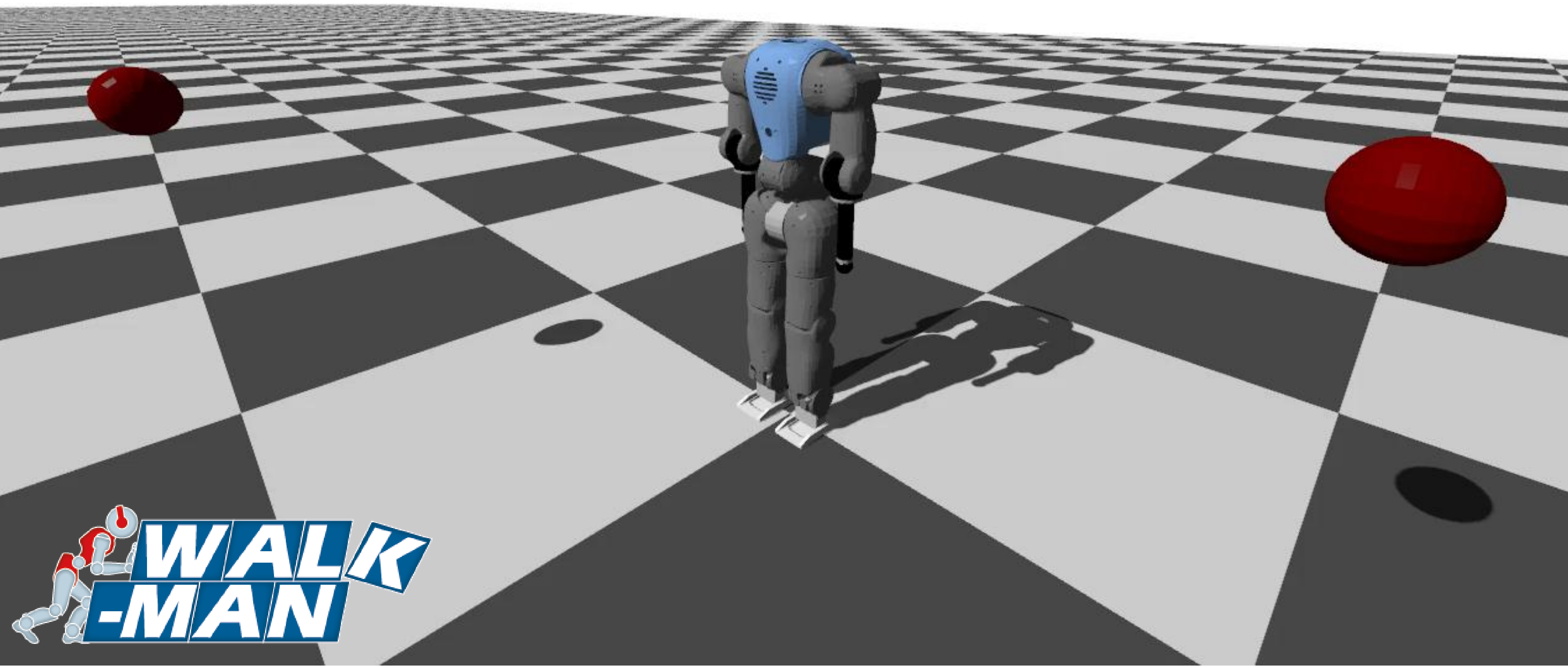
Distal joints might be more **sensory driven**

Ijspeert and Daley, J. of Exp. Biol., JEB 2023

High robustness against perturbations

Nicolas Van der Noot

Renaud Ronsse



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

Summary

Human locomotion strongly relies on reflexes and on descending modulation

CPGs likely play an important role to help **modulate locomotion** and to be more **robust against noise**.

More experiments and models are needed

Interestingly, there are impressive examples of restoring locomotion in paraplegic patients through spinal cord stimulation, see next.

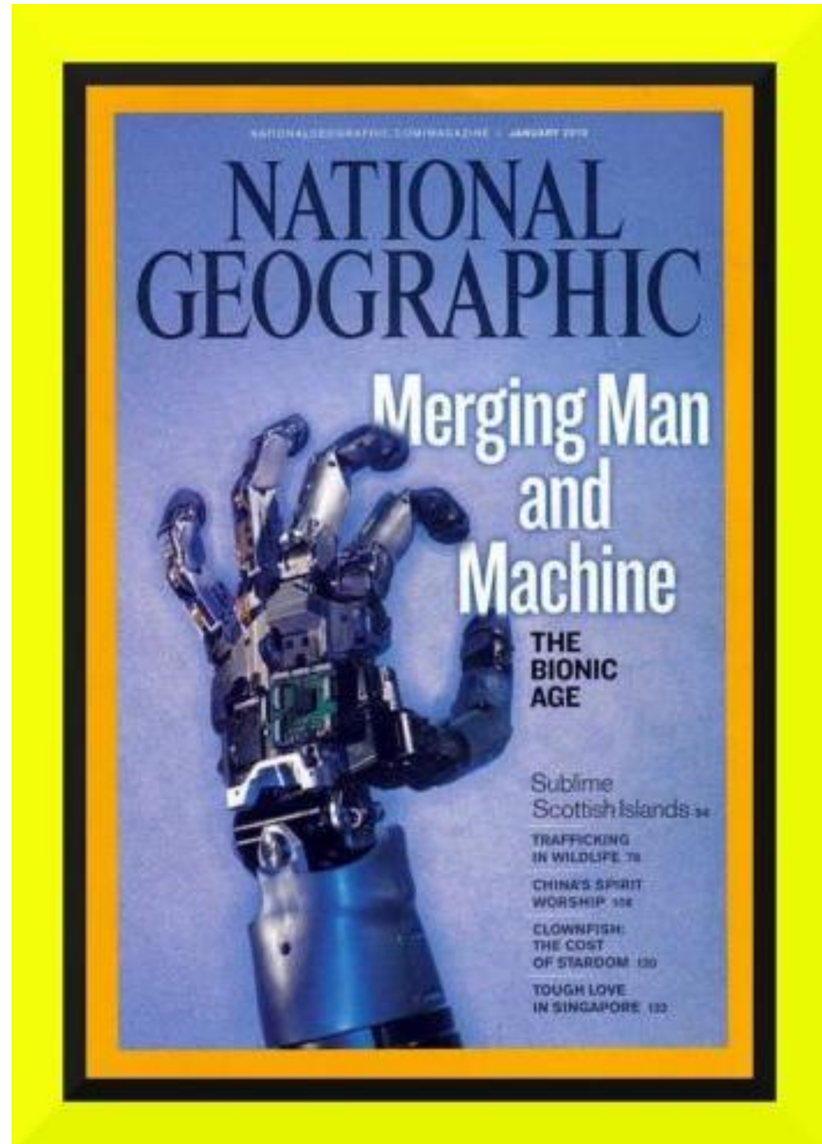
Lecture: Modeling human locomotion and neuroprosthetics

- Neuromechanical simulations of human locomotion

- **<u>Restoring mobility:</u>**
  - Prostheses
  - Orthoses
  - Spinal cord stimulation
  - Functional Electromyographic stimulation

- Restoring upper limb movements:
  - Arm/hand replacement
  - Cortical implants and population coding

Neuroprosthetics



Prosthesis versus orthosis

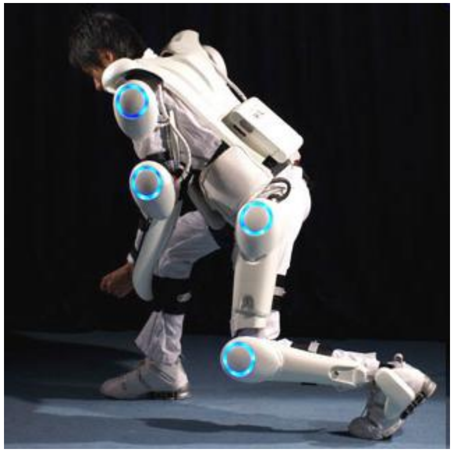
Prosthesis = limb replacement

COVVI, UK

Otto Bock, Germany

Orthosis = limb support

Emovo Care, Switzerland



HAL, Tsukuba University

Leg prostheses

- Different types:
  - Ankle or ankle-knee
  - Rigid or Passively articulated or Actuated
  - Every-day use or for sports

Flex-Foot Cheetah, Ossur

C-Leg, Otto Bock

- Main companies:
  - Otto Bock, http://www.ottobock.com/
  - Ossur, http://www.ossur.com

Example: C-Leg by Otto Bock

Active change of stiffness of the knee using a **hydraulic system**, load sensors and a microprocessor

Sensors estimate the phase, and whether the leg is in swing or stance

Rapid increase of stiffness during stance, low stiffness during swing.

Example: C-Leg by Otto Bock

https://www.youtube.com/watch?v=pm2r-K9MxPM

Example: Biom (Hugh Herr)

- TED talk by Hugh Herr: https://www.youtube.com/watch?v=CDsNZJTWw0w

Interesting part after 8:00

Active generation of torques, use of simulated muscles and reflex loops <u>like in Geyer's neuromechanical model</u>

M. F. Eilenberg, H. Geyer, H. Herr, IEEE Trans. Neural Syst. Rehabil. Eng. 18, 164–173 (2010).

Example: Biom (Hugh Herr)

M. F. Eilenberg, H. Geyer, H. Herr, IEEE Trans. Neural Syst. Rehabil. Eng. 18, 164–173 (2010).

Interesting features:

- Compared to other approaches that play a fixed torque pattern, the controller can **adjust the torque produced** by the prosthesis **depending on the slope of the terrain and the size of steps**.

- Tests on level ground and up and down a ramp
- Energy provided by the prosthesis was adapted to the type of terrain and was directly correlated to the ground slope angle.
- Gait characteristics were close to those of intact locomotion in terms of the measured ankle torque and ankle angle profiles.

- Compared to a passive-elastic prosthesis**: decreases metabolic cost by 8%** and **increases preferred walking speed by 23%** (H. M. Herr, A. M. Grabowski, Proc. R. Soc. B 279, 457–464 (2012).)

