Locomotion: its biological control - onto robots

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Locomotion and its biological control

In all animals locomotion involves:

- *Initiation from the organisms' brain or by sensory input*
- *Guidance and regulation from the brain*
- *Sensory inputs signaling the position of the body and limbs in the world*
- *Proper integration of organism's mechanics*
- *Feedforward signals from a central pattern generator (CPG)*
- *Massive feedback from CPG to brain and from cpg to sensory control mechanisms - largely POSTIVE feedback!*

What is REALLY necessary?

- Sensory feedback is clearly necessary – some animals depend upon feedback almost exclusively

- Mechanics of the animal is clearly what produces the movement – there is power in the mechanics of movement, and several robots have been built in which the approach of using the mechanics for propulsion is primary control mechanism

- Is a feedforward signal needed to drive muscles?

What is REALLY necessary?

- **Swimming – movement through an aqueous medium – cannot be purely passive**
  - ***Walking could be passive, but not during uphill motion***
- **There could be a clock to generate a rhythm**
  - ***But a clock is not dynamic or flexible enough***
  - ***The range of necessary frequencies is too great***
- **Sensory feedback is necessary, but by itself it won't be fast enough for very rapid locomotion**

Central pattern generator(CPG)

- The logic argues for a feedforward drive of muscles if one wants an all purpose organism or robot

- ALL animals, except walking stick, use a CPG to generate signals to drive the muscles during locomotion

Universal principles

- This lecture will focus on a few universal principles – phenomena that are seen in all animals.
  - *CPG and its production of feedforward signals*
  - *Two classes of sensory interactions with the CPG*
- Such universals should be highly efficient
  - *They have been selected repeatedly over evolutionary time*
  - *Have allowed animals to escape predators and survive to procreate*

Additional points to be presented

- I will also draw attention to some biological phenomena in motor control that might offer advantages for the design of robots
  - *Co-activation of antagonistic muscles*
  - *A highly non-linear sensor and its potential for control (if time allows)*

For motor control lecture tomorrow afternoon:

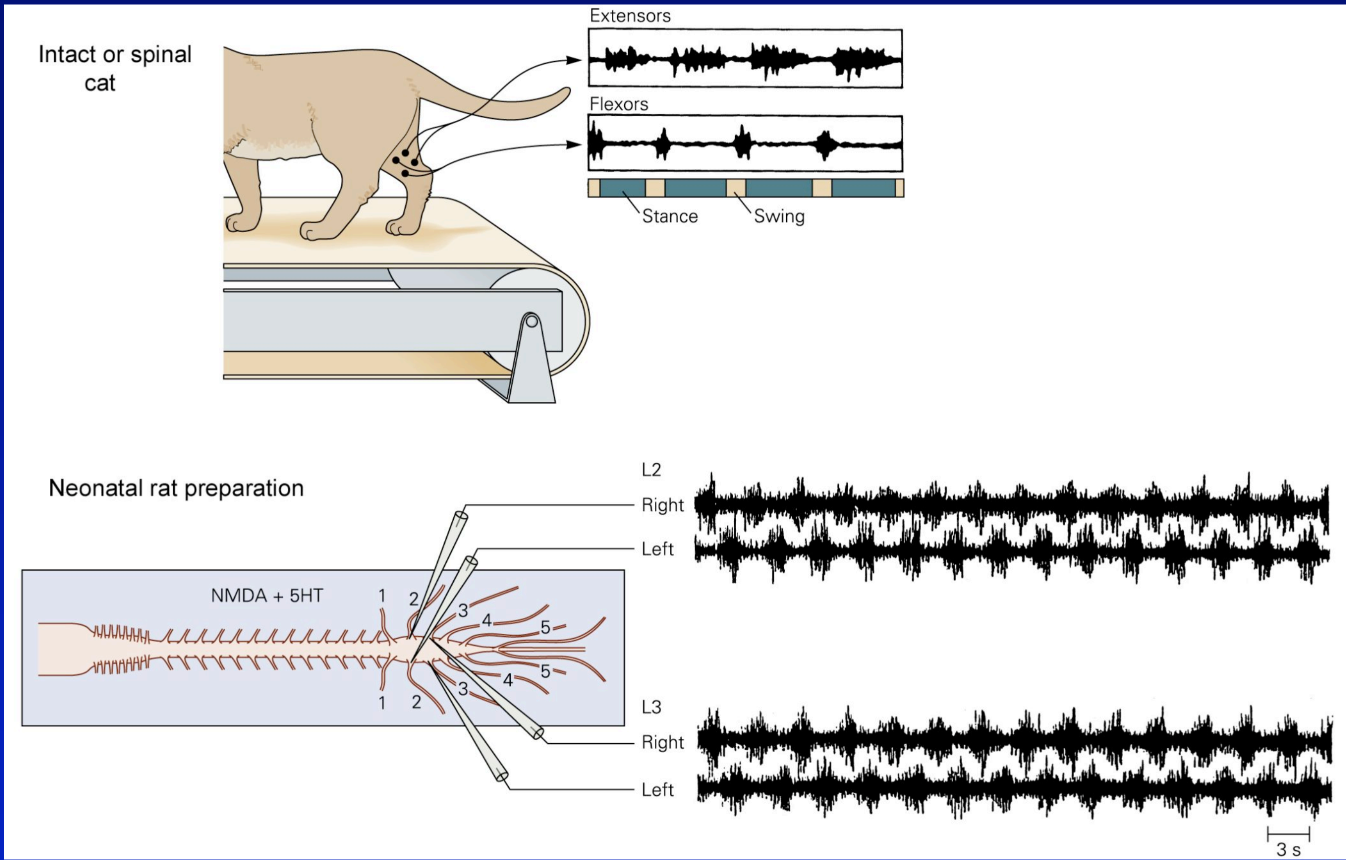
- **Going beyond locomotion to control of movement more generally especially in mammals:**
  - ***Details***
  - ***Facts***
  - ***Questions***

