ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

CPG as a cyclical movement controller

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Departamento de Engenharia Mecatrônica e Sistemas Mecânicos

Contents

Introduction

- Justification
  - Understanding the system
  - Intervention:
    - Rehabilitation
    - Training
  - Development of bioinspired control systems:

Duysens J, Forner-Cordero A. (2018). Walking with perturbations: a guide for biped humans and robots. Bioinspir Biomim. 2018 Sep 4;13(6):061001.

Duysens, Jacques; Forner-cordero, Arturo. A controller perspective on biological gait control: Reflexes and central pattern generators. Annual Reviews in Control. p.392 - 400, 2019.

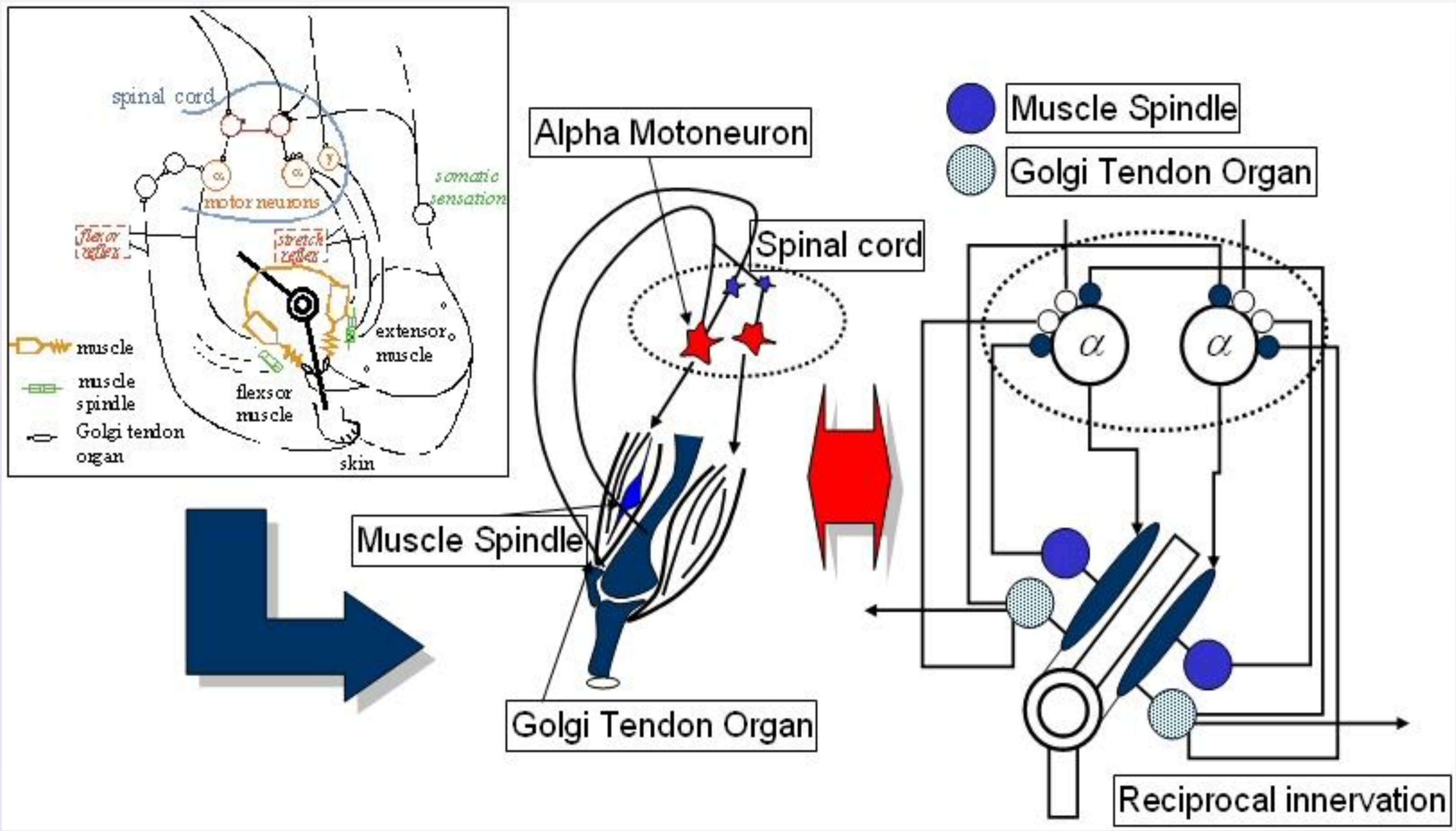
Biological and robotic CPGs

- Central pattern generators:
  - Biological or artificial neurons (or oscillators) capable of generating a movement pattern:
  - Autonomously:
    - It can work in the absence of stimulus
  - Modulated by:
    - Sensory stimuli
    - Higher centers

Advantages and disadvantages

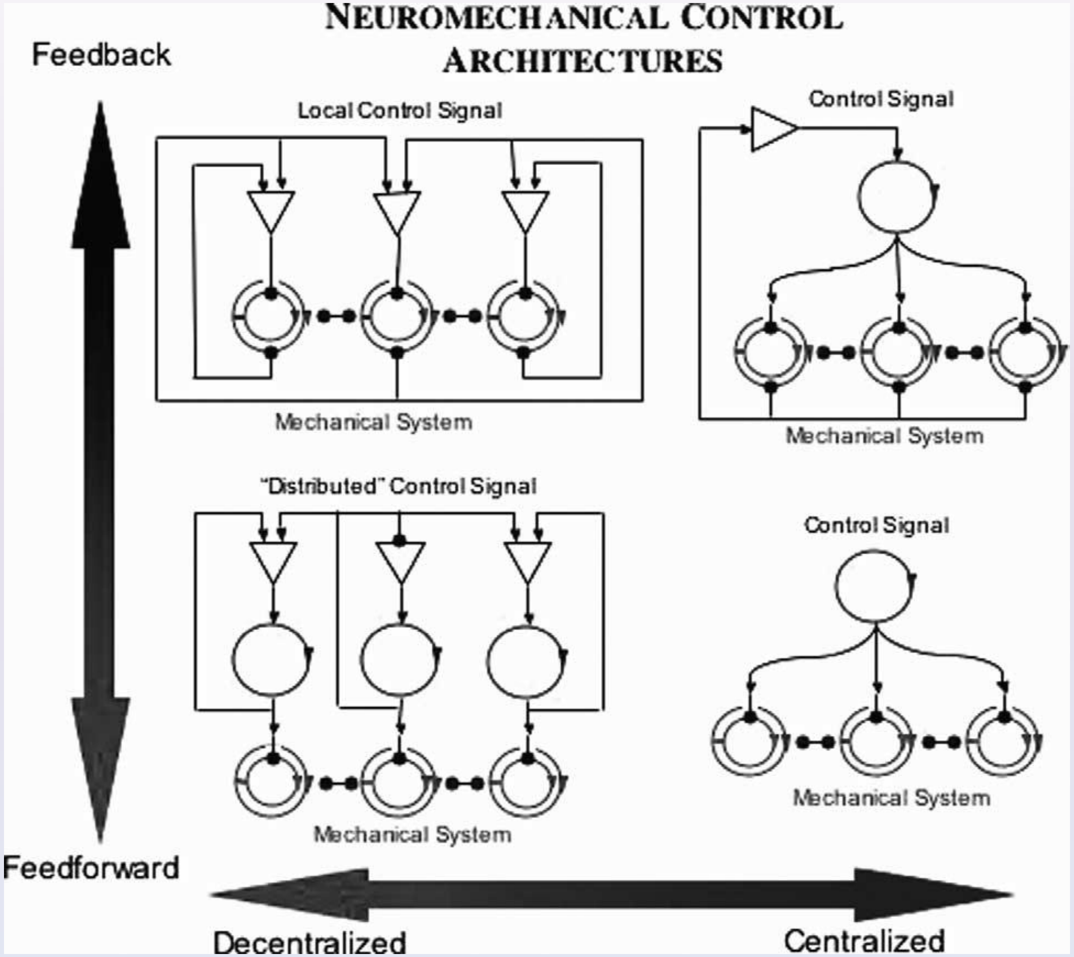
- “Entrainment” and adaptation:
  - Tune the controller with the plant and the environment.
  - Robustness against:
    - Perturbations
    - Parameters variation
- Difficult to tune:
  - Not clear procedures
  - Empirical adjustments

Motor control mechanisms



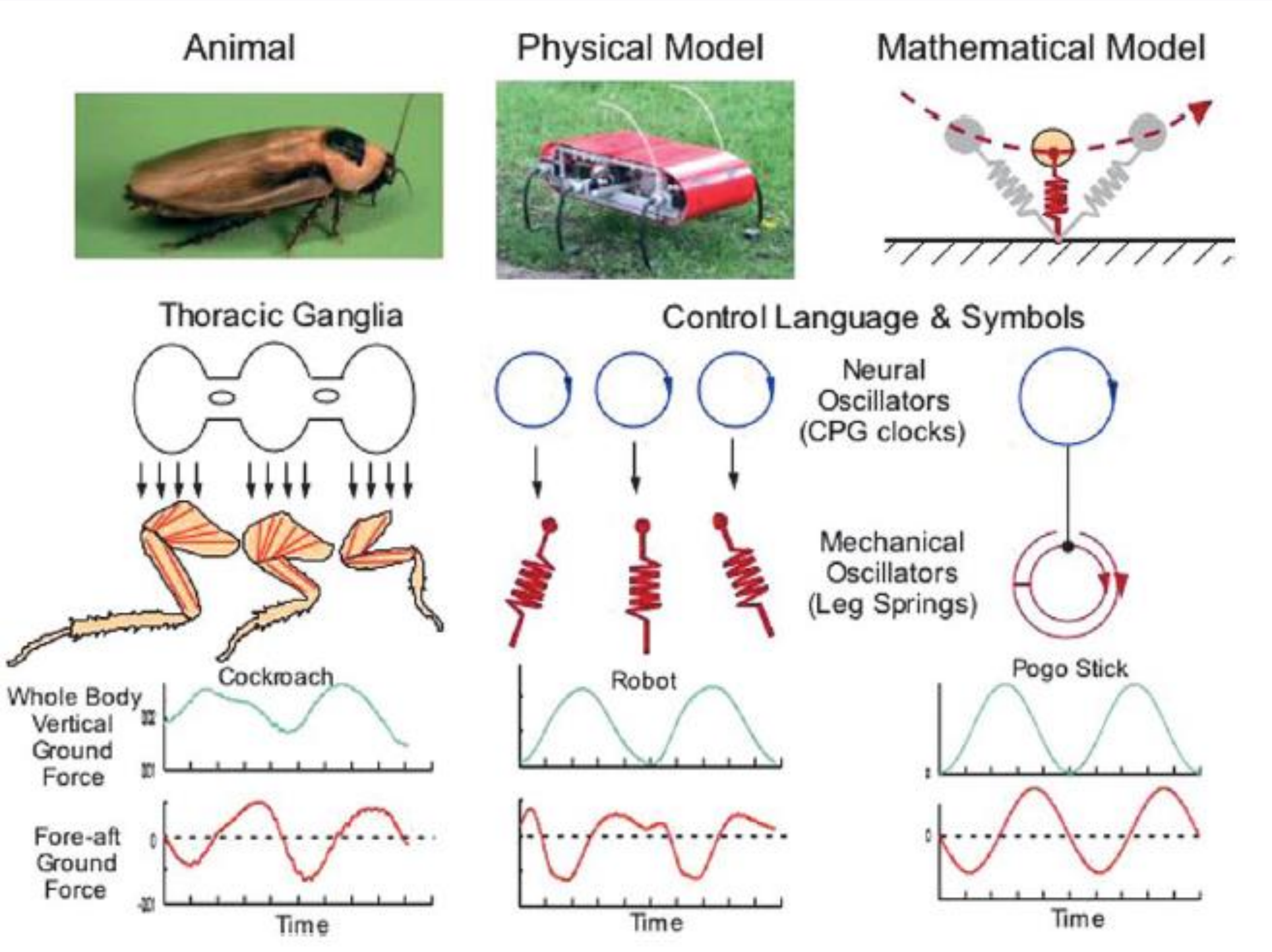
Robotics Lab. Japan Advanced Institute of Science and Technology (JAIST)

Motor control



Koditchek, Full and Buehler, 2004. Arth. Strut. Dev.

Motor control



Koditchek, Full and Buehler, 2004. Arth. Strut. Dev.

Goals

- Biological CPG:
  - Physiology and functional anatomy
  - Function and properties
  - Modeling
- Artificial CPGs:
  - Overview of the artificial systems
    - Assistance: interaction with the user
    - Biorobotics and biomimetic robotics

Contents

1. Introduction: Justification e goals

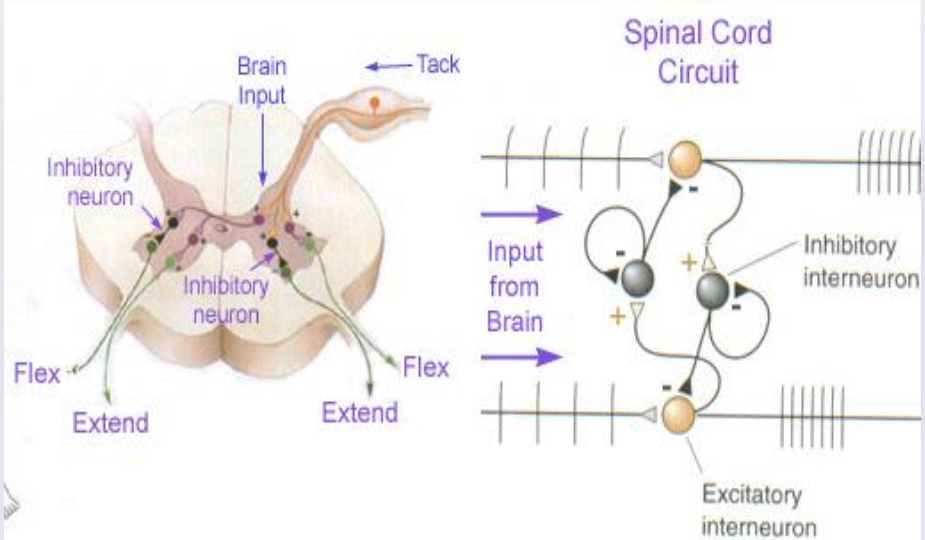
2. The biological Central Pattern Generator
   - Organization and structure
   - Operation principles

3. Artificial (biomimetic) CPG
   - Artificial-biological CPG comparison
   - Artificial CPGs
     – Matsuoka model, van der Pol oscillator

4. Walking robots applications
     – Bipeds
     – Quadrupeds and more...

Biological CPG. Neural Network

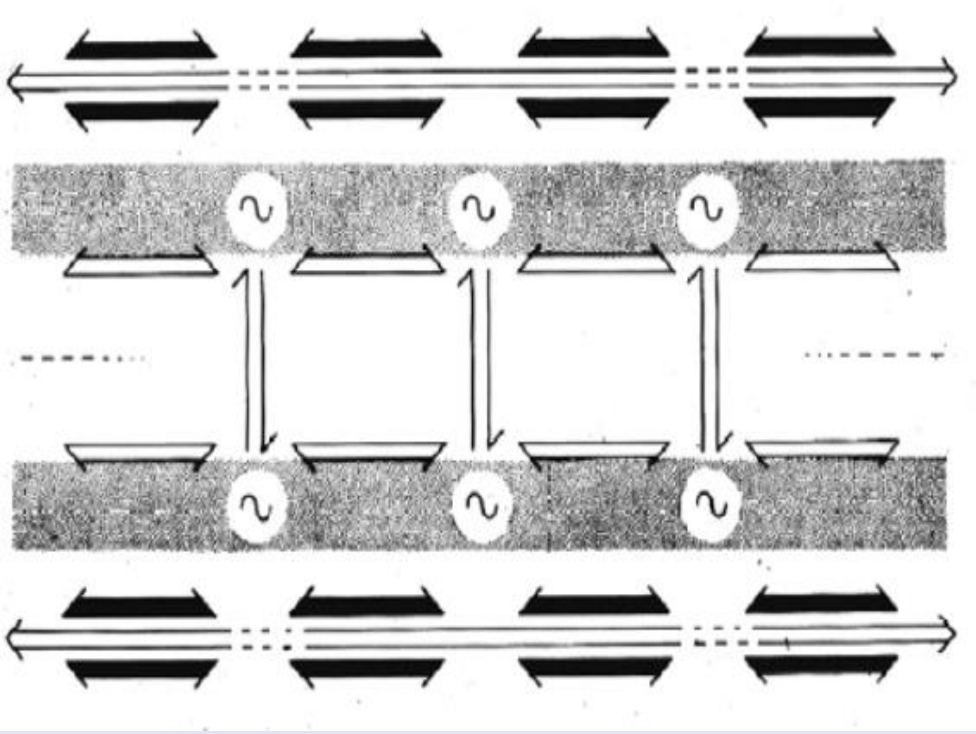
- Autonomous: generates rhythmic patterns
- Cyclical movements:
  - Locomotion
  - Mastication
- Modulation:
  - Sensory feedback
  - Cortical control (voluntary?)
- Processes:
  - Reciprocal inhibition
  - Self-inhibition

