Neuromorphic Design of Smart Prosthetic and Therapeutic Systems

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Complex visual fields

Color

Social behavior

Reward systems

Attention

Auditory cues

Risk aversion ?

Olfaction

Control of locomotion

Path planning

Sensorimotor integration

System state ⇔ performance

Hippocampus - path planning
dynamics at a fixed point?

Opportunities for Neuromorphic Engineers in Medical Rehabilitation

- smart prostheses
    - artificial limbs
    - electrical stimulation systems

Smart Prosthetics

November 9-11, 2006 - Irvine, CA

THE NATIONAL ACADEMIES
KECK FUTURES INITIATIVE

http://www.keckfutures.org/

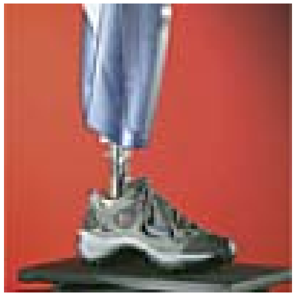
Goals:

- Enhance the climate for conducting interdisciplinary research and break down related institutional and systemic barriers
- Stimulate new modes of scientific inquiry
- Encourage communication between scientists and public

NAKFI - Themes to date:

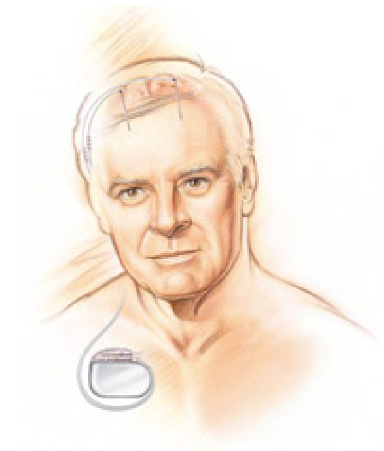
2008 - Complexity (Nov. 13-15, 2008)
2007 - Aging / Longevity (Nov. 15-18, 2007)
2006 - Smart Prosthetics
2005 - Genomics
2004 - Designing Nanostructures
2003 - Signaling

Prostheses of Today and Tomorrow



Victhom Human Bionics

Cleveland FES Center



Medtronic Corp.

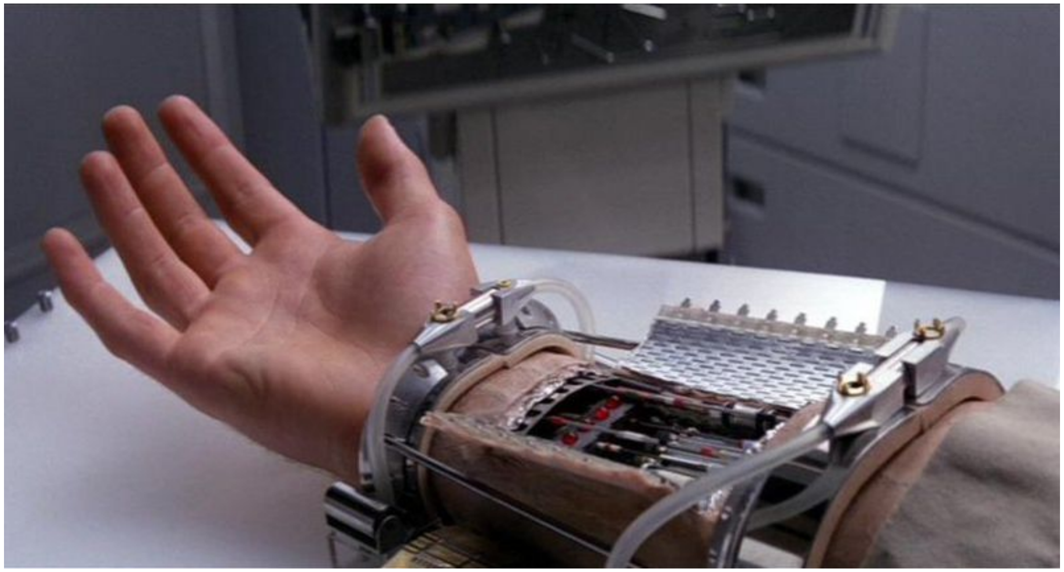
Cyberkinetics, Inc.

Cochlear Corp.

Motion Control Corp.

Alfred Mann Institute,

Prostheses of the Future



Intelligent

Responsive

Biomimetic

What?

Neural prostheses:

Hand grasp

Standing/stepping

Bladder/bowel control

Exercise

Memory/cognition

Neuromotor therapy

Vision

Hearing

Mechanical Prostheses:

Artificial limbs

Heart valves

Cerebral shunts

Why?

Limb loss

Spinal cord injury

Stroke

Brain injury

Parkinson’s Disease

Deafness

Blindness

Memory impairments

ALS

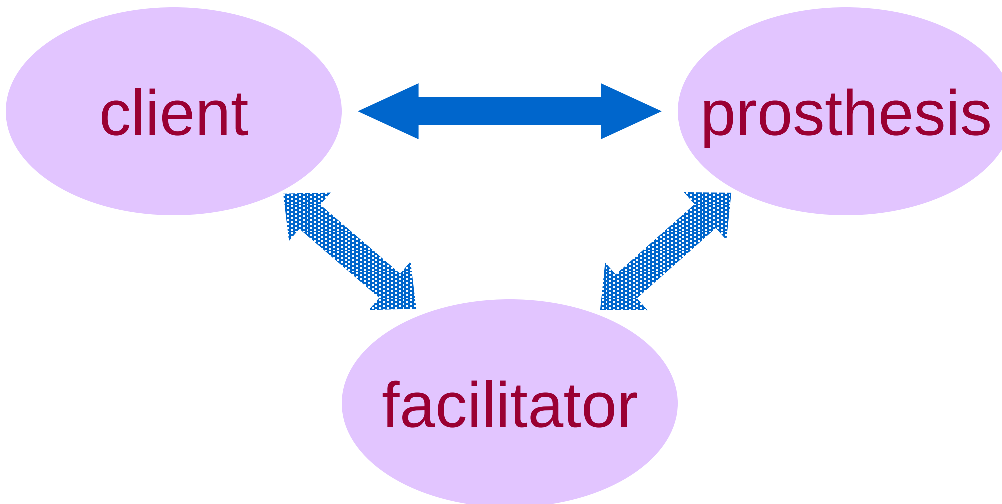
Cerebral palsy

Task Group Topics

- Describe a framework for replacing damaged cortical tissue and fostering circuit integration to restore neurological function.
- Build a prosthesis that will grow with a child (such as a heart valve or cerebral shunt, or a self healing prosthesis).
- Develop a smart prosthetic that can learn better and/or faster.
- Brain interfacing with materials: recording and stimulation electrodes.
- Refine technologies to create active orthotic devices.
- Structural tissue interfaces: enabling and enhancing continual maintenance and adaptation to mechanical and biologic factors.
- Sensory restoration of perception of limb movement and contact.
- Design a functional tissue prosthesis.
- Create hybrid prostheses that exploit activity-dependent processes.
- Can brain control guide or refine limb control?

Task Group 3:

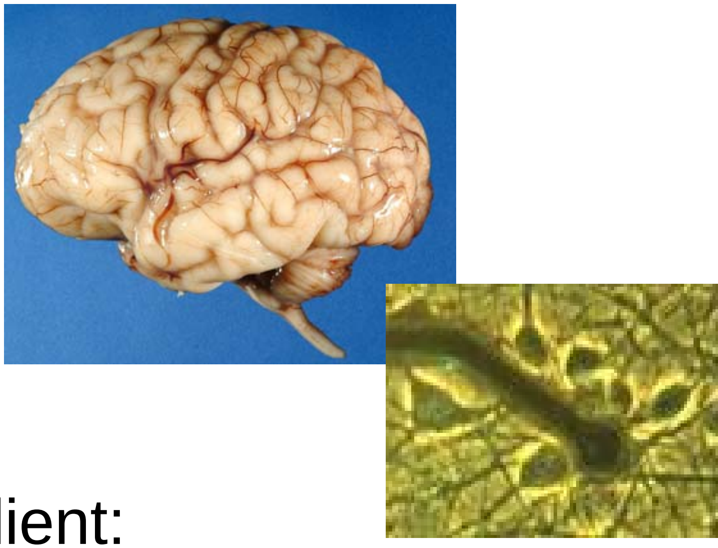
Develop a smart prosthesis that can learn better and/or faster.

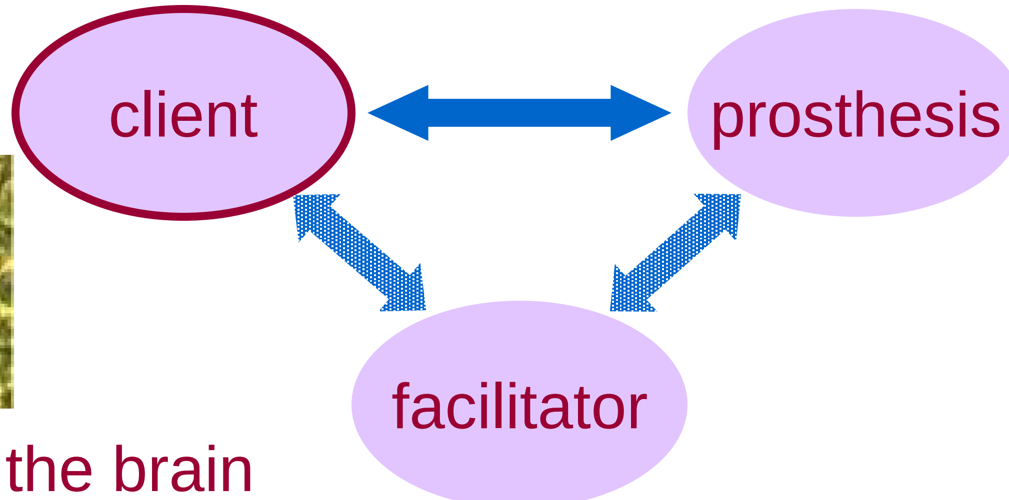


Task Group 3:

Develop a smart prosthesis that can learn better and/or faster.

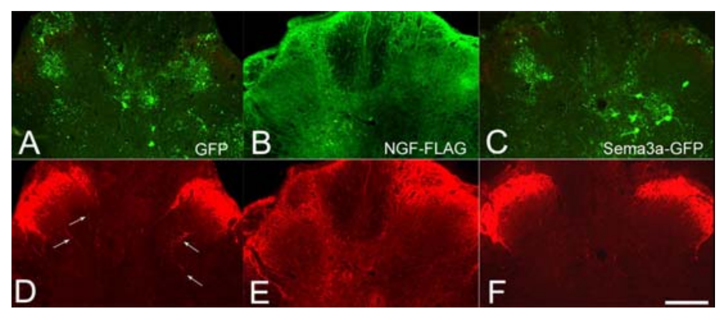
Knowledge/technology gaps:





client:

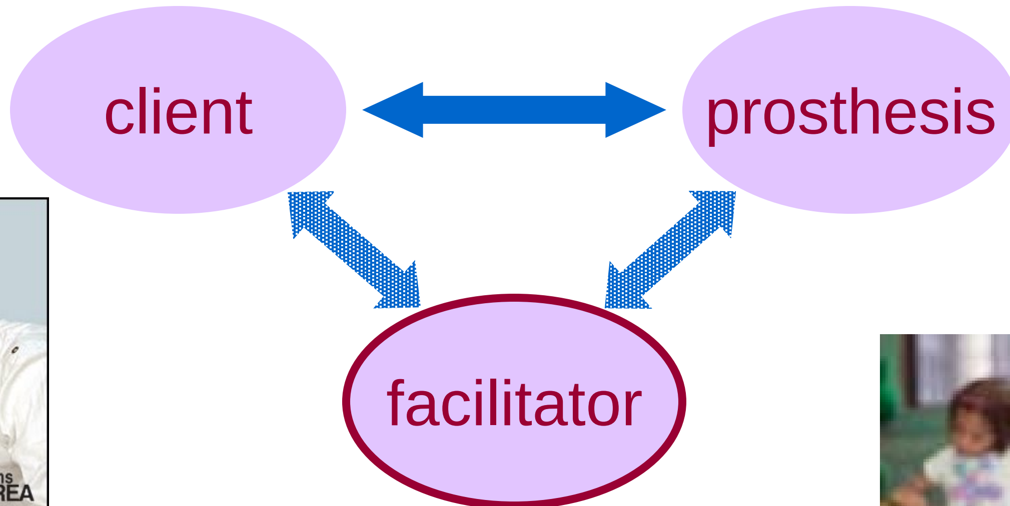
- representations used in the brain
- how to transmit information
- mechanisms of plasticity
- how to maximally exploit plasticity



Task Group 3:

Develop a smart prosthesis that can learn better and/or faster.

Knowledge/technology gaps:



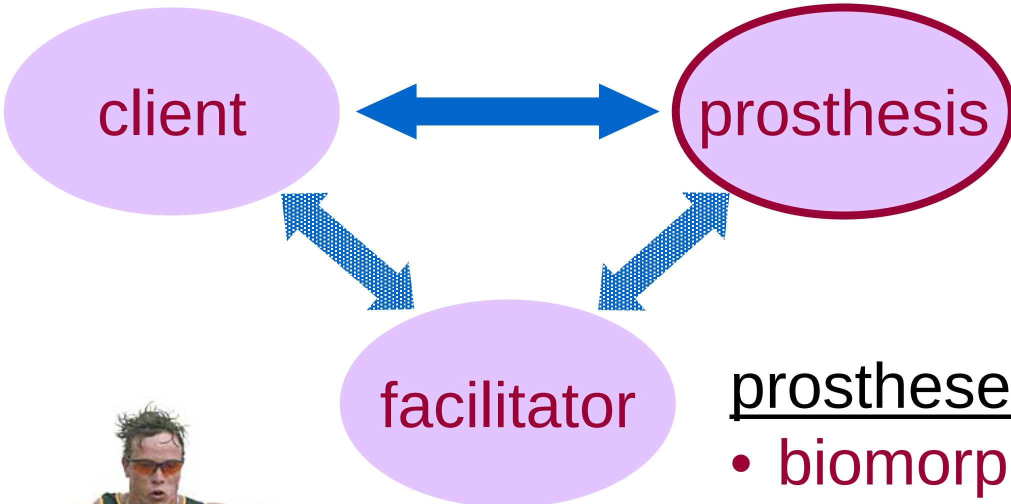
facilitator:

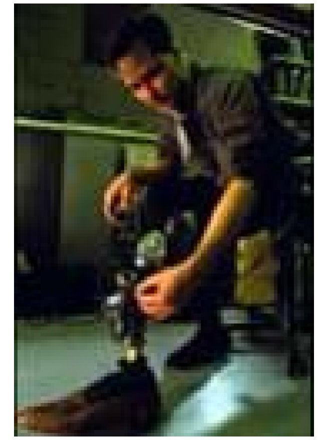
- identification of intermediate milestones (performance and neurophysiological)
- individuality of minimal detectable differences
- customizing for specific user groups
- engage the user

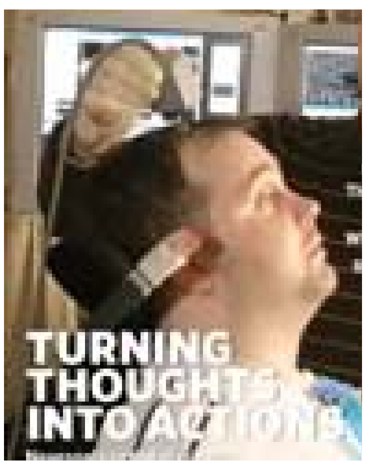
Task Group 3:

Develop a smart prosthetic that can learn better and/or faster.

Knowledge/technology gaps:







prostheses:

- biomorphic sensors/actuators for compatibility w/ neural reps
- detecting and communicating user intent and motor commands
- maintain/improve performance based on dynamic interface
- real-time machine learning
- redundancy for versatility, efficiency

Smart Prosthetics

November 9-11, 2006 - Irvine, CA

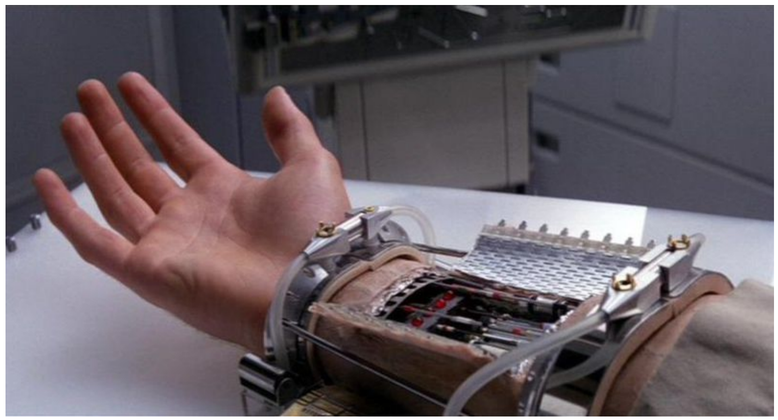
seamless integration

neuromorphic systems

biomimicry

high throughput, high fidelity

co-adaptation



automated fitting

maximizing plasticity

utilizing plasticity

autonomous
- direct control

coordination

versatility

ease-of-use

minimal cognitive demands

cooperative learning

redundancy

sensorimotor integration

amazondotcomification

where are the ‘smarts’?

information transmission/coding

self-repairing

Top five activities (from a list of 34) amputees would like to be able to perform with their electric prostheses

Transradial Users

1) Type/use a word processor
2) Open a door with a knob
3) Tie shoelaces
4) Use a spoon or fork
5) Drink from a glass.

Transhumeral Users

1) Type/use a word processor
2) Cut meat
3) Tie shoelaces
4) Open a door with a knob
5) Use a spoon or fork

Atkins et al., 1996

Command Input Source to Prosthesis

Non-Invasive

Surface EMG/ EEG

Implanted EMG

Direct peripheral nerve interface

Electrocorticogram

Recording w/ penetrating spinal/brain electrodes

Centrally Invasive

Sensory Feedback to User

Non-Invasive

Visual

Auditory

Cutaneous Stimulation

Peripheral Nerve Stimulation

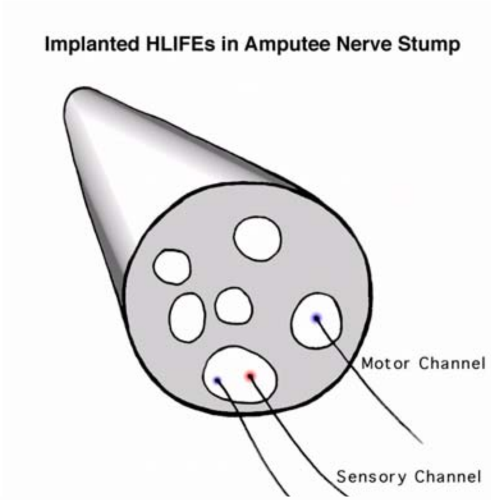
Recording w/ penetrating spinal/brain electrodes

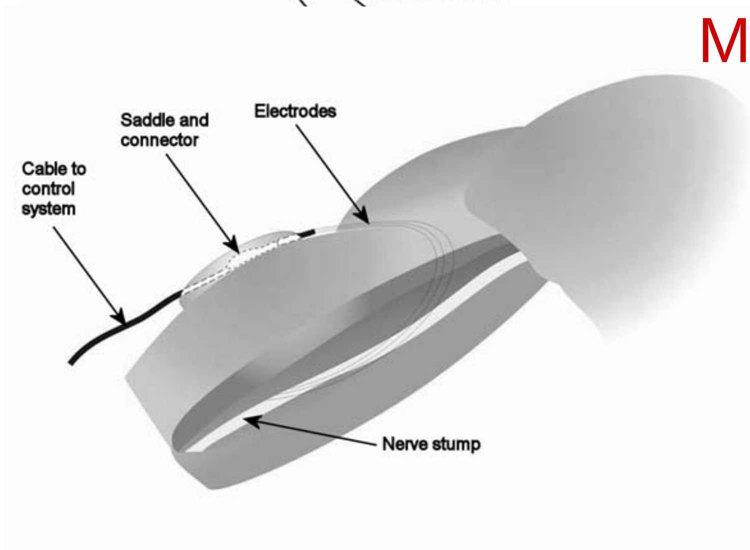
Centrally Invasive

If everyone is thinking alike then someone isn't thinking.