Onto Locomotor CPG in vertebrates

- Central pattern generator (CPG):
  - *Neural circuit that generates the feedforward signals to muscles during locomotion*
  - *CPG interacts strongly with sensory feedback, but can generate a default pattern in the absence of feedback*
  - *Interacts strongly with the brain, but can generate a default pattern without input from the brain*

Demonstration of CPG in mammals

- Spinal cat on a treadmill – no brain, but sensory feedback
- Neonatal rat – no feedback but brainstem

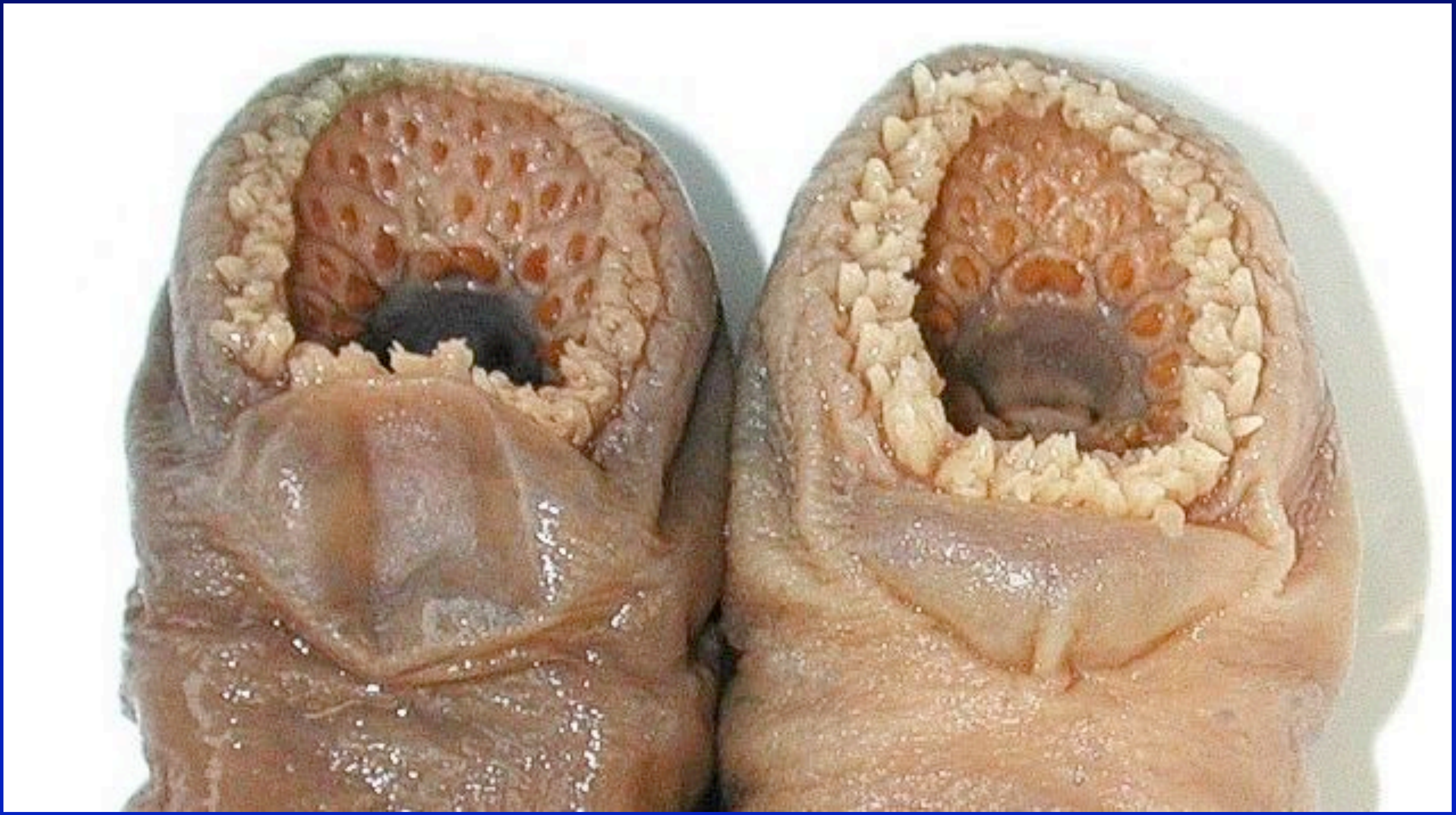


Meet the lamprey!