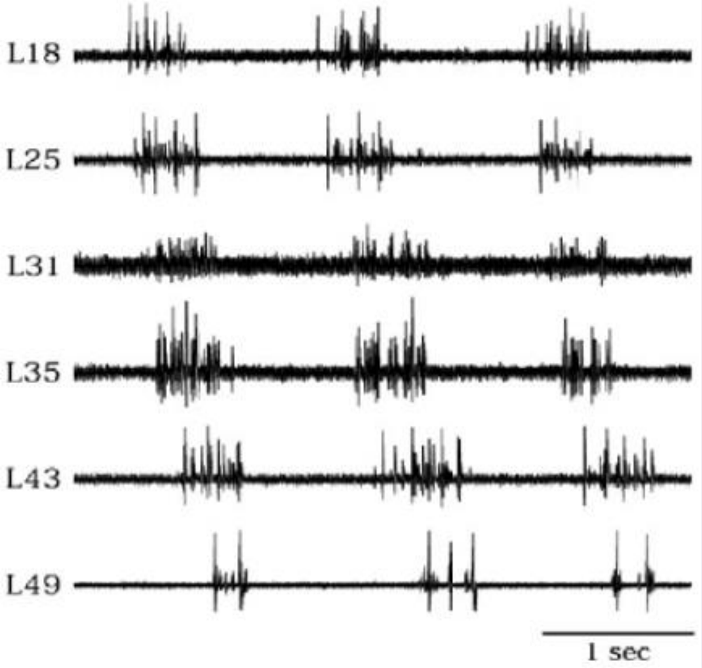


Anatomy

- Spinal cord:
  - Toraco-lumbar in humans?
- Small groups of autonomous neurons
  - Rhythmic pattern generation
  - Cortical loopss?
- Rhythm generation:
  - Neural interaction
  - Current interaction in individual neurons
- Half Center Oscillators:
  - Two coupled neurons with reciprocal inhibition

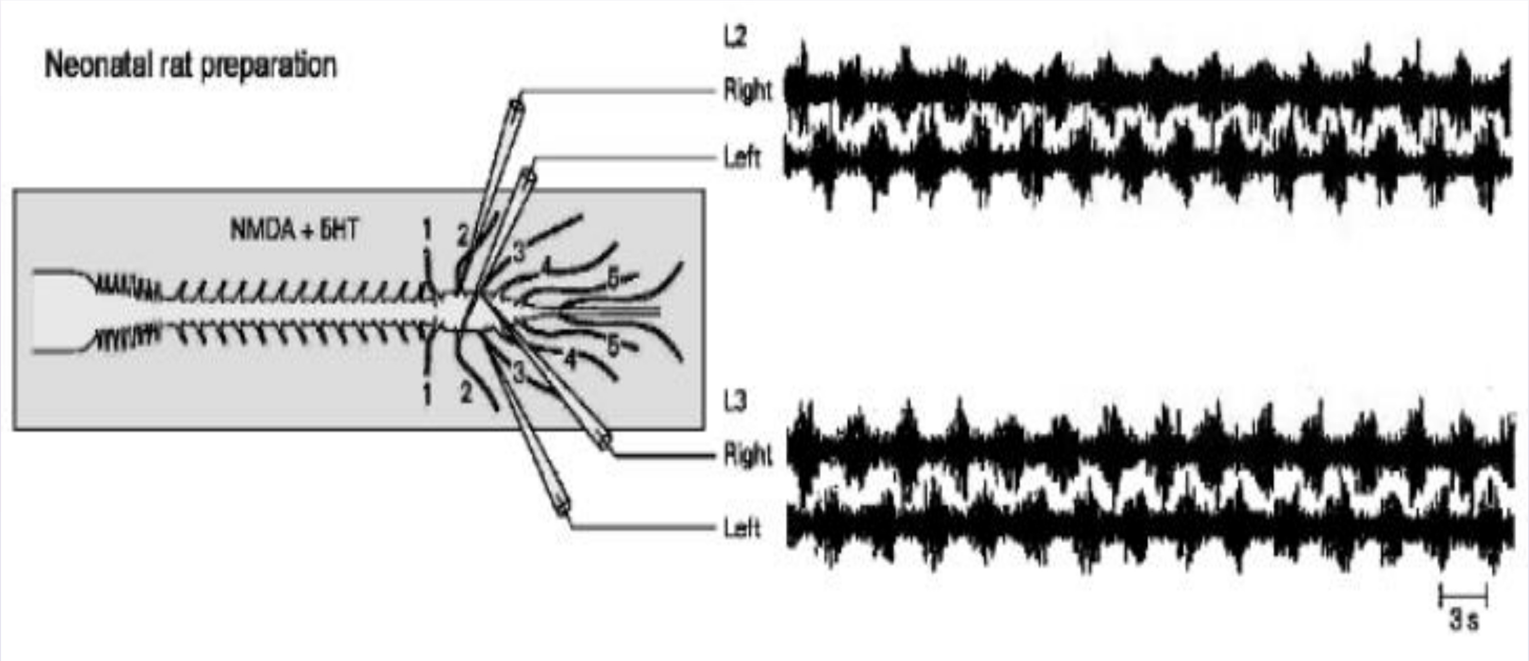
Lamprey





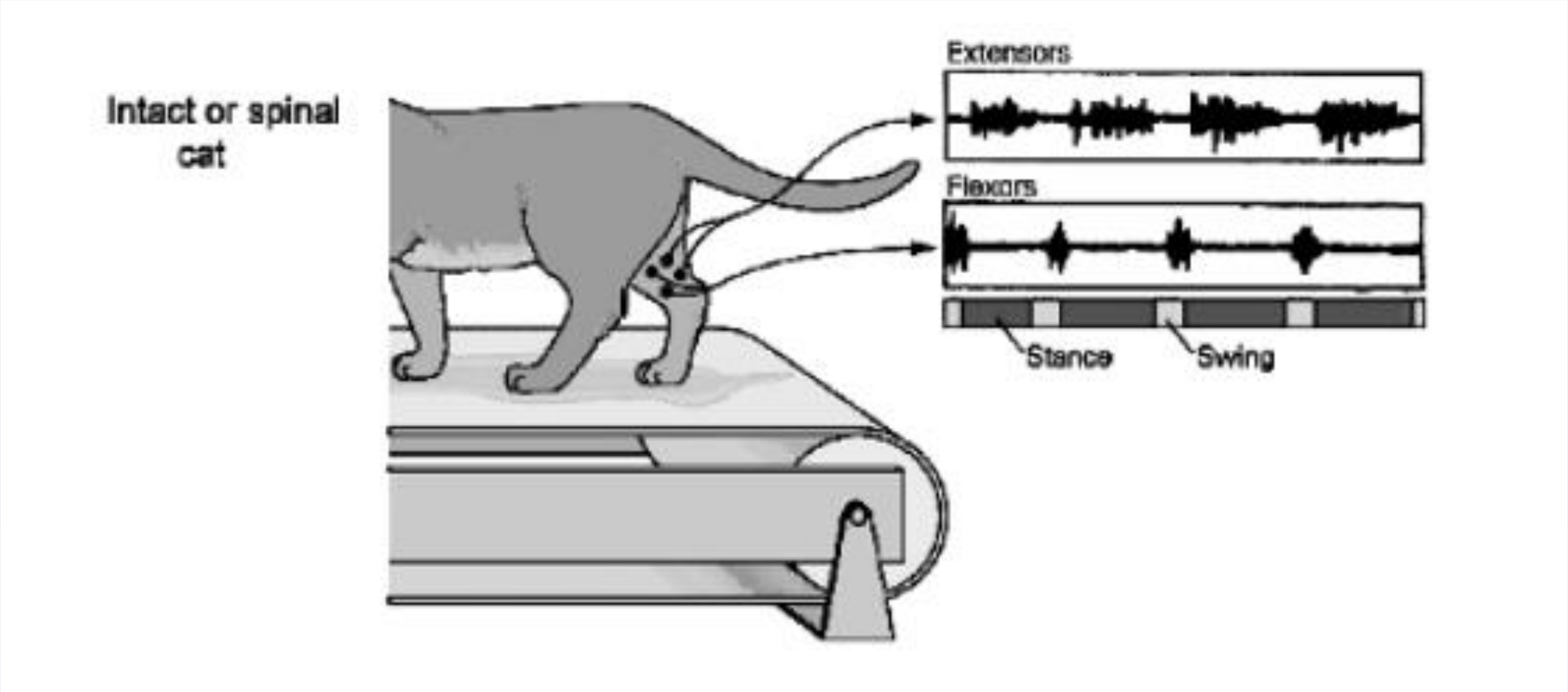
Cohen, 1987. J Comp. Physiol.

Rats



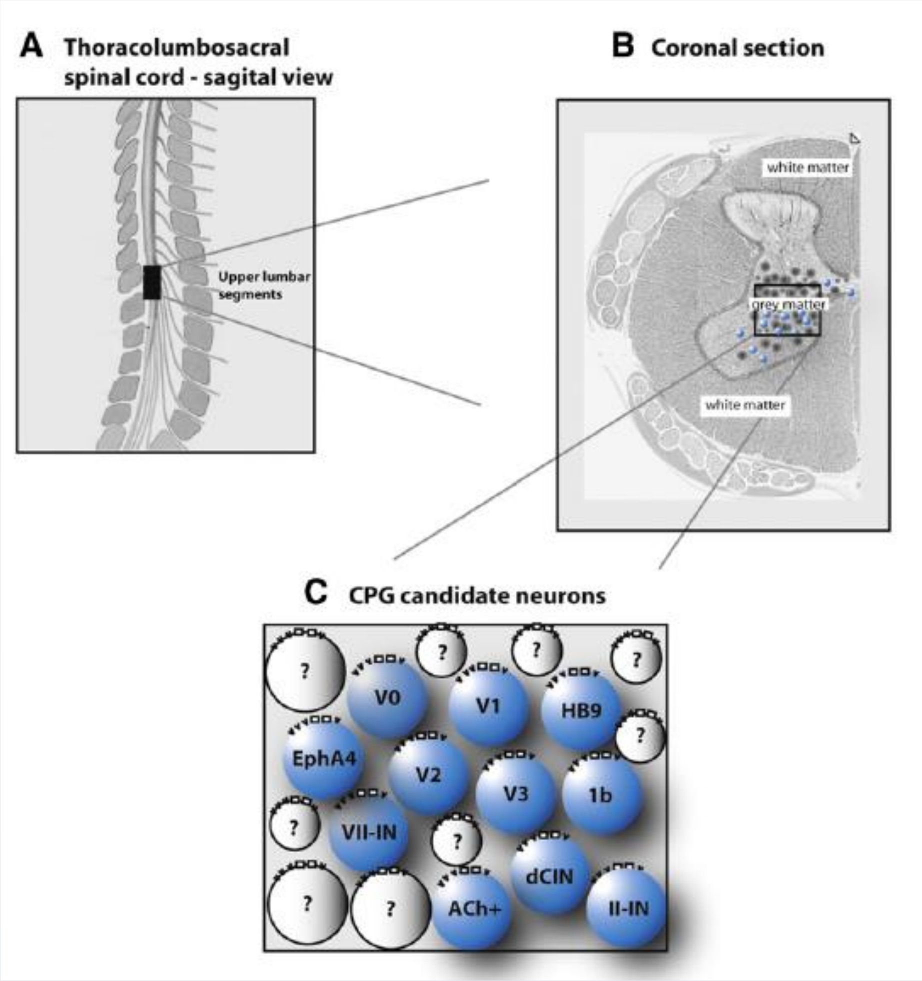
Cazalets Jet al. 1995 J. Neurosci.

Cats



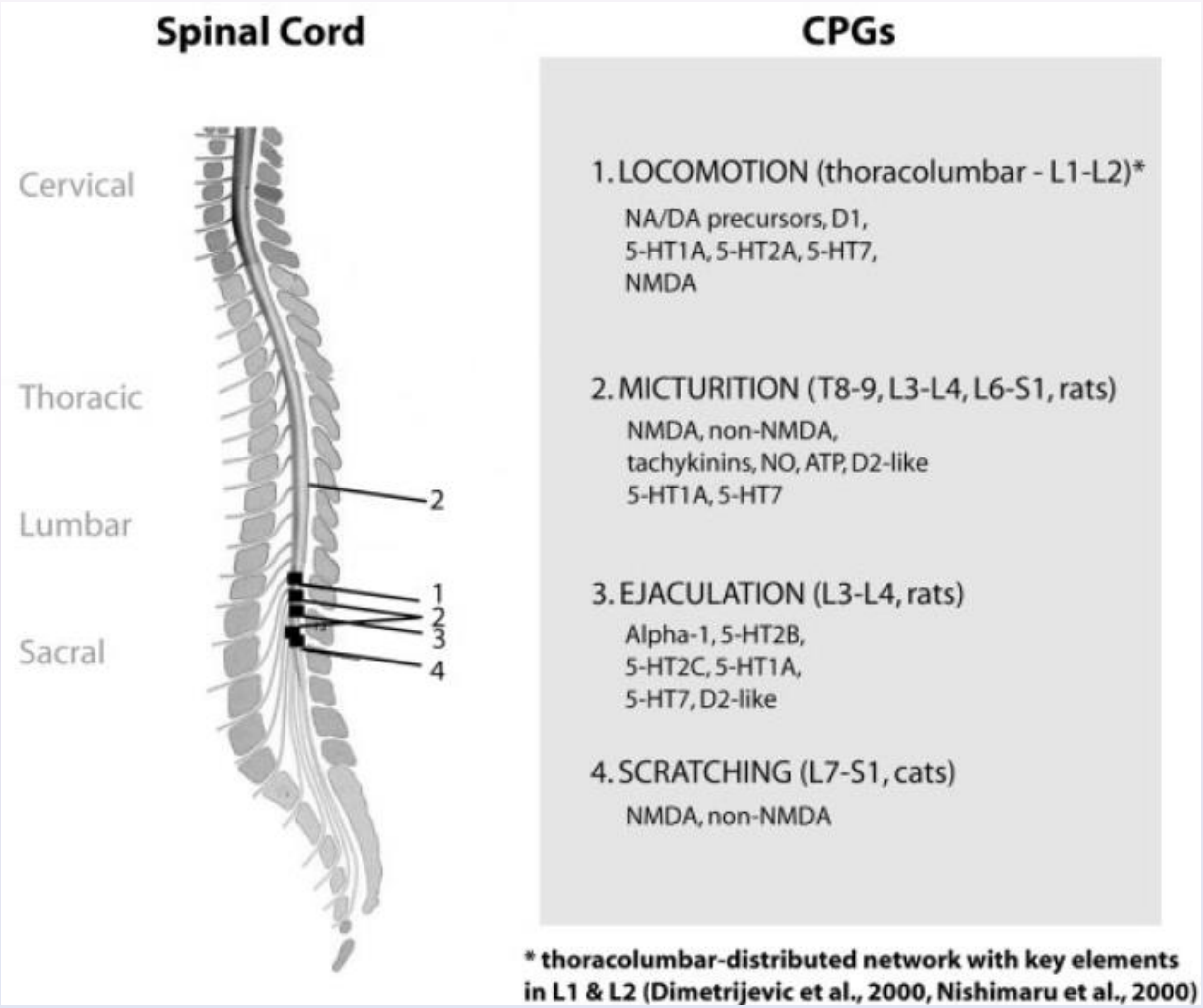
Kandel et al. 2000. Principles of Neural Science
Trabalhos de Pearson, Duysens, Stein.