Lecture: Modeling human locomotion and neuroprosthetics

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- Restoring mobility:
  - Prostheses
  - **<u>Orthoses</u>**
  - Spinal cord stimulation
  - Functional Electromyographic stimulation

- Restoring upper limb movements:
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  - Cortical implants and population coding

Orthoses and exoskeletons, some examples

XOS, Sarcos (Raytheon)
http://www.youtube.com/watch?v=Nhj3Z9o6t0g

HULC, Berkeley Bionics (Lockheed Martin)
http://www.youtube.com/watch?v=EdK2y3IphmE

Orthoses and exoskeletons, some examples

Full mobilization
Needs crutches

ReWalk
https://www.youtube.com/watch?v=2Xd27c-pz4Y#t=120

Partial mobilization
Needs crutches

HAL Cyberdine
https://www.youtube.com/watch?v=_8VhW9JIwUk

Full mobilization
Needs crutches

Ekso Bionics eLEGS
https://www.youtube.com/watch?v=WcM0ruq28dc

Full mobilization
No crutches

REX
https://www.youtube.com/watch?v=t2Q4UrxmwYE

Most exoskeletons aim at **full mobilization**, e.g. for fully paraplegic patients
Some aim at **partial support**, for myopathy or partially paraplegic patients

At EPFL TWIICE

M. Bouri

Recently adapted to back country skiing

One of the most lightweight exoskeletons for full mobilization

http://twiice.ch/

Tristan Vouga, Mohamed Bouri, and others

https://actu.epfl.ch/news/wiite-the-exoskeleton-for-backcountry-skiing/

TWIICE (EPFL)

Pilot: Silke Pan

REX exoskeleton

Exoskeletons:
ReWalk (ReWalk Robotics, Israel)
Twiice (EPFL)

CYBATHLON

Zurich, October 2016

Recent review paper

- Baud, R., Manzoori, A. R., Ijspeert, A., & Bouri, M. (2021). Review of control strategies for lower-limb exoskeletons to assist gait. *Journal of NeuroEngineering and Rehabilitation*, 18(1), 1-34.

- Comparison of different control approaches
- Classification depending on choice of high-level, mid-level and low-level control
- Covers 291 articles

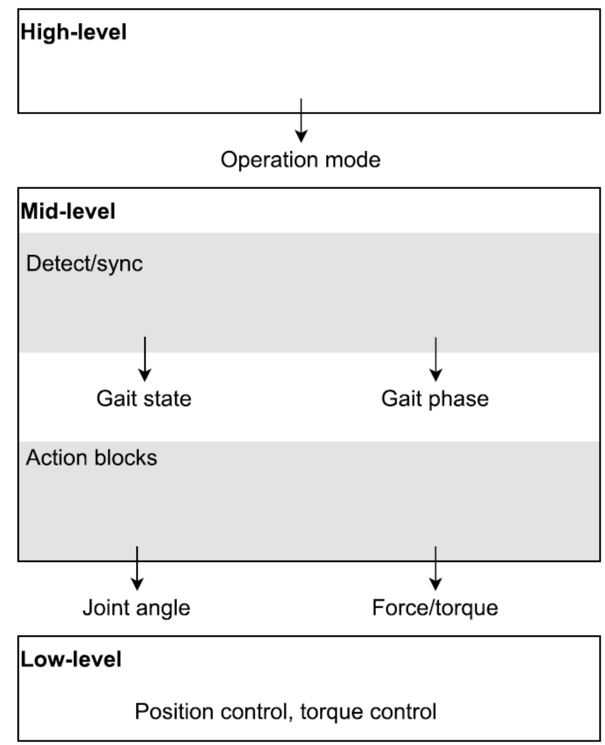


Fig. 2 Simplified diagram of the proposed classification

Most approaches use:

- Movements recognition
- Together with event trigger (e.g. touch-down)
- Impedance controller
- Torque control

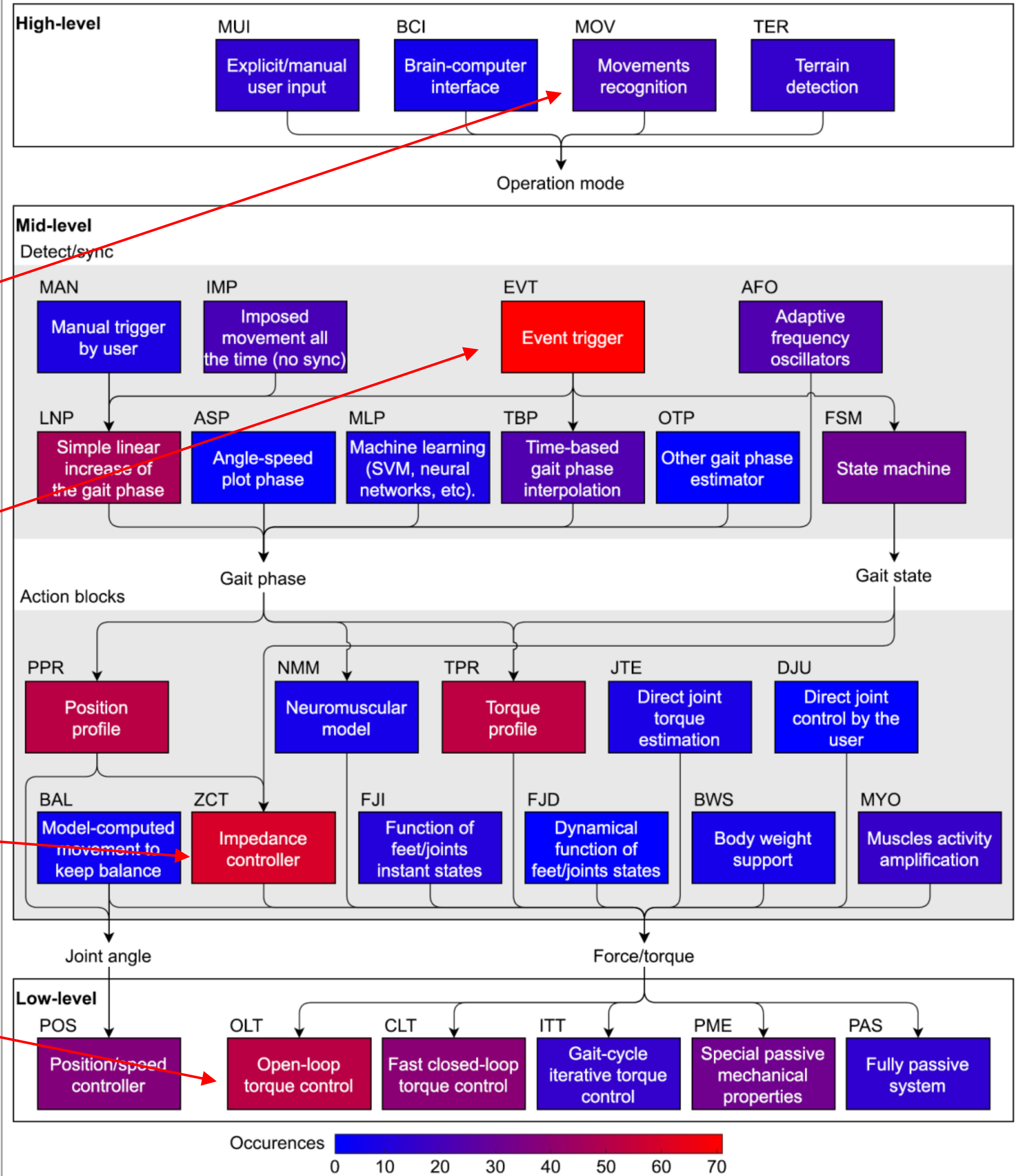


Fig. 3 Block diagram of the proposed classification of the control strategies subparts. The idea of this classification is that any controller in the literature can be represented by a path that joins the used control blocks. The path does not have to start from the high-level layer, and may start directly in the mid-level. A controller can have several parallel paths if the controller combines several strategies at the same time, or successively during the gait. Connecting lines show the common paths identified in the literature. However, it should be noted that the lack of a line between two blocks does not mean they cannot be related. For instance, the outcome of the high-level layer, the "operation mode", could affect any of the blocks of the middle-level, but it is not connected to them for the sake of readability

Lecture: Modeling human locomotion and neuroprosthetics

- Neuromechanical simulations of human locomotion

- Restoring mobility:
  - Prostheses
  - Orthoses
  - **<u>Spinal cord stimulation</u>**
  - Functional Electromyographic stimulation

- Restoring upper limb movements:
  - Arm/hand replacement
  - Cortical implants and population coding

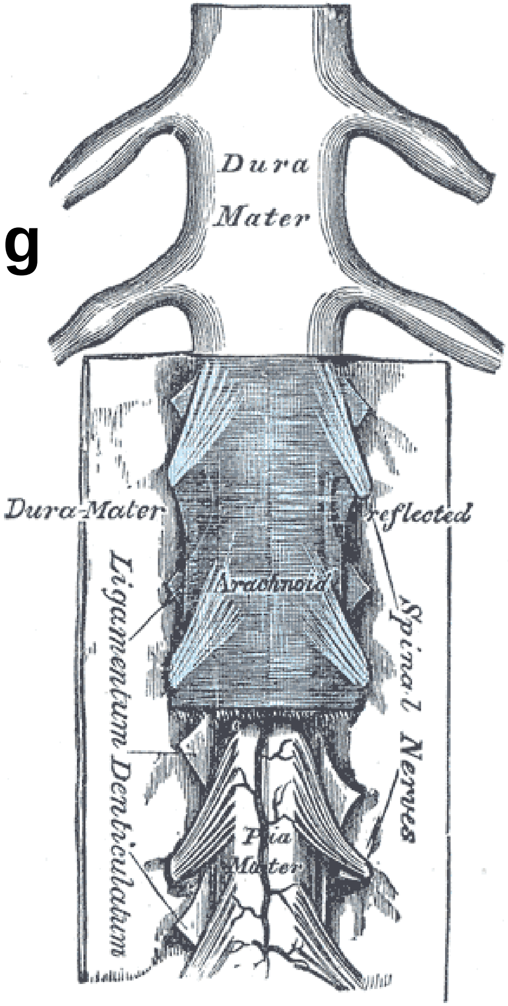
Spinal cord stimulation

Already done to **relieve chronic pain**.