No appendages

Swims with traveling wave motion

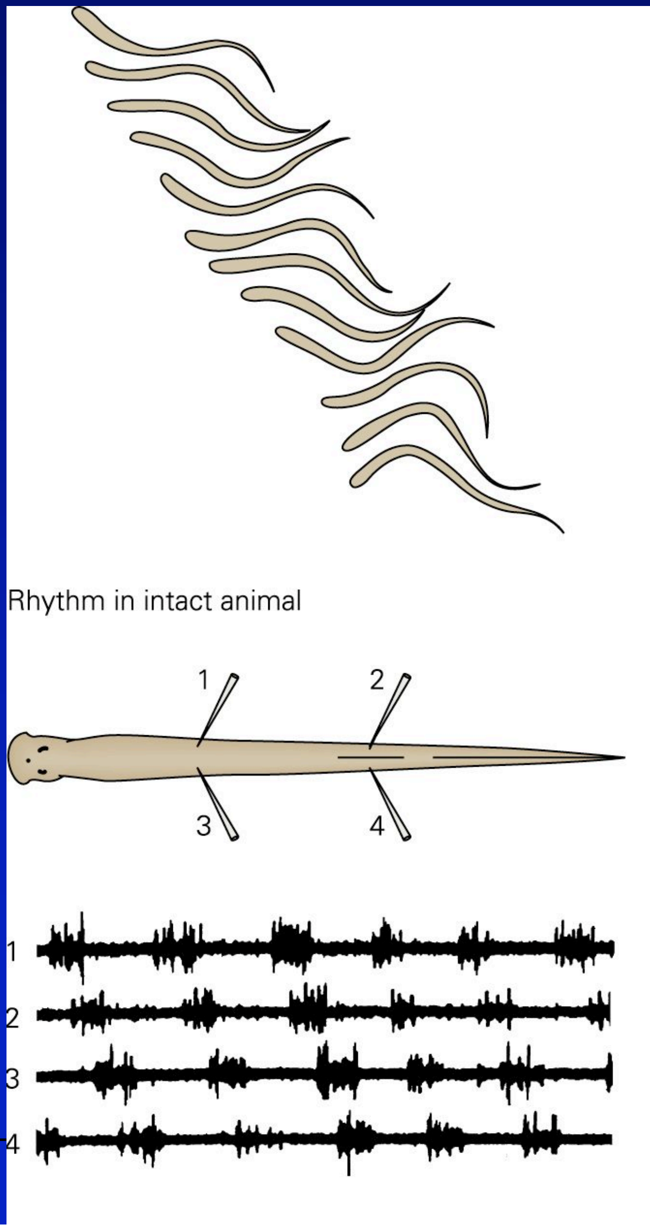
Meet the "lamprey"?



The REAL lamprey!

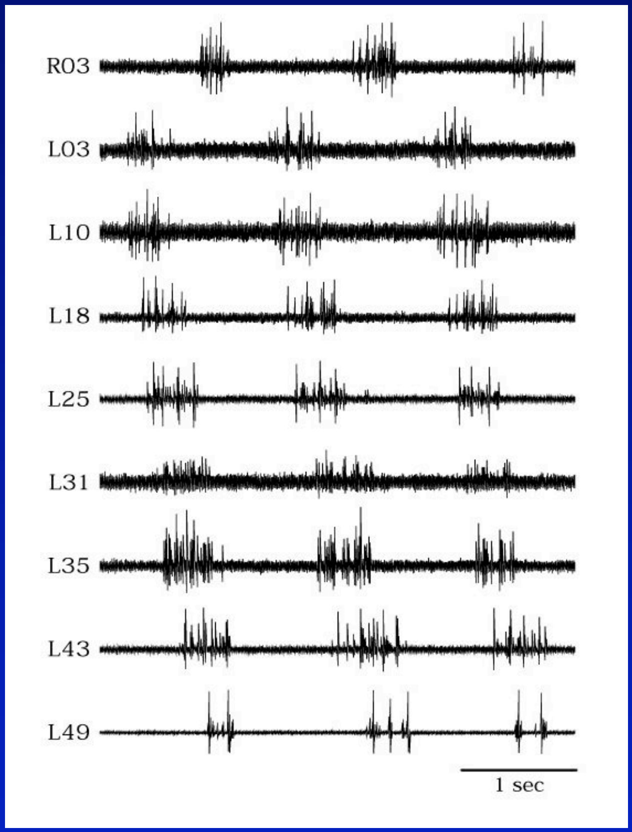
- Lamprey (9 eyes in Europe/8 eyes in Japan)
- Good vertebrate – all characteristics of higher vertebrates:
  - *But jawless*
  - *Basal vertebrate*
- Lamprey nervous system has the same organization as higher vertebrates
- It is possible to demonstrate a direct evolutionary path for the locomotor CPG from lamprey to human