Humans?



Guertin, 2009.
Brain Res Rev.

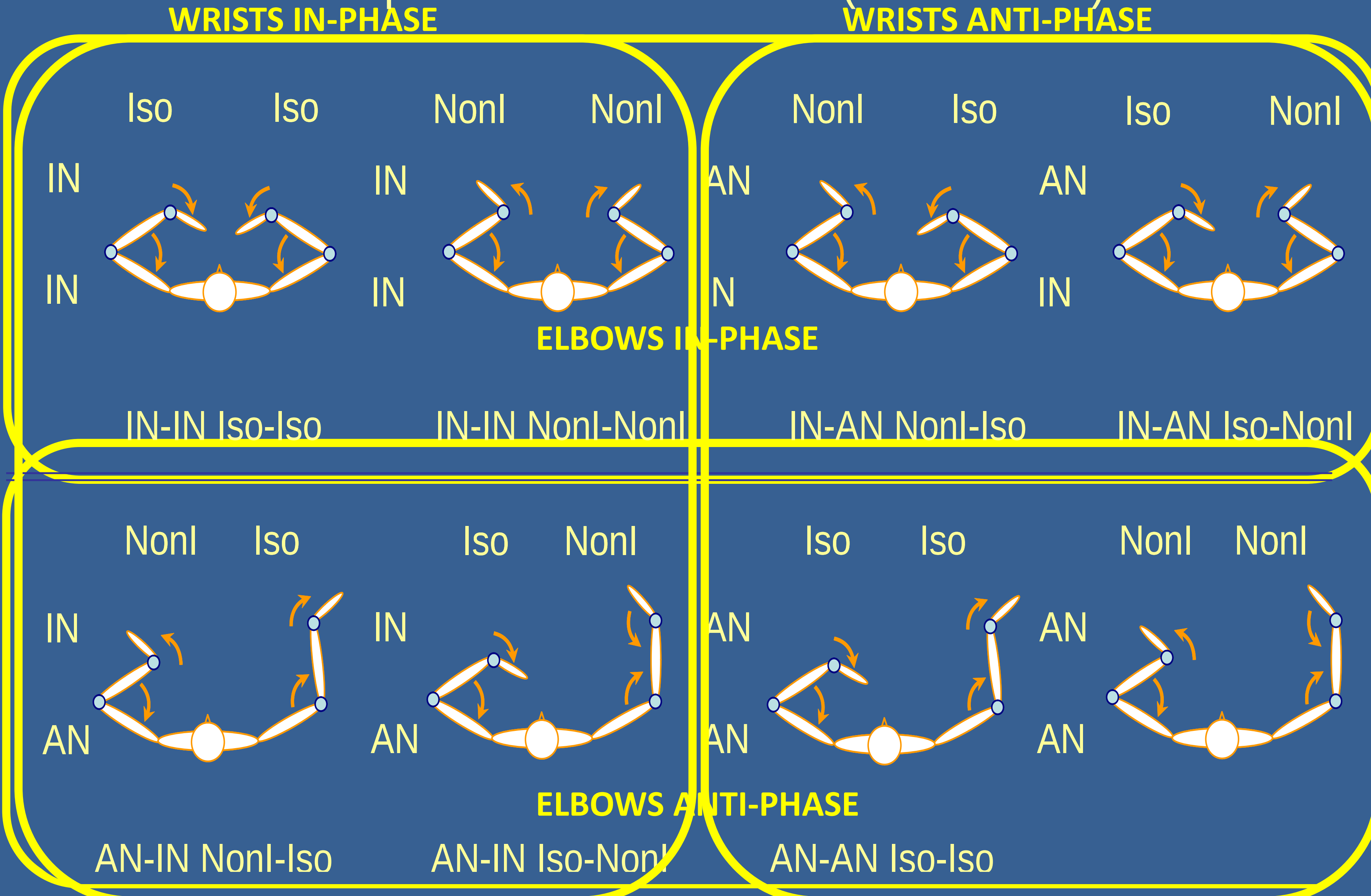
Humans?


Spinal Cord
CPGs
Cervical
Thoracic
Lumbar
Sacral
2
1
2
3
4
1. LOCOMOTION (thoracolumbar - L1-L2)*
NA/DA precursors, D1,
5-HT1A, 5-HT2A, 5-HT7,
NMDA
2. MICTURITION (T8-9, L3-L4, L6-S1, rats)
NMDA, non-NMDA,
tachykinins, NO, ATP, D2-like
5-HT1A, 5-HT7
3. EJACULATION (L3-L4, rats)
Alpha-1, 5-HT2B,
5-HT2C, 5-HT1A,
5-HT7, D2-like
4. SCRATCHING (L7-S1, cats)
NMDA, non-NMDA
* thoracolumbar-distributed network with key elements in L1 & L2 (Dimetrijevic et al., 2000, Nishimaru et al., 2000)

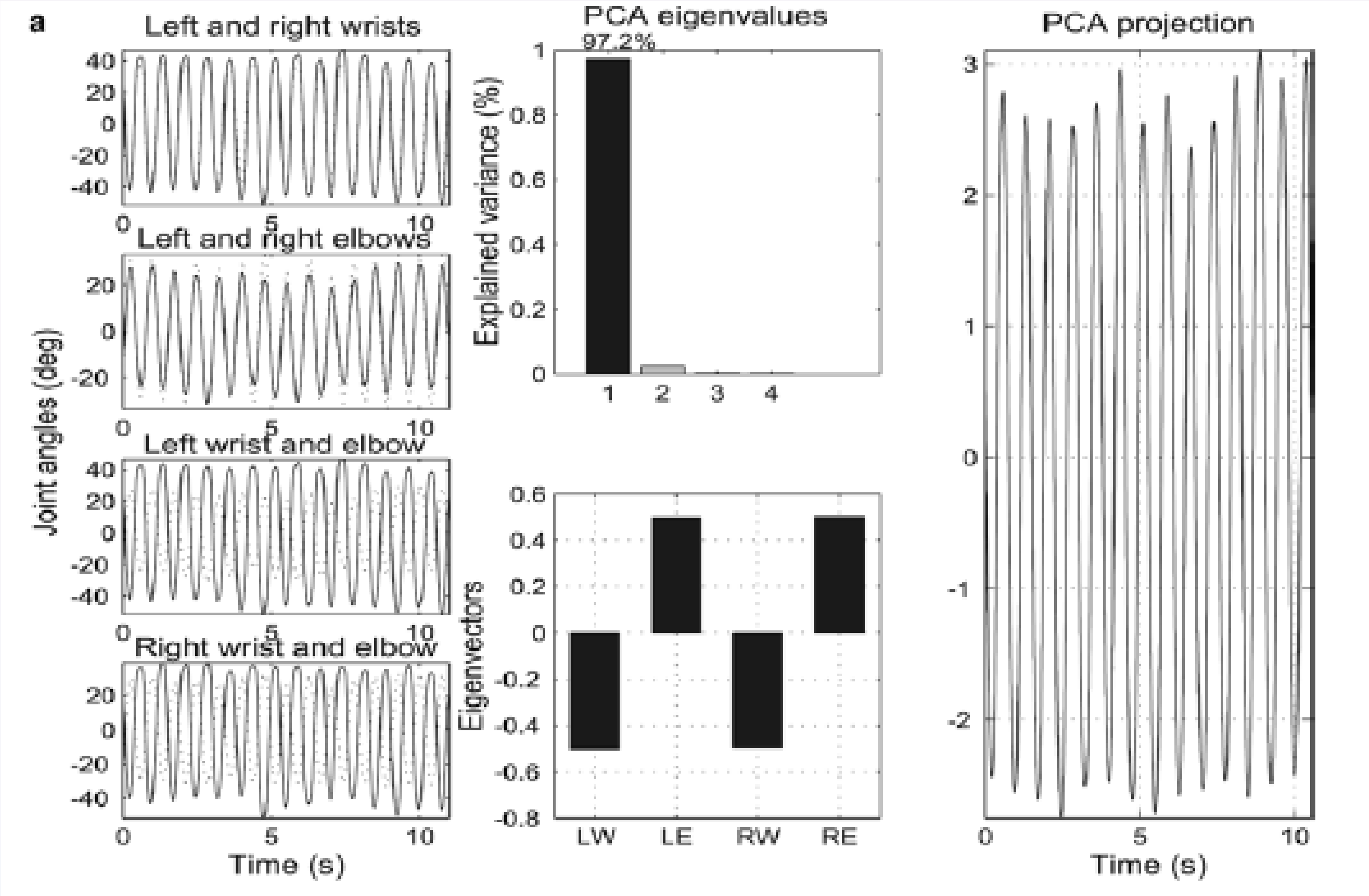
Evidence

- Hip flexion in paraplegics
- Rhythmic coupling of arms and legs during walking
- Other:
  - Preference for in-phase coordination patterns (Kelso et al, 1990).

Experimental conditions (elbow-wrist)



Li et al. (2005) Exp. Brain Res.



Forner-Cordero et al. 2005. Biol Cybern.