- General George S. Patton

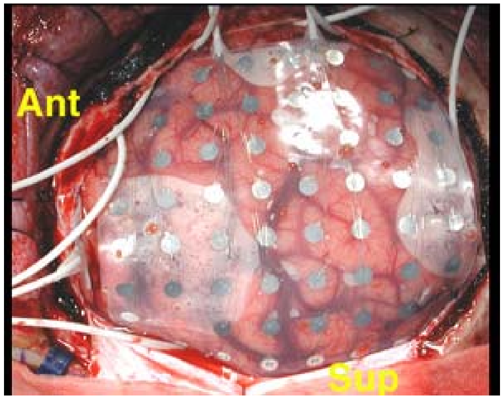
Peripheral Nerve





Horch; Utah, ASU

Electrocorticogram

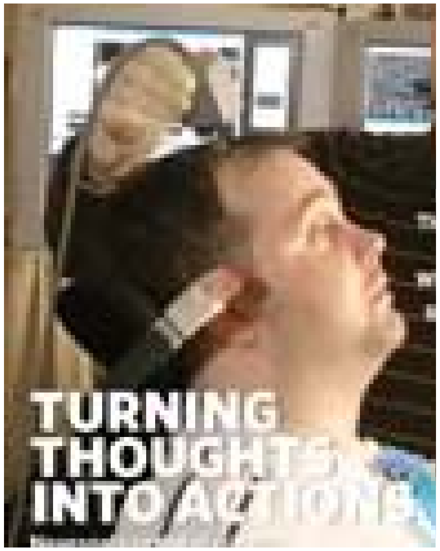


Moran & Leuthardt; Wash. U.
Williams; U. Wisconsin

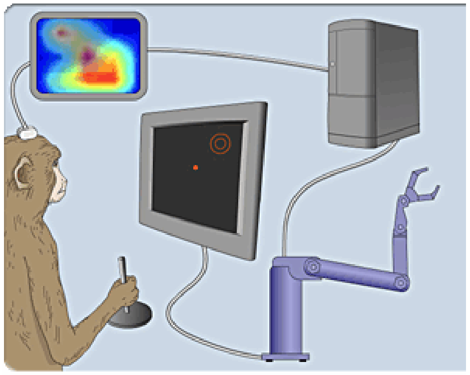
Muscle re-innervation

Kuiken; RIC

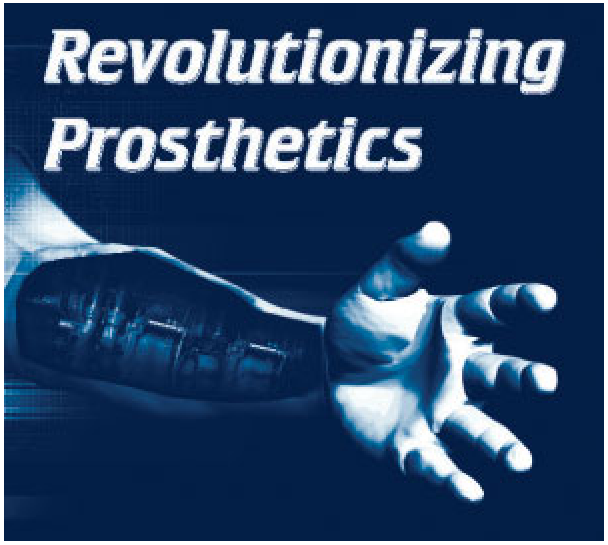
Intracortical arrays



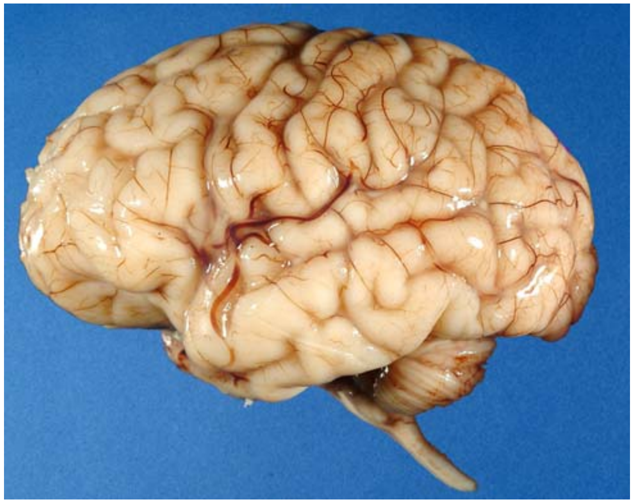
Donoghue; Brown U.
Cyberkinetics, Inc.



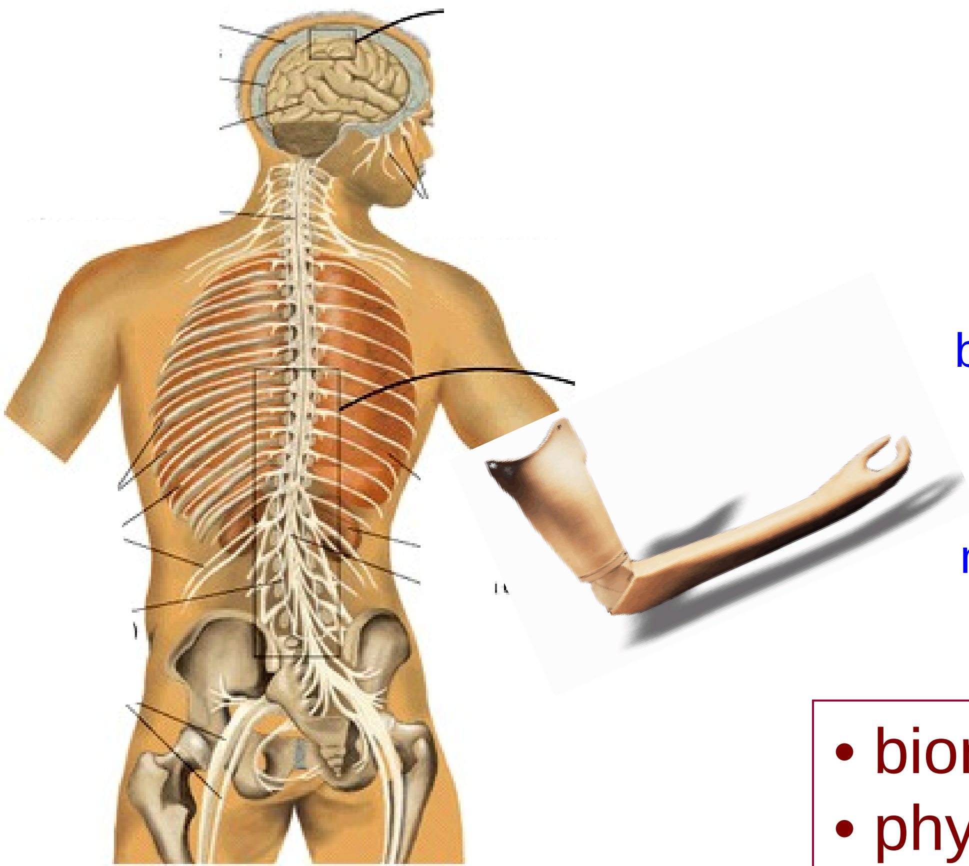
Nicolelis; Duke U.


Revolutionizing
Prosthetics

Where to put the 'smarts'
in smart prostheses?



Integrating Engineered and Physiological Systems



<u>Endogenous</u> system:	<u>Exogenous</u> system:
neural control	neuromorphic control
biological sensors	engineered sensors
muscles/ tendons	biomorphic actuators

- biomimicry
- physiological ⇔ engineered
- adaptive systems
- system integration

Hugh Herr, MIT

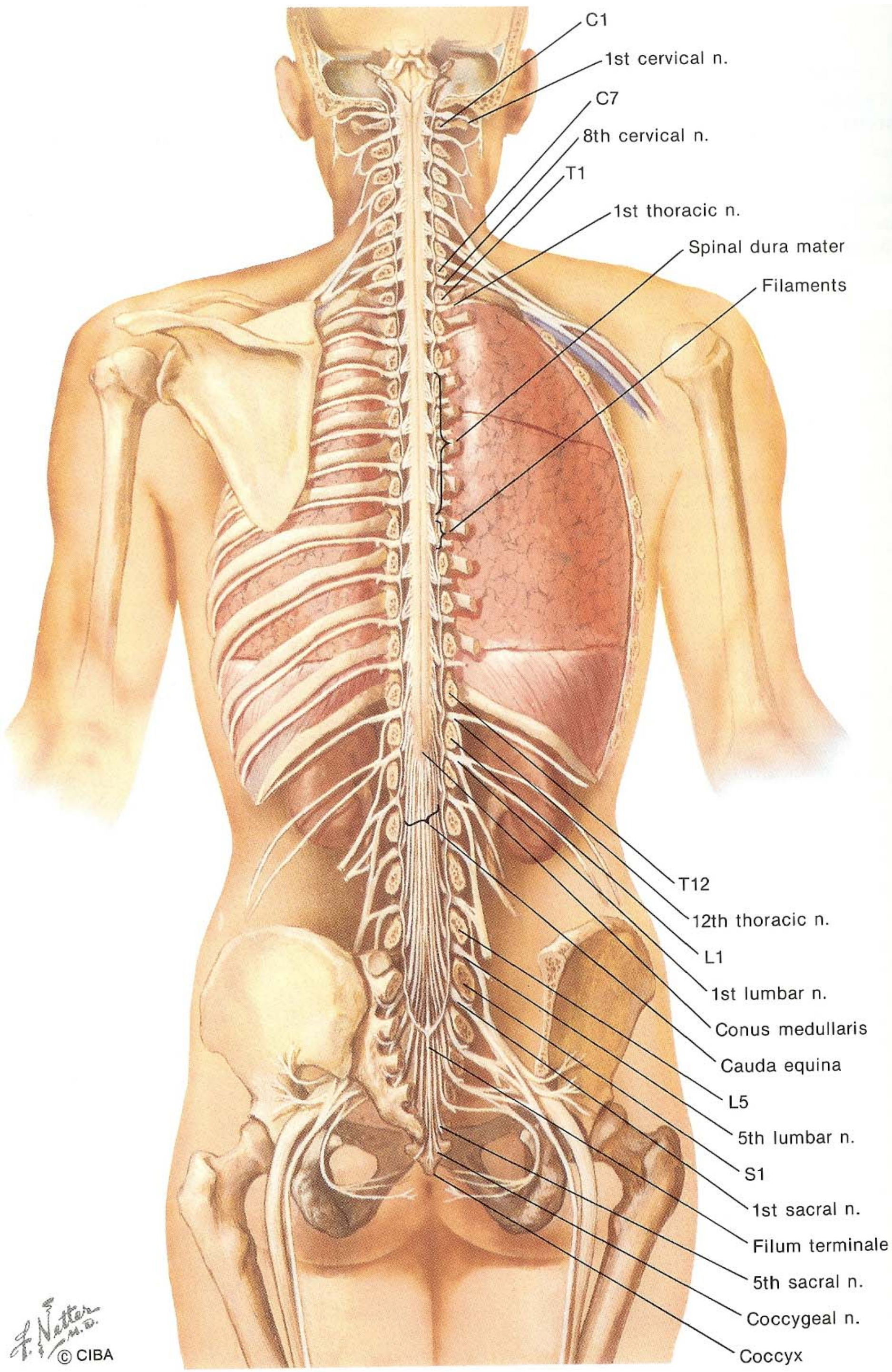
Oscar Pistorius

Spinal cord

Control of locomotion

Spinal cord injury

Locomotor retraining



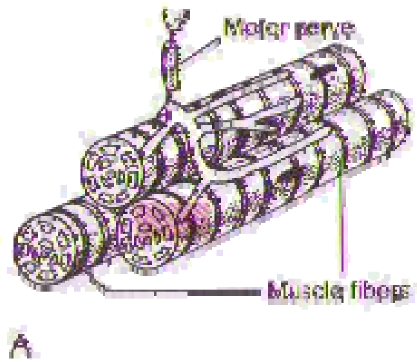
The spinal cord is a conduit for information transfer from the brain.

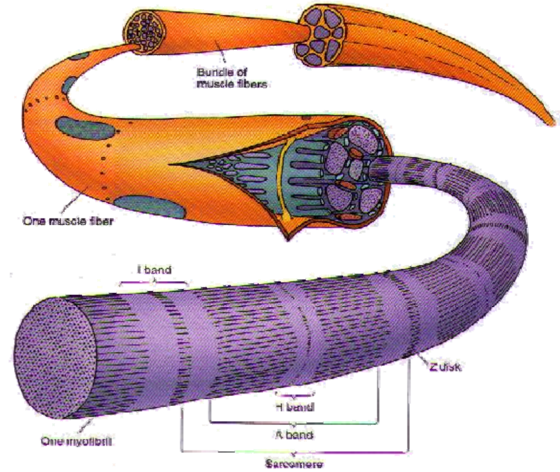
The spinal cord is a highly sophisticated computational structure that mediates a wide range of physiological functions.

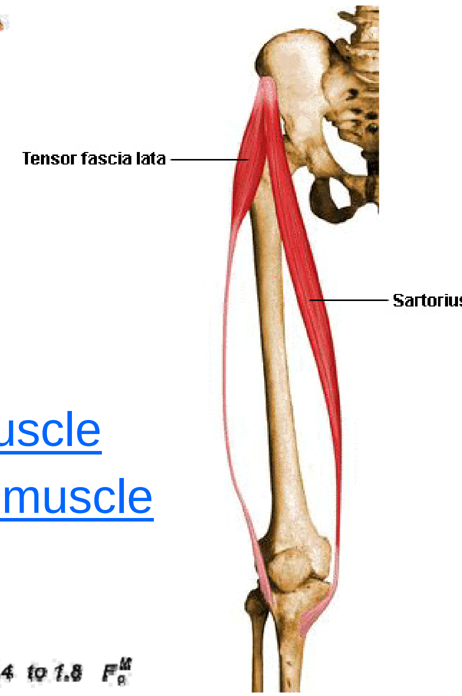
Key features of neuromotor control that are either mediated by or have implications for spinal cord organization

Rate coding

Reflexes







Recruitment modulation

Contraction dynamics

Co-contraction

Secondary action of a muscle

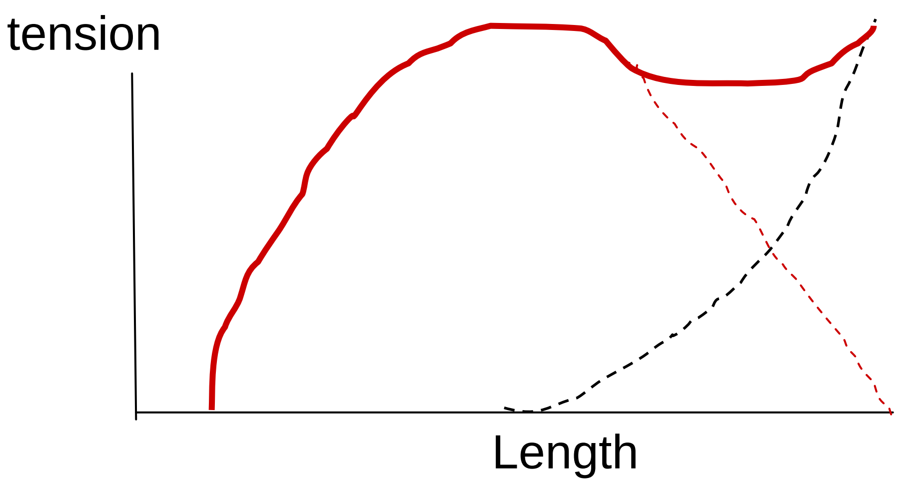
Biarticular muscle

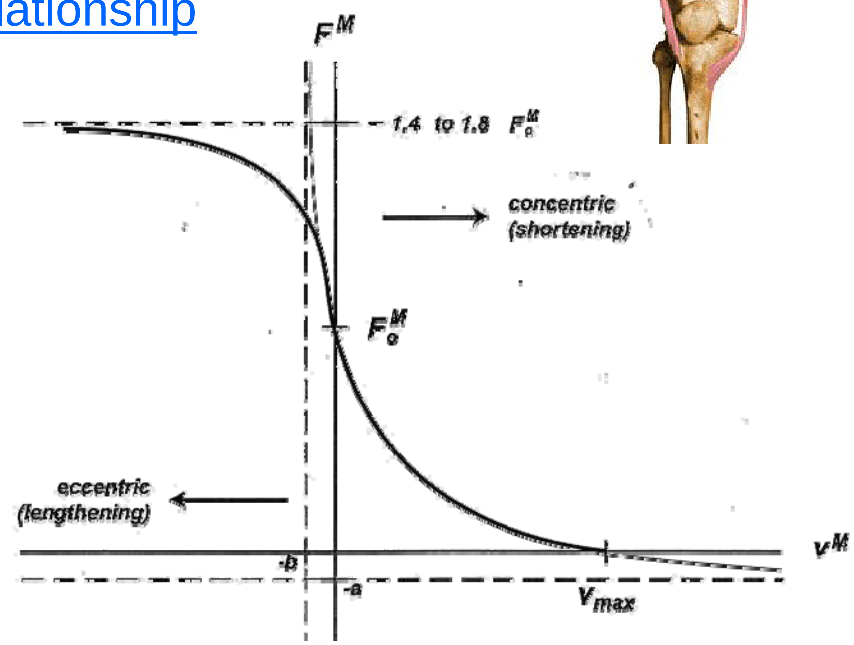
Fatigue

Force-velocity relationship

Length-tension

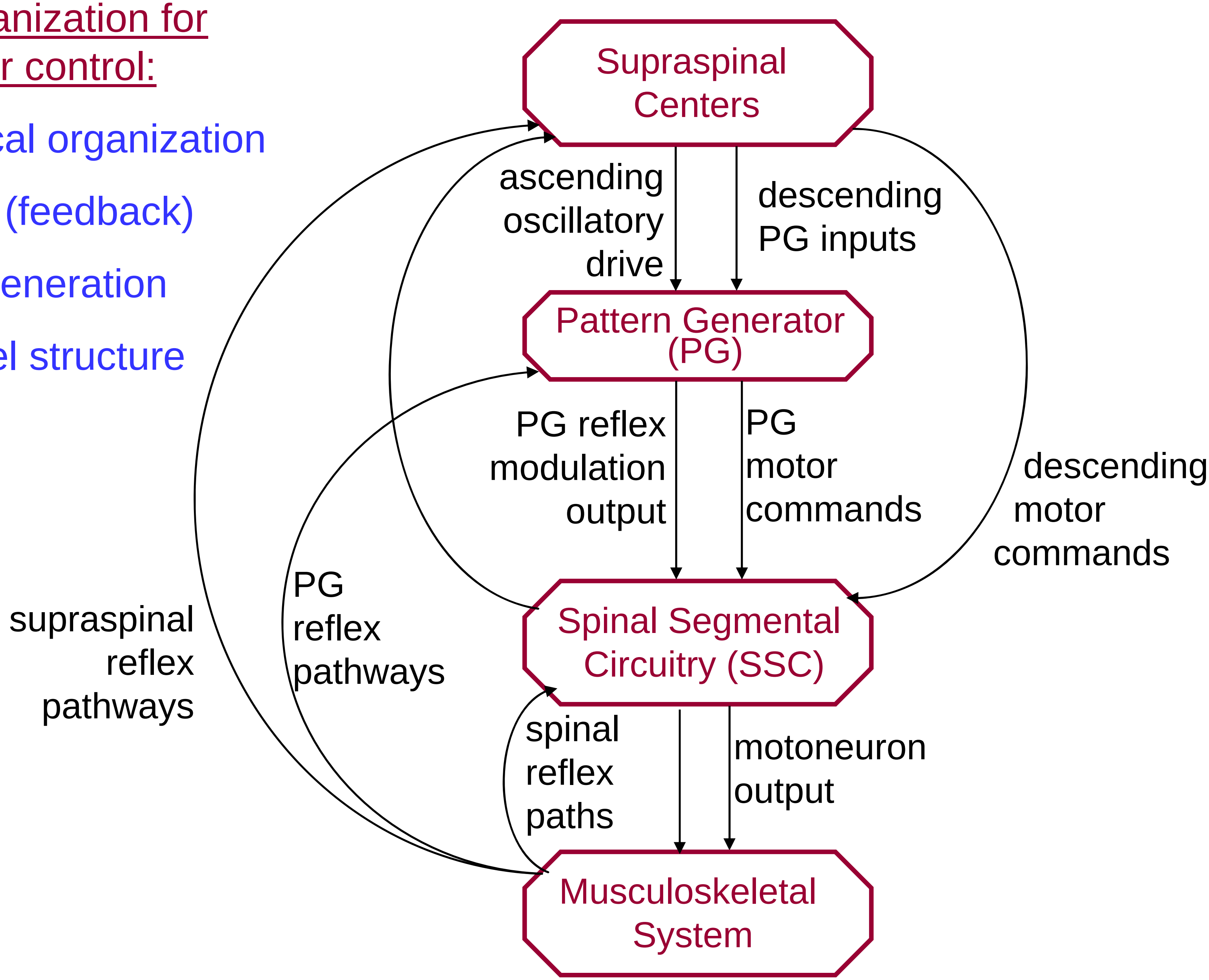
Stiffness

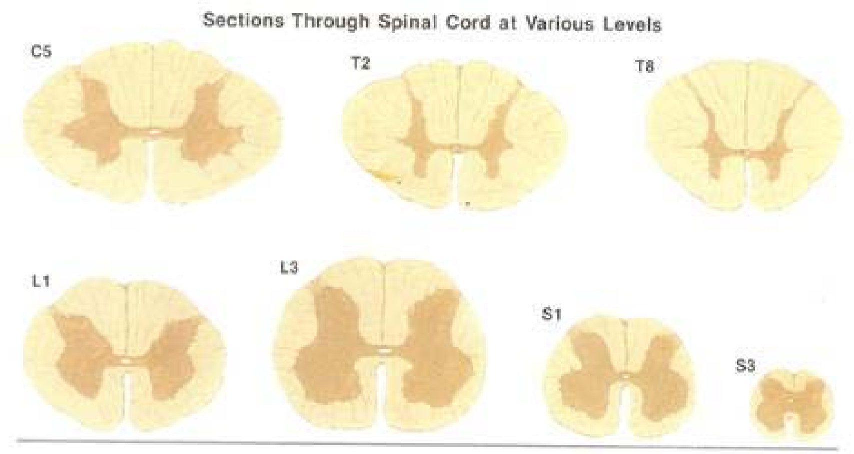


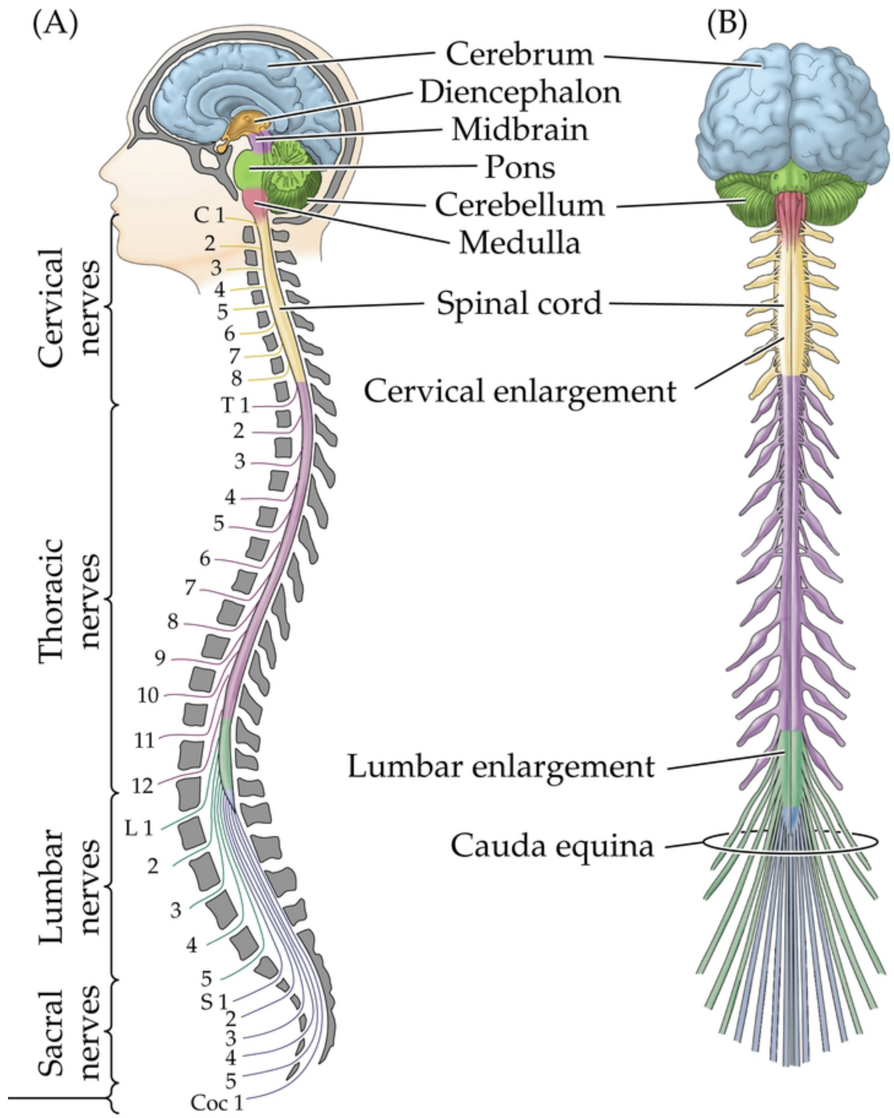


Neural organization for locomotor control:

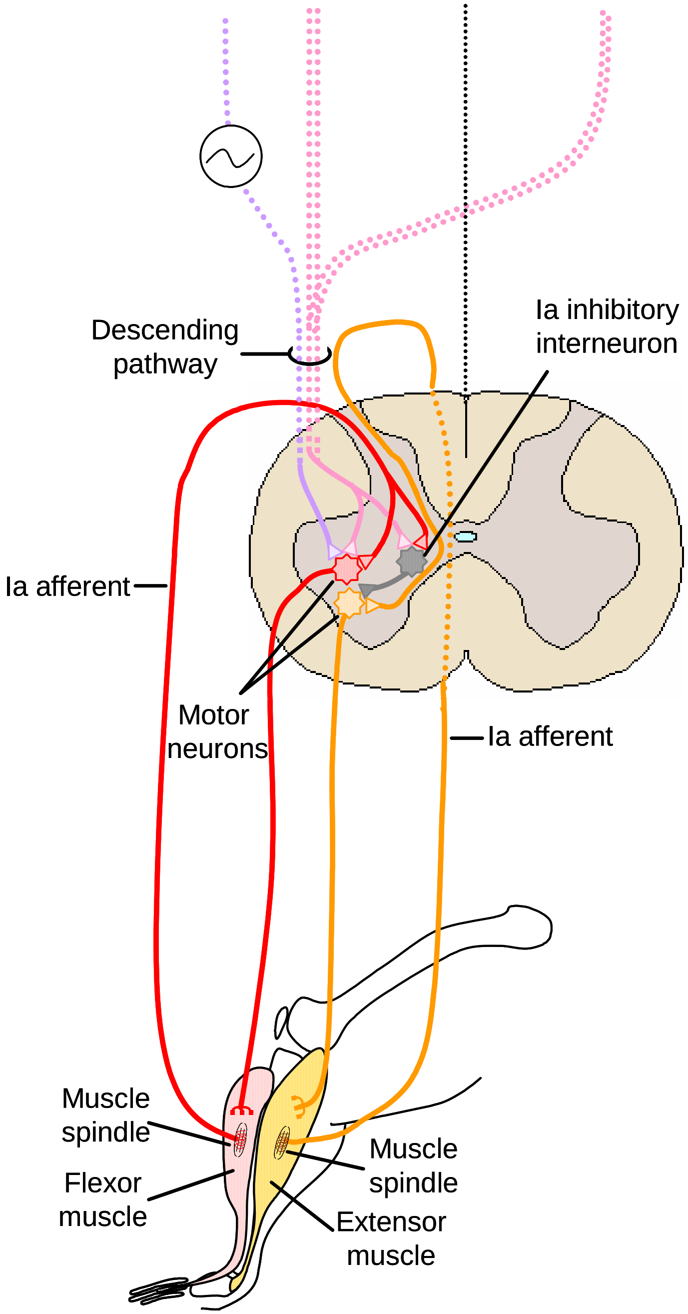
- Anatomical organization
- Reflexes (feedback)
- Pattern generation
- Multi-level structure



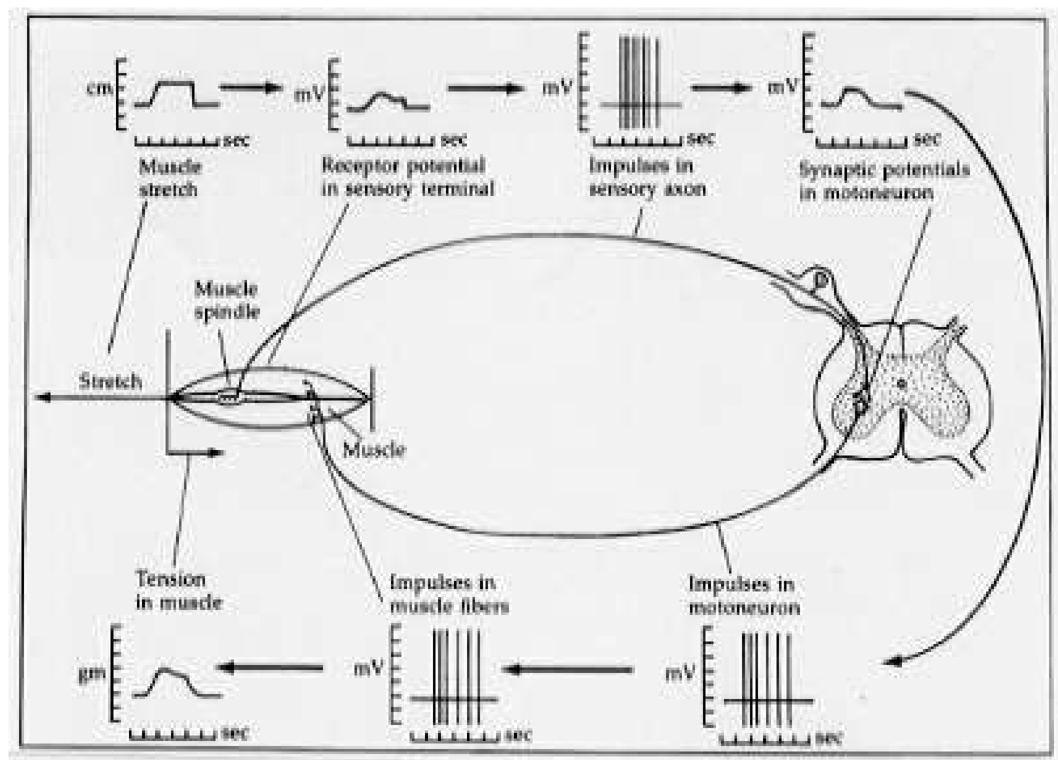




most inputs to motoneurons from the brain are indirect (via spinal interneurons)

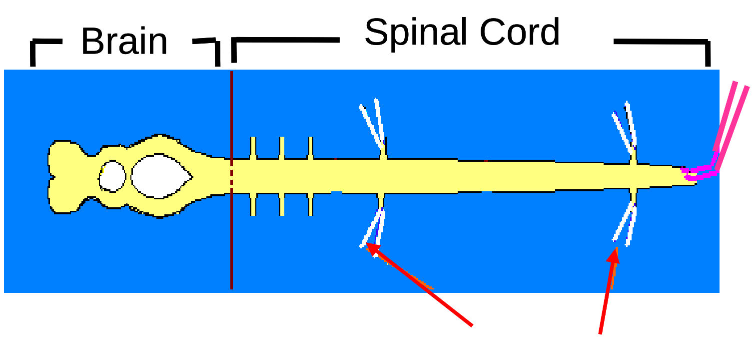


- spinal cord mediated reflexes
- supraspinal modulation

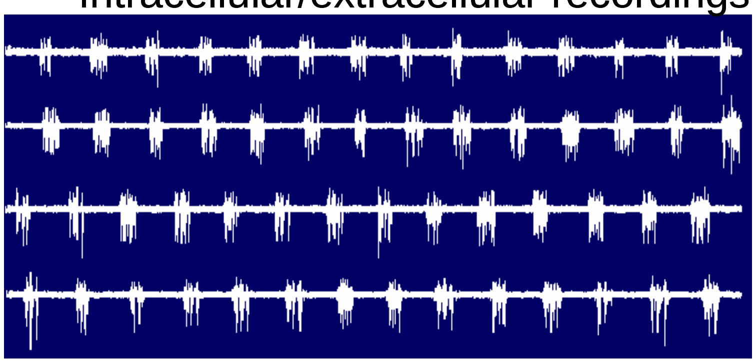


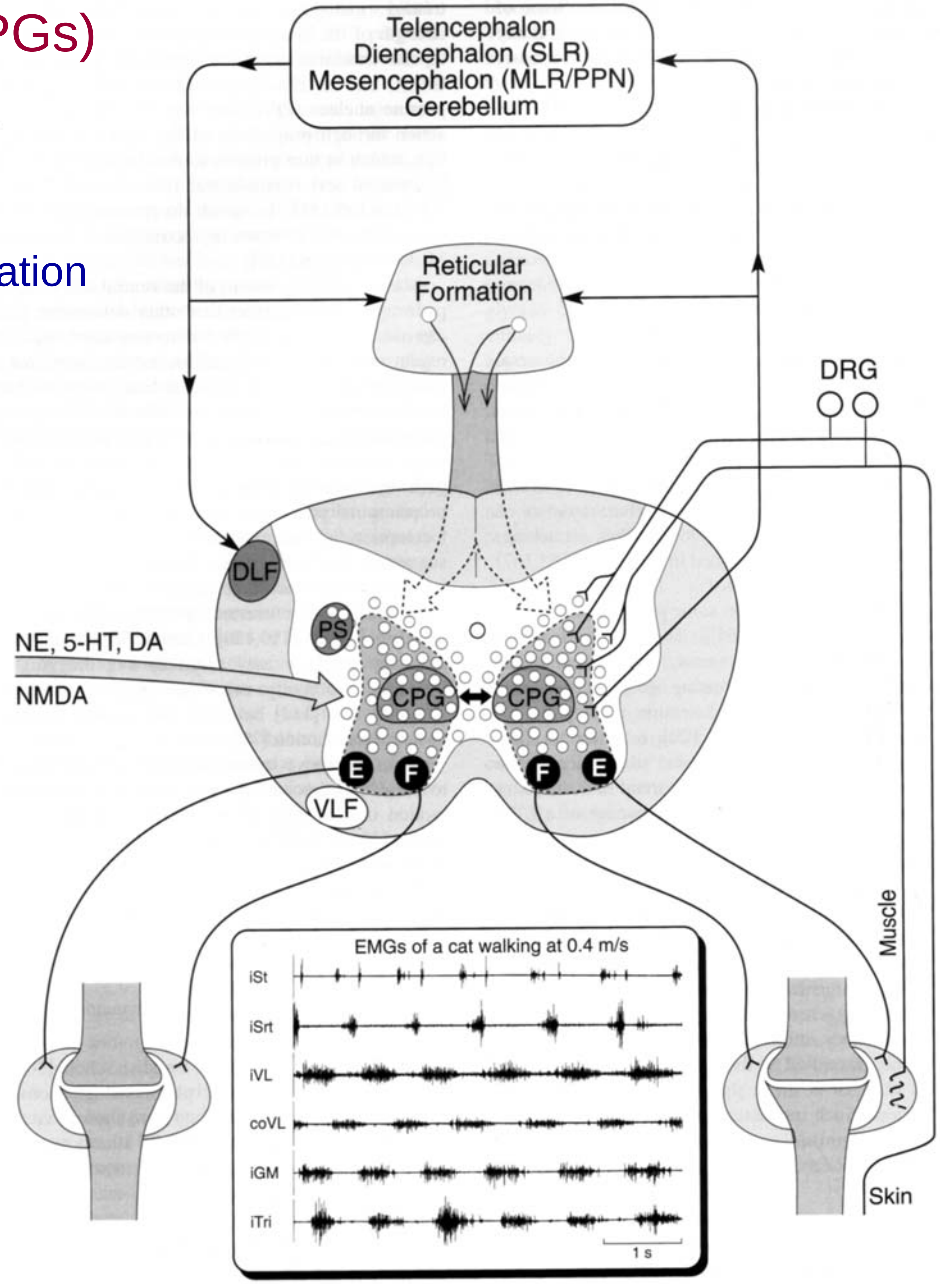
Spinal Central Pattern Generators (CPGs)

- CPG produces basic pattern of locomotion
- neuromodulators (5-HT, NE, DA, NMDA)
- sensory feedback integrated into CPG operation
- CPG activity is affected by training

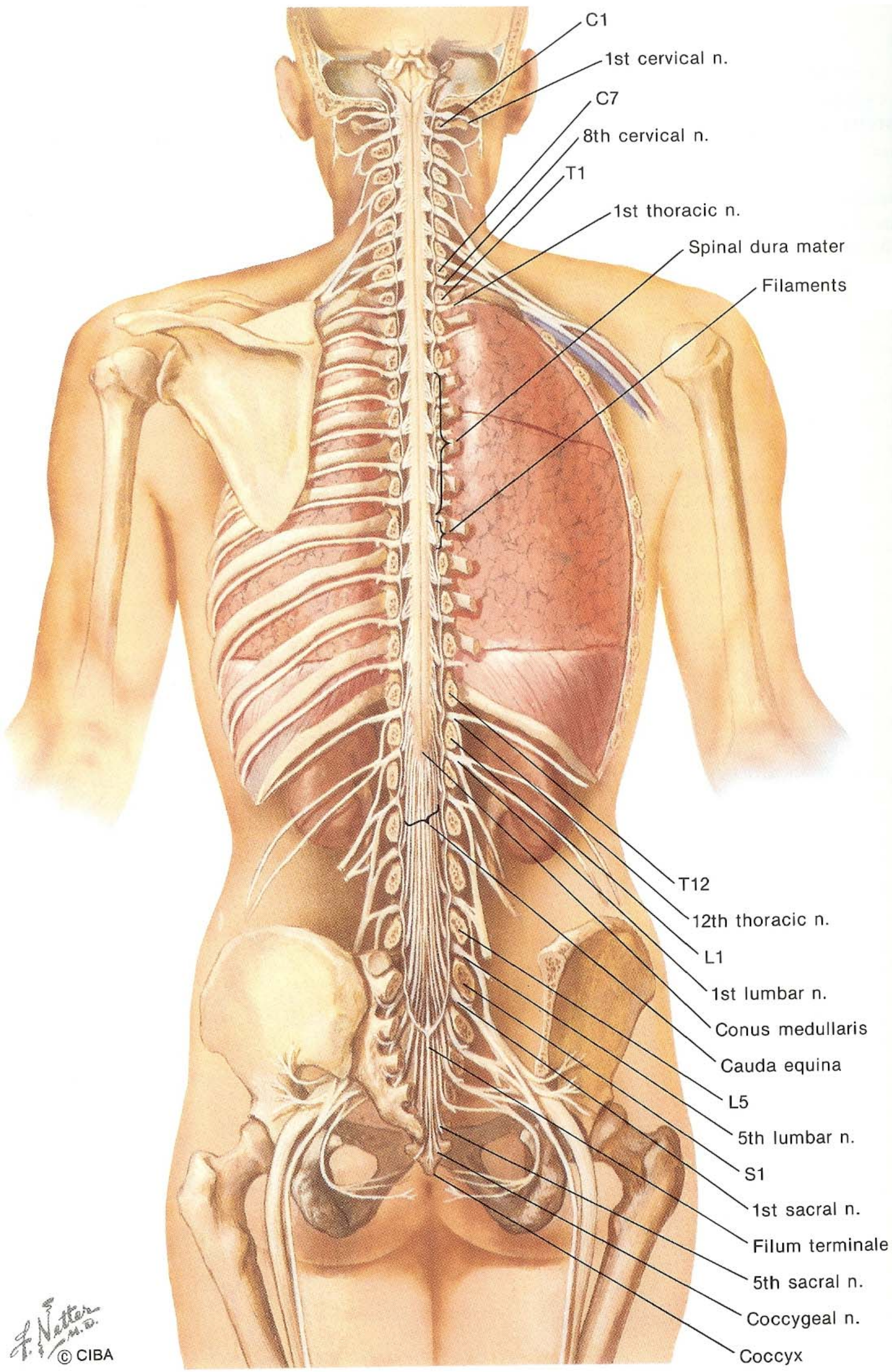


Intracellular/extracellular recordings





From Barbeau et al. **Brain Res. Rev**. 30: 27, 1999



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Using spinal cord models for locomotor control

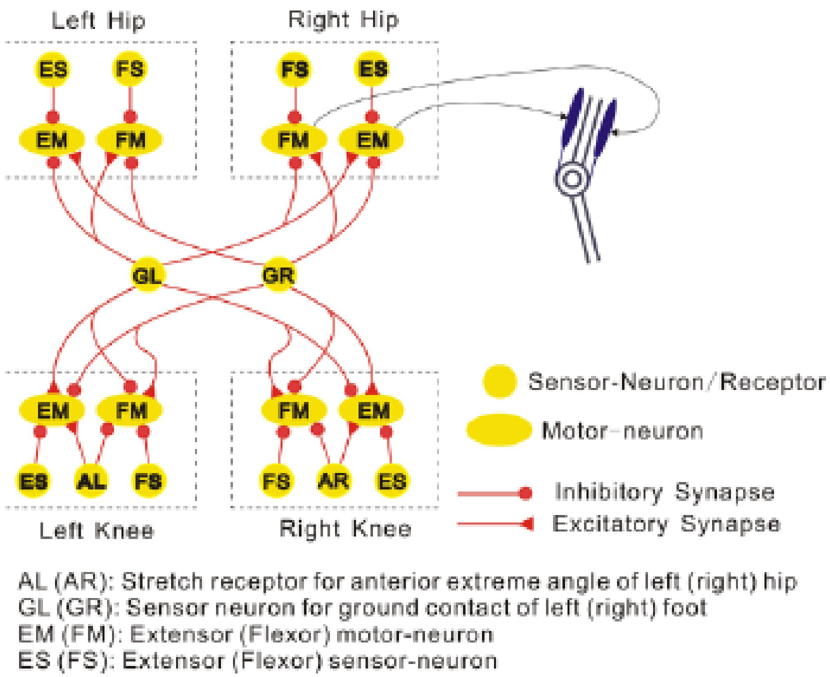
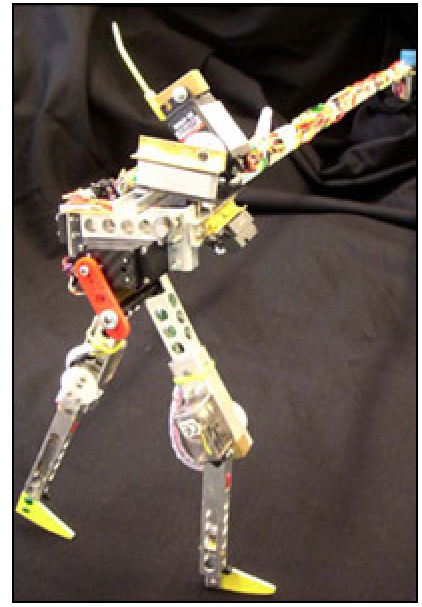


Figure 1. The circuit of the neuromuscular controller. Only the muscle pair of one joint is illustrated.



Woergoetter

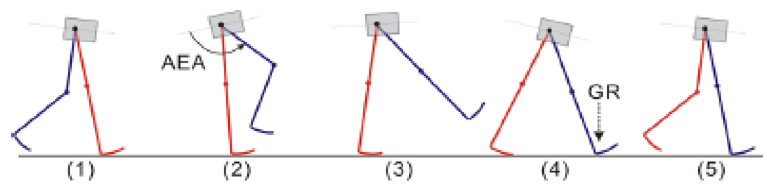
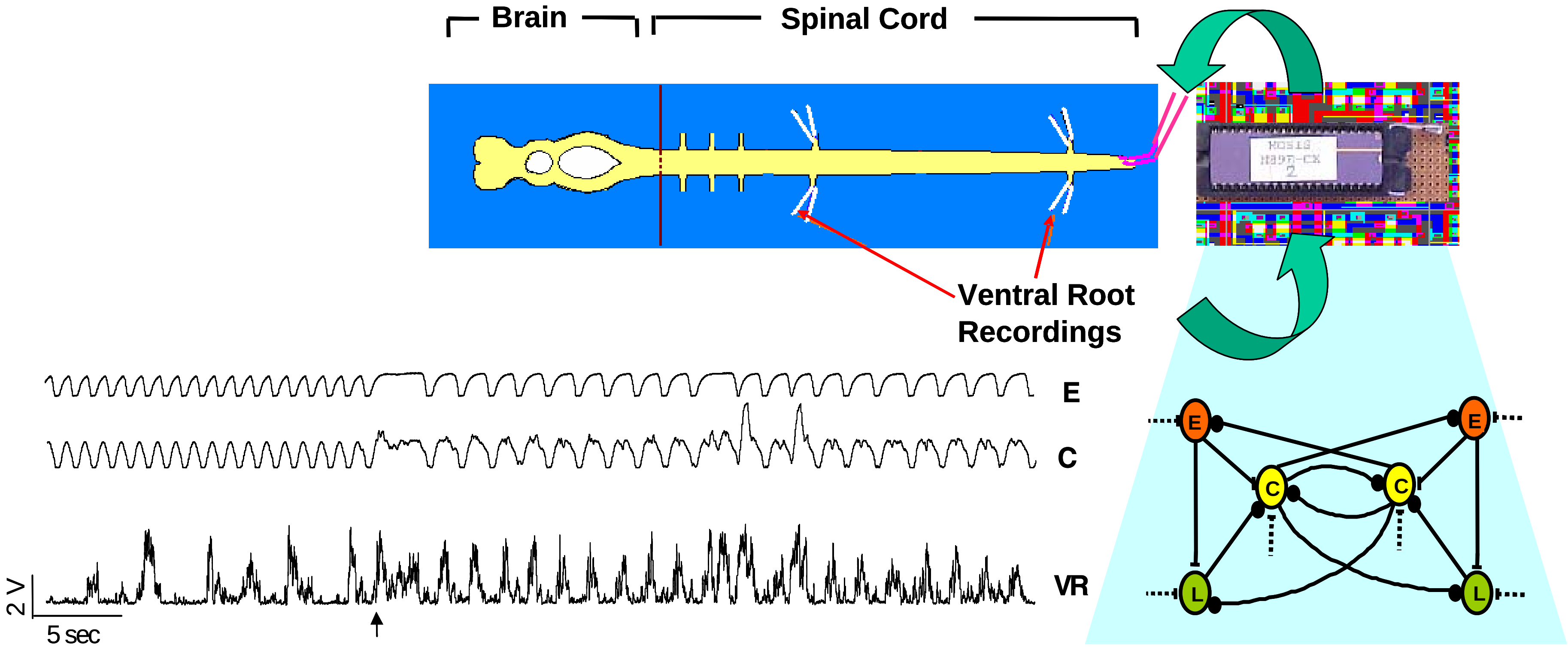


Figure 2. A series of frames of one walking step. At the time of frame 3, the stretch receptor (Anterior Extreme Angle signal, AEA) of the swing leg is activated, which triggers the extensor of the knee joint in this leg. At the time of frame 7, the swing leg begins to touch the ground. This ground contact signal triggers the hip extensor and knee flexor of the stance leg, as well as the hip flexor and knee extensor of the swing leg. Thus, the swing and stance legs swap their roles thereafter.