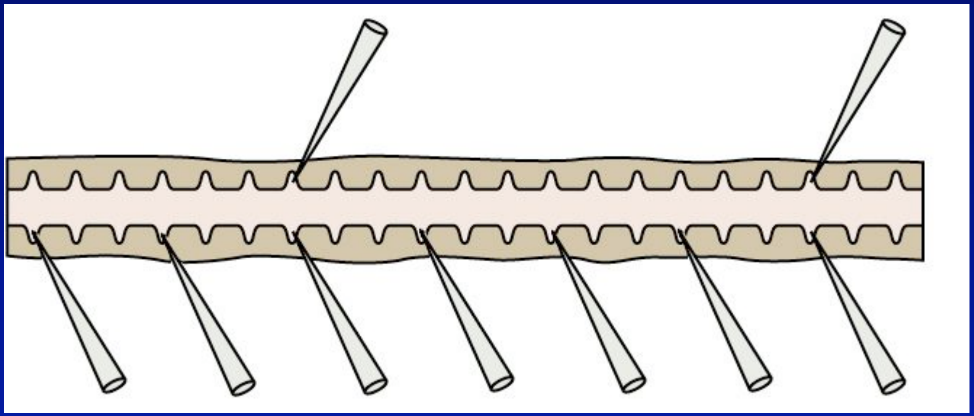
Lamprey swimming



- Traveling wave moves down the body
- Left and right sides alternate activity
- Activity travels uniformly down the body
- Constant phase relations among segments
- (data from T. Williams and P. Wallén)

Proof of spinal CPG





Work of Nicholas Mellen

- Isolated spinal cord of the primitive lamprey
  - *No brain*
  - *No sensory feedback*
  - *No movement*
- Full pattern generated
- Thus: spinal origin

Segmental Oscillator

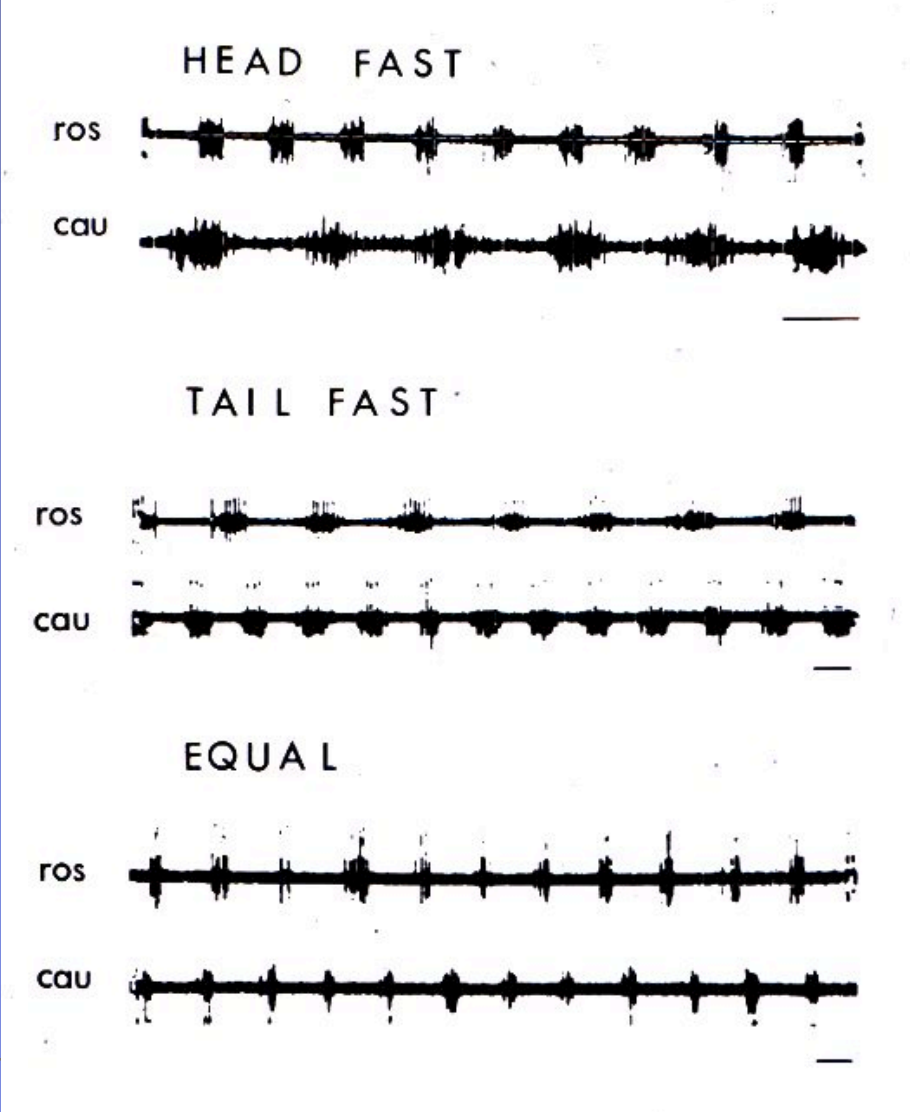
Fig. 6. Slowly oscillating membrane potential in spinal cord interneuron after administration of TTX to the bath ($2 \times 10^{-6} M$) containing 0.15 m*M* *N*-methylaspartate. [Modified from Grillner *et al.* (*36*)]

- **Intracellular recording from an interneuron in the presence of TTX (blocks spiking) – membrane potential is oscillating, most likely due to intrinsic properties of the membrane activated by drug NMDA (L-glutamate agonist)**
- **Typical: Segmental or unit oscillator consists of both induced oscillators and network oscillators – experimental evidence and models have suggested a basic structure, but incomplete**