Padrões coordenação

EW_ININ-Iso-Iso.swf

EW_ININ-N-N.swf

EW_INAN-Iso-N.swf

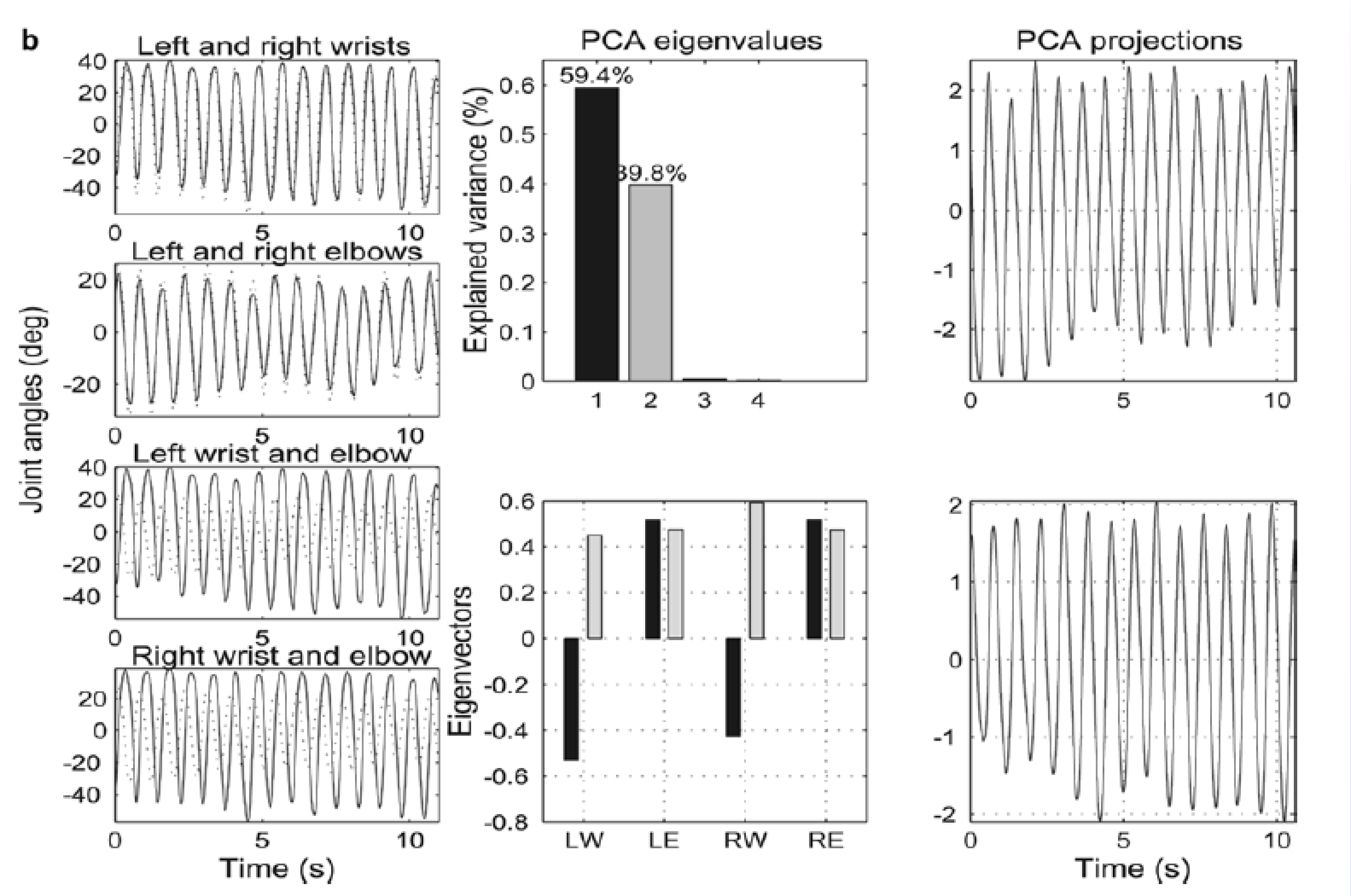
EW_INAN-Iso-N.swf

EW_ANIN-N-Iso.swf

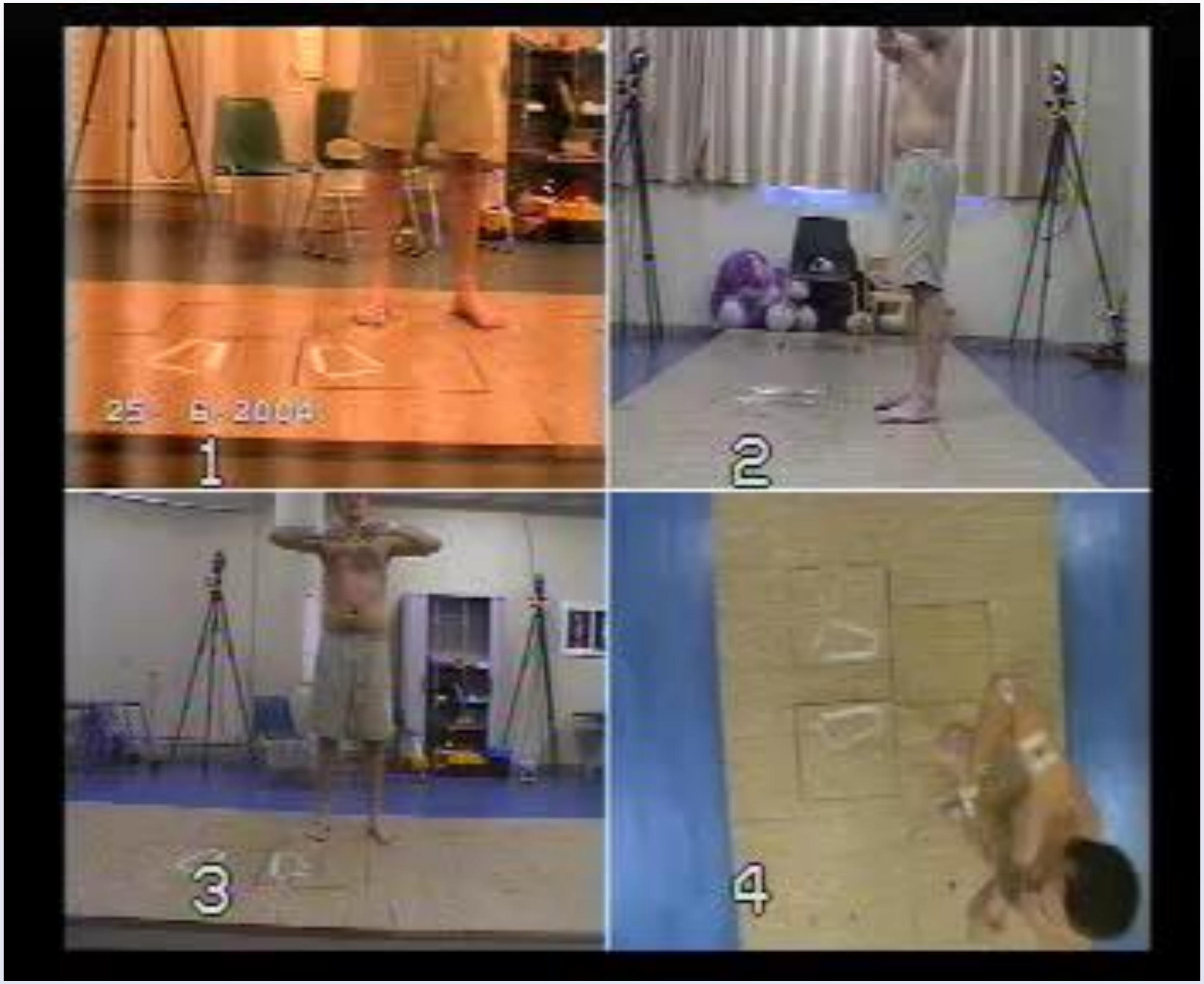
EW_ANIN-Iso-N.swf

EW_ANAN-Iso-Iso.swf

EW_ANAN-N-N.swf

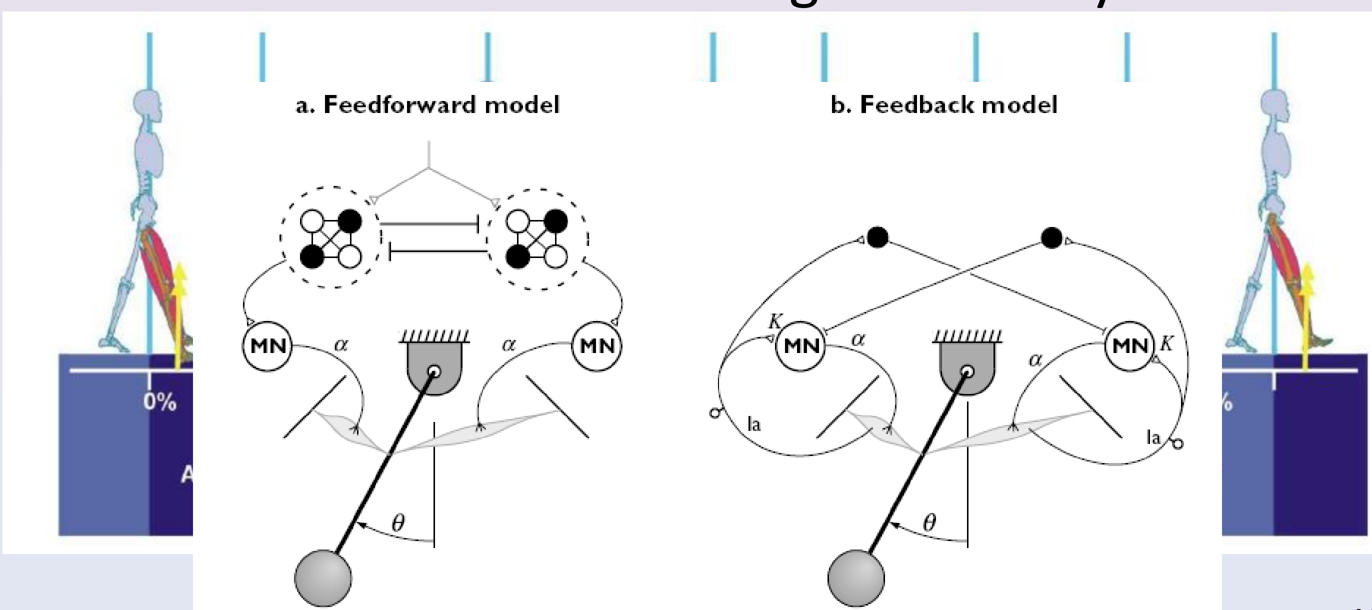


Forner-Cordero et al. 2005. Biol Cybern.


25 6 2004
1
2
3
4

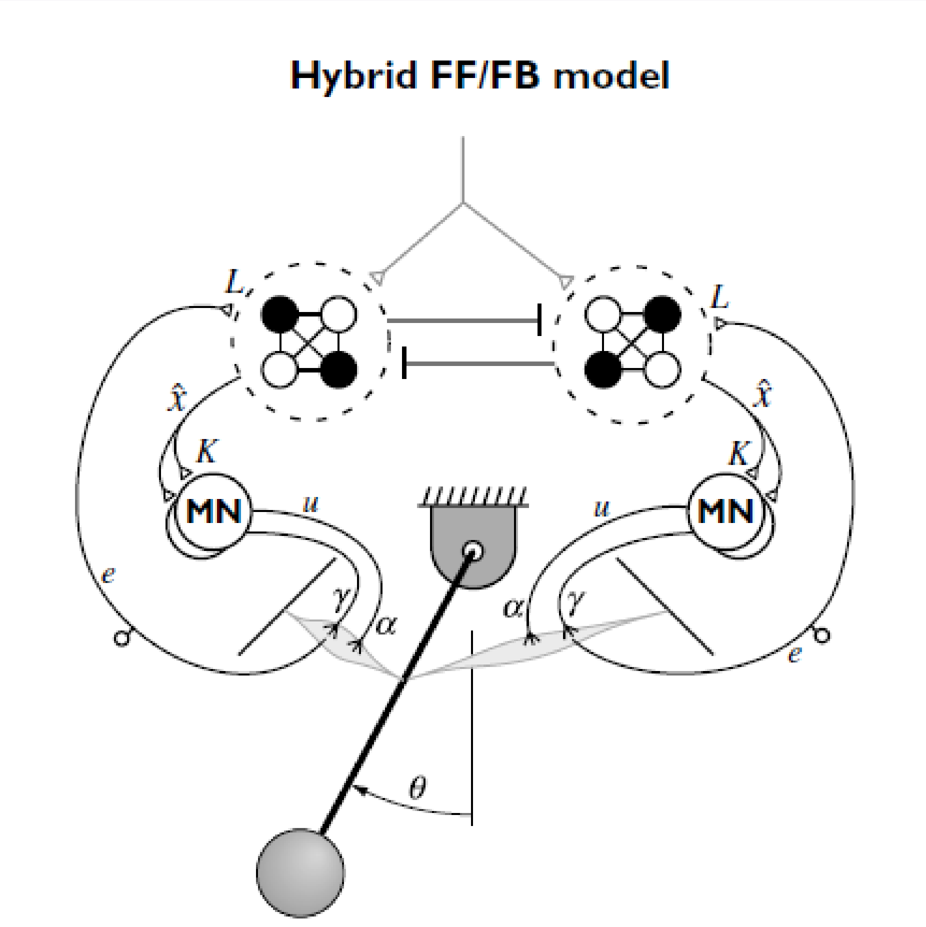
Human gait?

- “The human frame is built for walking. It has both the right kinematics and the right dynamics”.
- **Neurofisiology: CPGs + reflexes** .
  - **CPGs**: neural circuits that generate rhythmic activity



Kuo, 2002. Motor Control

New hypothesis: hybrid model

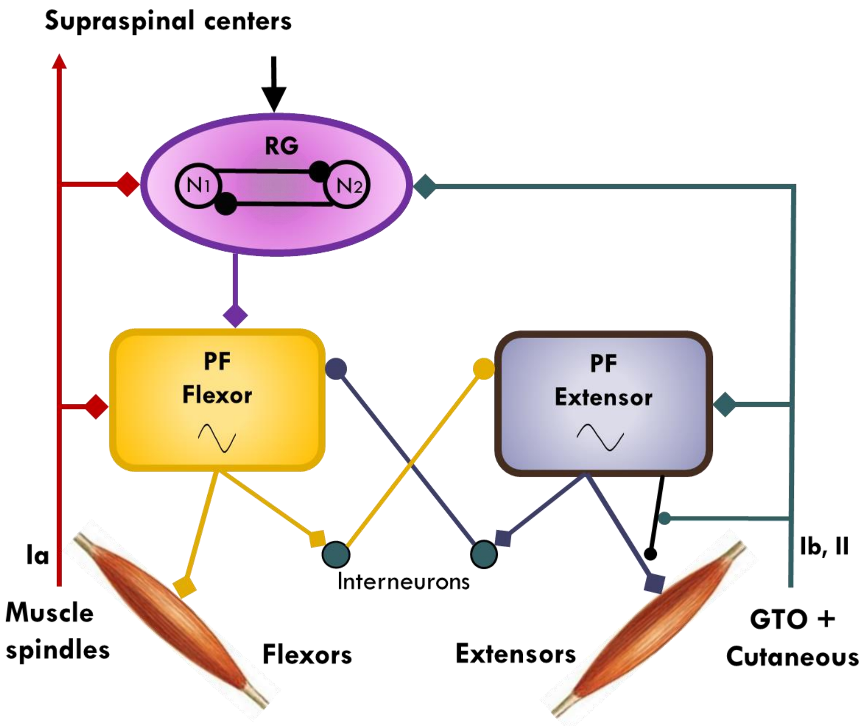


Kuo, 2002.
Motor Control.

Asymmetric CPG

Proposed control architecture:

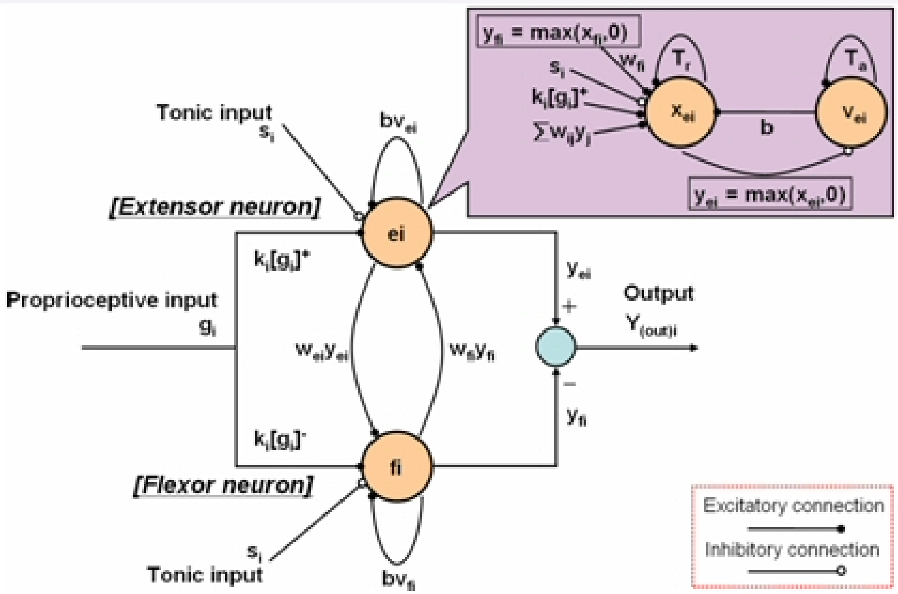
- Flexor function is mainly controlled by higher centers:
    - Gai initiation or termination
- Extensor function is mainly controlled by sensory afference:
    - Leg support during stance



Duysens&Forner-Cordero. Ann. Rev. Control, 2019

Contents

Matsuoka model



$$T_r \dot{x}_{ei} + x_{ei} = -w_{fi} y_{fi} - \sum_{j=1}^{n} w_{ij} y_j - b v_{ei} - \sum k_i [g_i]^+ + s_i \qquad T_a \dot{v}_{ei} + v_{ei} = y_{ei}$$

$$y_{ei} = [x_{ei}]^+ = \max(x_{ei}, 0)$$

$$T_r \dot{x}_{fi} + x_{fi} = -w_{ei} y_{ei} - \sum_{j=1}^{n} w_{ij} y_j - b v_{fi} - \sum k_i [g_i]^- + s_i \qquad T_a \dot{v}_{fi} + v_{fi} = y_{fi}$$

$$y_{fi} = [x_{fi}]^+ = \max(x_{fi}, 0) \quad (i = 1, 2, \cdots, n)$$

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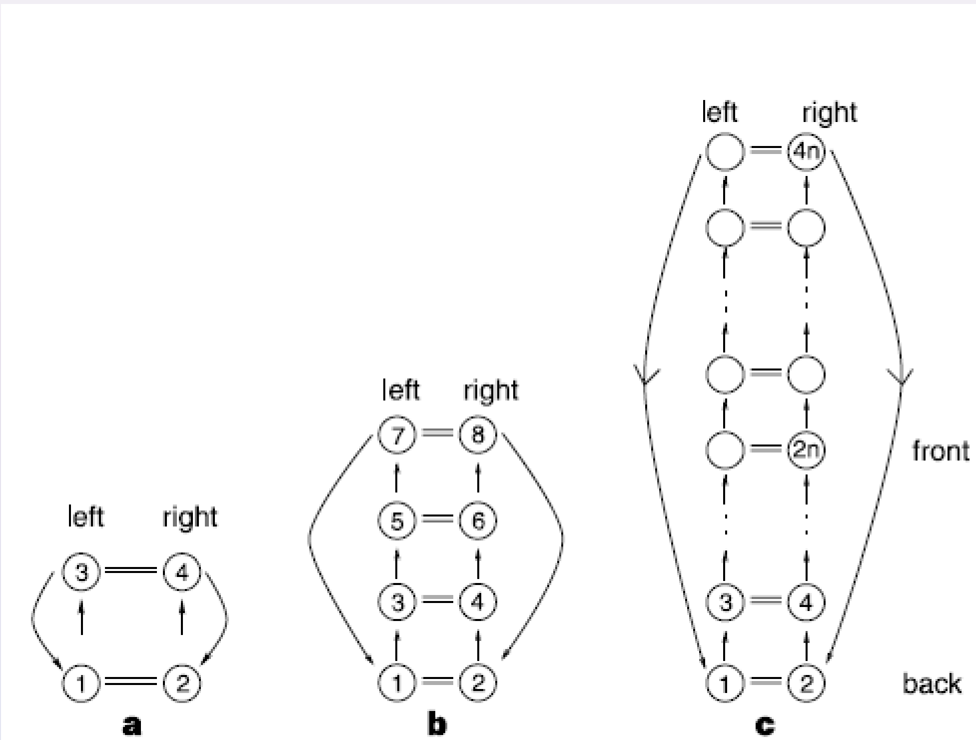
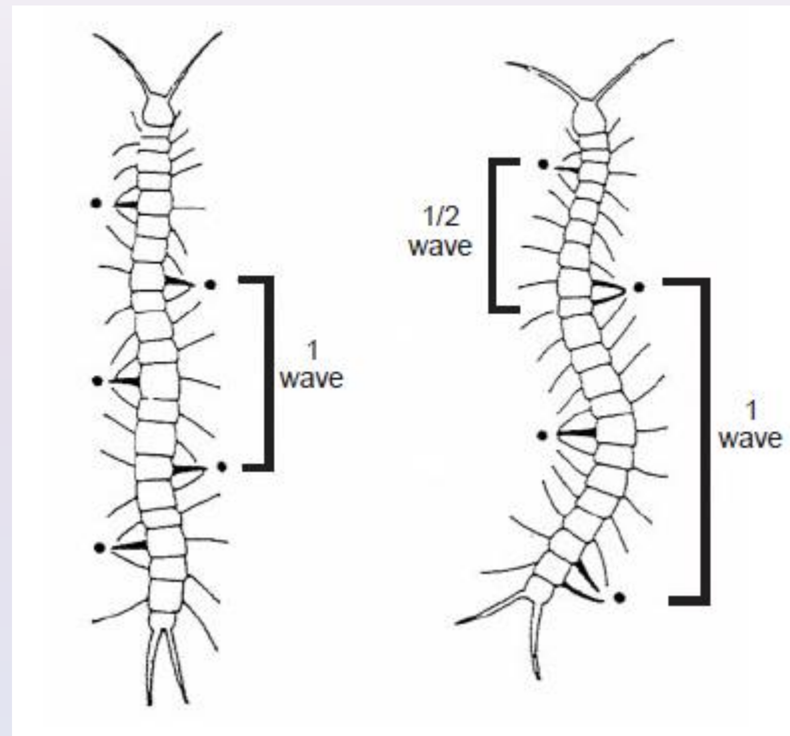
Theoretical model of locomotion