Hope for **locomotion: stimulate the descending pathways to initiate and modulate locomotion**

Different types of stimulation:
- **Electromagnetic stimulation**
- **Epidural stimulation**
- **Stimulation + pharmacology + robotic support**

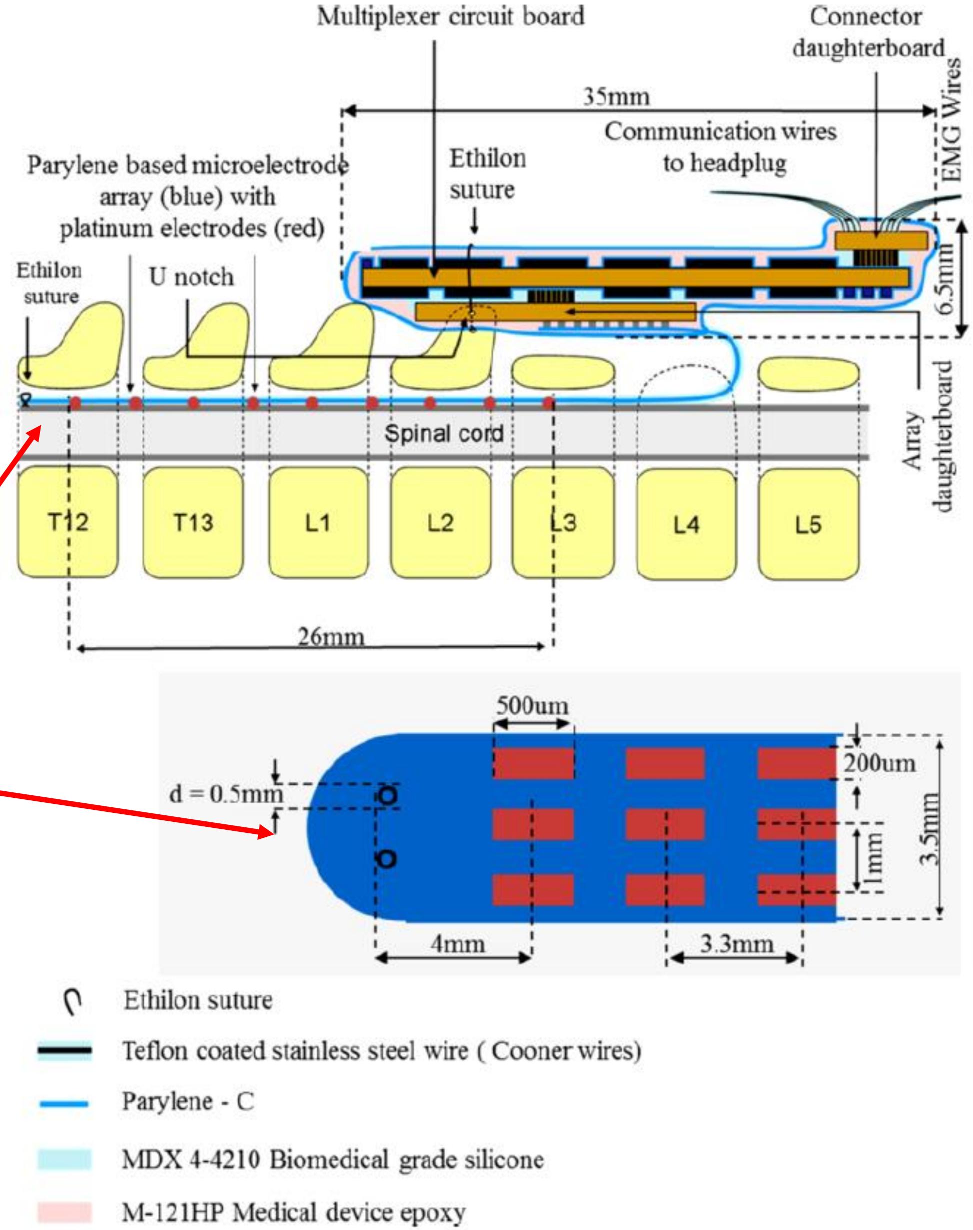
Epidural: On or around the dura mater, in particular, (of an anesthetic) introduced into the space around the dura mater of the spinal cord.



Example of electrode for epidural spinal stimulation

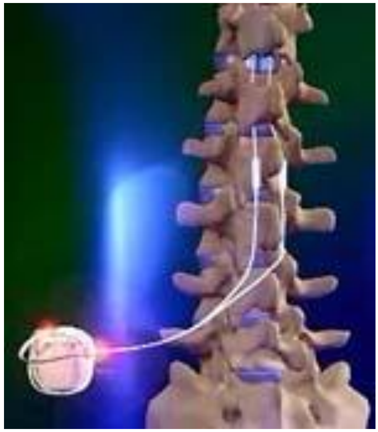
Gad, Parag, et al. "Development of a multi-electrode array for spinal cord epidural stimulation to facilitate stepping and standing after a complete spinal cord injury in adult rats." *Journal of neuroengineering and rehabilitation* 10.1 (2013): 2.

Flexible electrode, 9x3 channels



Spinal cord stimulation: chronic pain

- Key idea: **stimulate the dorsal roots** (sensory feedback) to relieve pain sensation.
- The stimulation can **replace pain with a pleasant sensation**.
- Used for various conditions: chronic back and leg pain, phantom limb pain, limb ischaemia (problems due to lack of blood flow),…
- 50-70 report % decrease of pain
- **Leads to reduction or stop of taking painkillers**
- Allows some patients to return to active lives



- CAMERON, TRACY. "Safety and efficacy of spinal cord stimulation for the treatment of chronic pain: a 20-year literature review." *J Neurosurg (Spine 3)* 100 (2004): 254-267.
- http://www.spine-health.com/treatment/back-surgery/spinal-cord-stimulation-chronic-pain
- http://www.spine-health.com/video/spinal-cord-stimulator-implant-video

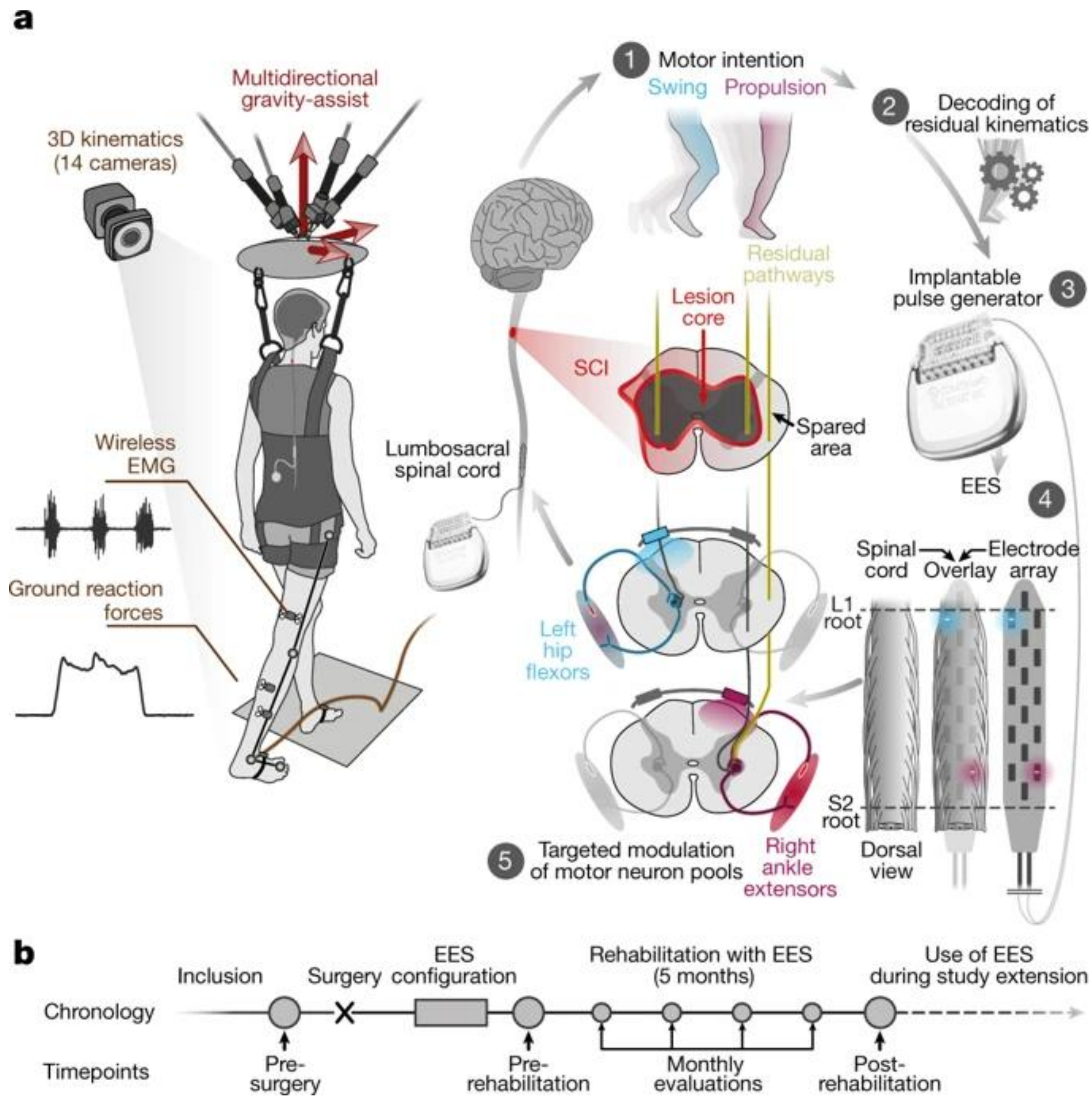
Restoring locomotion in humans (Courtine)

- Very impressive results in recent years.
- For instance:

  Wagner, F. B., Mignardot, J.-B., Goff-Mignardot, C. G. L., Demesmaeker, R., Komi, S., Capogrosso, M., … Courtine, G. (2018). Targeted neurotechnology restores walking in humans with spinal cord injury. *Nature*, *563*(7729), 65. https://doi.org/10.1038/s41586-018-0649-2

- Epidural electrical stimulation (EES) of the spinal cord
- Key ideas:
  - Careful selection of which parts of the spinal cord to stimulate
  - **State-dependent phasic stimulation**
  - **Robotic gravity assistance**, important to unload limbs

Restoring locomotion in humans (Courtine)