Behavior of Segmental Oscillators

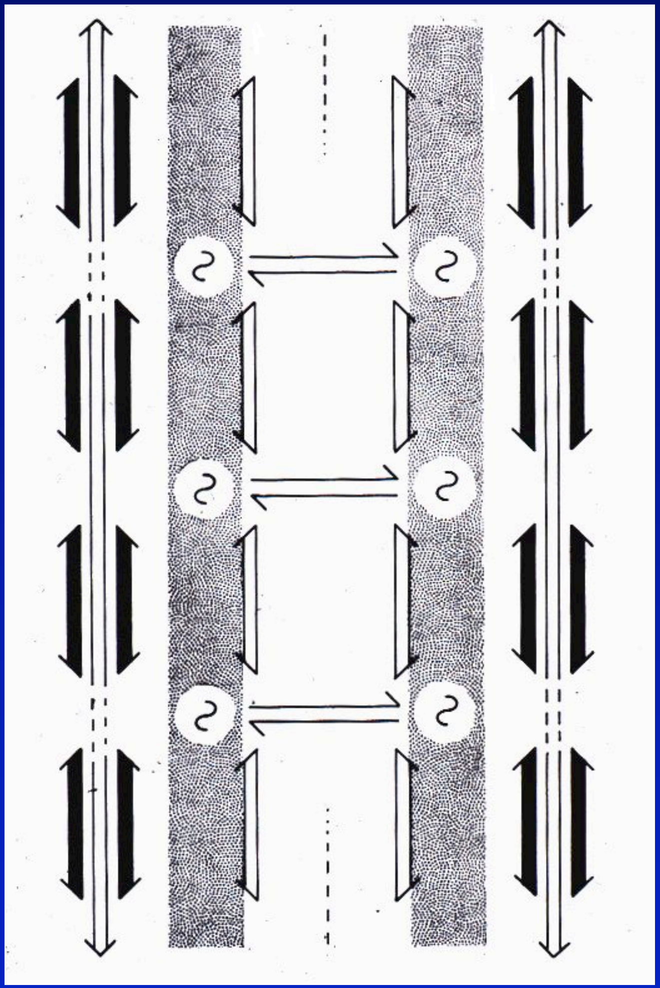
Spinal cords cut into two pieces

- **Oscillators have characteristic frequency under a given set of conditions**
- **Frequencies along the spinal cord are not systematically organized**
- **Only the intersegmental coupling maintains them at a single common frequency**



Structure and organization of CPG

- Basic structure in all vertebrates:
  - *CPG is distributed – not localized to single segment or region*
  - *Segmental oscillators – neural circuitry partially understood*
  - *Coupled across and up and down the spinal cord*



- Oscillator is:
  - *Non-linear, flexible and stable to perturbations*
  - *Capable of a wide range of frequencies*

Assumptions

- Single segment is two coupled oscillators
  - *Each hemisegment is one oscillator*
- Structure of oscillatory network is irrelevant
  - *We need only the phase of the oscillator on its limit cycle*
- Coupling is a function of the phase difference between the two oscillators that are coupled

Modeling the CPG as a chain of coupled oscillators

From Cohen, Holmes and Rand, 1982.

Later generalized by Kopell and Ermentrout

This general framework has been the backbone of theoretical work on coupled oscillators for over 20 years.

Two oscillators:

$$\dot{\theta}_1 = \omega_1 + \alpha_a H_a(\theta_2 - \theta_1),$$
$$\dot{\theta}_2 = \omega_2 + \alpha_d H_d(\theta_1 - \theta_2),$$

where

- θ_1 and θ_1 are absolute phases (mod 1).
- ω_1 and ω_2 are uncoupled frequencies.
- H_a and H_d are coupling functions.
- α_a and α_d are coupling strengths.

Chain of oscillators:

$$\dot{\theta}_i = \omega_i + \sum_{k=i-n}^{i-1} \alpha_k H_k(\theta_{i-k} - \theta_i), \quad i = 1, \ldots, n.$$