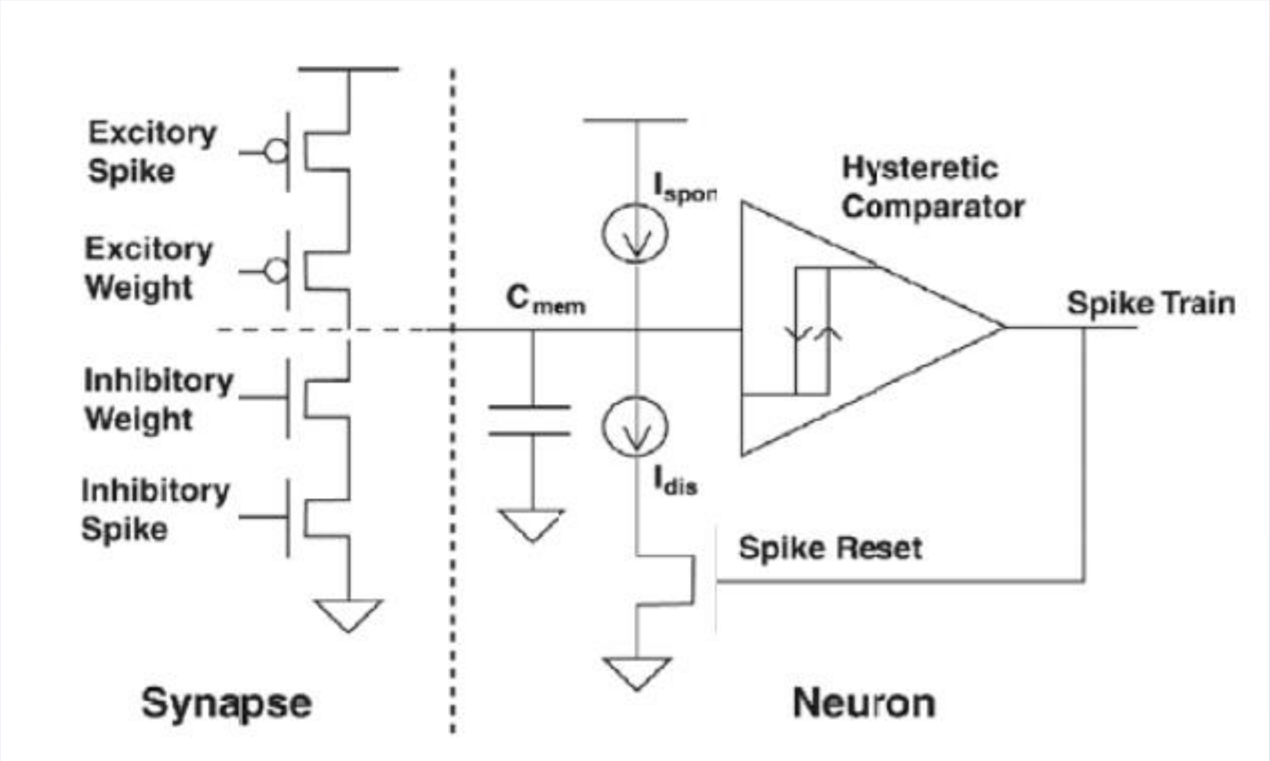




Golubitsky et al, 1999. Nature

Models

- Integrated circuit simulate CPG
  - » Lewis et al. 2000. Biol Cybern.



CPG models

- Matsuoka:
  - (Matsuoka, 1985. Biol. Cybern.)
  - Activation and fatigue
  - Half Center Oscilators
- Van der Pol
  - Non-linear oscilators
- Other

Matsuoka model

- Activation and neuron state:

$$\tau_u \cdot \dot{x}_i = -x_i - \beta \cdot v_i - \sum w_j^i \cdot y_j + u_0 + feed_i$$

Neuron state

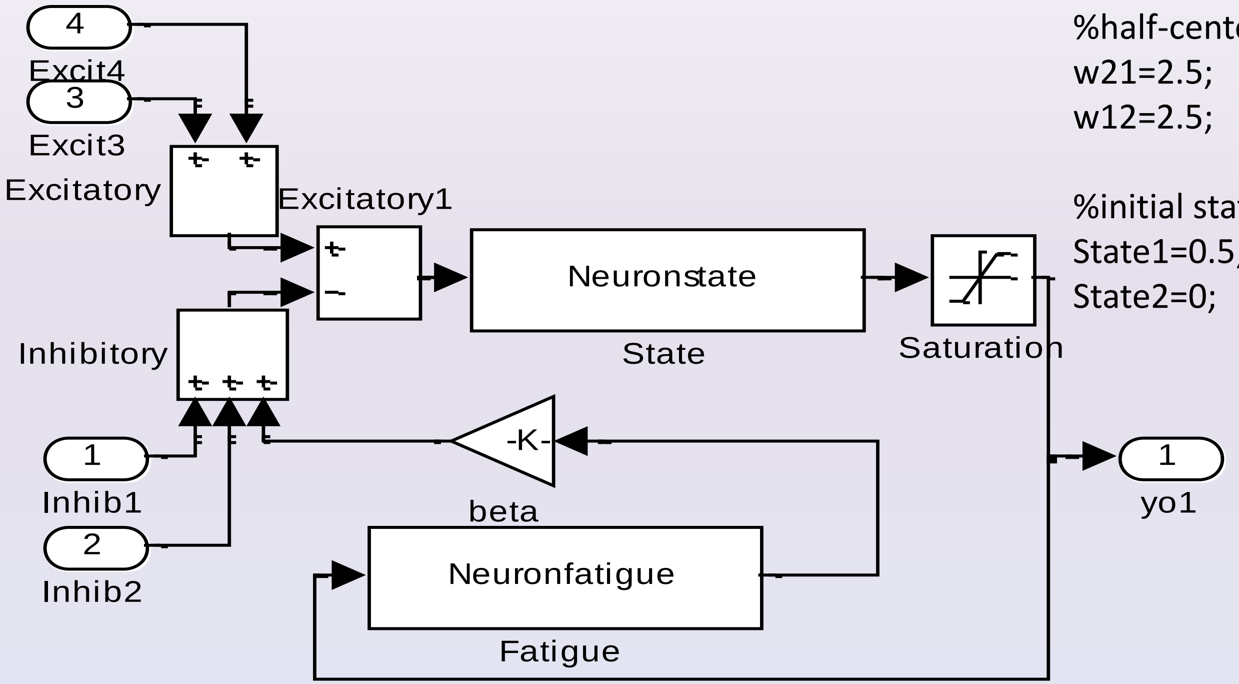
Weighted inputs from other neurons

Neuron fatigue

$$\tau_v \cdot \dot{v}_i = -v_i + \max(0, y_j)$$

External inputs:
- Higher levels
- Sensory inputs

Matsuoka model



%neuron paramters
Tu=0.3;
Tv=0.6; %ratio Tu/Tv=0.5
bbeta=2.5;
%half-center connection
w21=2.5;
w12=2.5;

%initial states of the neurons
State1=0.5;
State2=0;

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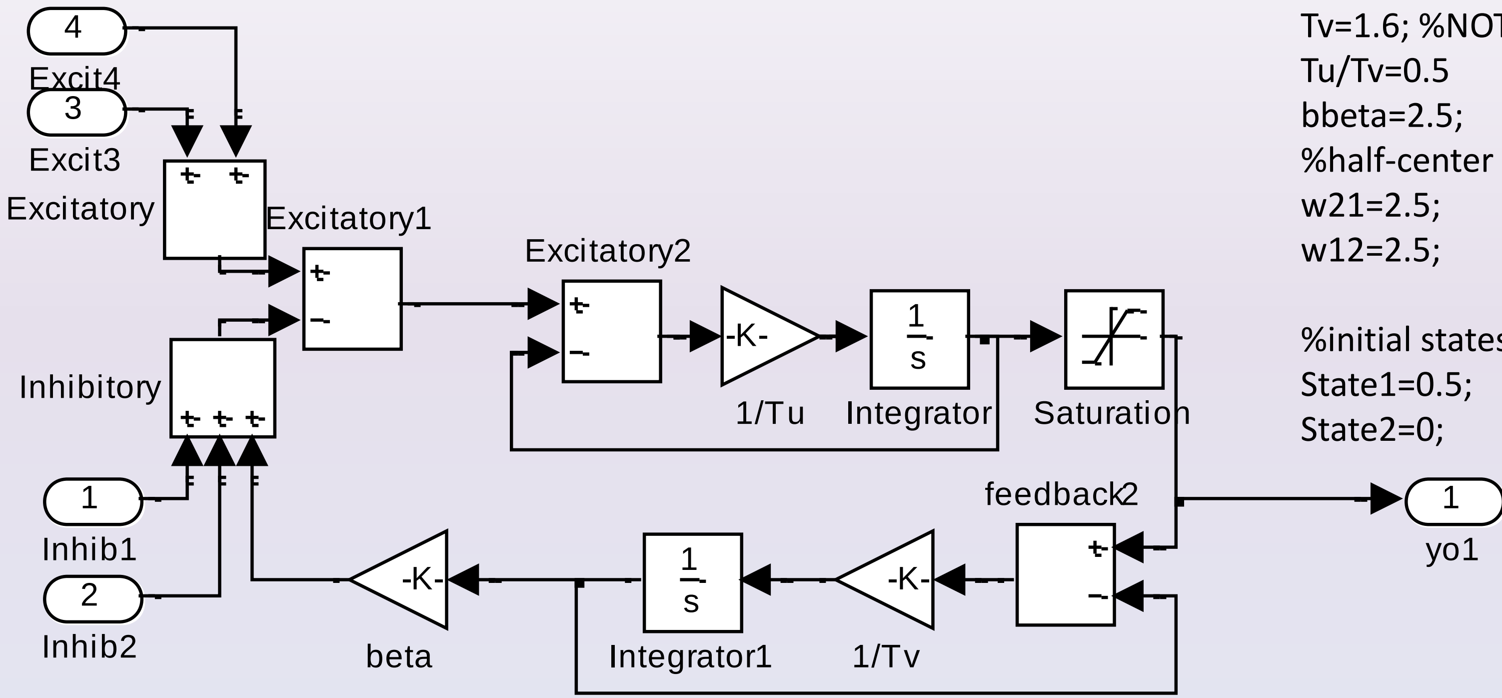
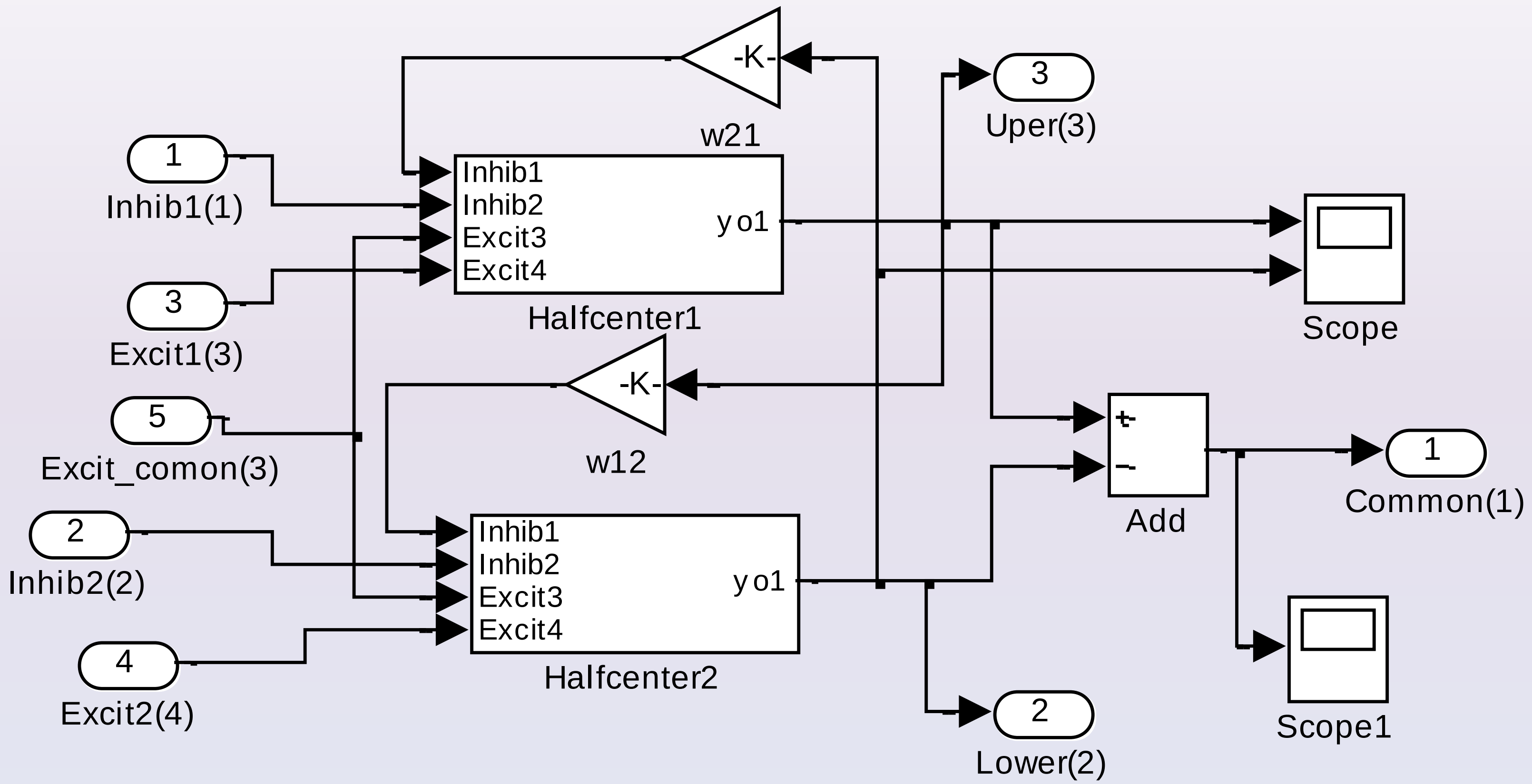
Matsuoka model