Using spinal cord models for locomotor control

Hybrid Carbon:Silicon system



Jung, et al. 2001

- neuromorphic aVLSI circuit
- real-time closed loop
- 1:1 phase coupling

Spinal Cord Injury (SCI)

250,000 people with SCI in US

'complete' vs. 'incomplete'

cervical - thoracic

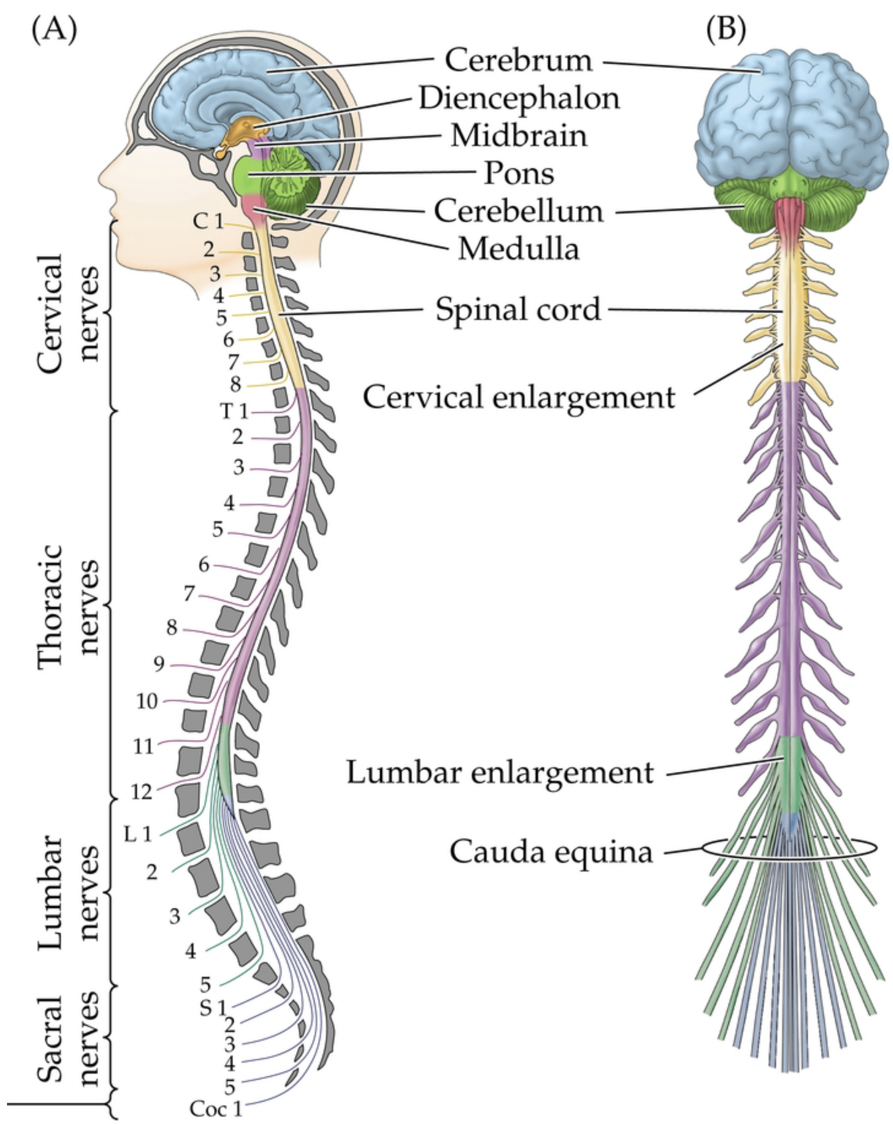
Personal impact:

- sensorimotor function
- mobility and transfers
- cardiovascular function
- bladder/bowel
- respiration
- sexual function
- exercise and recreation

Costs of Spinal Cord Injury:

- health care costs in $billions/yr
- lost productivity
- reduced quality of life

Spinal Cord Injury



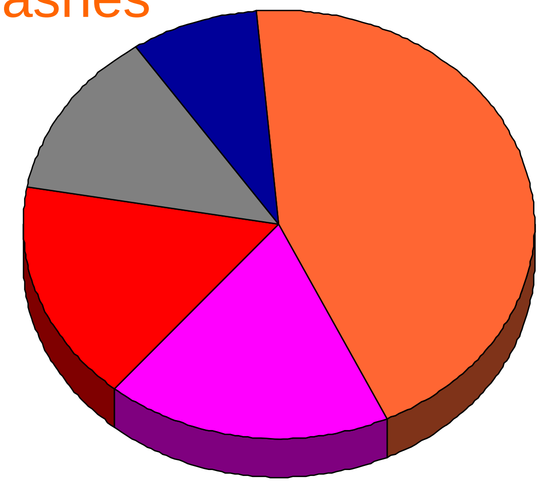
ASIA IMPAIRMENT SCALE

- ☐ **A = Complete:** No motor or sensory function is preserved in the sacral segments S4-S5.
- ☐ **B = Incomplete:** Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5.
- ☐ **C = Incomplete:** Motor function is preserved below the neurological level, and more than half of key muscles below the neurological level have a muscle grade less than 3.
- ☐ **D = Incomplete:** Motor function is preserved below the neurological level, and at least half of key muscles below the neurological level have a muscle grade of 3 or more.
- ☐ **E = Normal:** motor and sensory function are normal

Spinal Cord Injury

Causes of SCI:

- motor vehicle crashes
- falls
- acts of violence
- sports
- other



(250,000 people with SCI in US)

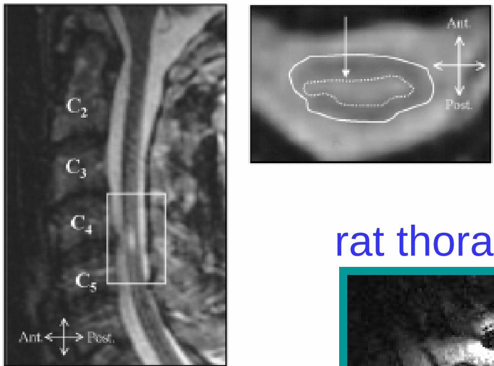
At the time of injury:

- 63% are < 30 years old
- 80% are employed or in school
- 90% have not gone beyond high school
- 54% are unmarried

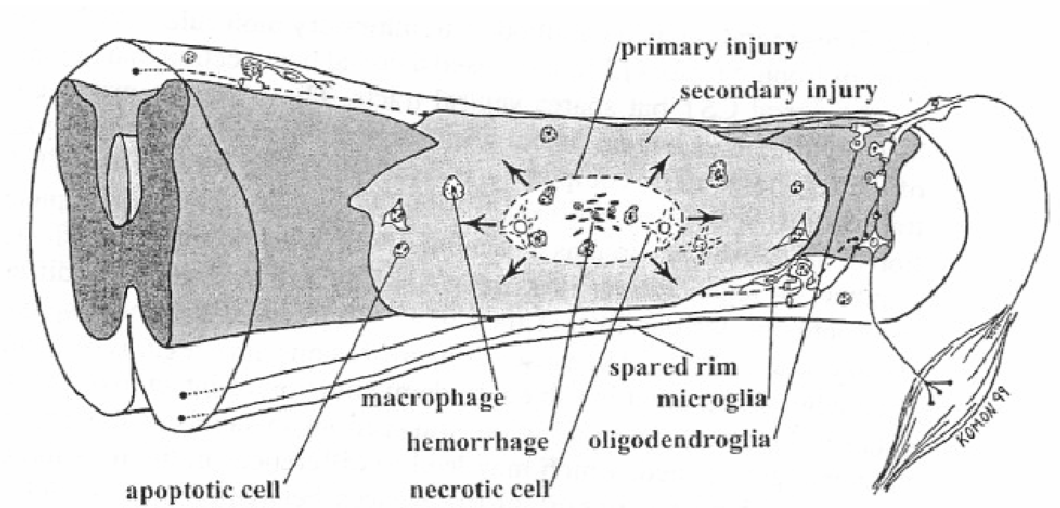
Neurologic level of injury => degree of impairment

- thoracic level lesion => paraplegia (46.2%)
- cervical level lesion => tetraplegia (52.9%)

Spinal Cord Injury: Clinical Outcomes from the Model Systems, Stover, DeLisa, & Whiteneck, Aspen Publishers,1995 human cervical injury

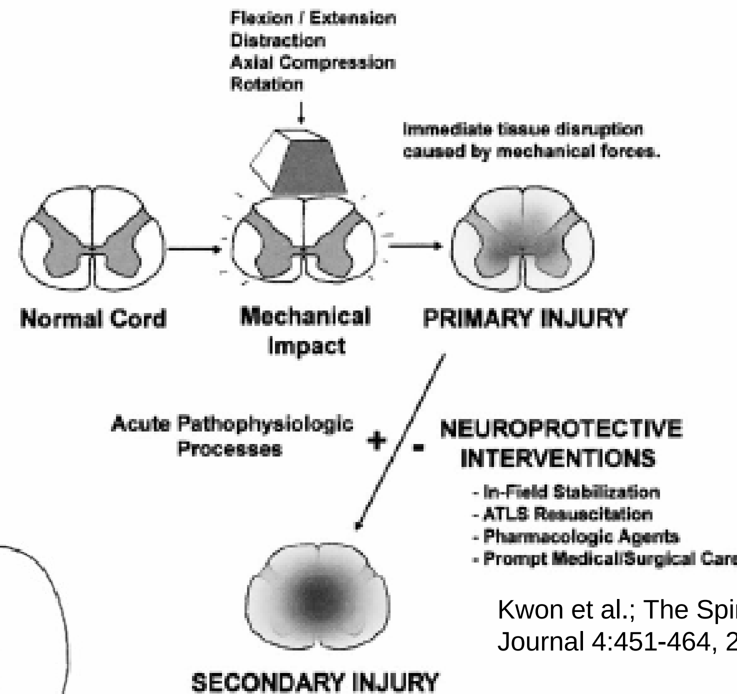


rat thoracic injury



Primary injury due to mechanical impact

Secondary injury due to inflammation and response cascade

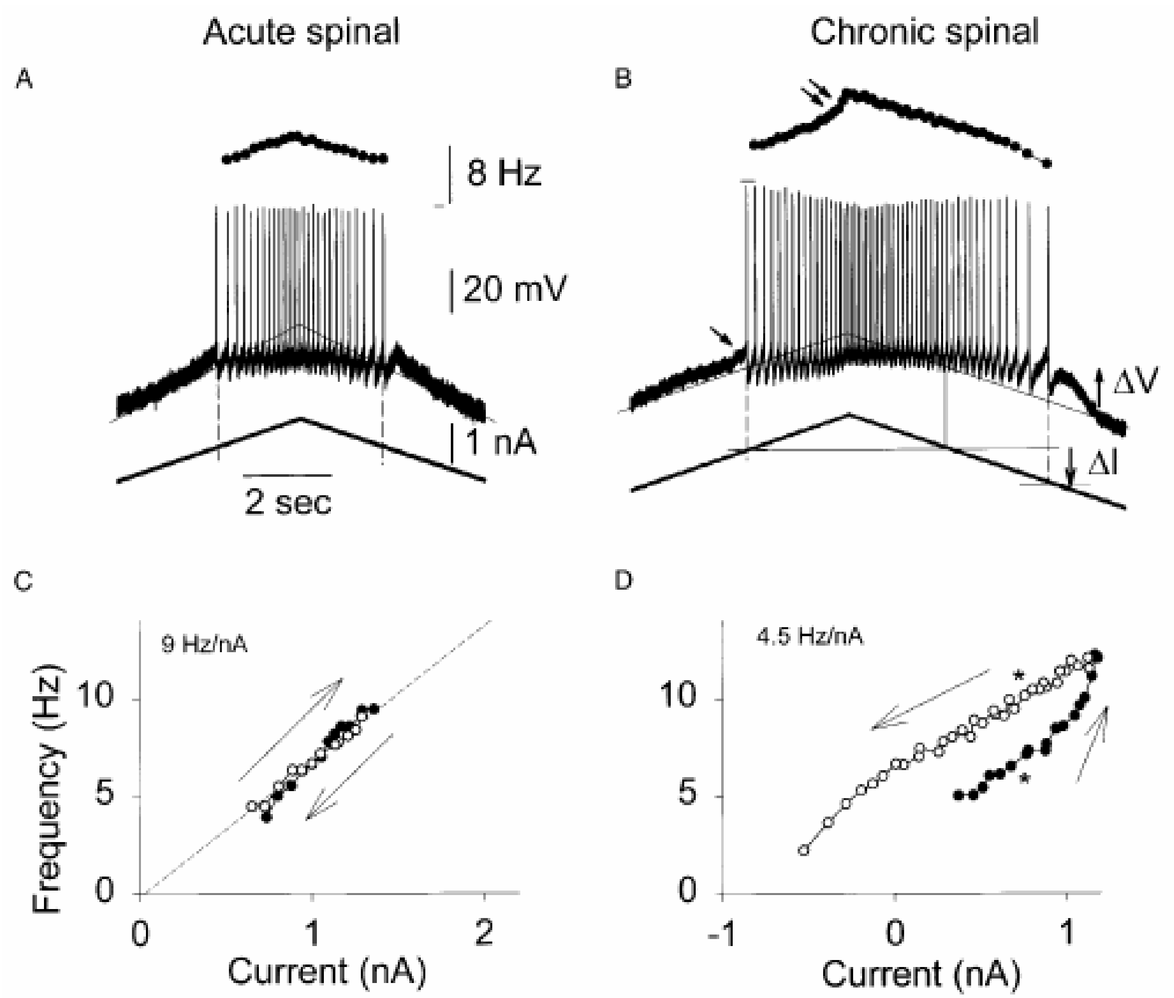


Kwon et al.; The Spine Journal 4:451-464, 2004

A window of opportunity for neuroprotective interventions

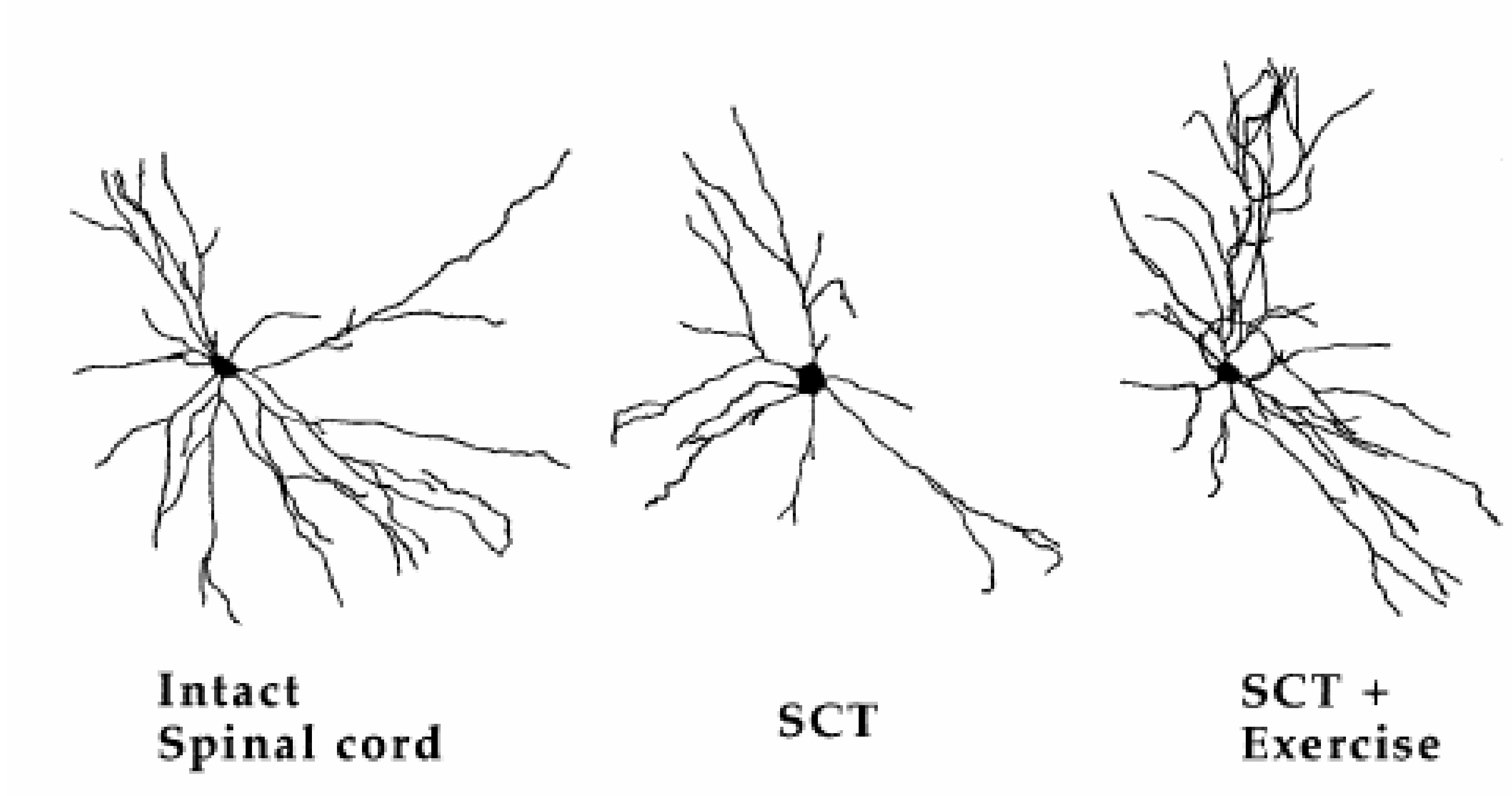
In: Neurobiology of Spinal Cord Injury, Edts.R.J. Kalb and S.M. Strittmatter, Humana Press, Totowa, N.J.