Coupling among oscillators

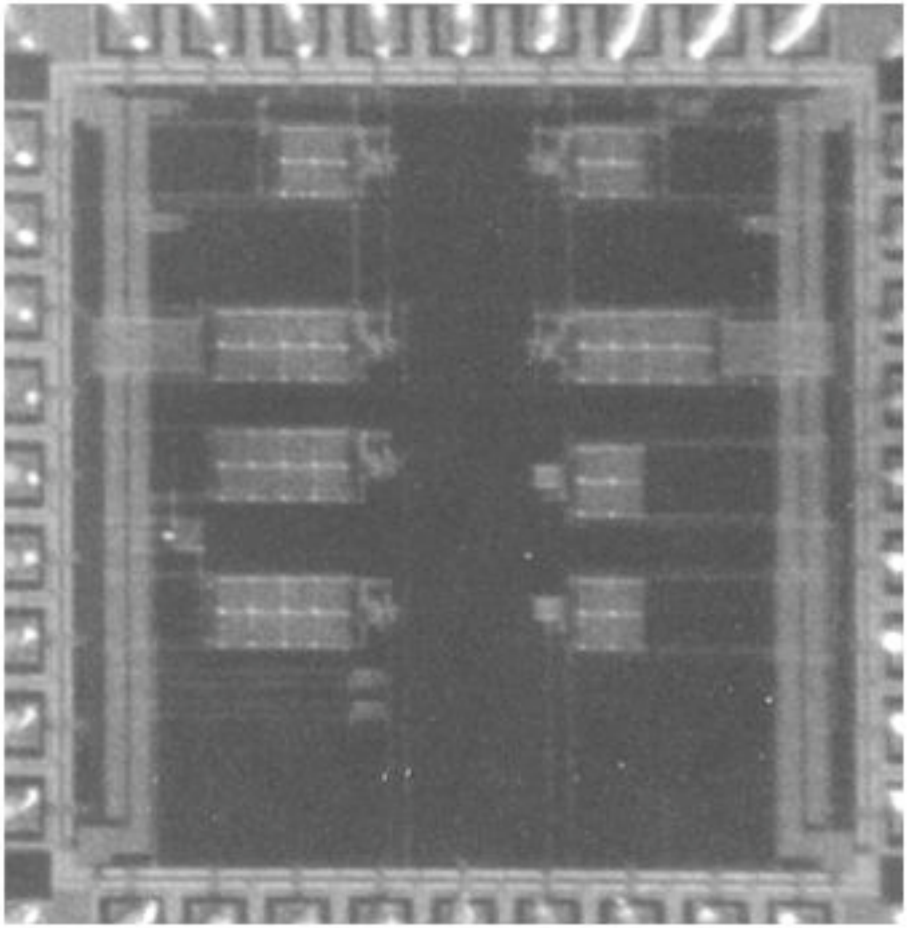
- Coupling varies across species:
  - *Strong when behavior is simple*
  - *Weak or flexible when behavior is complex*

- Lampreys: very strong coupling – few behaviors
- Humans and non-human primates: weak or flexible coupling – diverse and varied behaviors

Hardware Implementation I

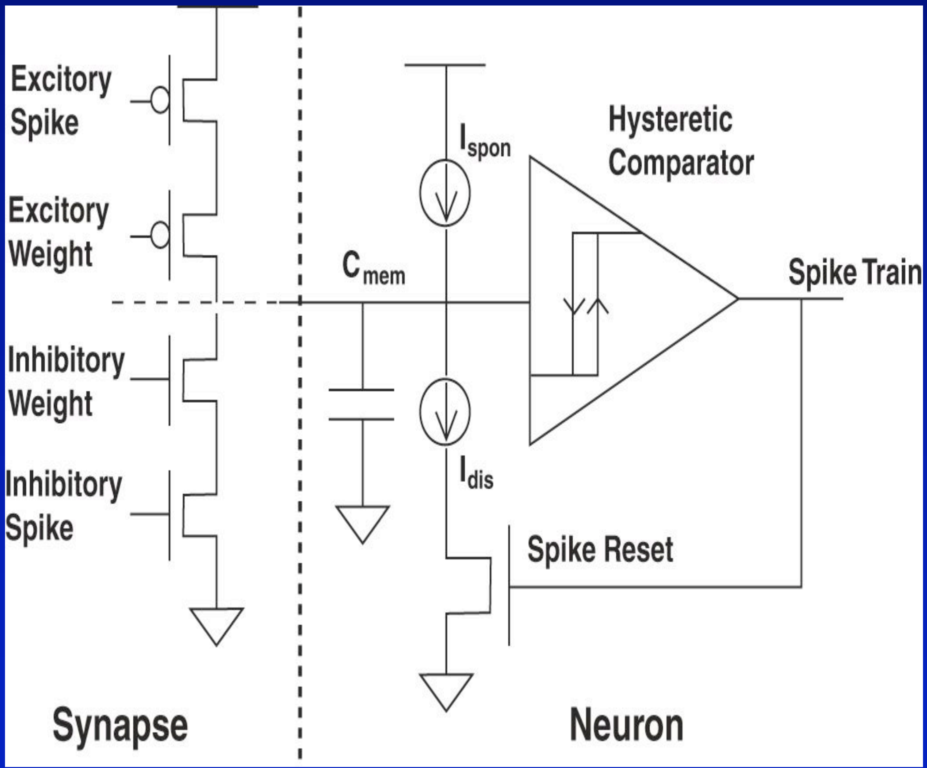
Chip Layout

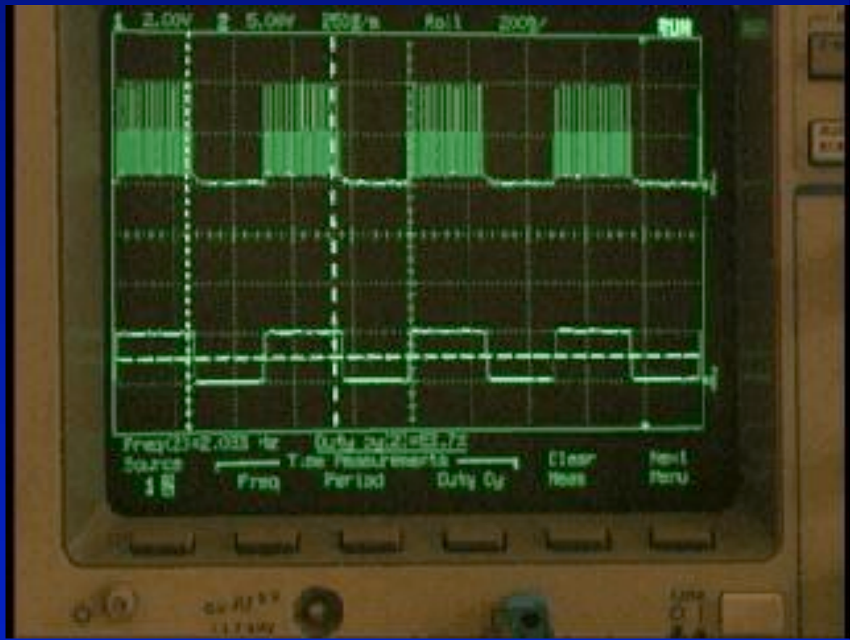
Real Chip
.4 mm Sqr (1.2 micron)
< 1 microwatt