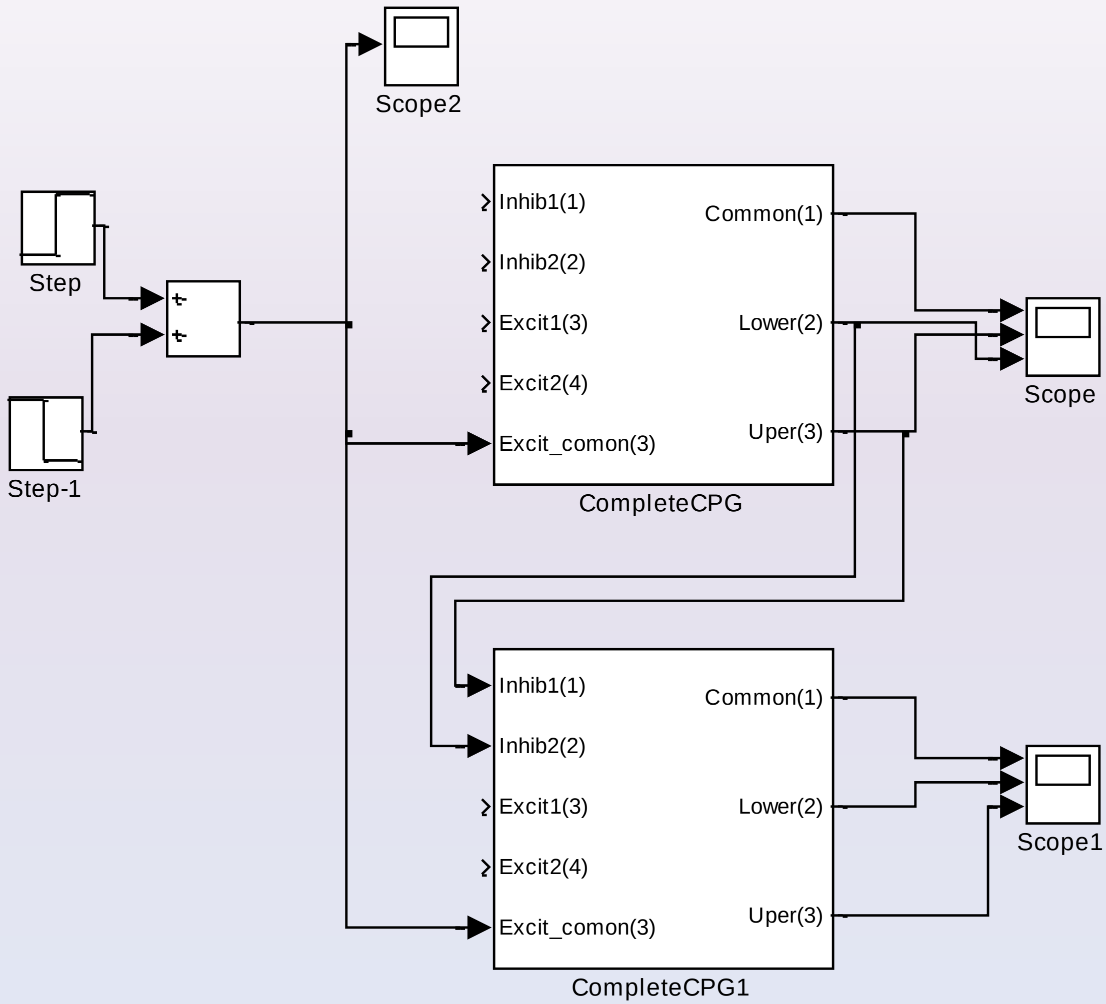
%neuron paramters
Tu=0.4;
Tv=1.6; %NOT ratio
Tu/Tv=0.5
bbeta=2.5;
%half-center connection
w21=2.5;
w12=2.5;

%initial states of the neurons
State1=0.5;
State2=0;

Matsuoka model



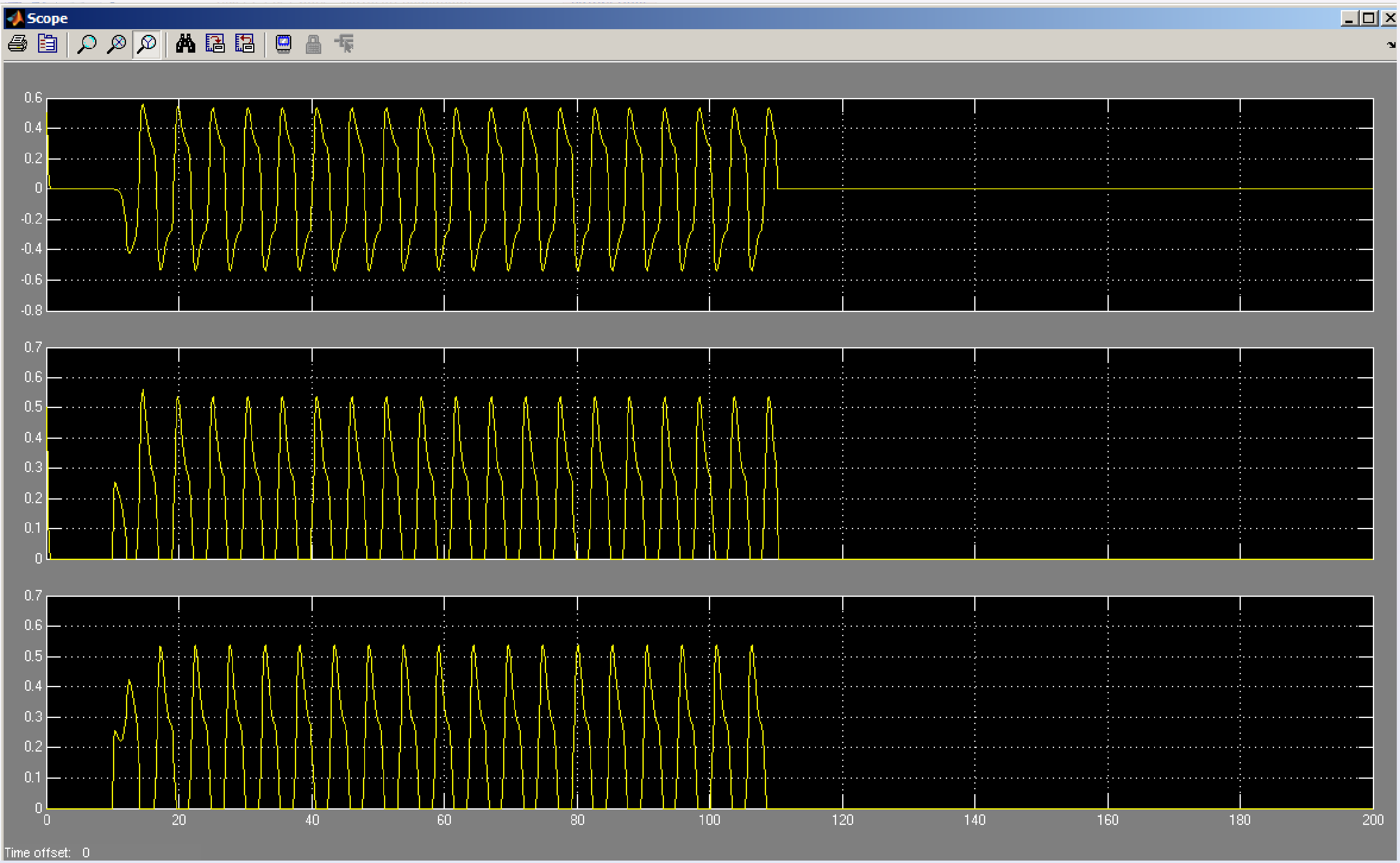
Matsuoka model



Matsuoka model

- Parameter adjustments:
  - Criteria to guarantee convergence to limit cycle
  - Experimental adjustment of the weights
- It does not exist a general methodology
  - Empirical adjustments
- Network topology dependence

Matsuoka model

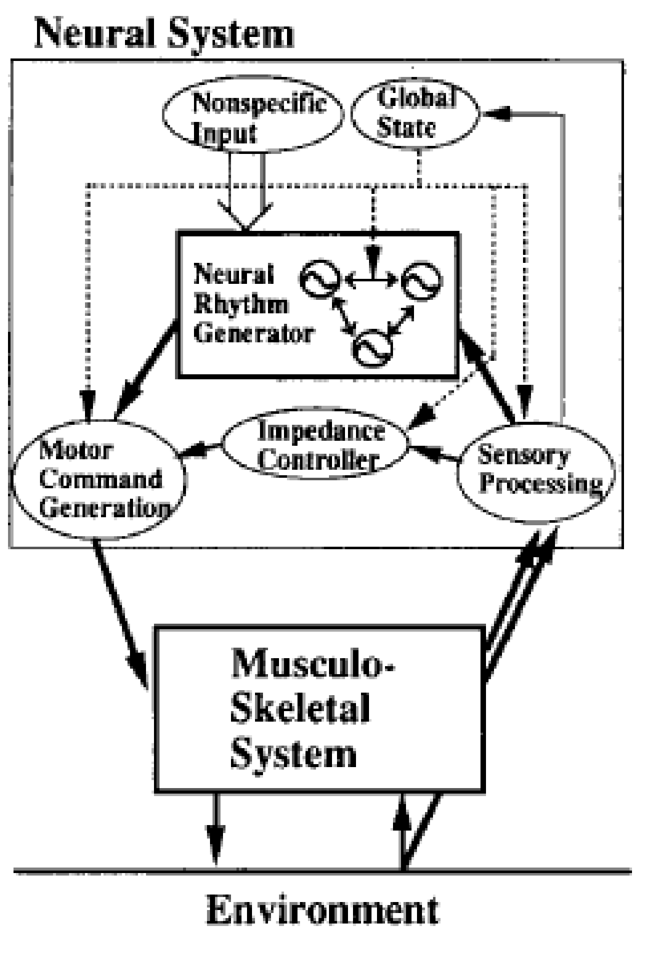


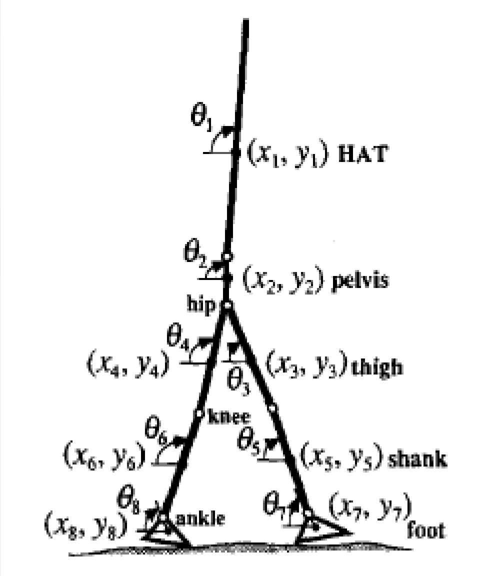
Contents

Biped robots

- Simulations:
  - Taga, 1995: Biped gait
  - Others
- Real robots:
  - Morimoto, 2004
  - Nakanishi,

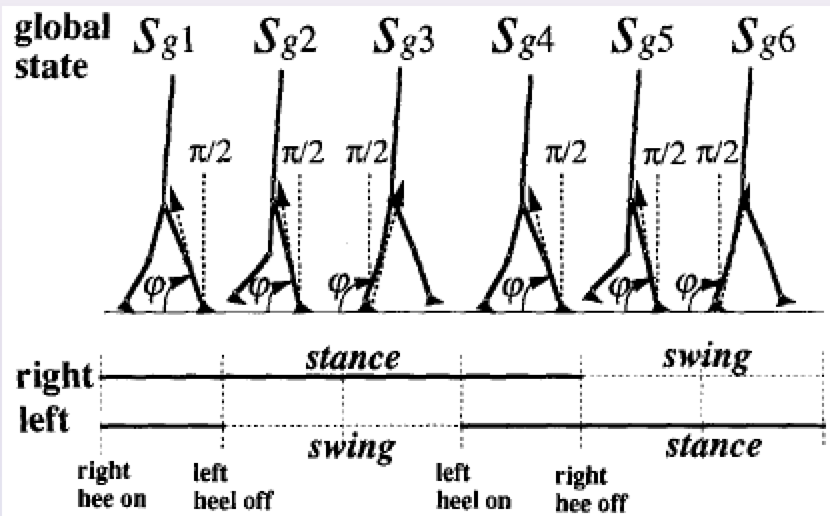
Taga model

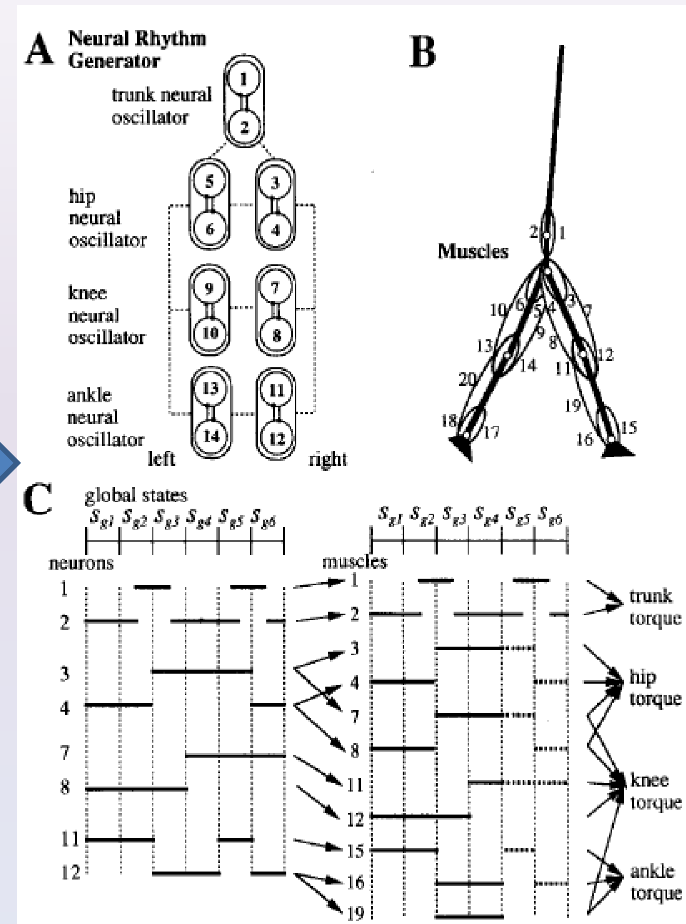




Taga, 1995. Biol. Cybern.

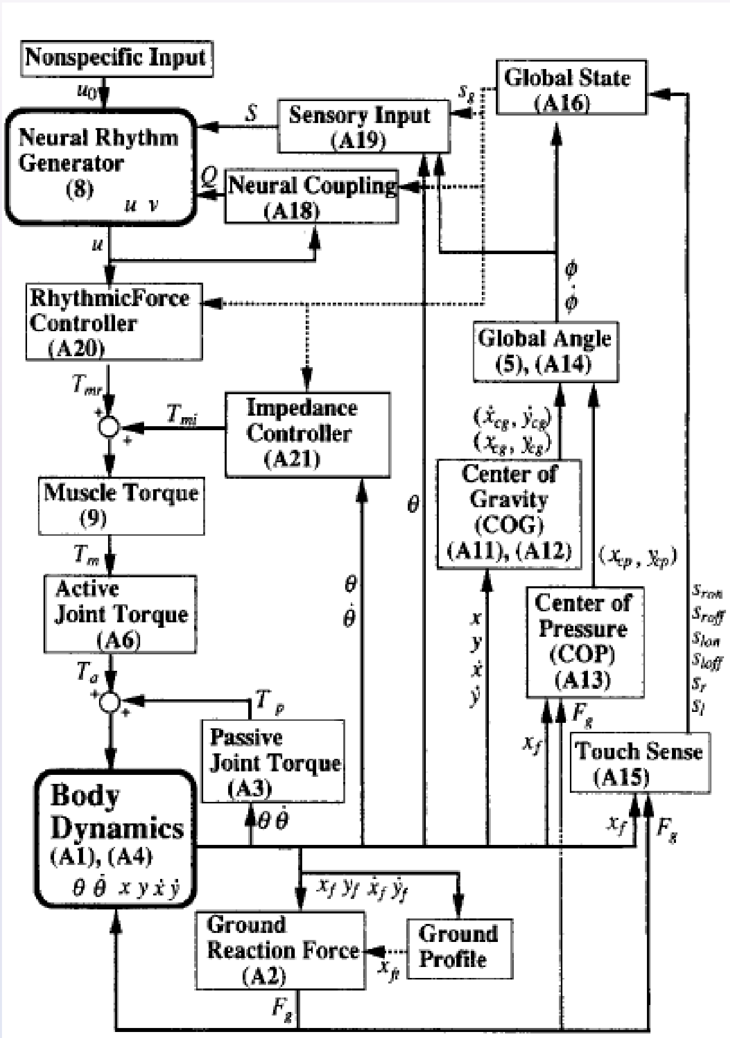
Taga model

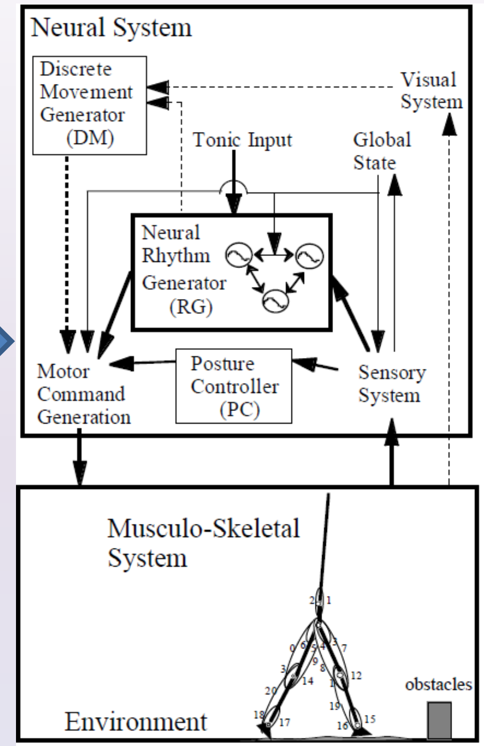


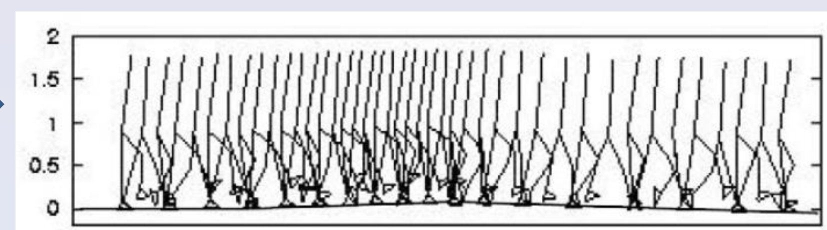


Taga, 1995. Biol. Cybern.