Intrinsic properties of motoneurons change after SCI



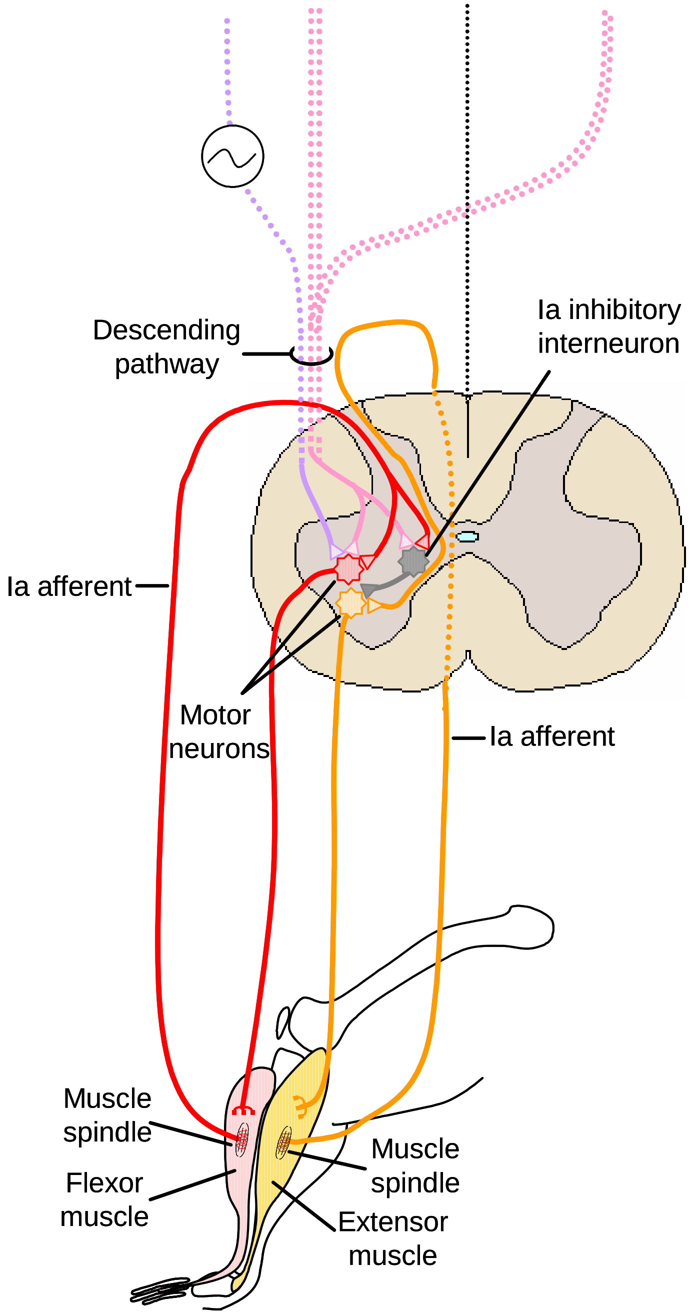
From Bennett et al. **J. Neurophysiol**. 86: 1955, 2001

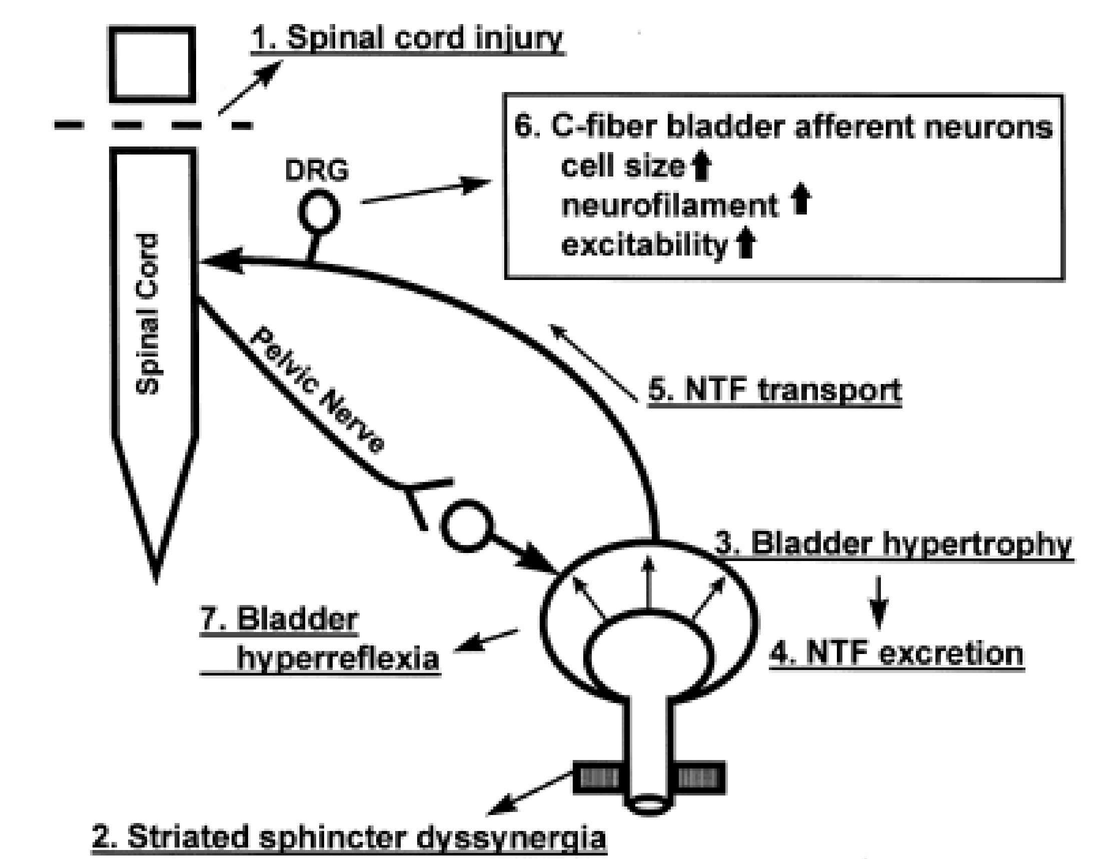
Motoneurons atrophy after spinal injury; exercise preserves structure



From Gazula et al. **J. Comp. Neurol**. 476: 130, 2004

SCI affects reflex modulation ➔ spasticity





Bladder-sphincter dyssynergy
➔ bladder hyperreflexia

Yoshimura, *Prog. Neurobiol.* 1999

Promoting Locomotor Recovery after Incomplete SCI

Partial Weight Bearing Therapy (PWBT)

www.litegait.com

www.robomedica.com

If everyone is thinking alike then someone isn't thinking.

- General George S. Patton

Therapist-assisted

Harkema

Reflex stimulation

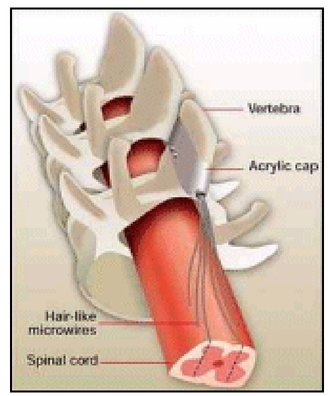
Field-Fote

Epidural Spinal Cord Stimulation

Herman, He
Dimitrievic

Robot-assisted

Columbo; (Lokomat)



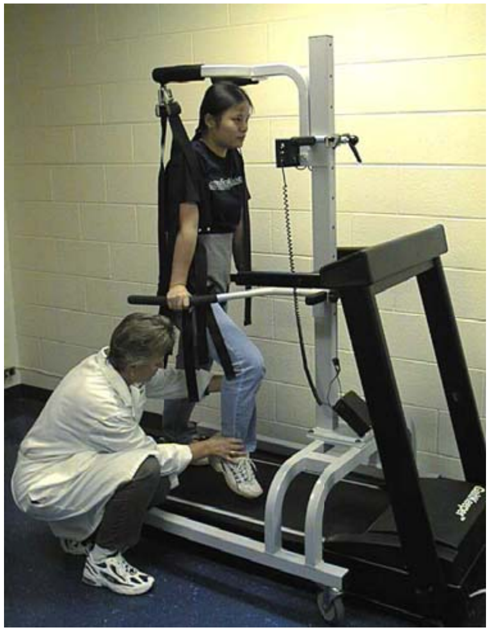
Intraspinal Microstimulation

Mushahwar, Horch, Prochazka

Treadmill Training

Neuromuscular Stimulation

Neuromorphic Adaptive Control



Promoting Functional Recovery After SCI

- overhead harness reduces load
- treadmill assists with movement
- cyclic loading pattern
- exploits activity-dependent plasticity

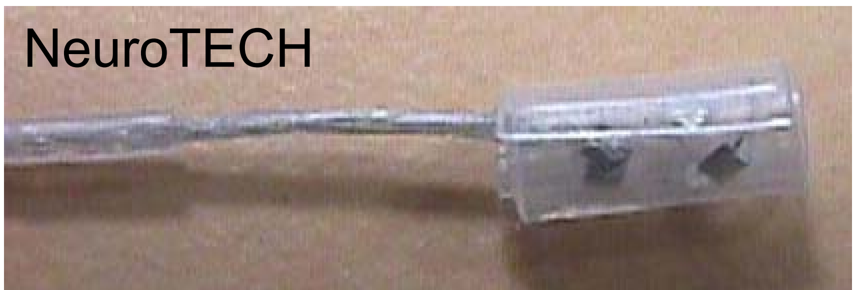
Supplement with Neuromuscular Electrical Stimulation

➔ more complete sensory pattern to spinal cord?

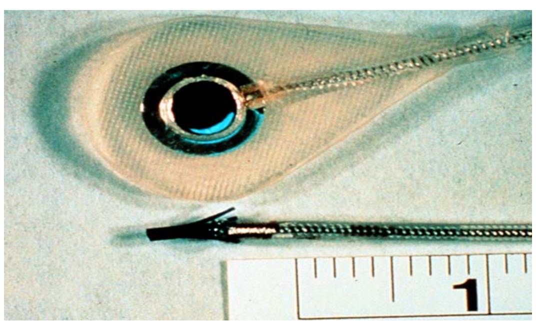
➔ increased (or more functional) plasticity?

Neuromuscular Stimulation: electrode types

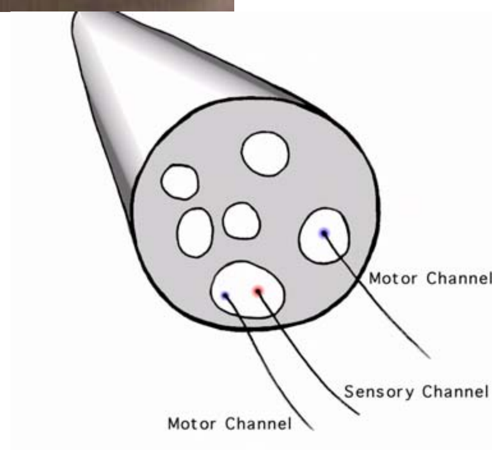
- surface
- intramuscular
- intraneural
- cuff
- epimysial



NeuroTECH

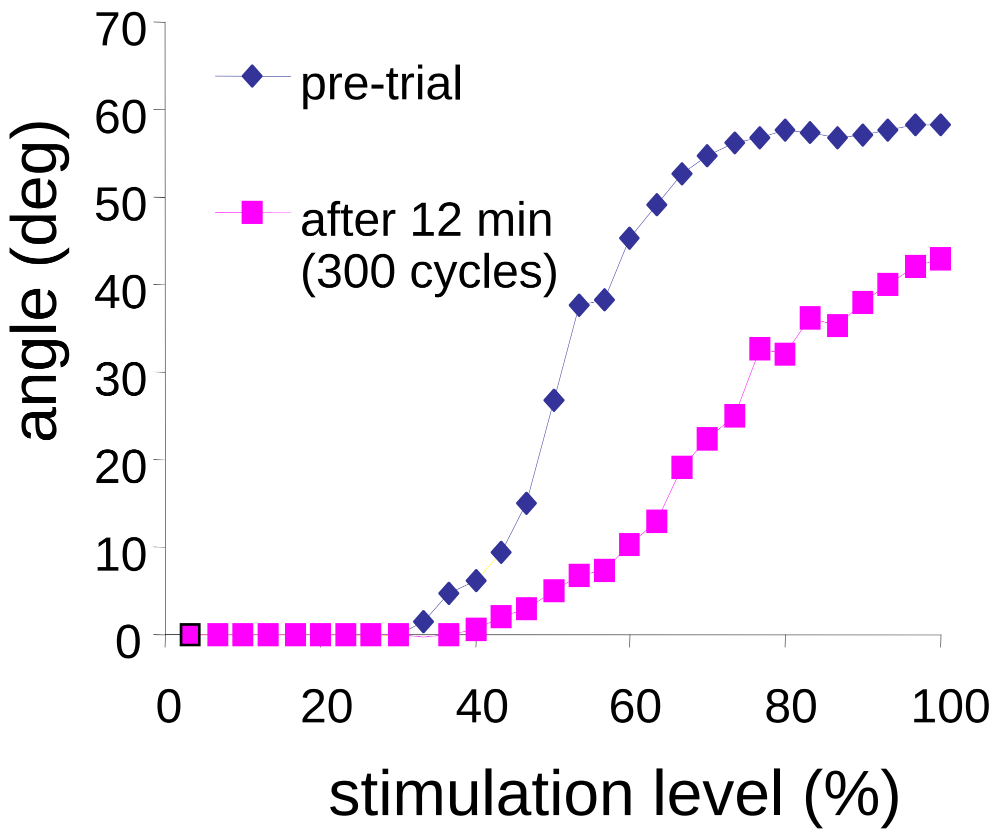


Case Western Reserve Univ.



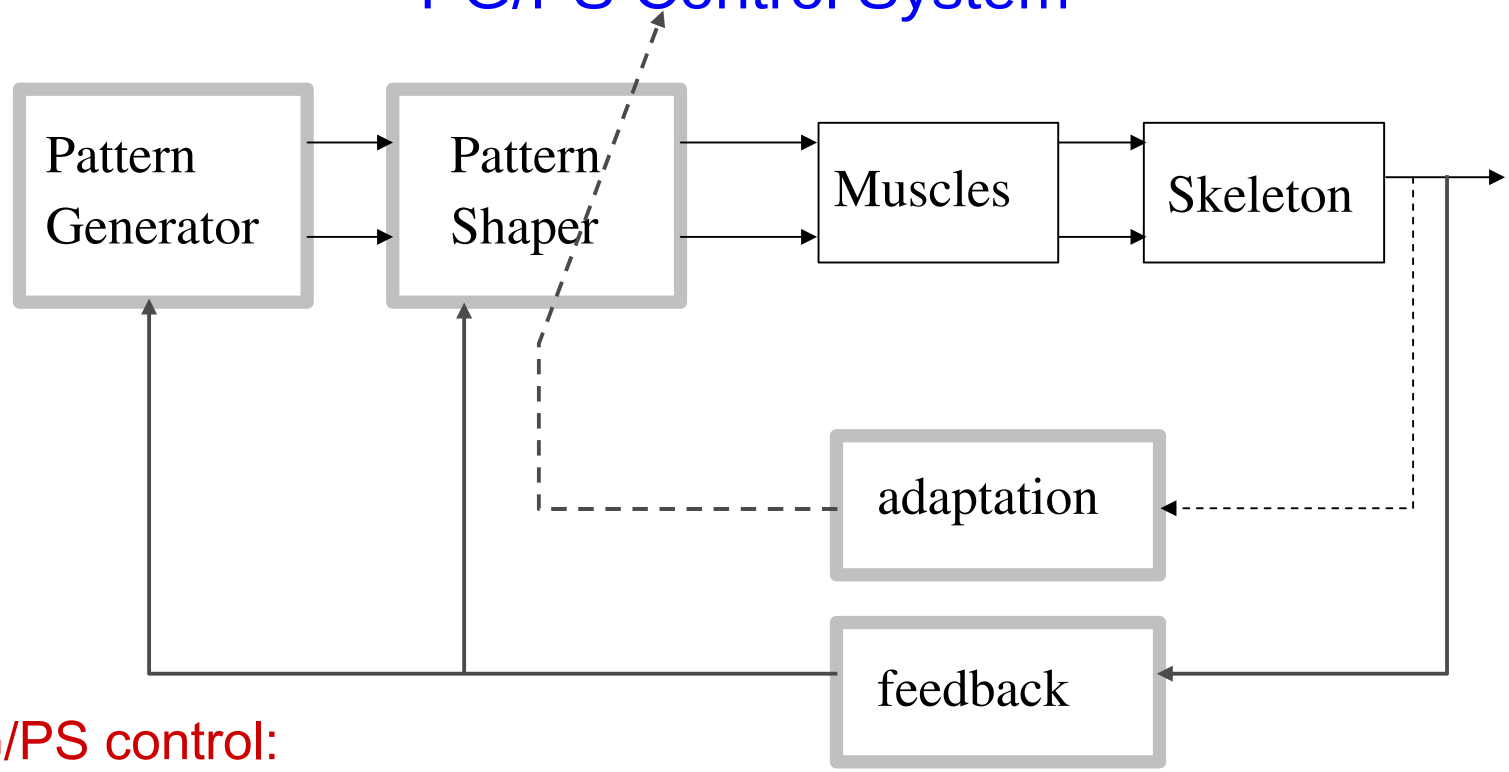
U. Utah

Muscle nonlinearities are exacerbated by recruitment properties and fatigue



- limited input range
- steep-slope regions
- changes with fatigue

PG/PS Control System



PG/PS control:

- PG generates cyclic pattern
  - structure based on neural model
- PS fine tunes the pattern
  - single layer adaptive neural network

Objectives:

- customize stimulation
- account for nonlinearities, dynamics, etc.
- adjust for fatigue

PG Neuron Equations

Membrane dynamics:

$$dV_{m_i}(t)/dt = (I_{syn_i}(V_m, t) + I_{PM_i}(V_m, t) + I_{inj_i} - V_{m_i}(t) / R_{m_i}) / C_{m_i}$$

Output function (firing rate):

$$y_i(t) = \frac{1}{1 + e^{-2m_i(V_{m_i}(t) - V_{o_i})}}$$

Membrane currents:

$$I_{syn_i}(t) = \sum y_j(t) g_{syn_{ij}} (E_{syn_{ij}} - V_{m_i}(t))$$

$$I_{PM_i}(t) = I_{NMDA_i}(t) + I_{KCa_i}(t)$$

PG Pacemaker Currents

$$I_{PM_i}(t) = I_{NMDA_i}(t) + I_{KCa_i}(t)$$

Burst initiation:

$$I_{NMDA_i}(t) = K_{NMDA_i} g_{NMDA_i} p_i(t)(E_{NMDA_i} - V_{m_i}(t))$$

$$\frac{d\, p_i(t)}{dt} = A_{\alpha_i} e^{((V_{m_i} - E_r)/C_{\alpha_i})} (1 - p_i(t)) - A_{\beta_i} e^{((E_r - V_{m_i})/C_{\beta_i})} p_i(t)$$

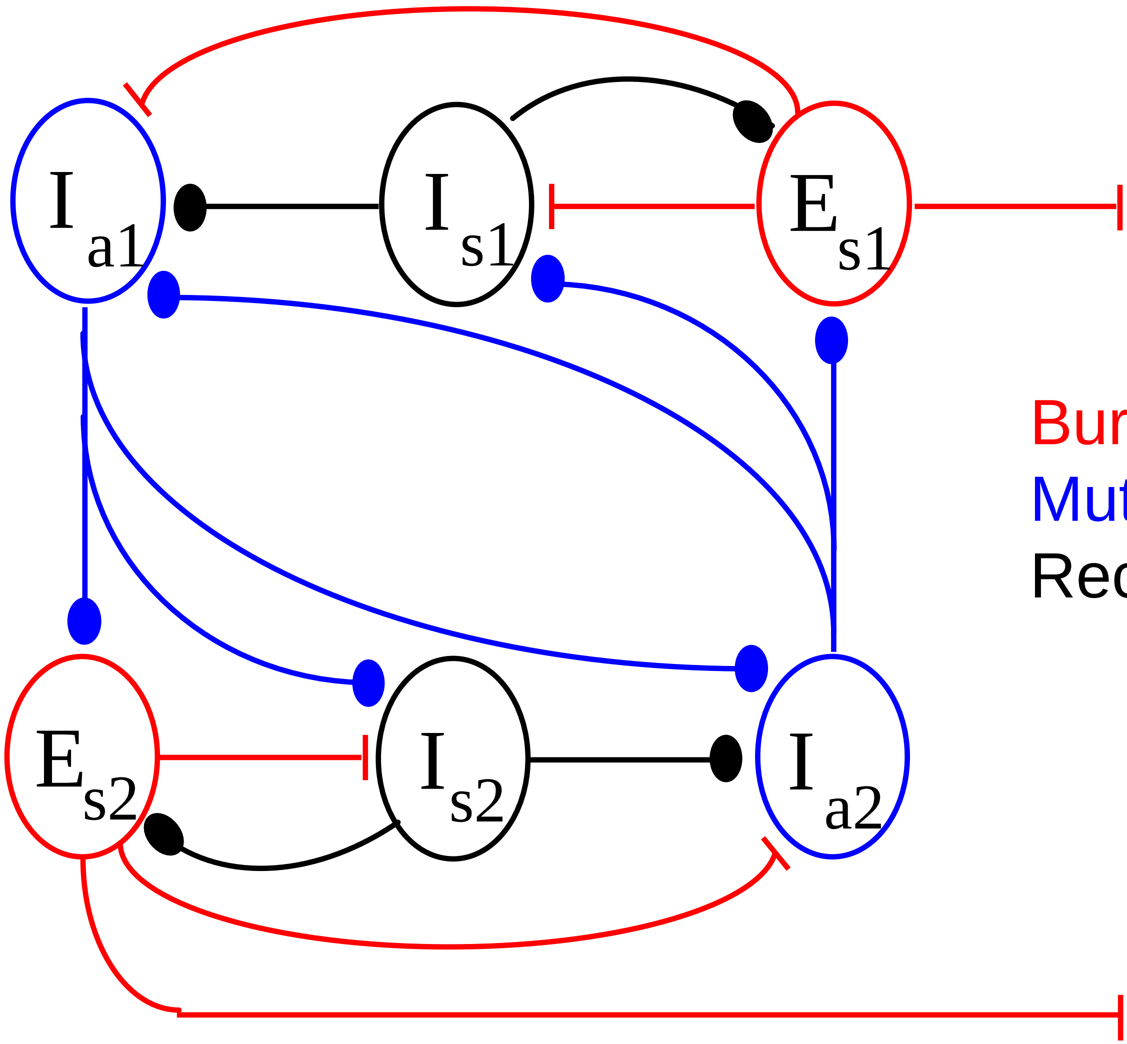
Burst termination:

$$I_{KCa_i}(t) = g_{KCa_i} [Ca_{NMDA_i}(t)](E_{KCa_i} - V_{m_i}(t))$$

$$\frac{d[Ca_{NMDA}(t)]_i}{dt} = p_i(t)\rho_{NMDA_i} K_{NMDA_i}(E_{CaNMDA_i} - V_{m_i}(t)) - \delta_{NMDA_i}[Ca_{NMDA}(t)]_i$$