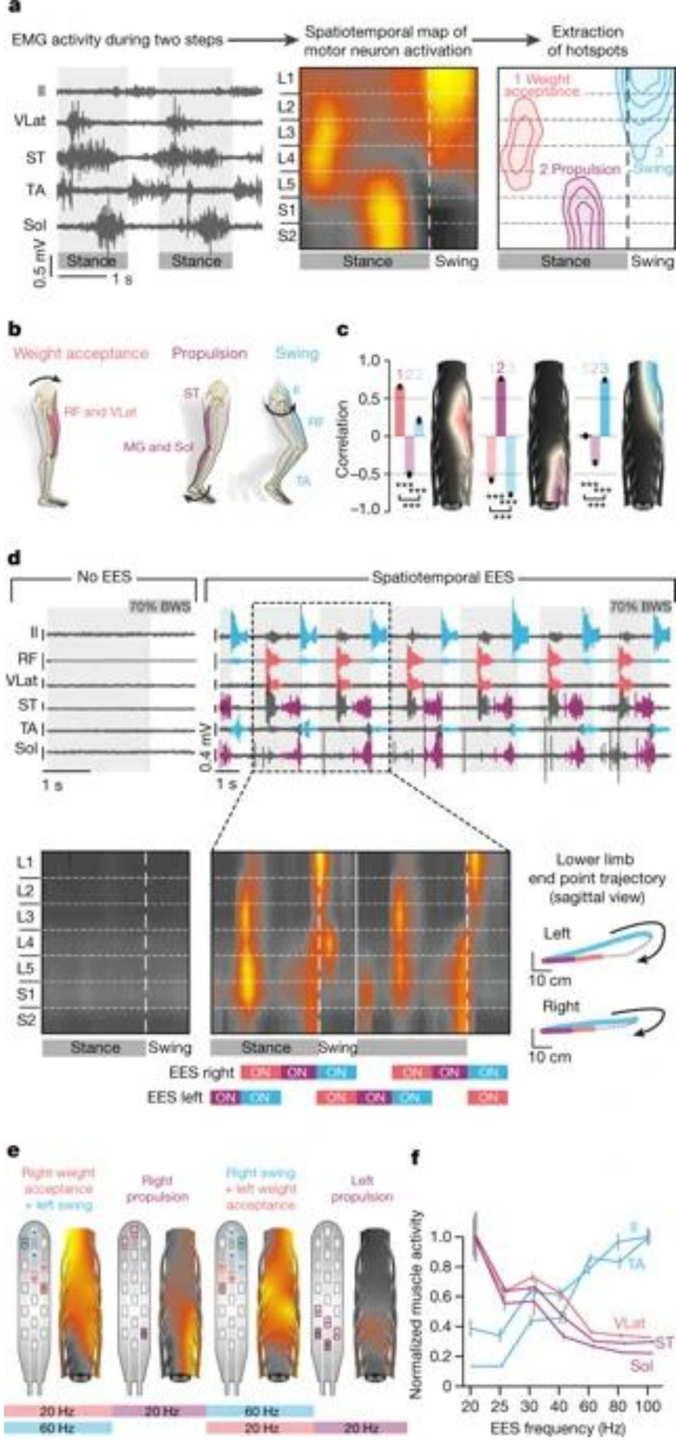


Phasic stimulation

The **spatial stimulation pattern** is carefully chosen (i.e. which electrodes)

The **stimulation is phasic** (as opposed to tonic, as in previous work) and **depends on the estimated phase of the movement** (e.g. different between swing and stance).

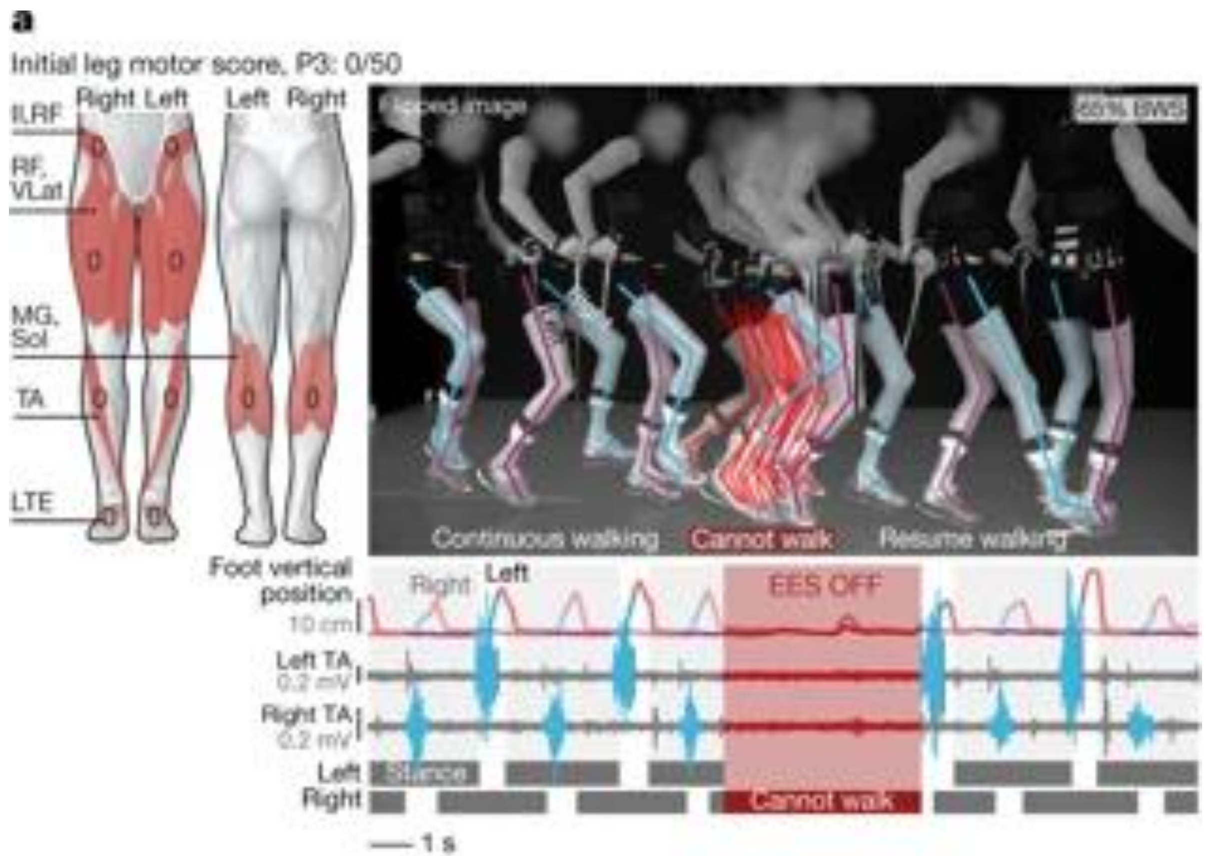
The stimulation is done through the dorsal roots, i.e. stimulation of sensory pathways



Restoring locomotion in humans (Courtine)

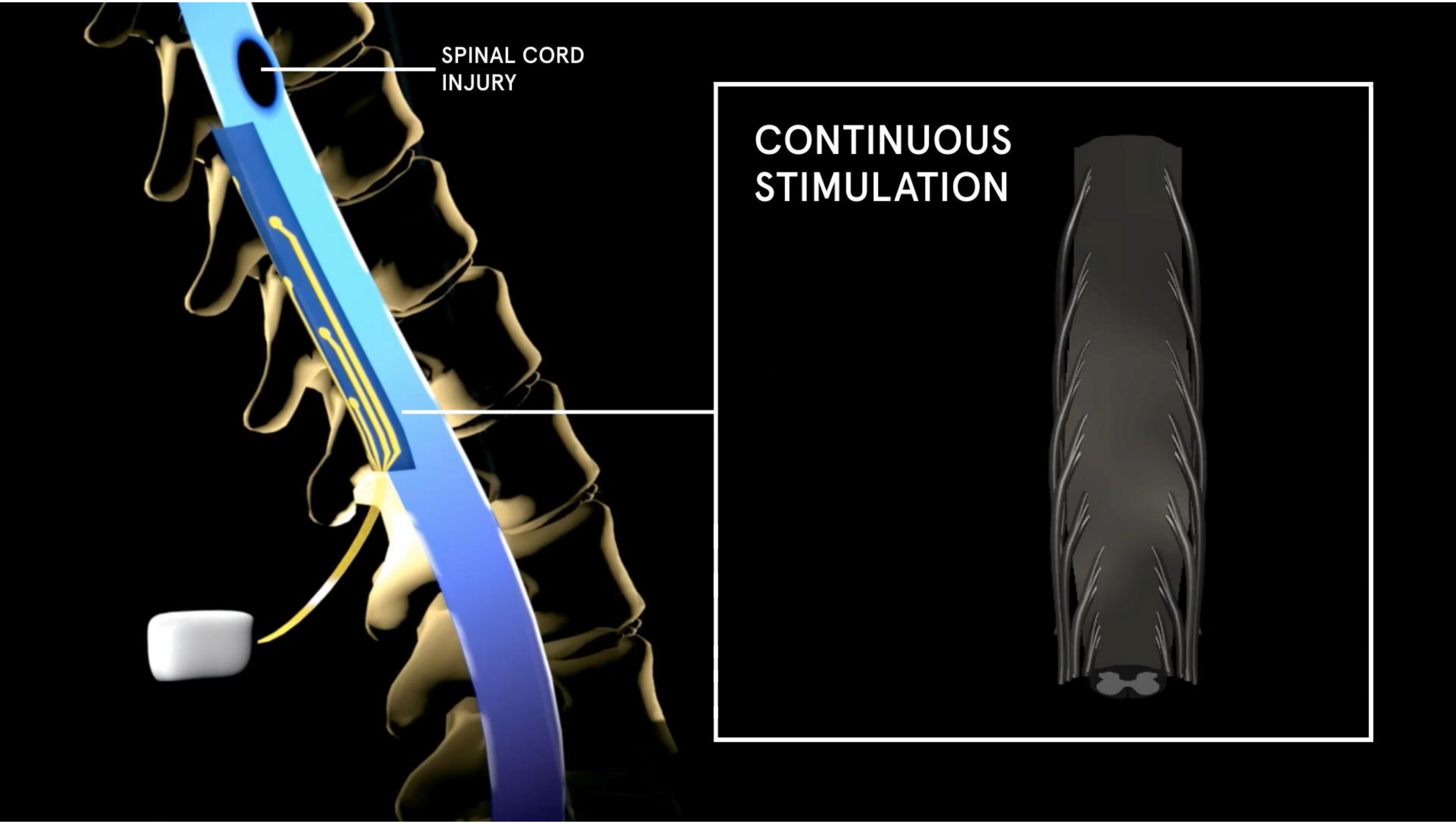
The EES is necessary for locomotion, at least at the beginning.