Hardware Implementation of a CPG

Basic Neuron Element in aVLSI chip: The oscillator



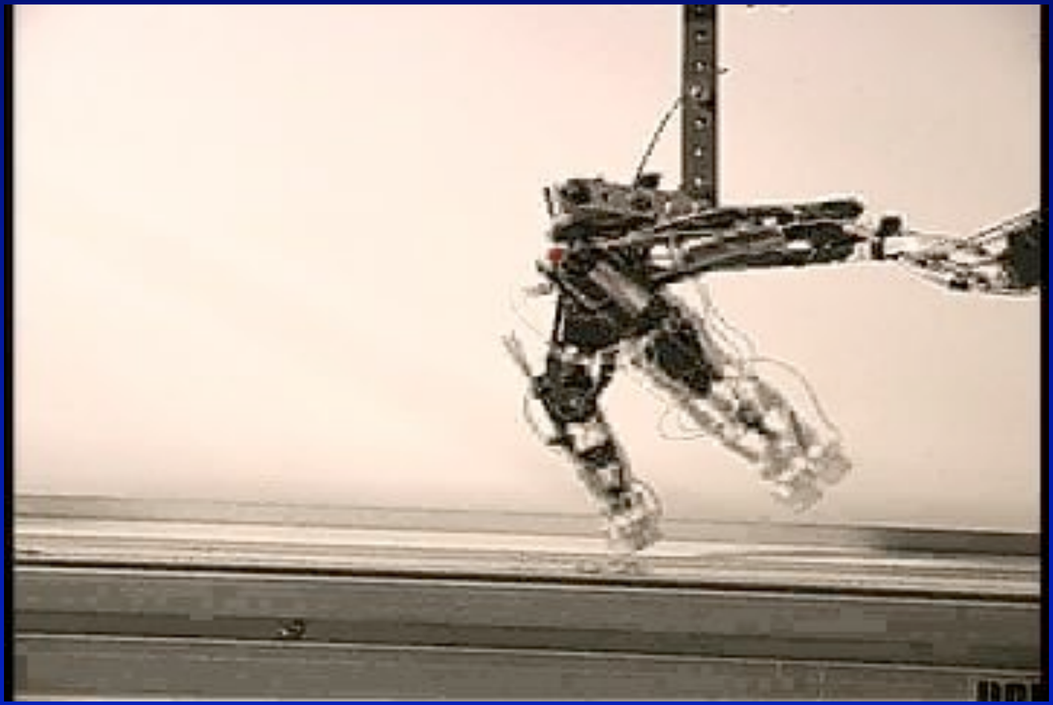


Chip design by Ralph Etienne-Cummings

Coupling the oscillators

- **Segmental oscillators must be coordinated by intraspinal connections**
  - *Traveling wave motion in fish and lampreys*
  - *Coordinated joint and limb movements in legged vertebrates*

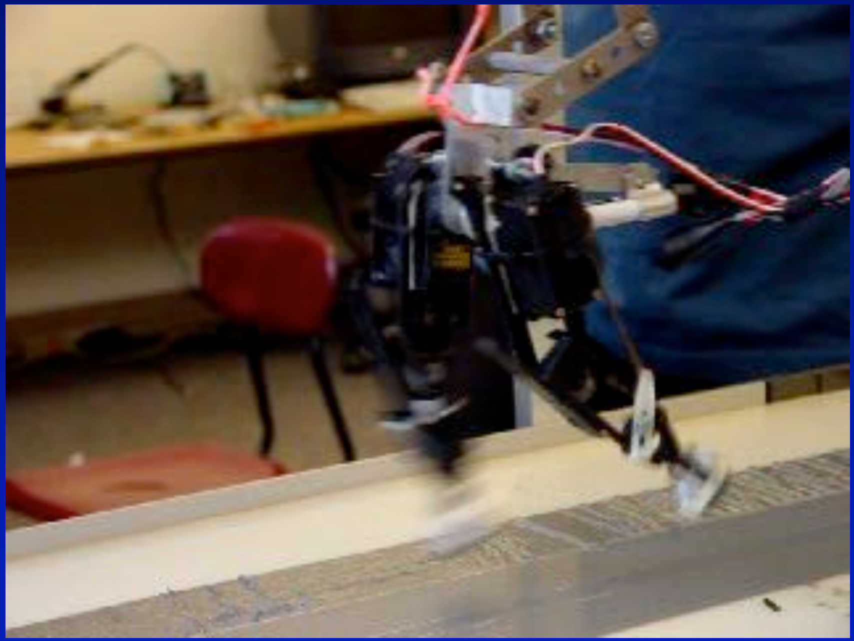
Bipedal running: two coupled limb oscillators