Adapted from Brodin, 1991

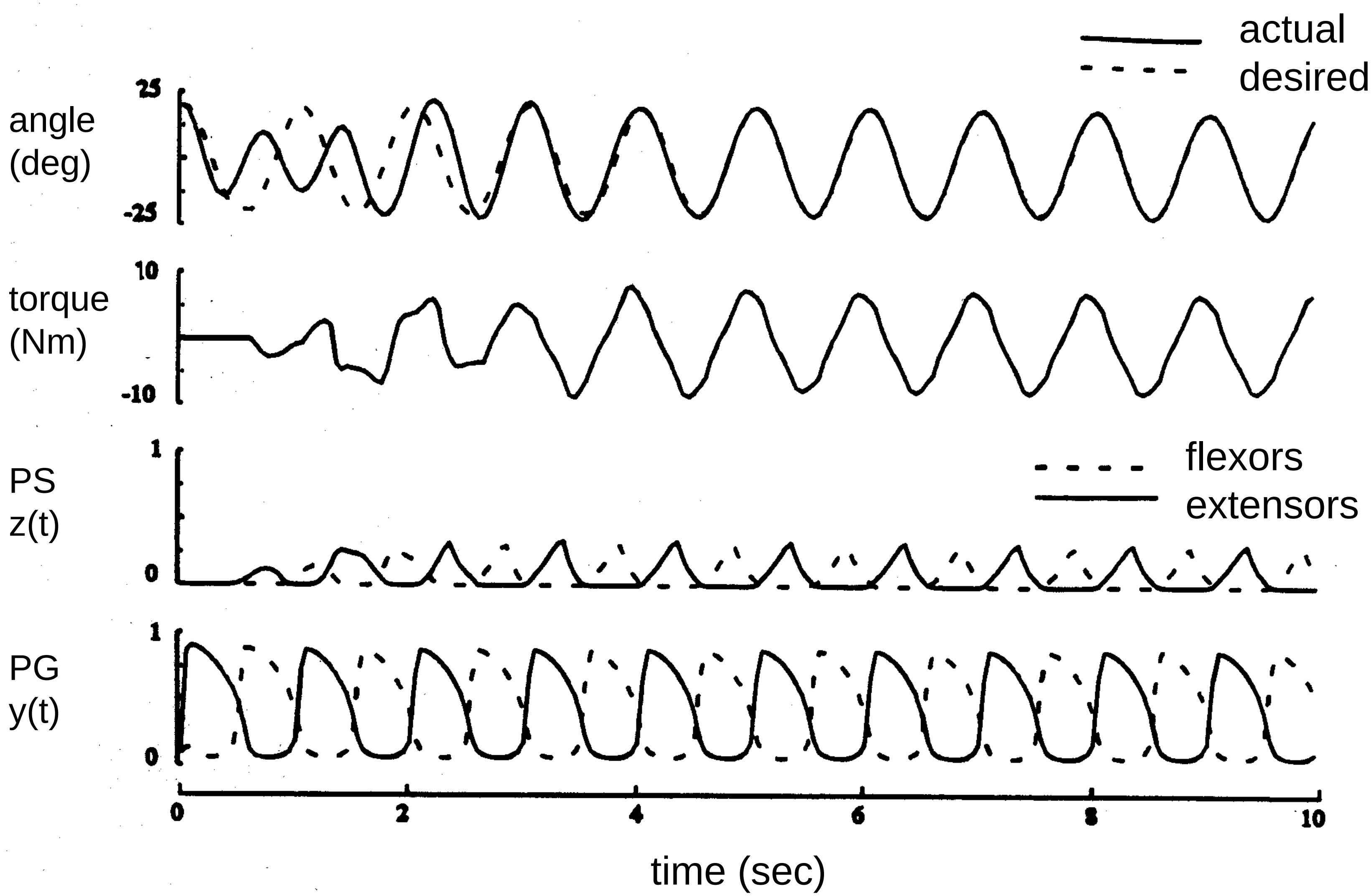
PG Circuit

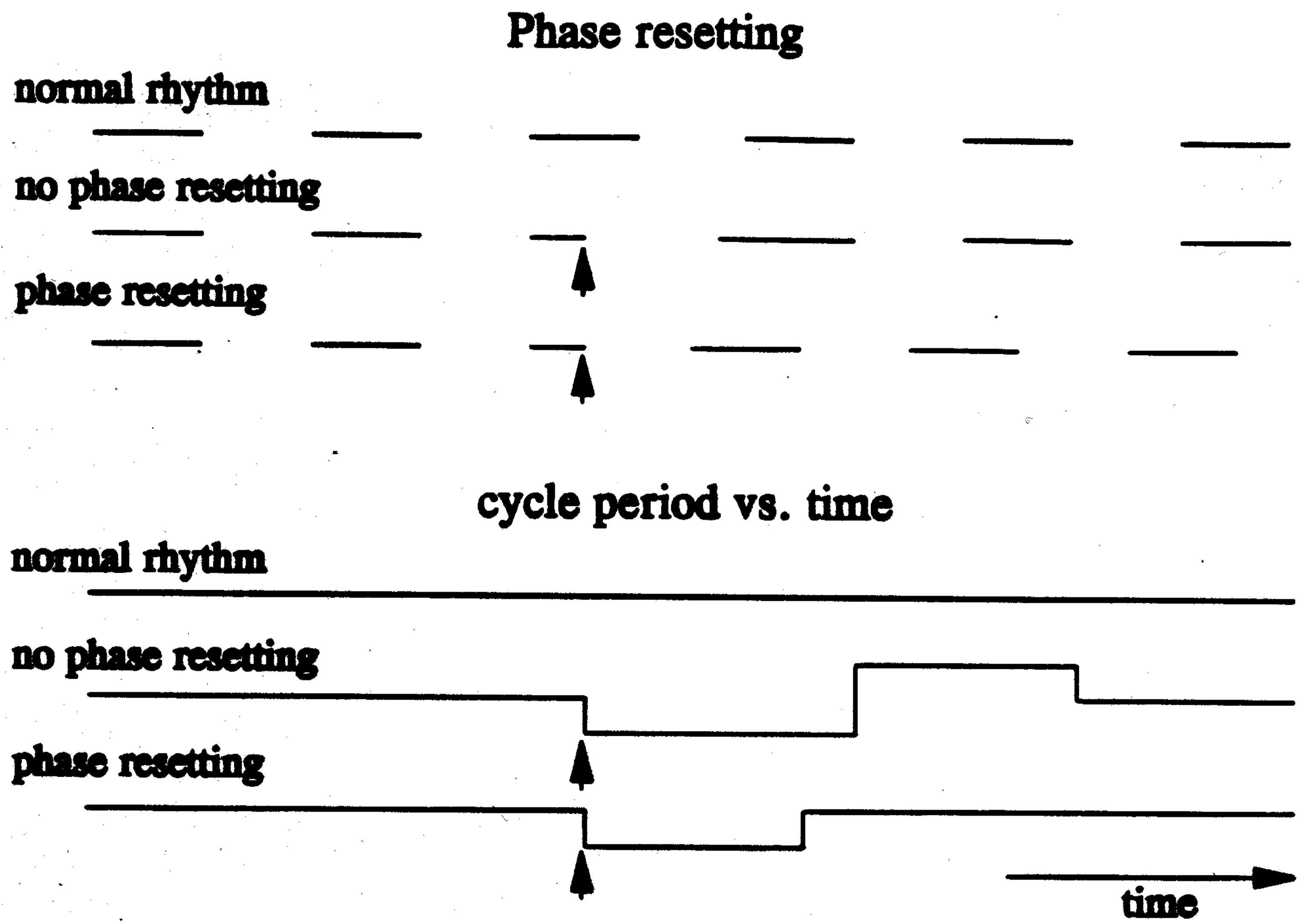


Burst initiation
Mutual inhibition
Reciprocal inhibition

Es – Exciter of synergists
Is – Inhibitor of synergists
Ia – Inhibitor of antagonists

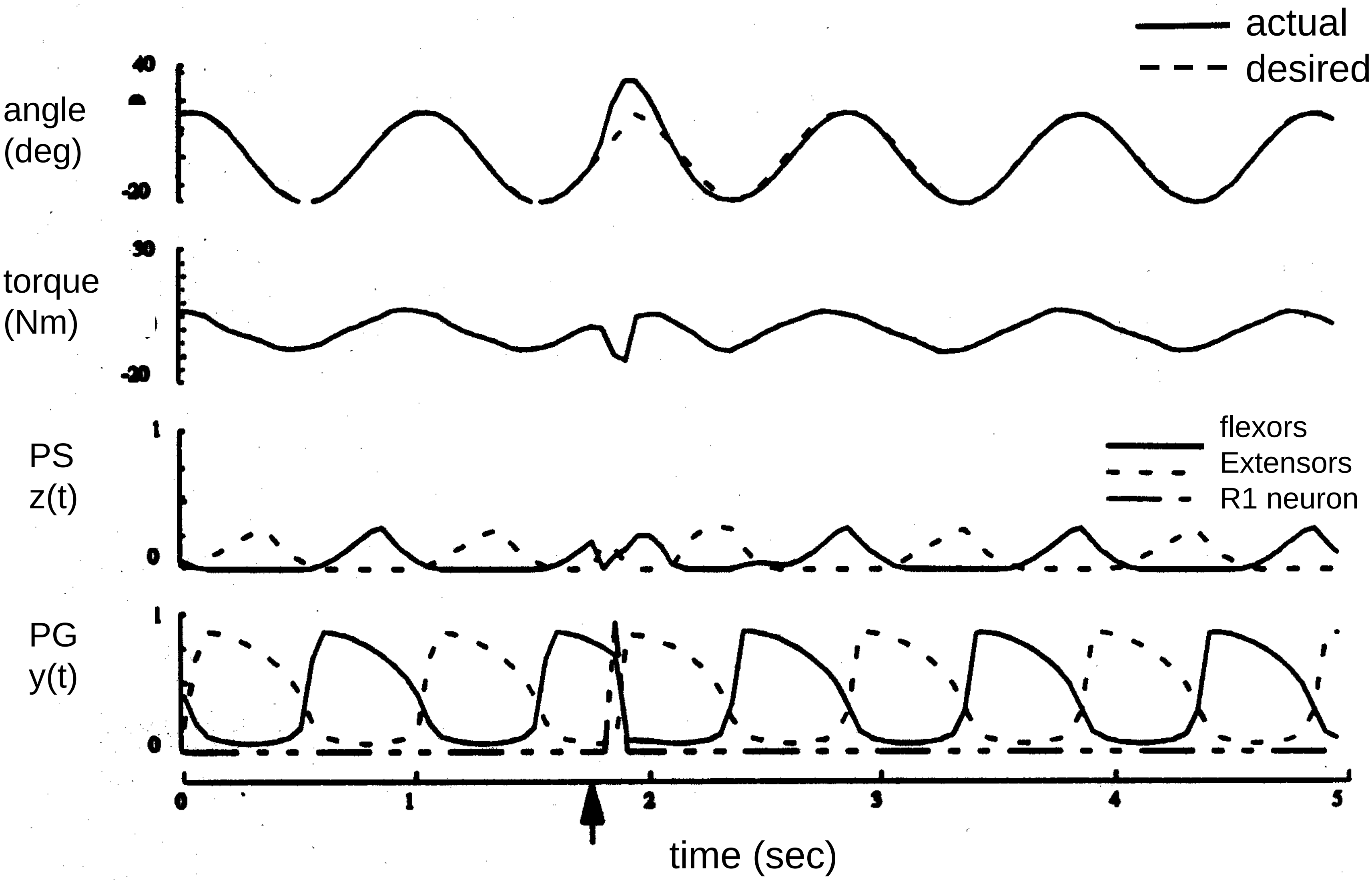
– Inhibitory synapse
– Excitatory synapse


actual
desired
angle
(deg)
25
-25
torque
(Nm)
10
-10
PS
z(t)
1
0
flexors
extensors
PG
y(t)
1
0
0
2
4
6
8
10
time (sec)

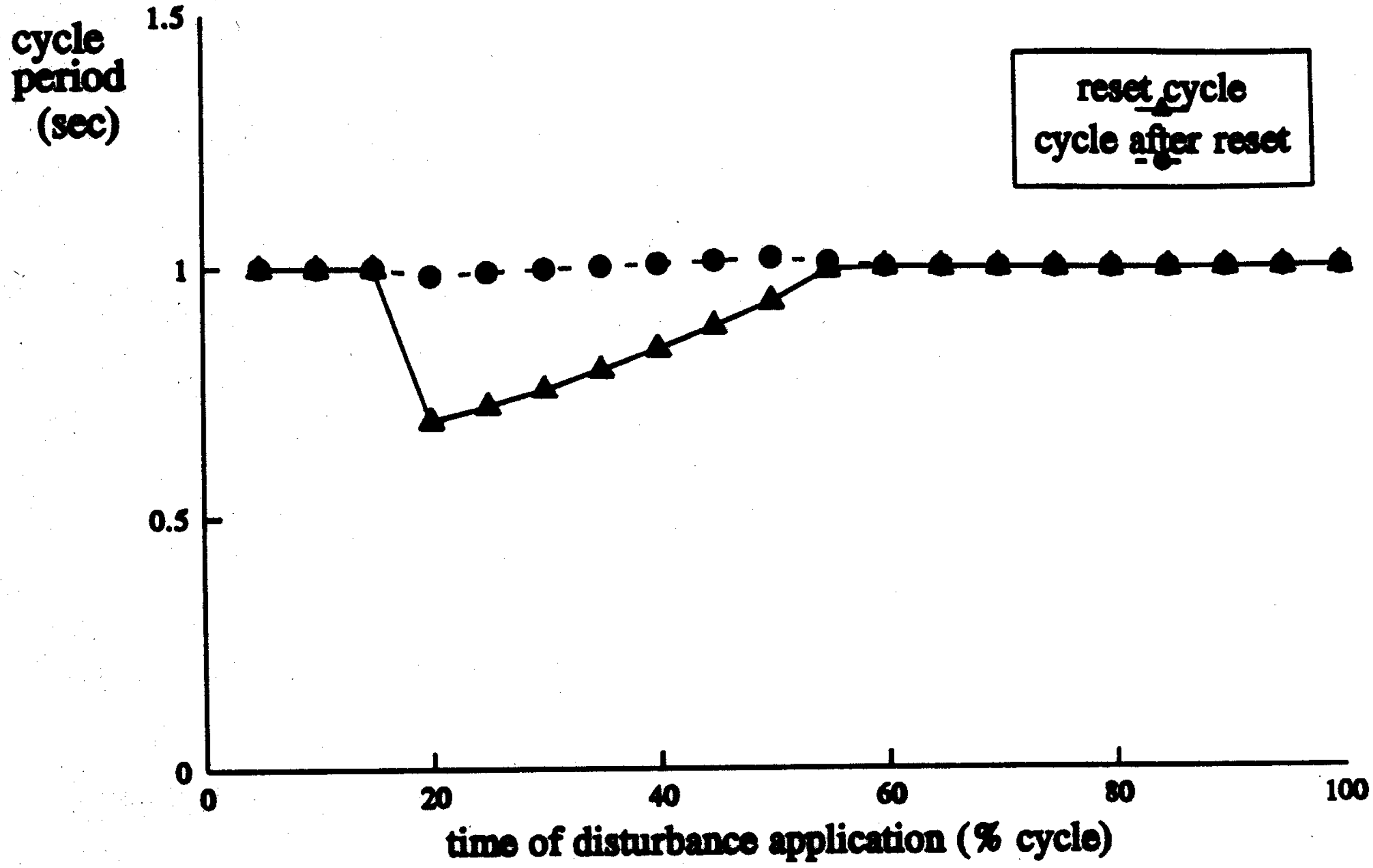


Phase resetting
normal rhythm
no phase resetting
phase resetting
cycle period vs. time
normal rhythm
no phase resetting
phase resetting
time

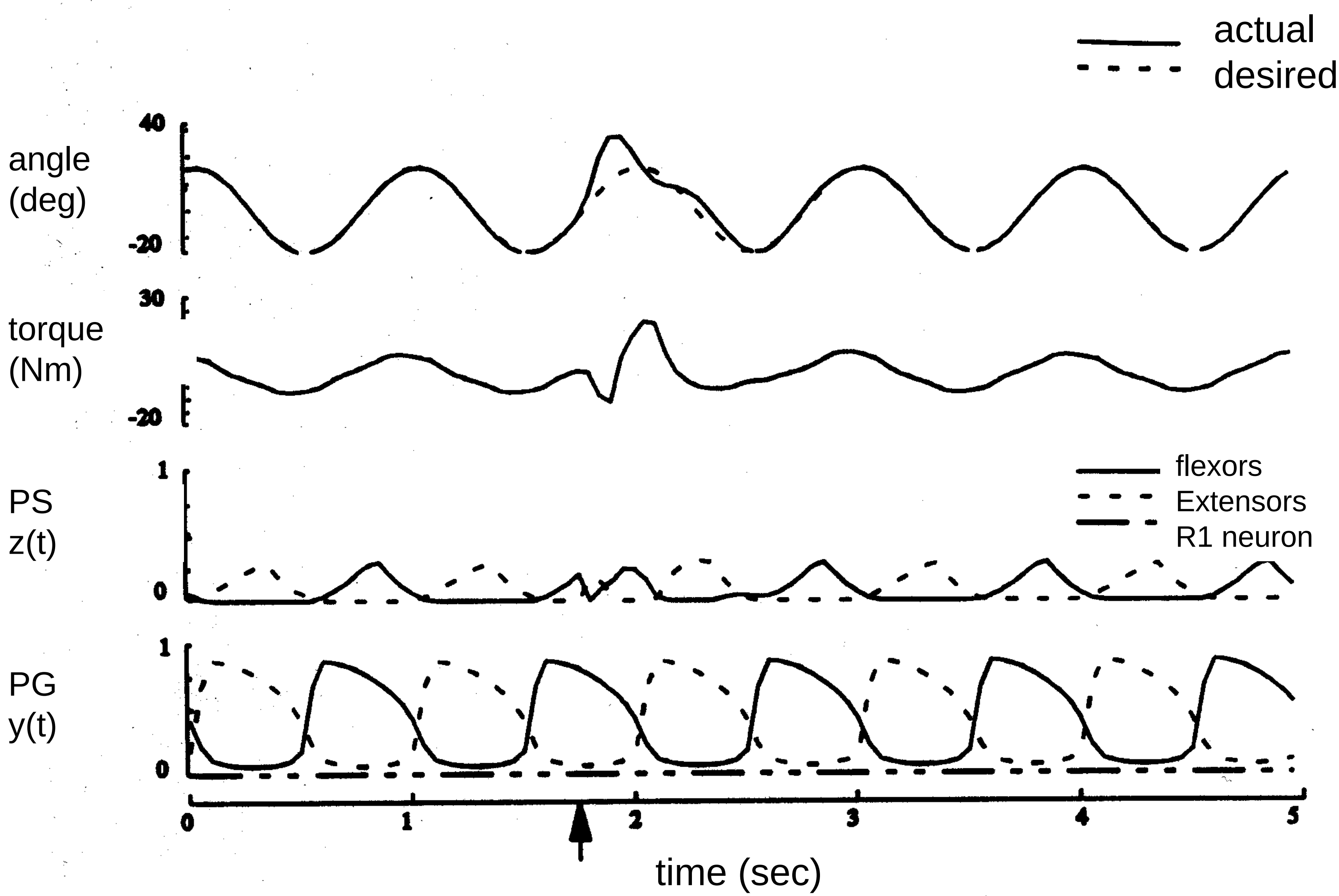
Reflexes with phase-resetting



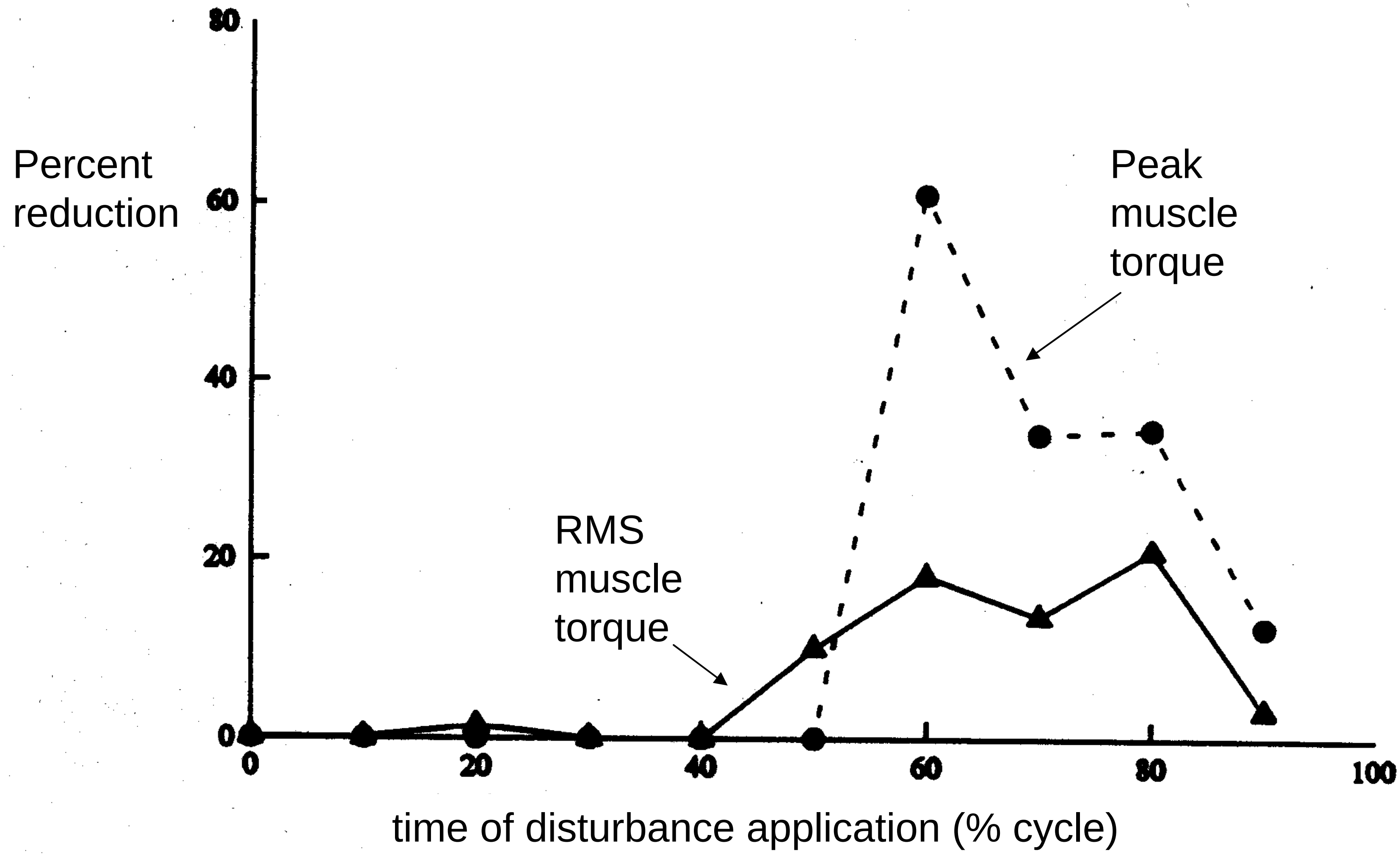
Phase-dependent reflexes



Reflexes without phase-resetting



Phase-dependent reflexes



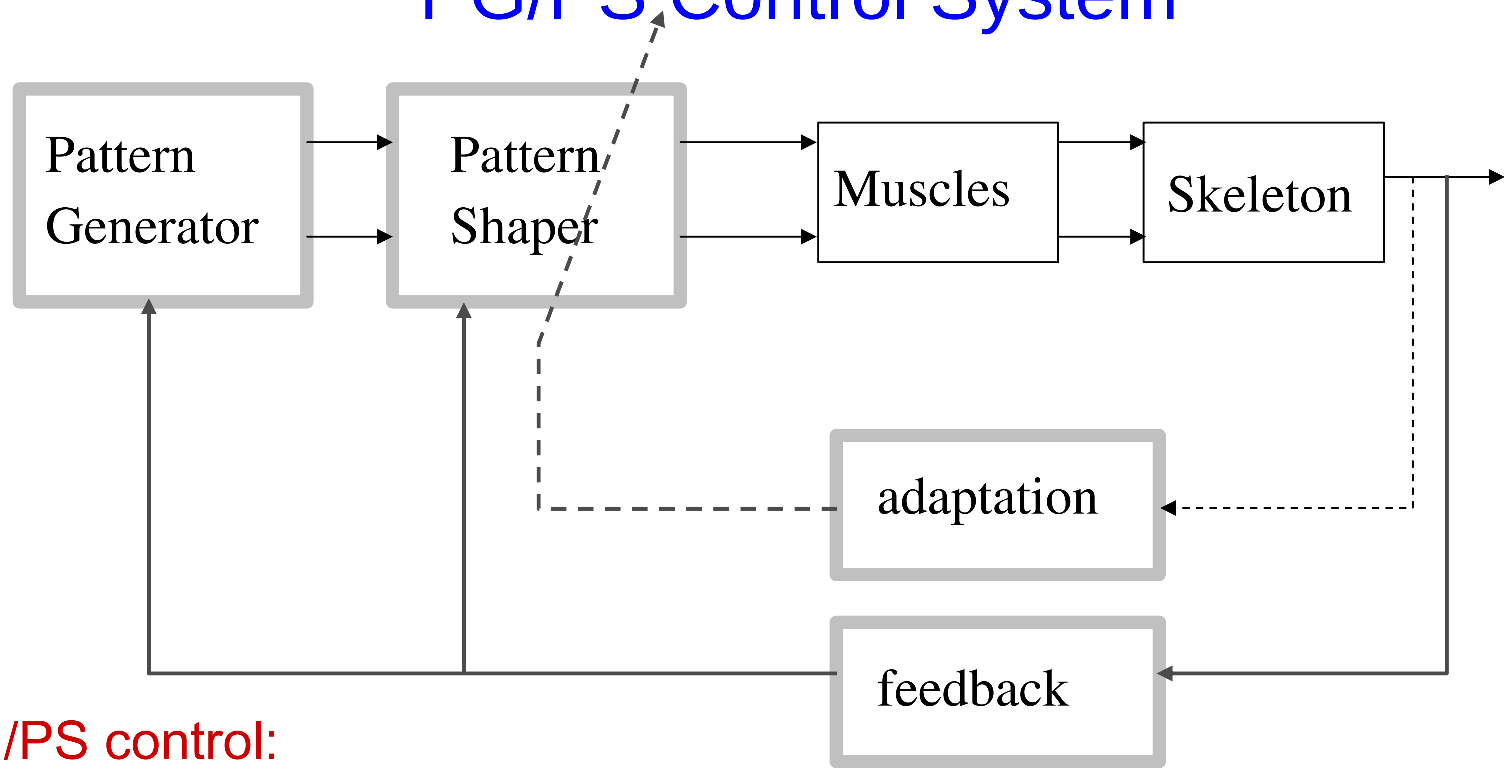
PG model provides:

- basic movement rhythm
- phase-resetting
- phase-dependent reflexes
- cycle period adjustments

Needs:

- localized learning
- more complex movement patterns
- additional reflexes

PG/PS Control System



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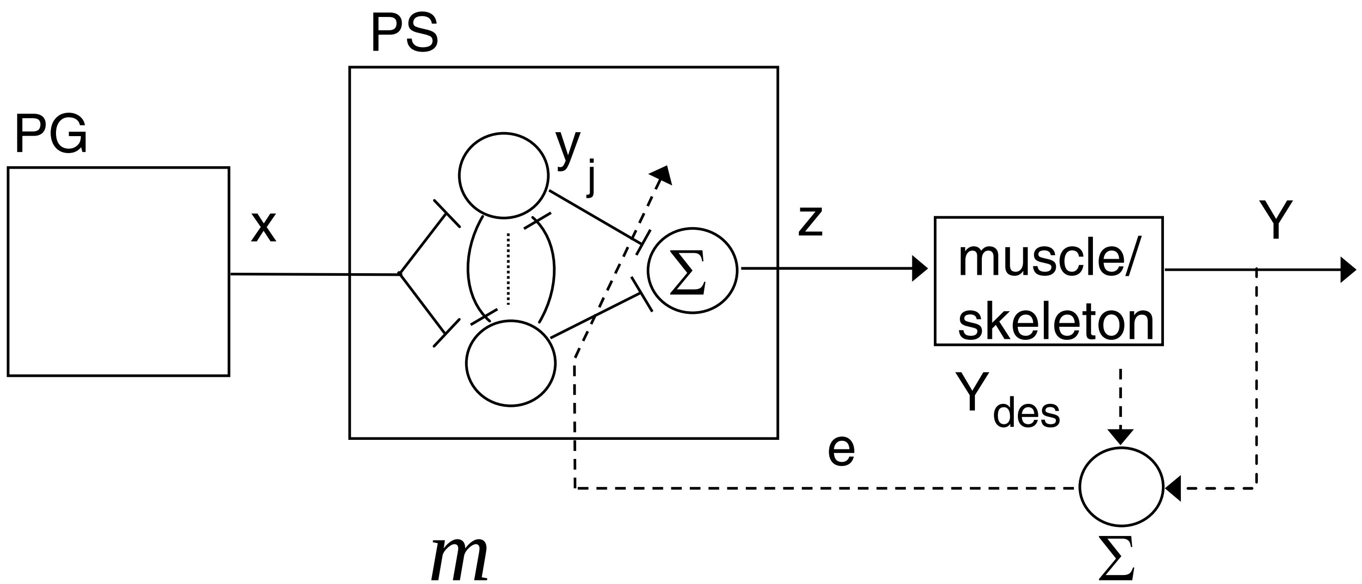
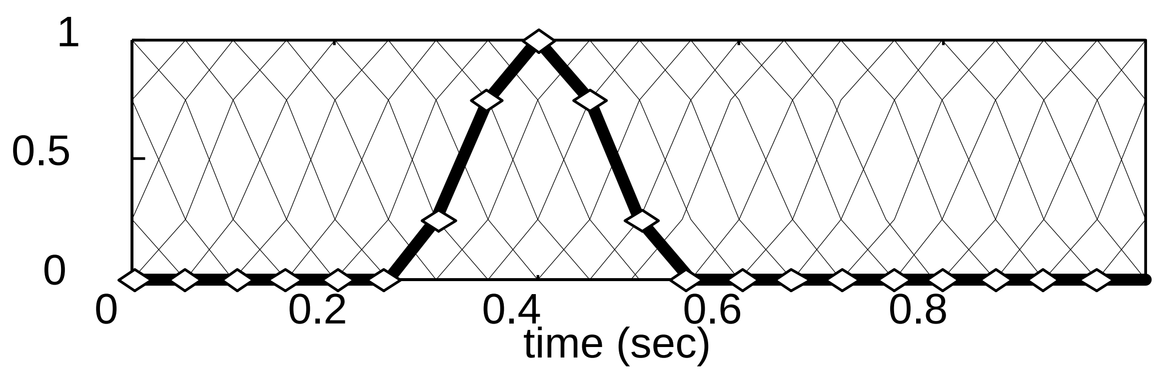
PS Neuron Equations



$$z_k(t) = \sum_{j=1}^{m} w_{kj}(t) y_{kj}(t)$$

individual PS neuron activity levels, y_{1j}



PS Learning

Hebbian learning algorithm:

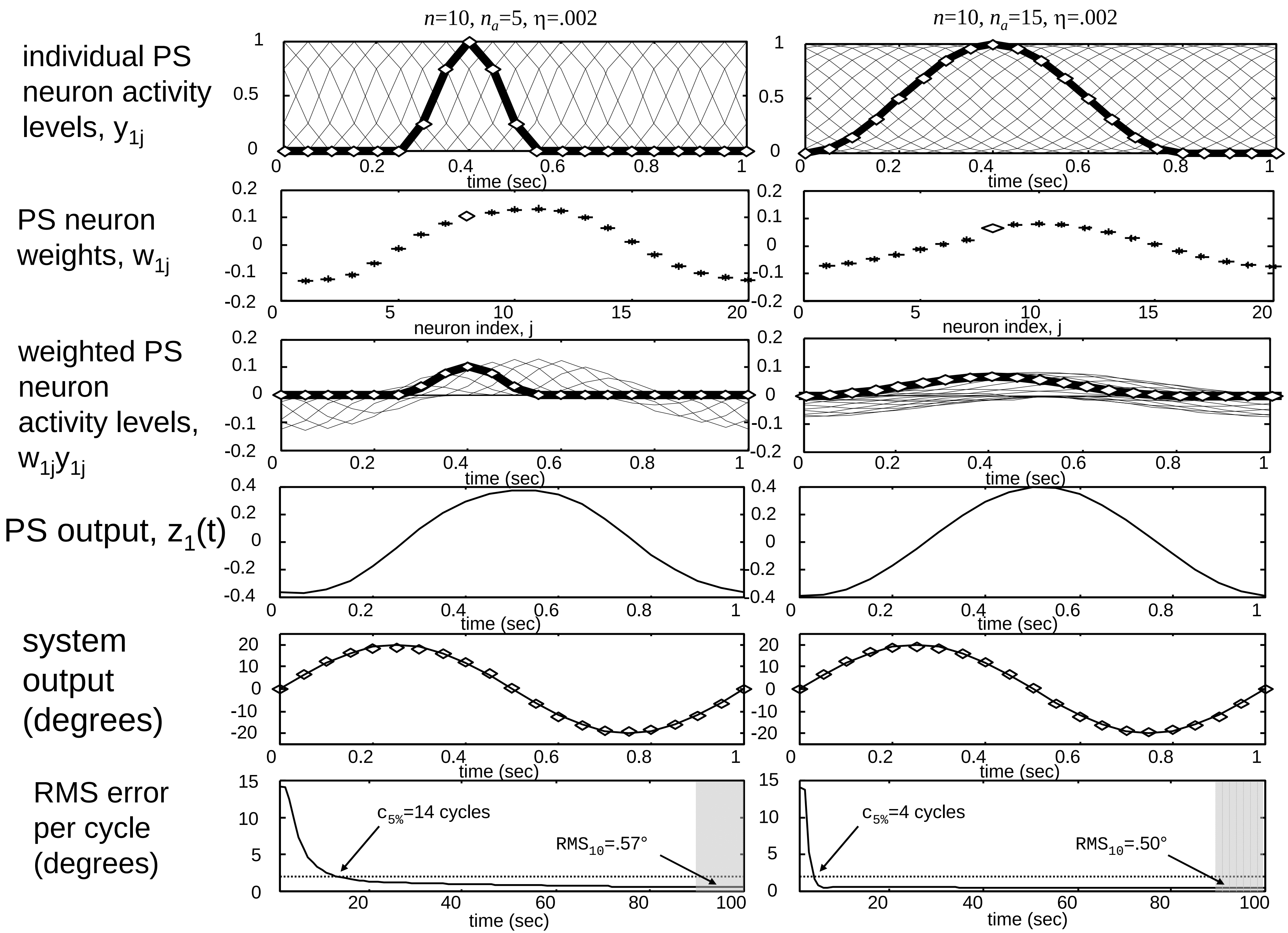
$$\Delta w(t) = \eta \;\; y_{post}(t) \;\; y_{pre}(t)$$

Heterosynaptic Hebbian learning algorithm:

$$\Delta w(t) = \eta \;\; y_{a}(t) \;\; y_{pre}(t)$$

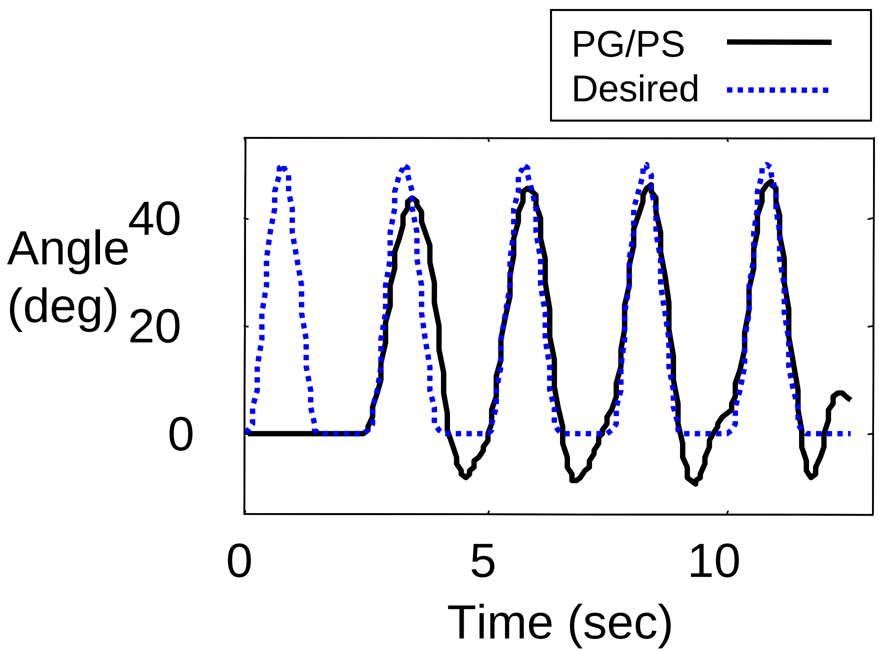
Time-averaged learning algorithm:

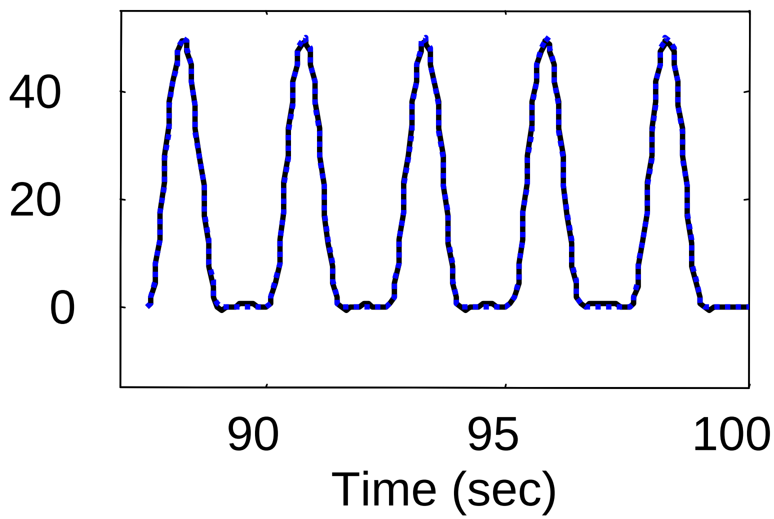
$$\Delta w_{kj}(t) = \eta \; e(t) \; \sum_{n} \frac{1}{n} y_{kj}(t - nT)$$

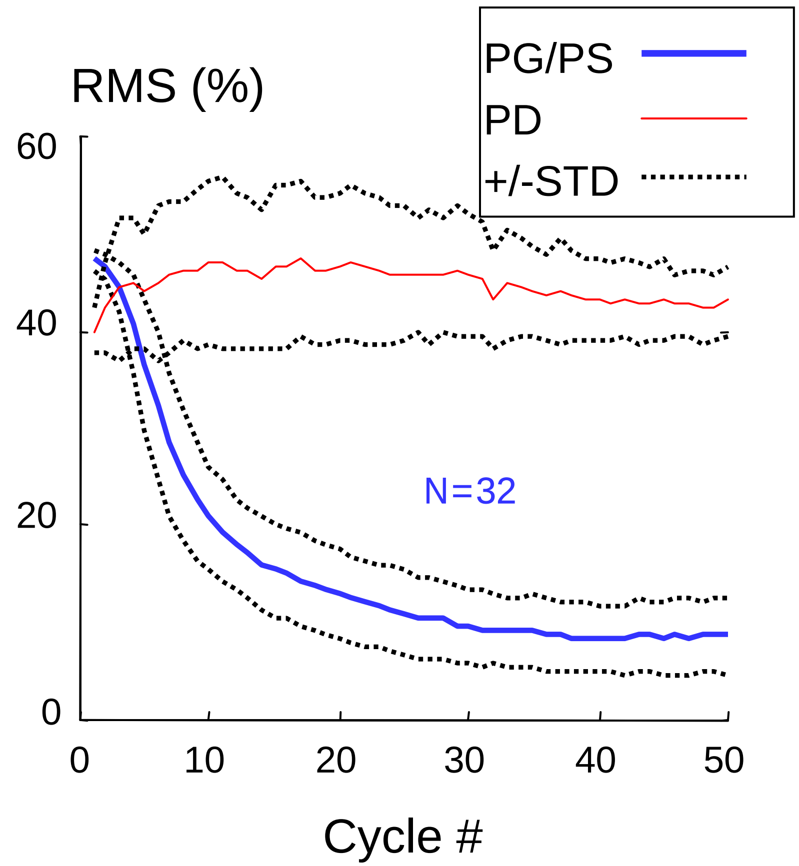


n=10, n_a=5, η=.002
n=10, n_a=15, η=.002
individual PS neuron activity levels, y1j
PS neuron weights, w1j
weighted PS neuron activity levels, w1jy1j
PS output, z1(t)
system output (degrees)
RMS error per cycle (degrees)
time (sec)
neuron index, j
c5%=14 cycles
RMS10=.57°
c5%=4 cycles
RMS10=.50°