For some patients, voluntary leg movements and walking capacities without EES appeared over the course of the rehabilitation program



Supplementary Video 2 Spatiotemporal EES enables voluntary walking

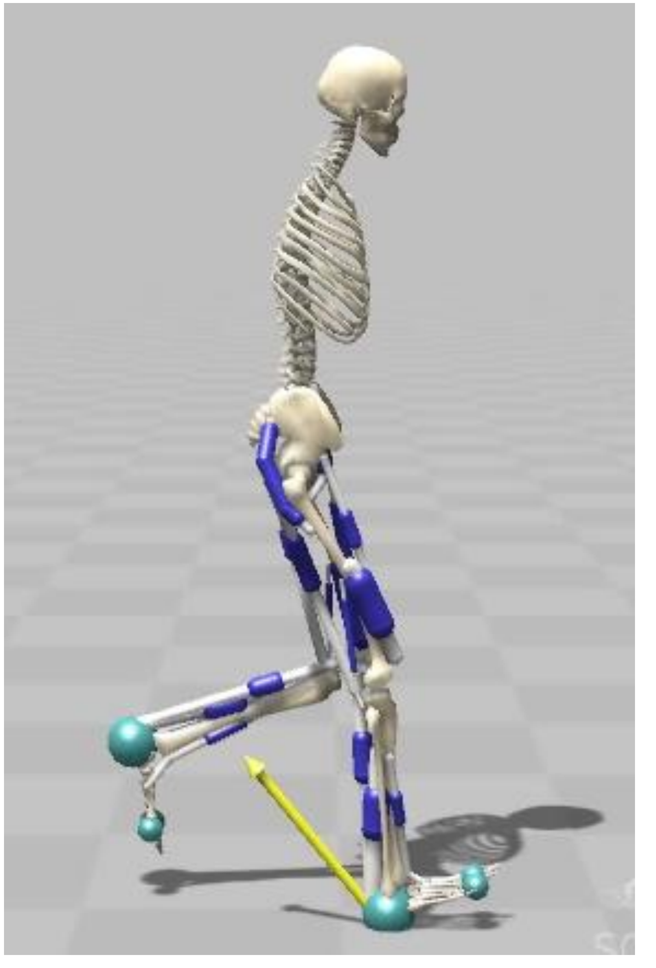
https://static-content.springer.com/esm/art%3A10.1038%2Fs41586-018-0649-2/MediaObjects/41586_2018_649_MOESM4_ESM.mp4



Wagner, et al. “Targeted Neurotechnology Restores Walking in Humans with Spinal Cord Injury.” *Nature* 563, no. 7729, 2018

Link to neuromechanical simulations

- Neuromechanical simulations could help:
  - To **understand how the stimulation affect the spinal circuits** (stimulation of dorsal roots and sensory pathways)
  - To **optimize the stimulation patterns**
  - Possibly **to tune them for different motor behaviors** (e.g. larger steps, larger ground clearance, etc.)



Di Russo et al. ***J. Neural Eng.***. 2023

Lecture: Modeling human locomotion and neuroprosthetics

- Neuromechanical simulations of human locomotion

- Restoring mobility:
    - Prostheses
    - Orthoses
    - Spinal cord stimulation
    - **Functional Electromyographic stimulation**

- Restoring upper limb movements:
    - Arm/hand replacement
    - Cortical implants and population coding

FES- Functional Electromyographic stimulation

Idea: use surface or implanted electrodes for stimulating muscles

Interesting aspect: **use the body's own actuators**

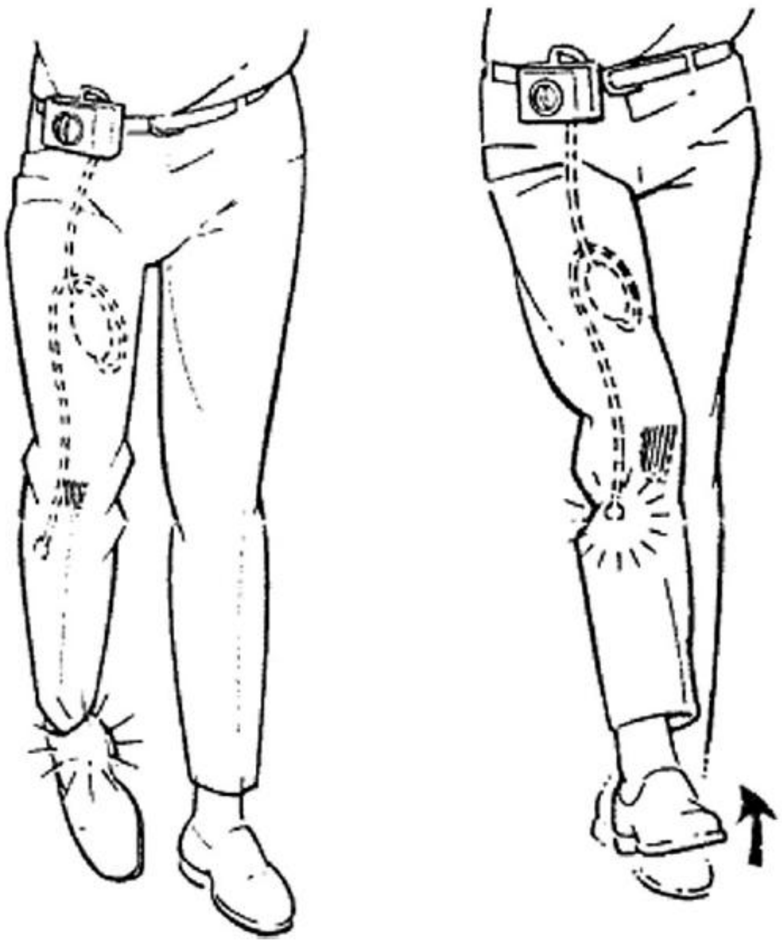
Has been used for: Standing up, drop foot, bladder function, simple locomotion, sometimes together with exoskeletons (Walktrainer project) or with bikes.

Electrodes: on surface, or implanted (e.g. BIONS)

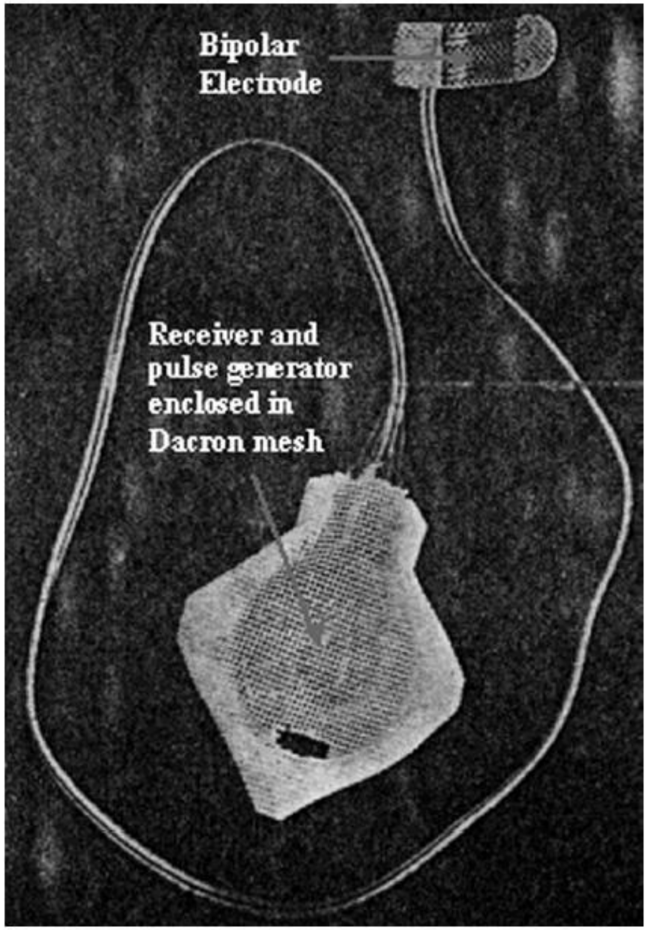
Problems: invasive, muscle fatigue, difficult control.

Needs a good understanding of muscle properties to get the right torques out of electrical stimulation.

FES- Drop Foot after stroke



(a)



(b)

Fig. 5. (a) Representation of the Rancho Los Amigos implanted DFS. (b) Implanted assembly of the Rancho Los Amigos implanted peroneal stimulator (Waters *et al.* 1975, reproduced with permission).

For a review, see Lyons et al 2002

FES- standing up and locomotion

For a review see (Graupe 2005)

http://www.youtube.com/watch?v=1AoH7fr9iMI

Parastep system by http://www.sigmedics.com

Lecture: Modeling human locomotion and neuroprosthetics

- Neuromechanical simulations of human locomotion

- Restoring mobility:
  - Prostheses
  - Orthoses
  - Spinal cord stimulation
  - Functional Electromyographic stimulation

- **Restoring upper limb movements:**
  - **Arm/hand replacement**
  - **Cortical implants and population coding**

Arm/hand replacement

Rehabilitation Institute of Chicago

Multiple problems need to be solved:

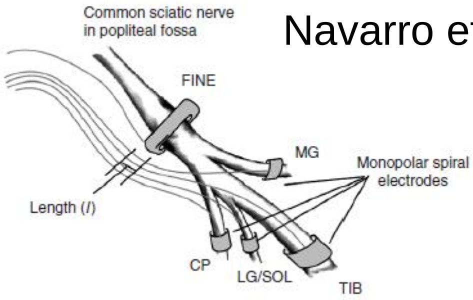
- Mechatronics
- Interface: Where and how?
- The control of a arm-hand prosthesis is more complicated than a lower-limb prosthesis.

Neural interfaces for arm prostheses

Different options:

1. **Recording of EMGs** (e.g. of biceps)

2. **Nerve cuffs as electrodes**



Navarro et al 2005

3. **Targeted Reinnervation for Transhumeral Amputees**

4. **EEG recordings**

5. **Cortical implants**

Targeted Reinnervation for Transhumeral Amputees

- **Technique developed at the** Rehabilitation Institute of Chicago.

- Idea: use a surgical technique called targeted muscle reinnervation (TMR). The goal of TMR surgery is to utilize the brain commands that still attempt to reach the missing limb. These commands travel down nerves that were severed during amputation and are no longer received by muscles. **If these nerves are connected to different muscle sites, they can cause these other muscles to contract, producing the signals used to control myoelectric prostheses**. The control is intuitive since the “right” nerves are used.