Taga model





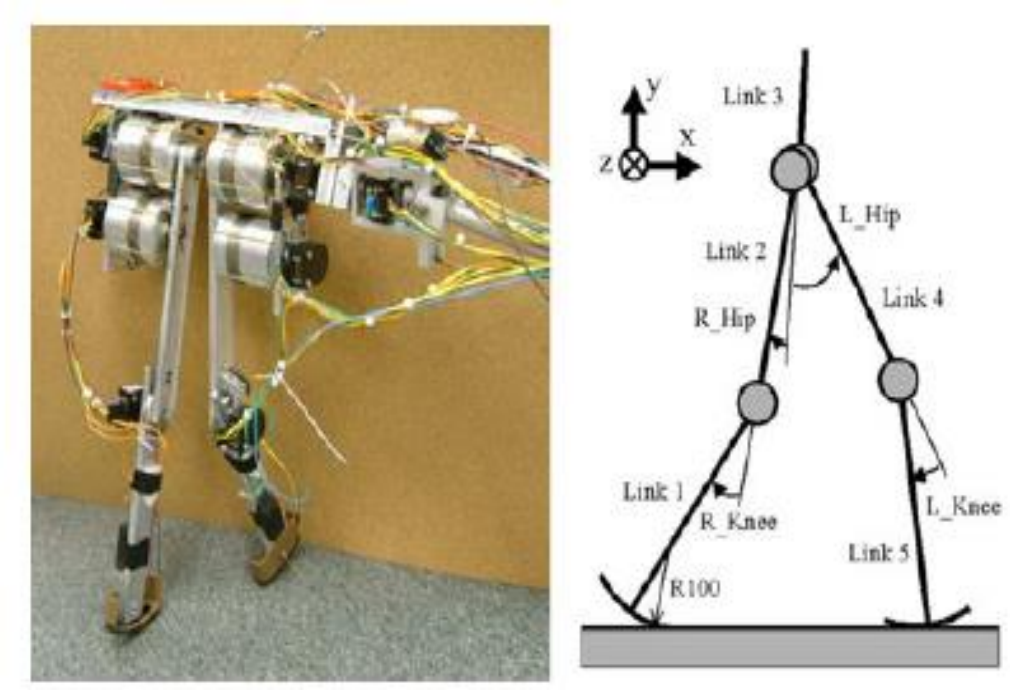


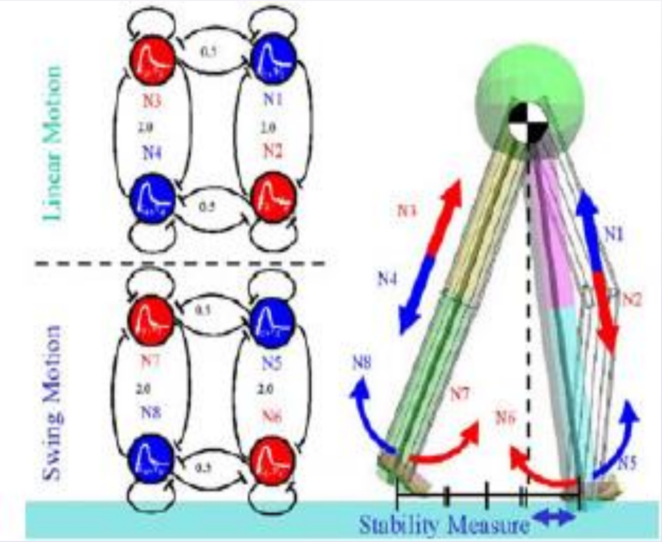
Taga, 1995. Biol. Cybern.

Morimoto Robot

Uses two CPGs to generate:

1. Linear motion
2. Oscillatory motion

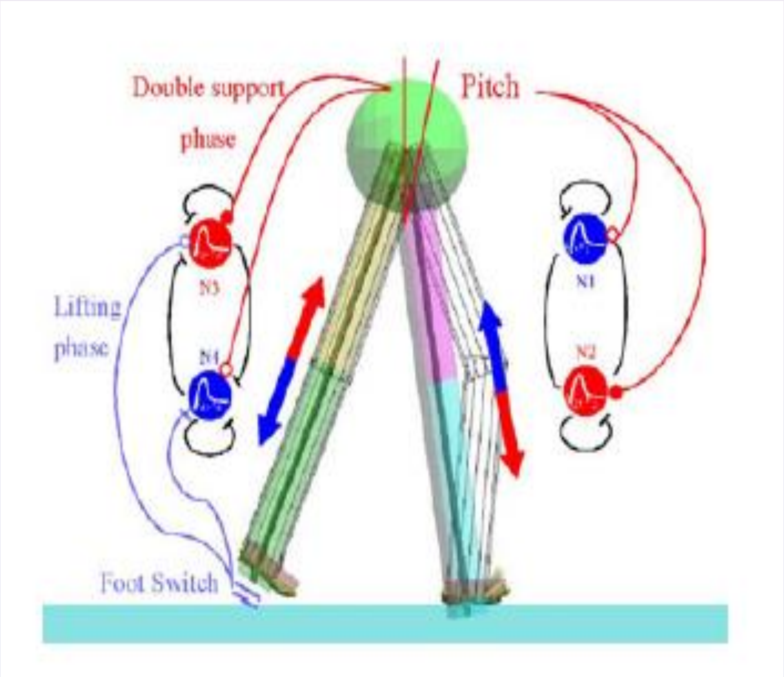


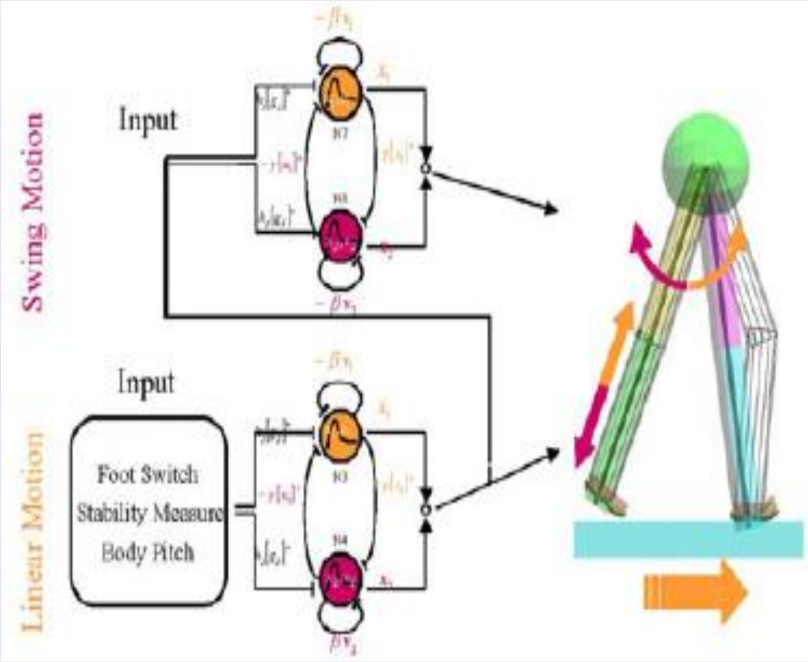


Morimoto et al. ICRA2004

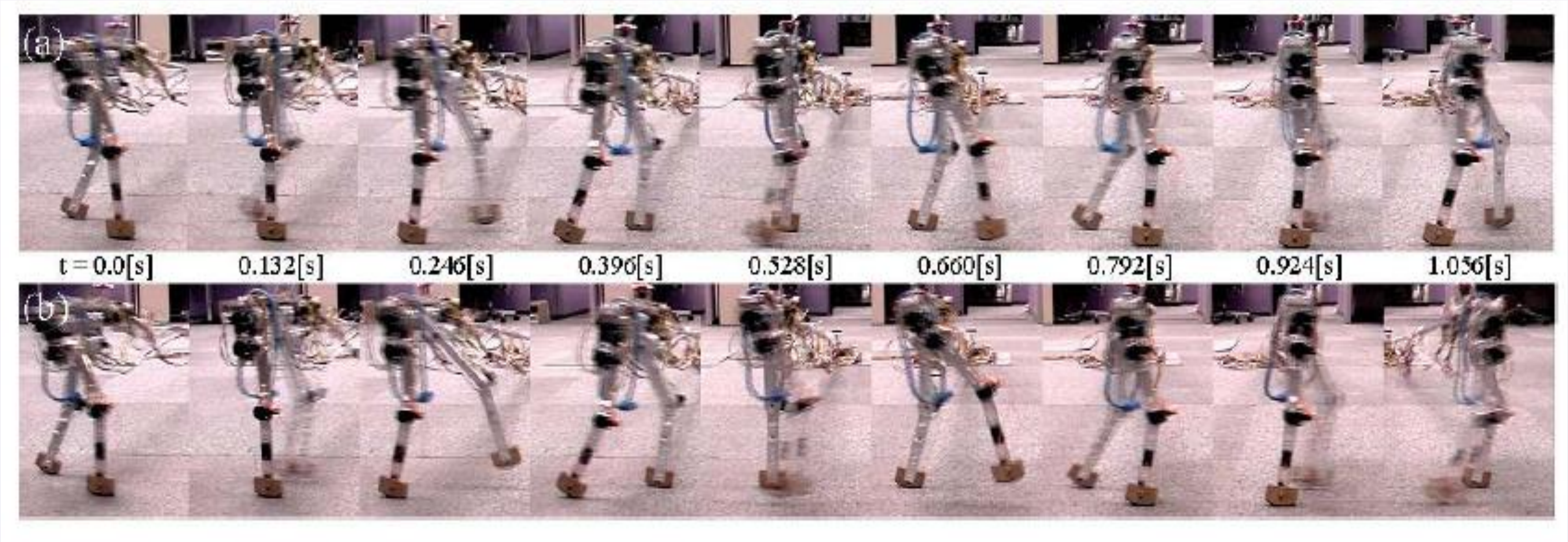
Morimoto Robot

Uses sensory feedback to modulate the gait cycle





Morimoto et al. ICRA2004

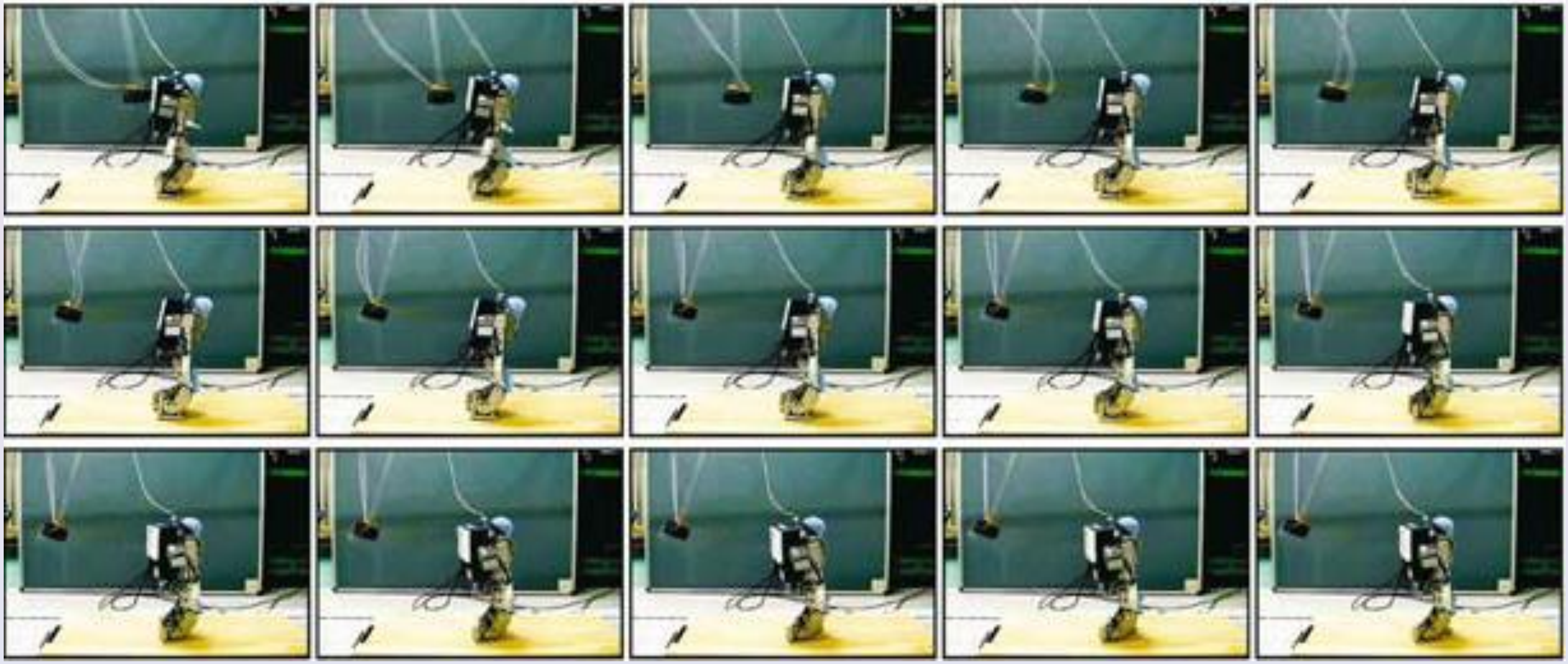


Morimoto et al. ICRA2004

Nakanishi Robot

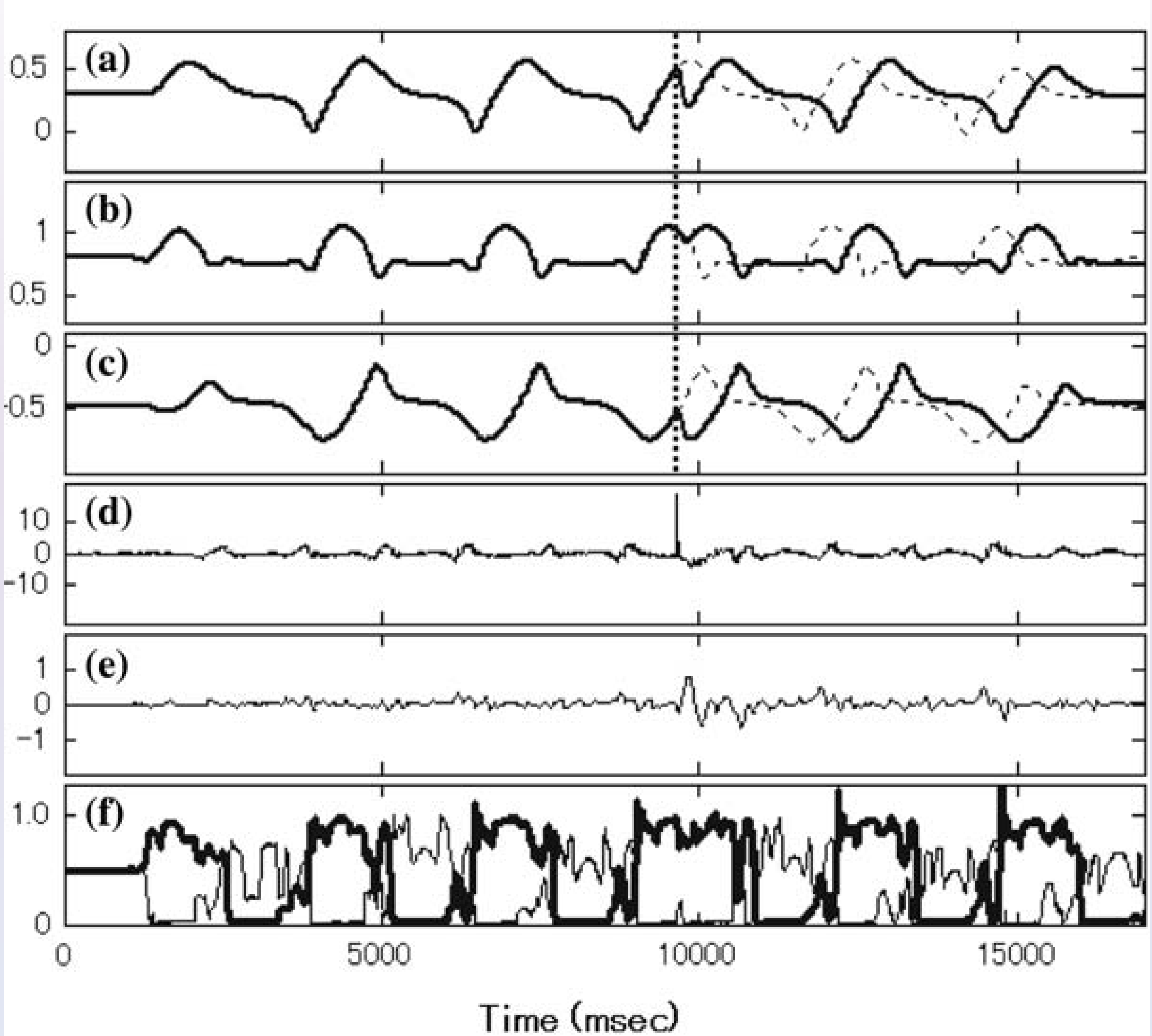
Resets the CPG phase

Response to perturbations: robot push on the back



Nakanishi et al, 2006. Biol. Cybern.

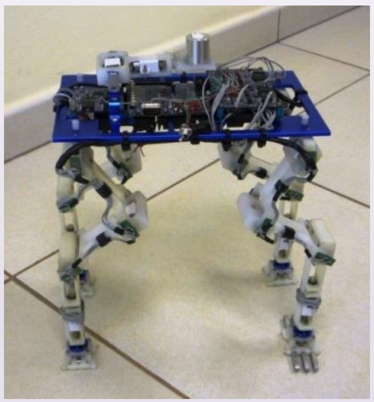
Nakanishi Robot

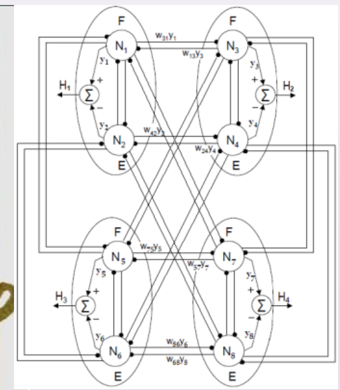


Nakanishi et al, 2006. Biol. Cybern.

Laboratório de Biomecatrônica

- Bioinspired robots





Kamambaré, Robot camaleão (Bernardi R, Forner-Cordero A, Cruz J 2011)

http://www.youtube.com/watch?feature=player_detailpage&v=Bjy4TeEvnT8

Video Kamambaré

GAIT CONTROL
BIPED ROBOTS

GAIT CONTROL BIPED ROBOTS

- Biological models of gait control: Asymmetrical CPG
- Biped stability criterion: Predicted Step Viability
- Experimental study of gait: subliminar perturbations with metronome
- Bipo: Biped robot controller design and construction

GAIT CONTROL BIPED ROBOTS

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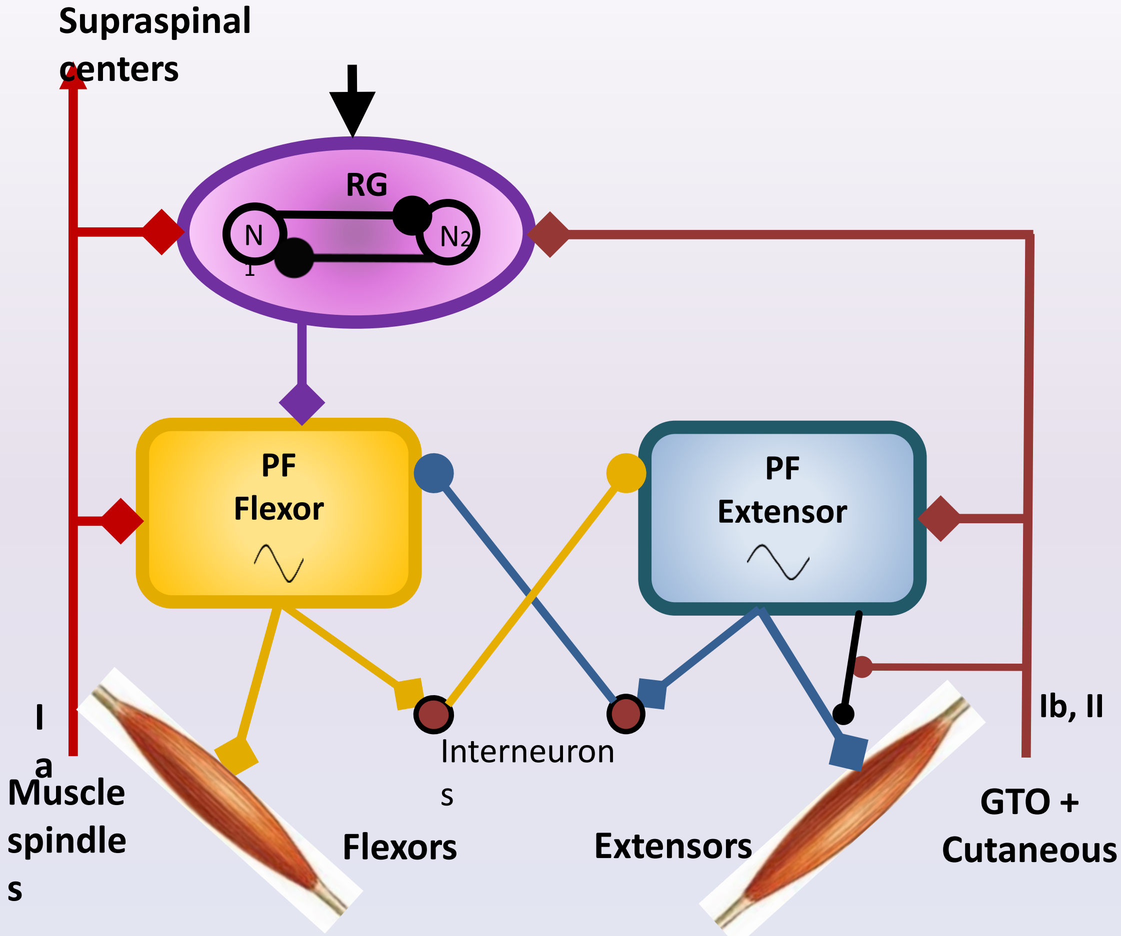
Supraspinal centers
RG
N1
N2
PF Flexor
PF Extensor
I a
Muscle spindles
Interneurons
Flexors
Extensors
Ib, II
GTO + Cutaneous

GAIT CONTROL BIPED ROBOTS

Biological models of gait control: Asymmetrical CPG

Biped stability criterion: Predicted Step Viability

Experimental study of gait: subliminar perturbations with metronome

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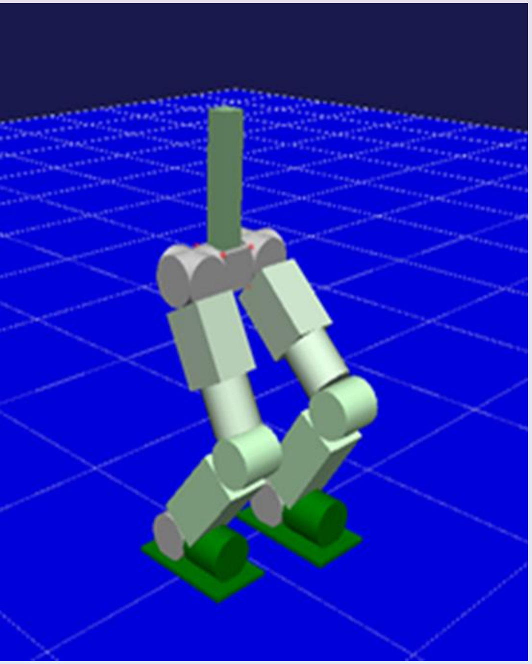
Predicted step viability

Journal of the Brazilian Society of Mechanical Sciences and Engineering (2019) 41:548
https://doi.org/10.1007/s40430-019-2052-9

TECHNICAL PAPER

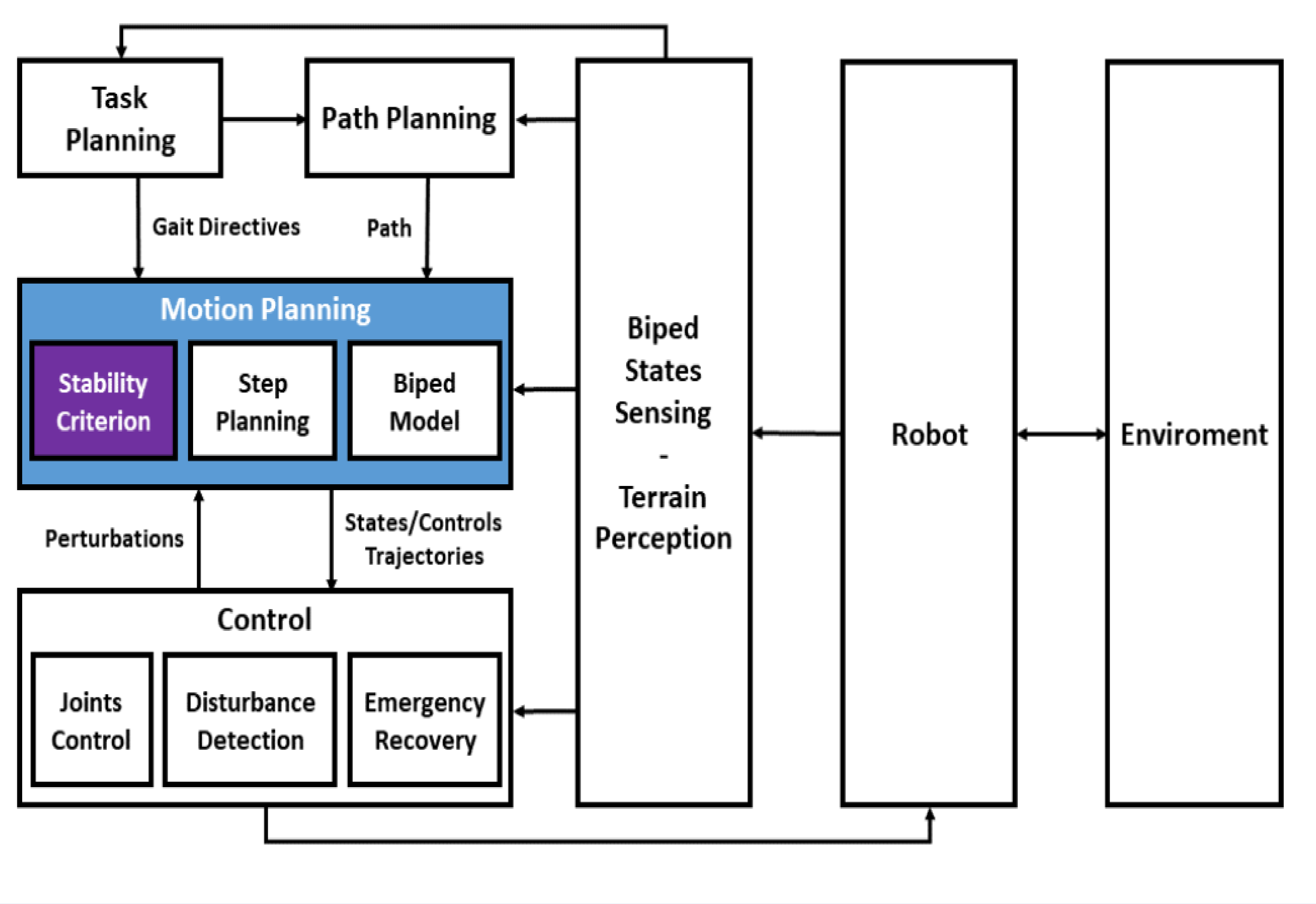
Predicted Step Viability: a stability criterion for biped gait

Luis Filipe Rossi[1] · Pedro Parik-Americano[1] · Ivan Fischman Ekman Simões[1] · Arturo Forner-Cordero[1]



- The robot should walk to complete a given task (Task Planning) along a certain path (Path Planning).
- Stability criterion is part of the Motion Planning in which the step is prescribed (e.g., walk on flat surface).
- The analytical model of the biped is similar to the concept of the internal model in human motor control and it is used by the controller to synthesize gait.

Diagram gait control structure of biped robots



Rossi et al JBSMSE, 2019

GAIT CONTROL BIPED ROBOTS

Biological models of gait control: Asymmetrical CPG

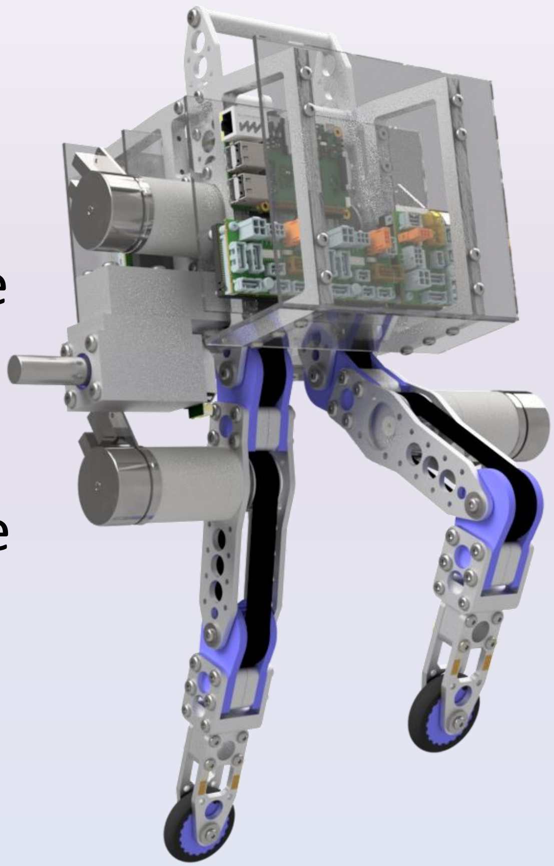
Biped stability criterion: Predicted Step Viability

Experimental study of gait: subliminar perturbations with metronome

Bipo: Biped robot controller design and construction

Bipedal Locomotion Research

- Development of a control algorithm for walking capable of withstand different types of perturbation and adapt for different walking conditions.
- Design and build a biped robot to serve as a testbed for different control strategies.
- Validate the proposed controller on the real robot
- MSc Student: Ivan Fischman Ekman Simões



Simões&Forner-Cordero ICAR, 2019

Obrigado