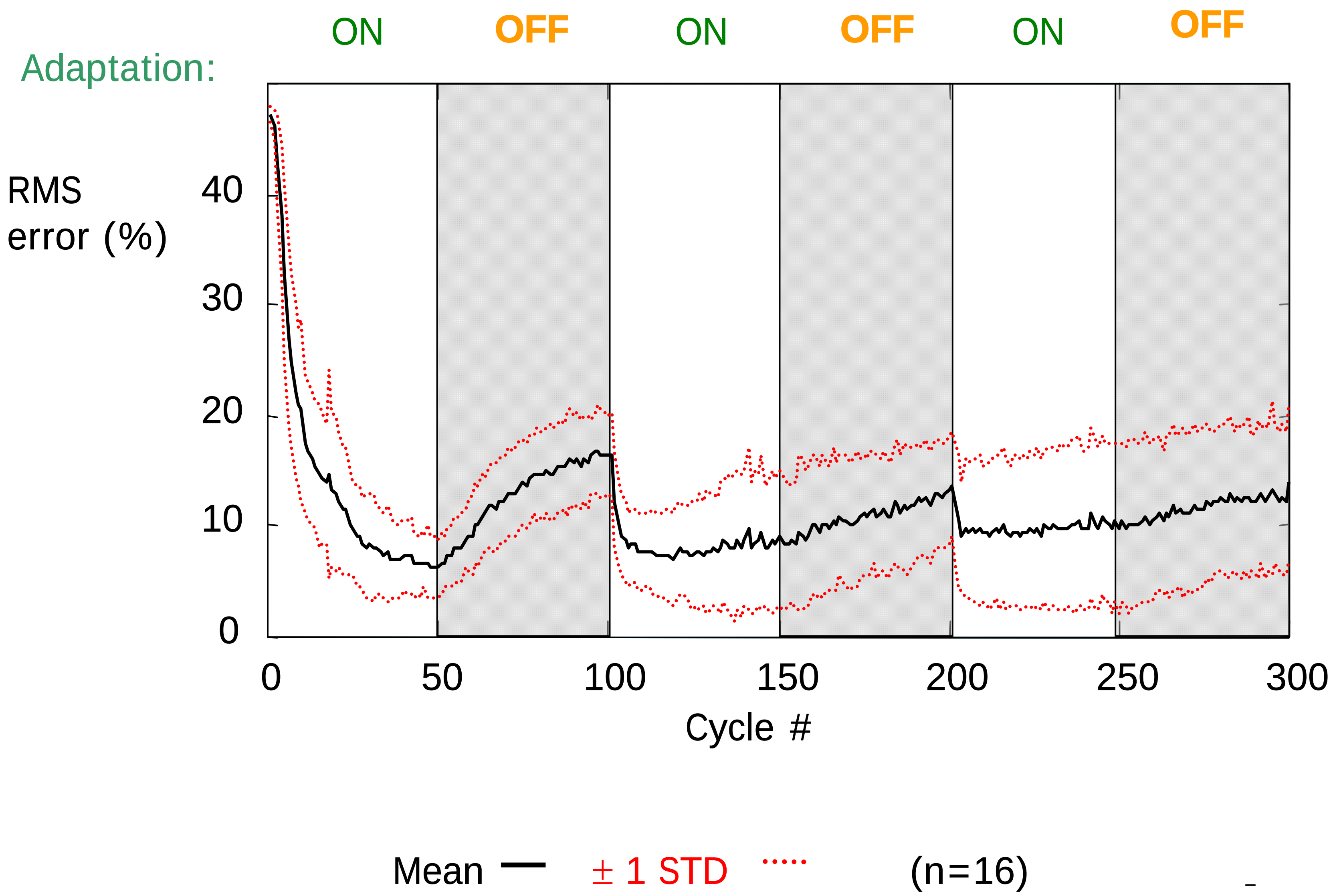
PG/PS Control



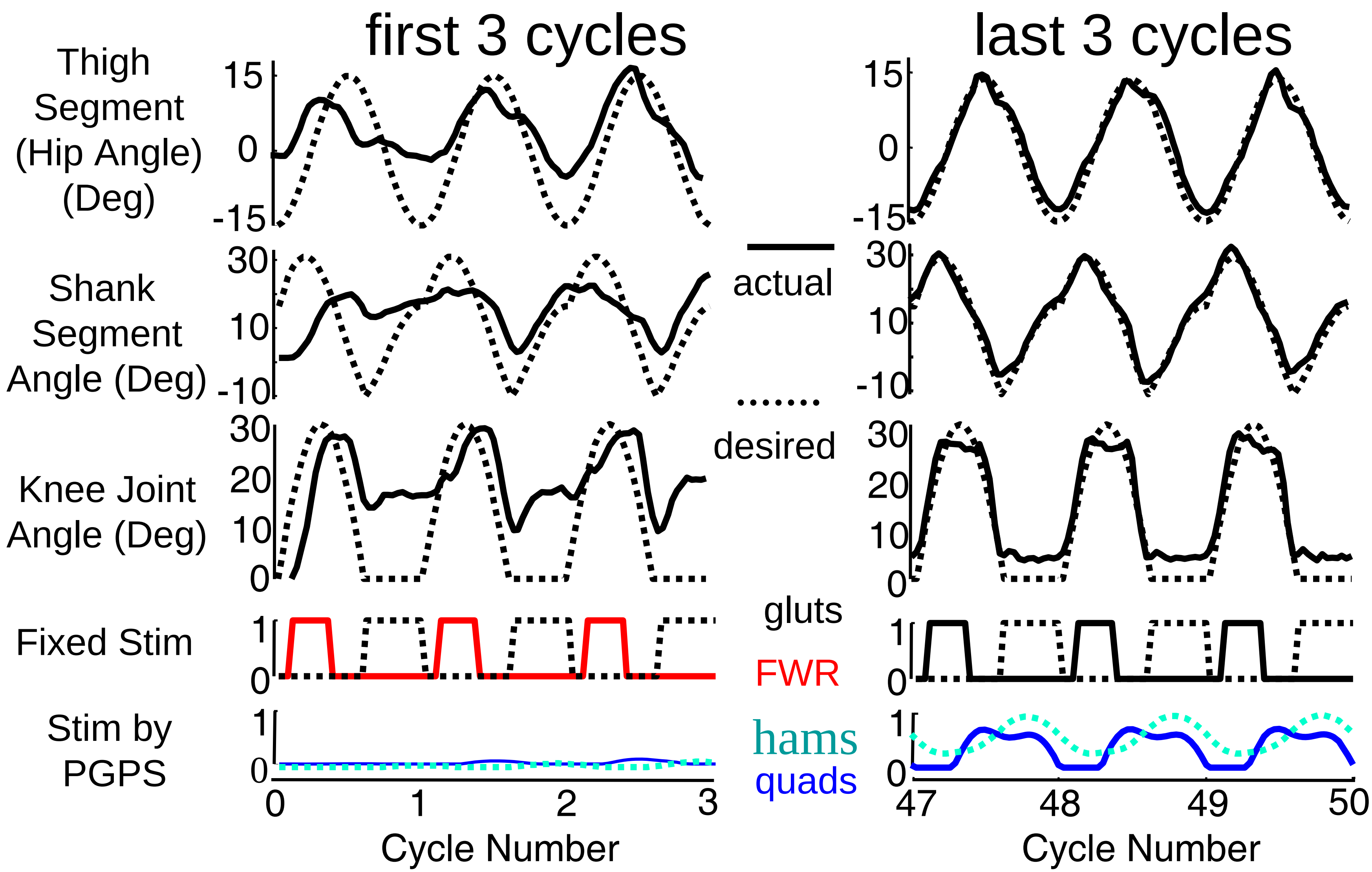


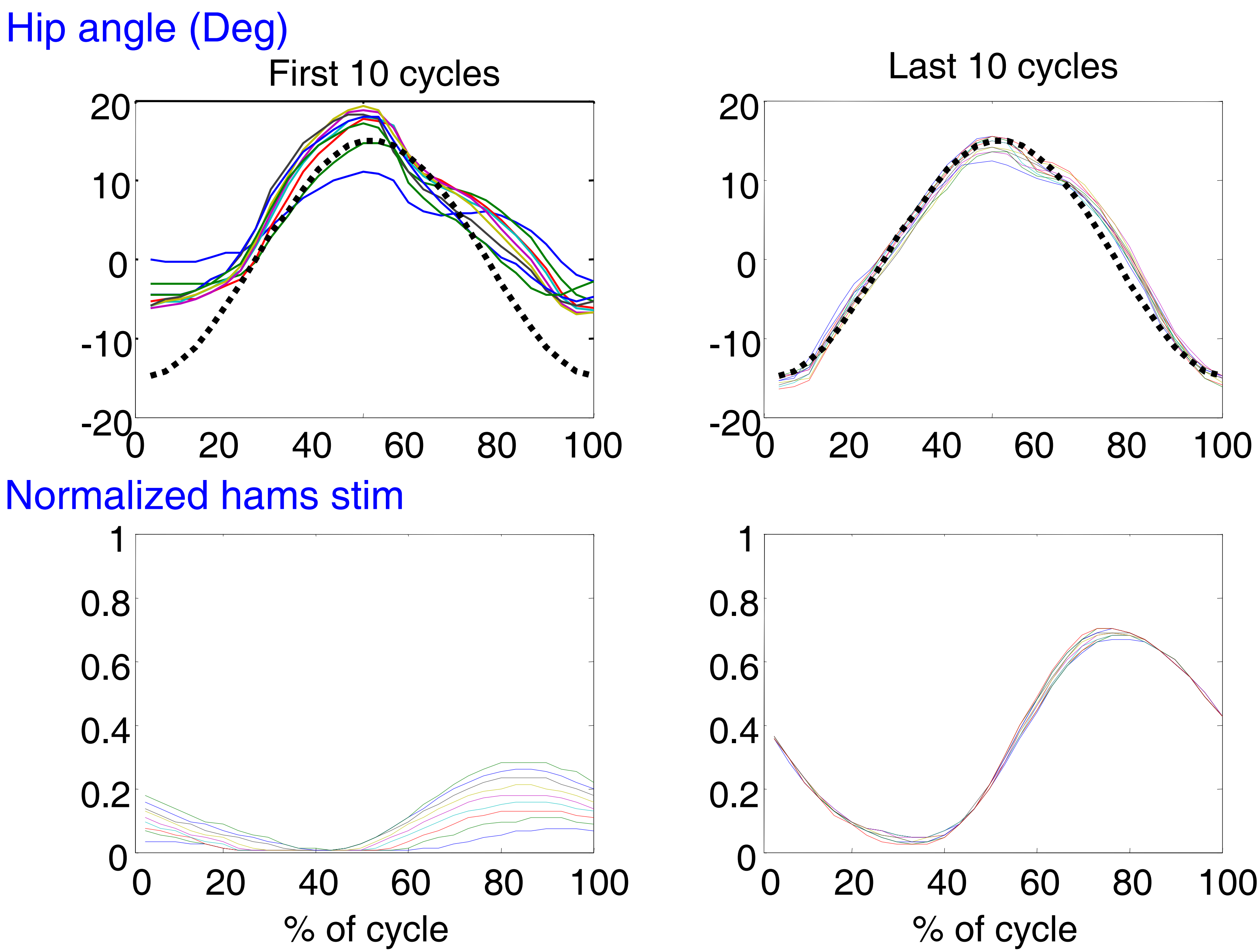


Adapting to account for fatigue



control of multi-segment movements

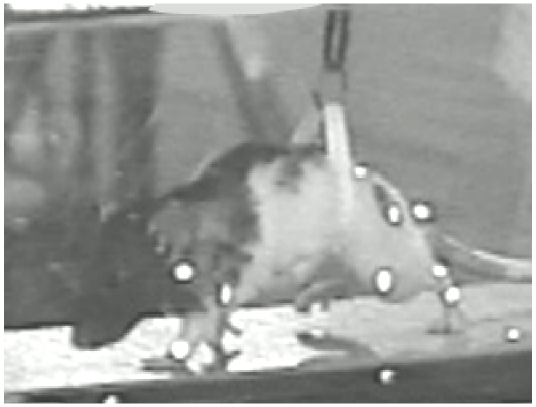


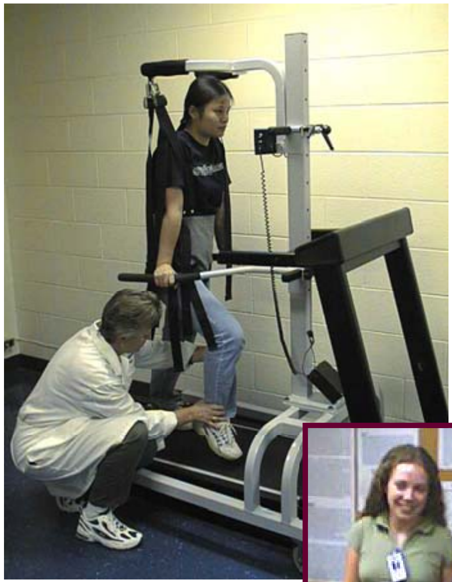


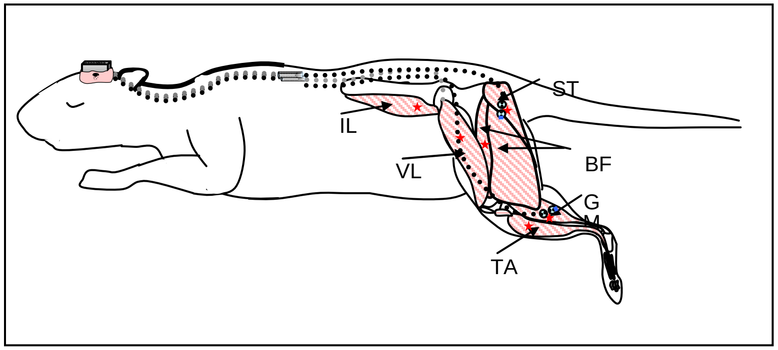
Hip angle (Deg)
First 10 cycles
Last 10 cycles
20
10
0
-10
-20
0
20
40
60
80
100
Normalized hams stim
1
0.8
0.6
0.4
0.2
0
% of cycle
% of cycle

Pre-clinical

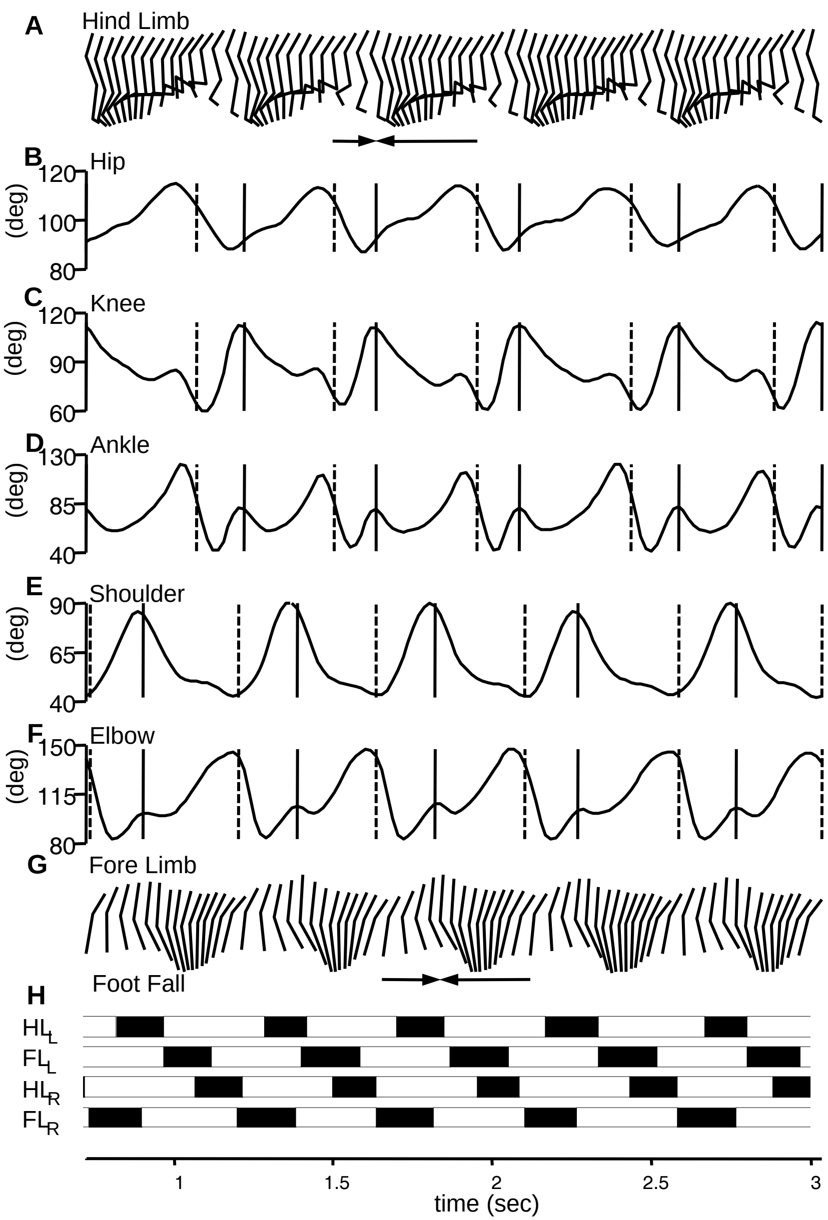
Human



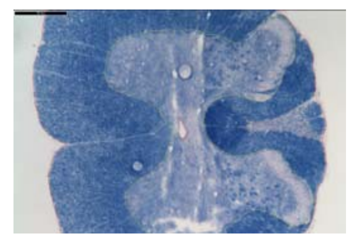


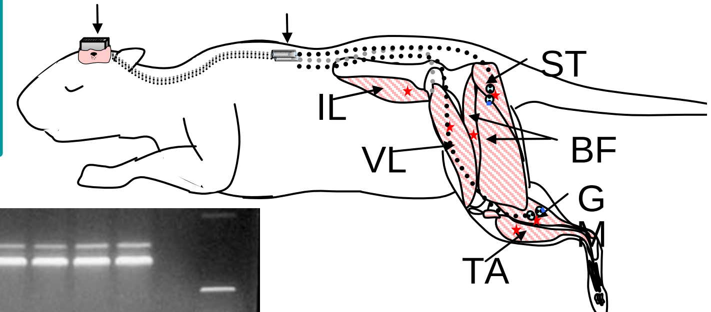


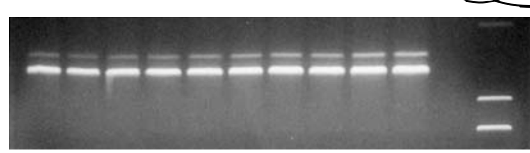
Pre-clinical model development (Jung, et al., ASU)



Thota et al. J. Neurotrauma 22(4): 442-465, 2005



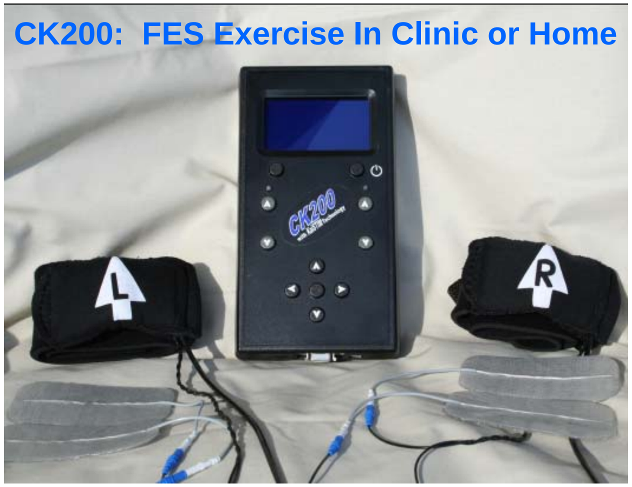




Can we control the stepping movement?

Can we promote functional plasticity?

Commercial partnership: customKYnetics, Inc.



Adaptive Stimulator for Exercise and Rehabilitation

Stimulation-Augmented Exercise and Neuromotor Therapy

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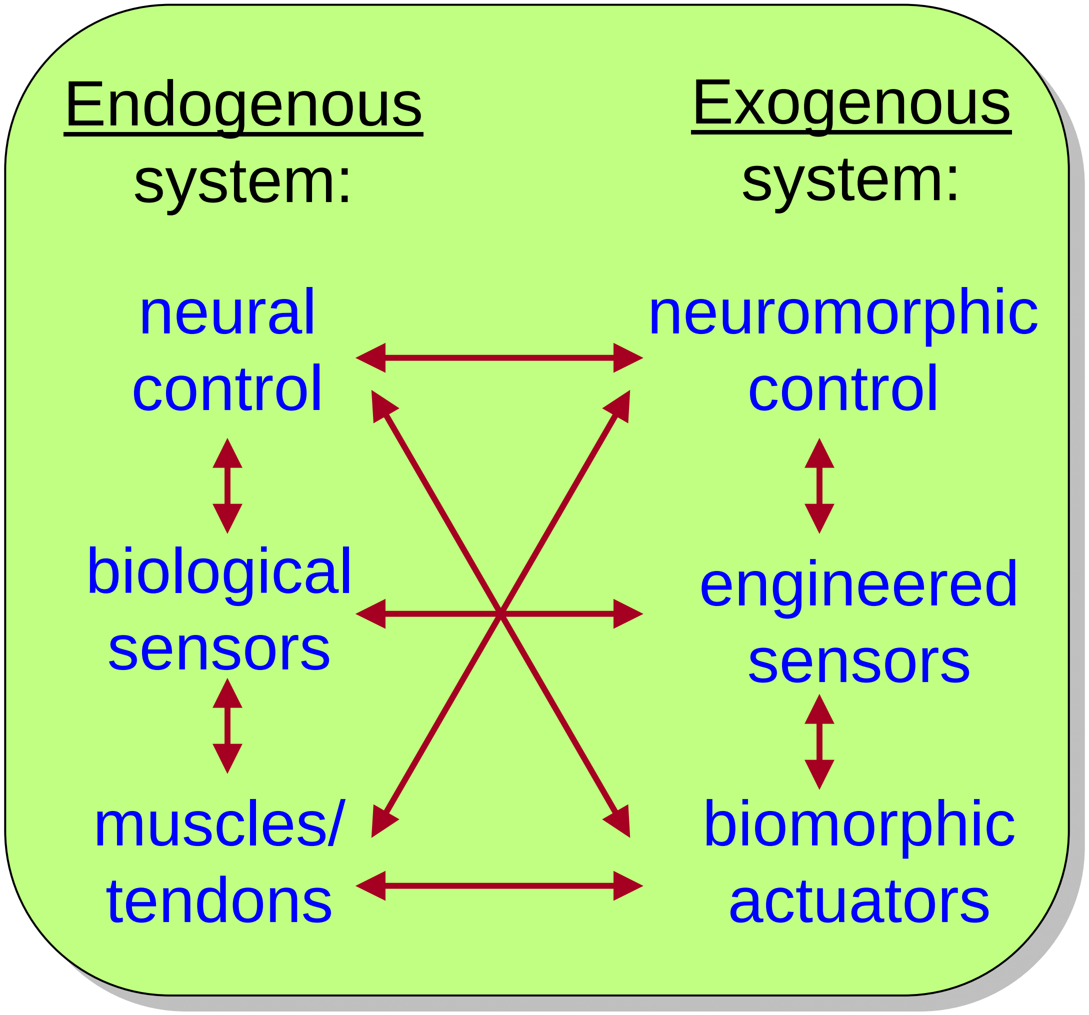
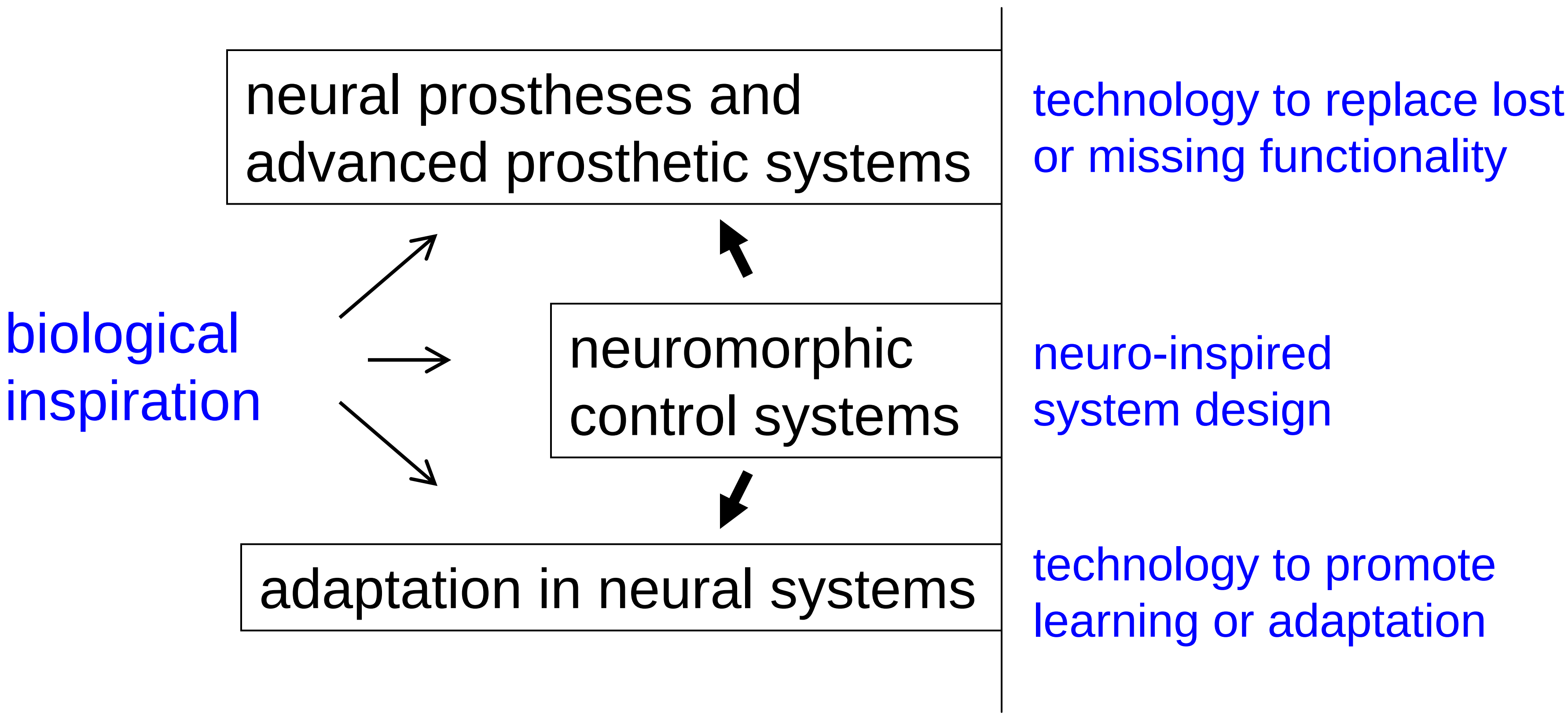
Disclosure: J. Abbas is part-owner and co-founder of customKYnetics, Inc.

Integrating physiological and artificial systems

- biomimicry
- intact ⇔ artificial
- system integration



Center for Adaptive Neural Systems



Neuromorphic Design of Smart Prosthetic and Therapeutic Systems

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BARROW Neurological Institute

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