- **The targeted muscle acts as a natural amplifier** for the neuronal signals produced by the transferred residual nerves **(Wikipedia).**

Targeted Reinnervation for Transhumeral Amputees

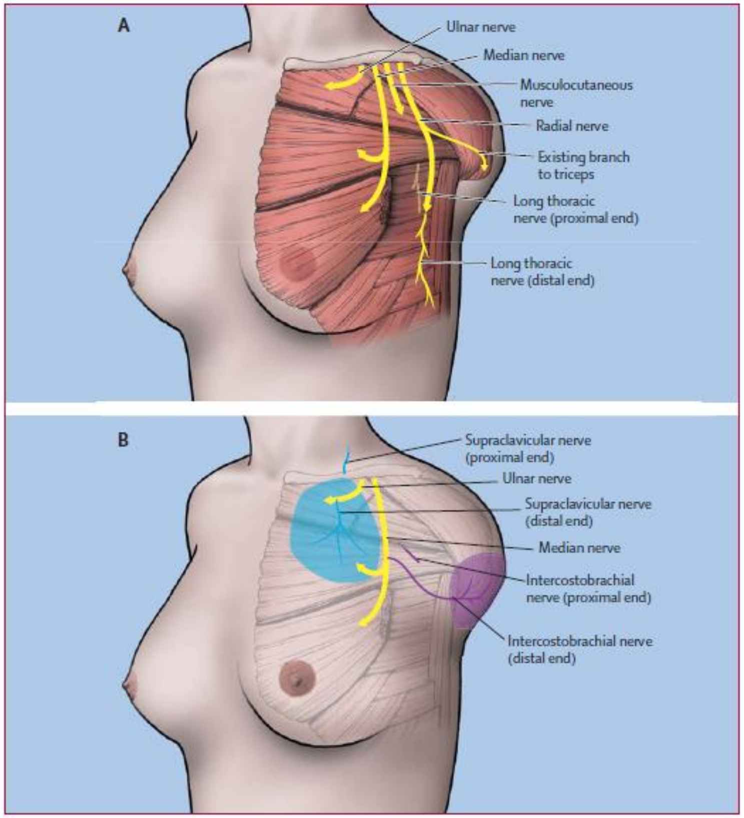


Figure 7: **Diagram of targeted reinnervation surgery**
(A) Targeted muscle reinnervation. The musculocutaneous, ulnar, and median nerves were transferred to separate segments of the pectoralis major muscle. The long thoracic nerve innervating the inferior three slips of serratus anterior was divided and the distal segment was coapted to the radial nerve. (B) Targeted sensory reinnervation. The supraclavicular cutaneous nerve was cut and the distal segment was coapted to the side of the ulnar nerve. The intercostobrachial cutaneous nerve was cut and the distal end was coapted to the side of the median nerve.

Kuiken TA, Miller LA, Lipschutz RD, Lock BA, Stubblefield K, Marasco PD, Zhou P, Dumanian GA. Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study. Lancet. 2007 Feb 3;369(9559):371-80.

Targeted Reinnervation for Transhumeral Amputees

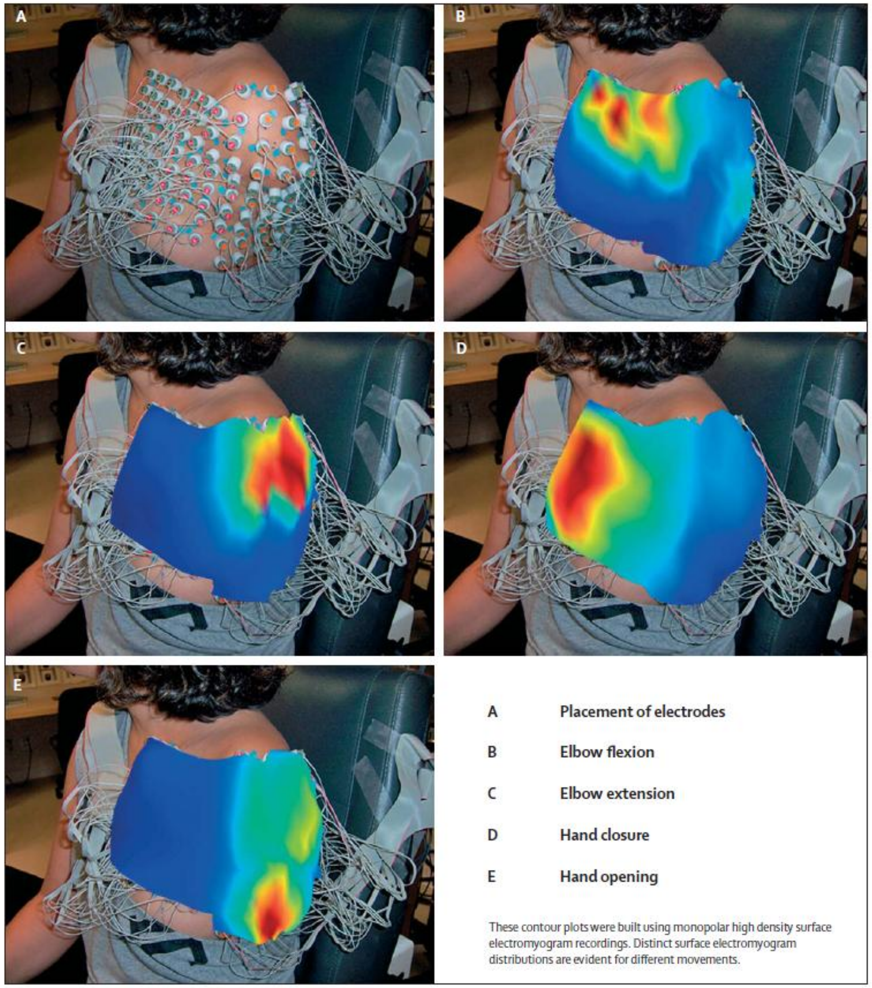


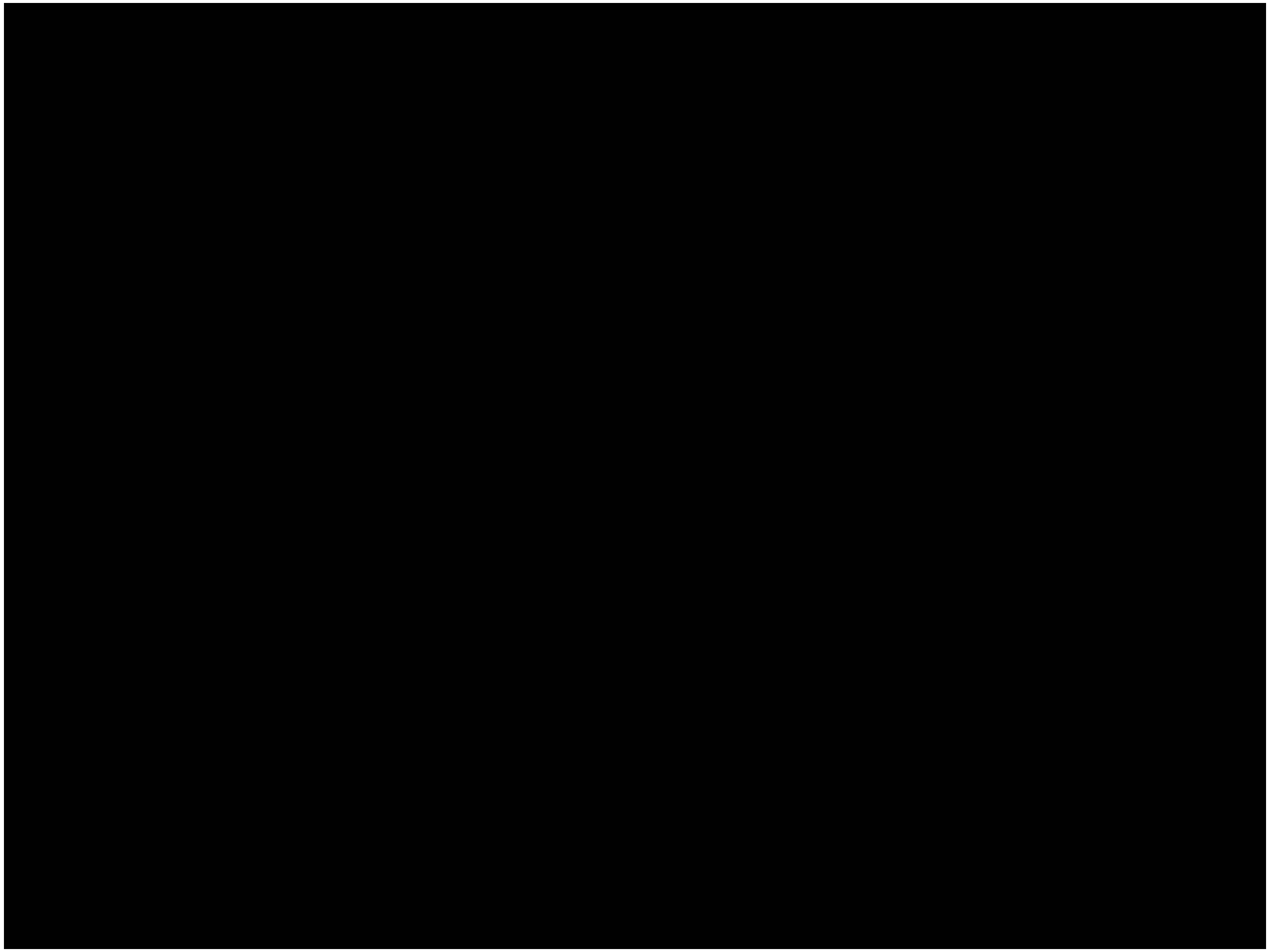
Figure 9: Map of surface electromyogram amplitude for four different movements

Kuiken TA, Miller LA, Lipschutz RD, Lock BA, Stubblefield K, Marasco PD, Zhou P, Dumanian GA. Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study. Lancet. 2007 Feb 3;369(9559):371-80.

Targeted Reinnervation for Transhumeral Amputees

Rehabilitation Institute of Chicago
http://www.ric.org/research/centers/cbm/index.aspx

Targeted Reinnervation for Transhumeral Amputees

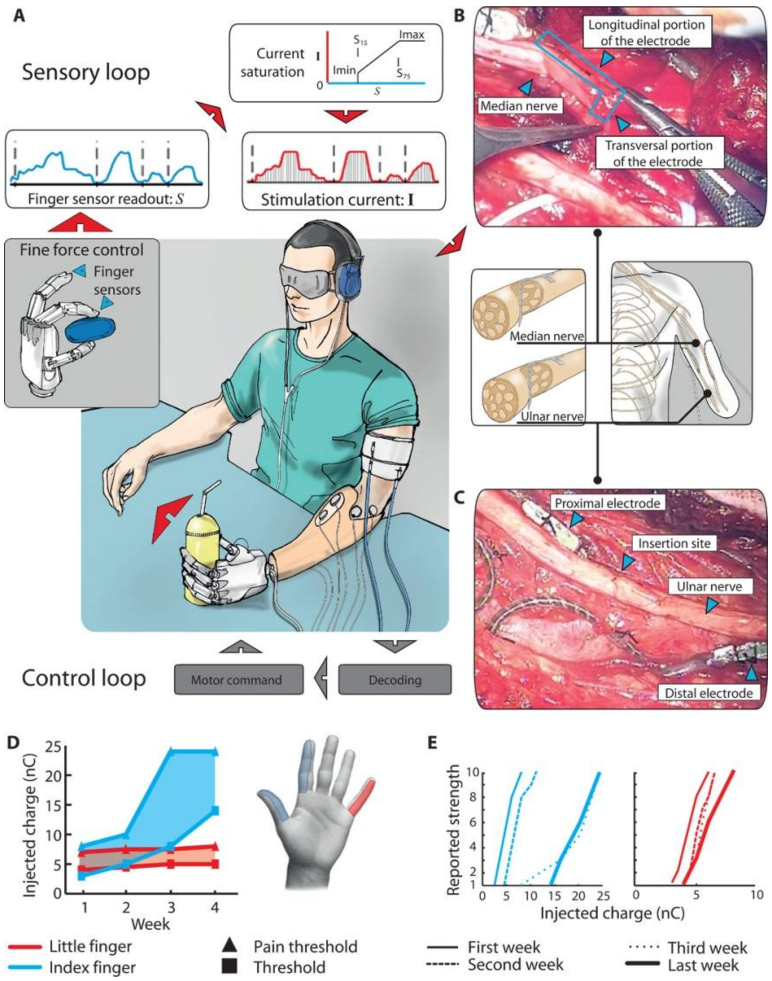


Rehabilitation Institute of Chicago
http://www.ric.org/research/centers/cbm/index.aspx

Challenge: sensory feedback

One big challenge: **how to provide sensory feedback to the user.**

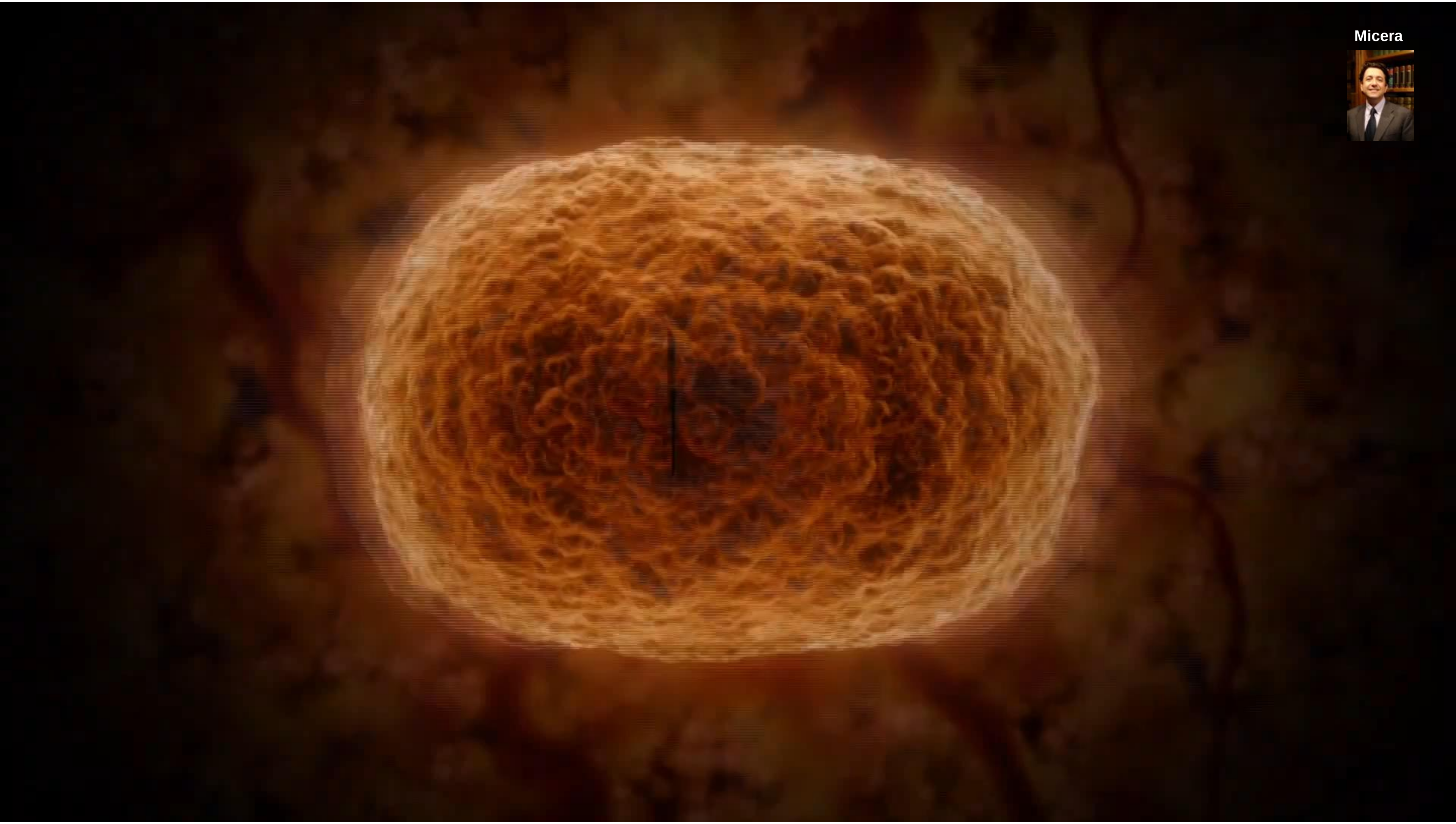
Nice work by Micera, Courtine, and colleagues at EPFL with **nerve stimulation** using transversal multichannel **intrafascicular electrodes**



S. Raspopovic et al. Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses, in Science Translational Medicine, vol. 6, num. 222, 2014.

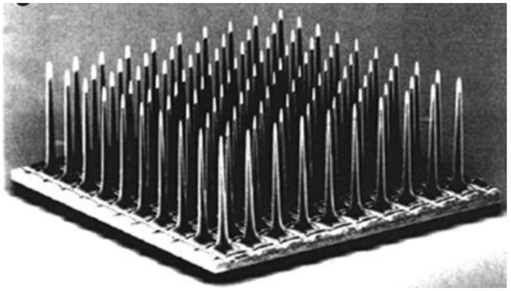
http://infoscience.epfl.ch/record/198047?ln=en

Wearable Robotics: sensorized hand



https://www.youtube.com/watch?v=QtPs8d4JbwY

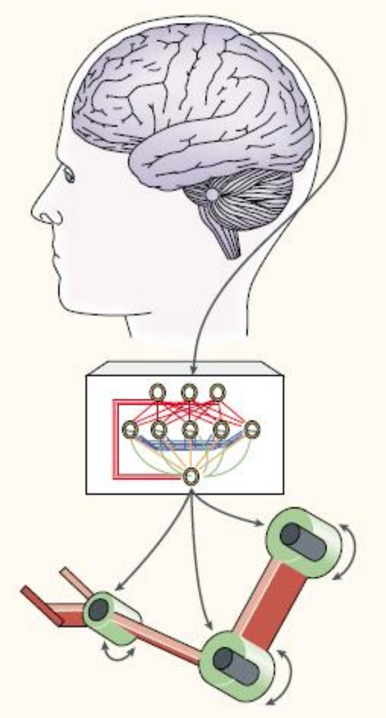
Cortical implants and population coding



Advances in **multi-array electrodes**

And in the **understanding of movement coding in the cortex**

have allowed the design of **cortical interfaces**



(Nicolelis 2003)

Motor cortex, arm movements

Works very well in many cases!

E.g. **encoding of arm movements in the motor cortex**

The direction of motion can be predicted from the population vector

$$\vec{v}_{pop} = \sum_{a=1}^{N} \left(\frac{r}{r_{max}} \right)_a \vec{c}_a \,.$$

See the **population code** we saw in last lecture

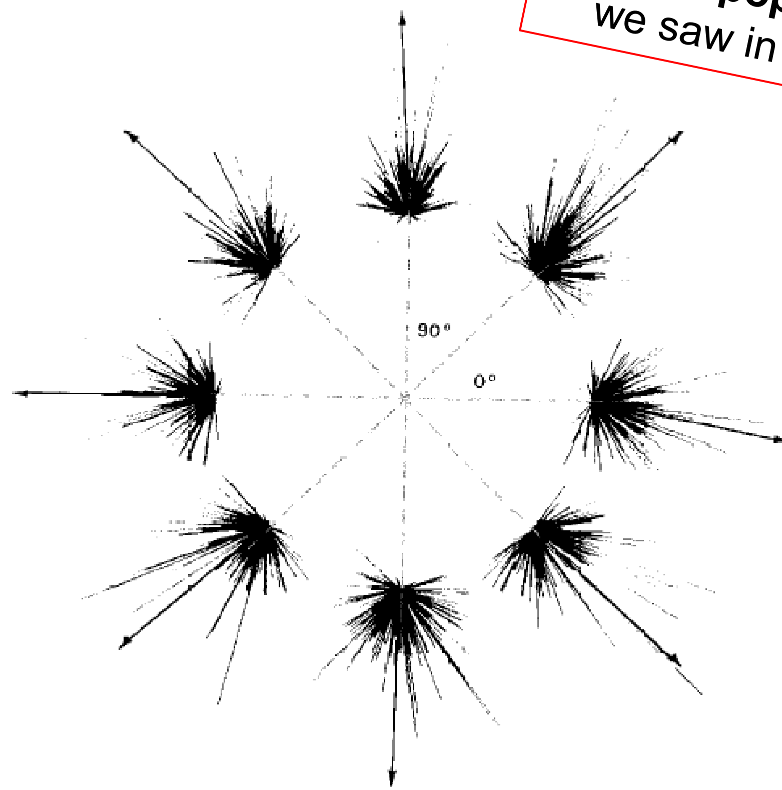
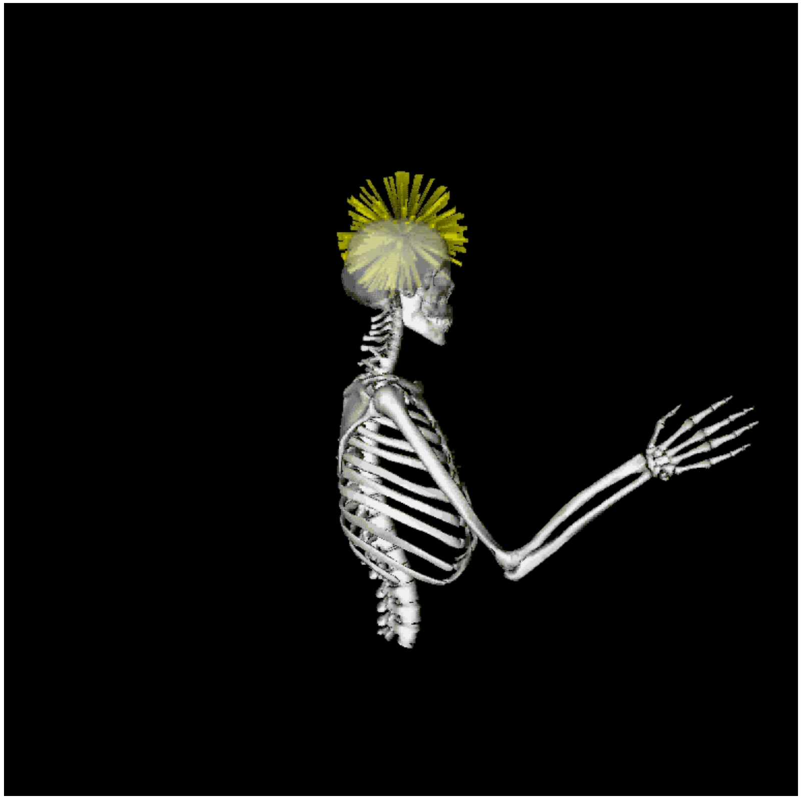


Figure 3.6: Comparison of population vectors with actual arm movement directions. Results are shown for eight different movement directions. Actual arm movement directions are radially outward at angles that are multiples of 45°. The groups of lines without arrows show the preferred direction vectors of the recorded neurons multiplied by their firing rates. Vector sums of these terms for each movement direction are indicated by the arrows. The fact that the arrows point approximately radially outward shows that the population vector reconstructs the actual movement direction fairly accurately. (Figure adapted from Kandel et al., 1991 based on data from Kalaska et al., 1983.)

Interfacing with a robot

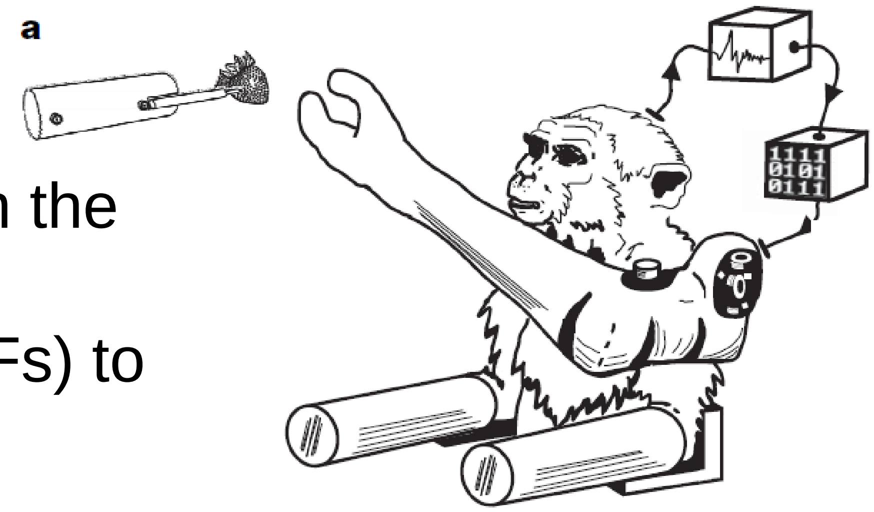
- Understanding this population coding has allowed the design of **neuroprosthetic interfaces with robot arms**.



Andrew Schwarz and colleagues, U. of Pittsburgh

Meel Velliste, et al, *Cortical control of a prosthetic arm for self-feeding*, Nature, Vol 453, pp 1098-1101, 2008

Experimental setup



- **Intracortical microelectrodes** in the primary cortex
- **Control of a robotic arm** (5 DOFs) to feed itself

- Monkeys first learned to control the arm with a joystick
- Then **control from the cortical recordings using real-time extraction algorithms**: encoding of the velocity of the endpoint + decision to open/close the gripper

Andrew Schwarz and colleagues, U. of Pittsburgh
Meel Velliste, et al, *Cortical control of a prosthetic arm for self-feeding*, Nature, Vol 453, pp 1098-1101, 2008

Extraction algorithms

- Population vector algorithm
- **Uses directional tuning of each recorded unit**
- Vector sum of the preferred directions weighted by the instantaneous firing rates.
- **3D velocity of end-point + aperture velocity of fingers**
- These signals are integrated to get positions.
- Inverse kinematics to get joint angles
- 30ms time steps (~continuous)
- Interestingly, bell-shaped velocity profile

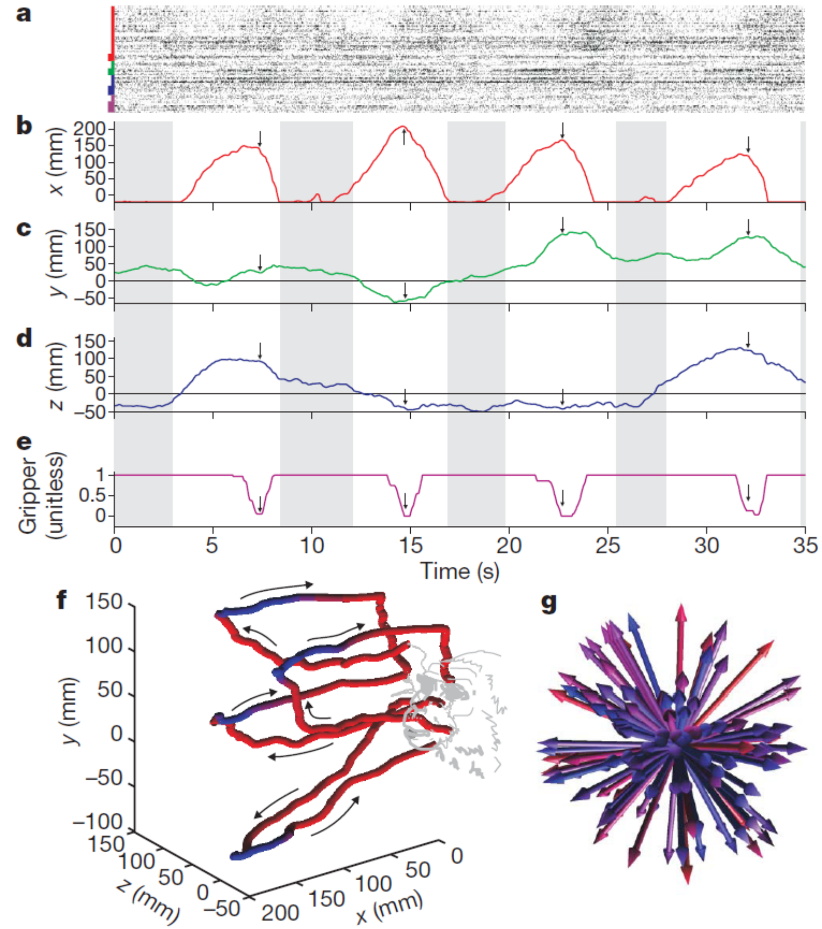


Figure 2 | Unfiltered kinematic and spike data. a, Spike rasters of 116 units used for control. Rows represent spike occurrences for each unit, grouped by major tuning component (red, *x*; green, *y*; blue, *z*; purple, gripper). Groups are further sorted by negative major tuning component (thin bar) versus positive (thick bar). **b–d,** The *x*, *y*, and *z* components, respectively, of robot endpoint position. Grey background indicates inter-trial intervals. Arrows indicate gripper closing at target. **e,** Gripper command aperture (0, closed; 1, open). **f,** Spatial trajectories for the same four trials. Colour indicates gripper aperture (blue, closed; purple, half-closed; red, open). Arrows indicate movement direction. **g,** Distribution of the four-dimensional preferred directions of the 116 units used. Arrow direction indicates *x*, *y*, *z* components, colour indicates gripper component (blue, negative; purple, zero; red, positive).

Interfacing with a robot

Andrew Schwarz and colleagues, U. of Pittsburgh

Emergent licking behavior

Andrew Schwarz and colleagues, U. of Pittsburgh

Cortical interface in humans

Has now been tested in a few **tetraplegic patients**, see for instance:

Hochberg, Leigh R., et al. "Reach and grasp by people with tetraplegia using a neurally controlled robotic arm." *Nature* 485.7398 (2012): 372-375.

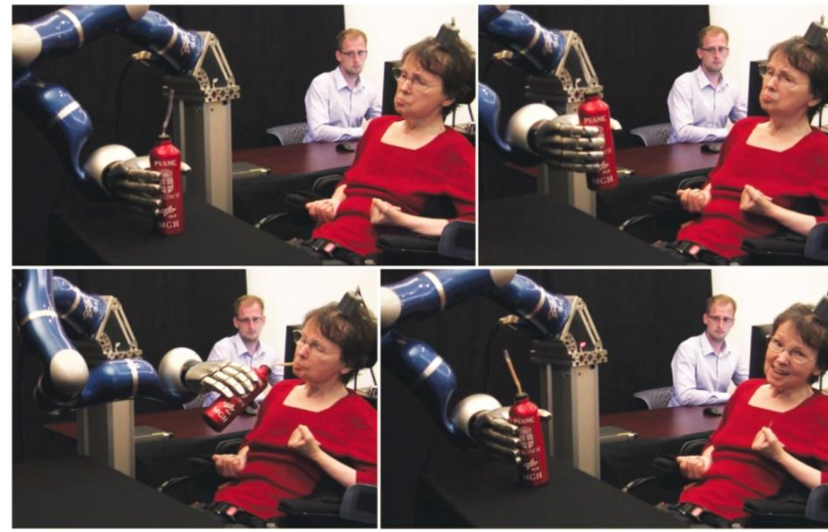


Figure 2 | Participant S3 drinking from a bottle using the DLR robotic arm. Four sequential images from the first successful trial showing participant S3 using the robotic arm to grasp the bottle, bring it towards her mouth, drink coffee from the bottle through a straw (her standard method of drinking) and place the bottle back on the table. The researcher in the background was positioned to monitor the participant and robotic arm. (See Supplementary

https://www.youtube.com/watch?v=cg5RO8Qv6mc

Conclusion

This was just a rapid overview of neuroprosthetics with some bridges to topics of the course.

Take home message: **computational modeling has a key role to play in neuroprosthetics.**

For going more in-depth, follow courses by Silvestro Micera and Gregoire Courtine (neuroprosthetics center)

End of the lecture and the course

Deadline for Project 2: **Friday 06/06/2025** 23:59

Please evaluate the course online, many thanks!!

THANK YOU
FOR FOLLOWING THE COURSE !!