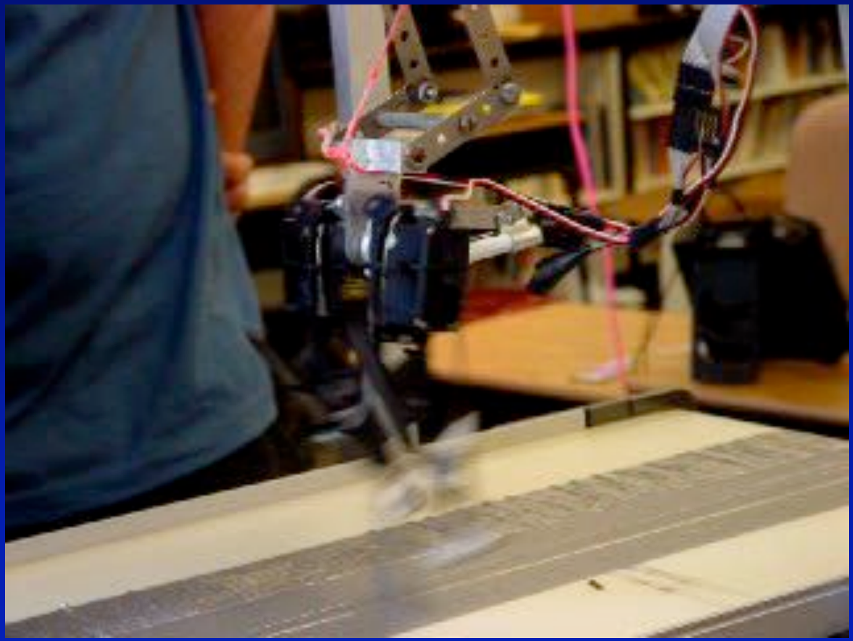
- *Successive conditions:*
- *1. Uncoupled*
- *2. Unidirectional coupling*
- *3. Bidirectional coupling*

Limbs by Iguana Robotics:
Anthony Lewis

Done here at Telluride!



Uncoupled



Coupled: Inhibitory Asymmetric Weights

CPG and movement

- Role of the CPG:
  - *Compress the degrees of freedom of the limbs and body*
  - *Adaptively organize movement*

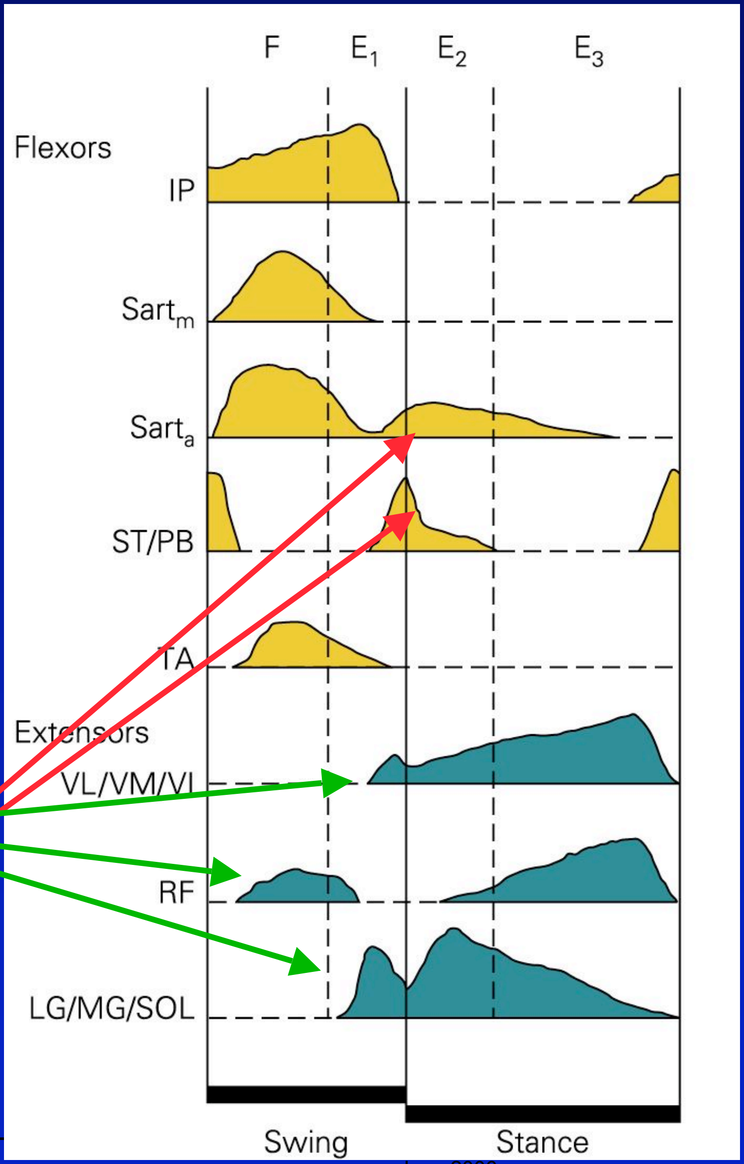
First proposed by Nicholas Bernstein

More later Friday afternoon

Motor pattern in limbs

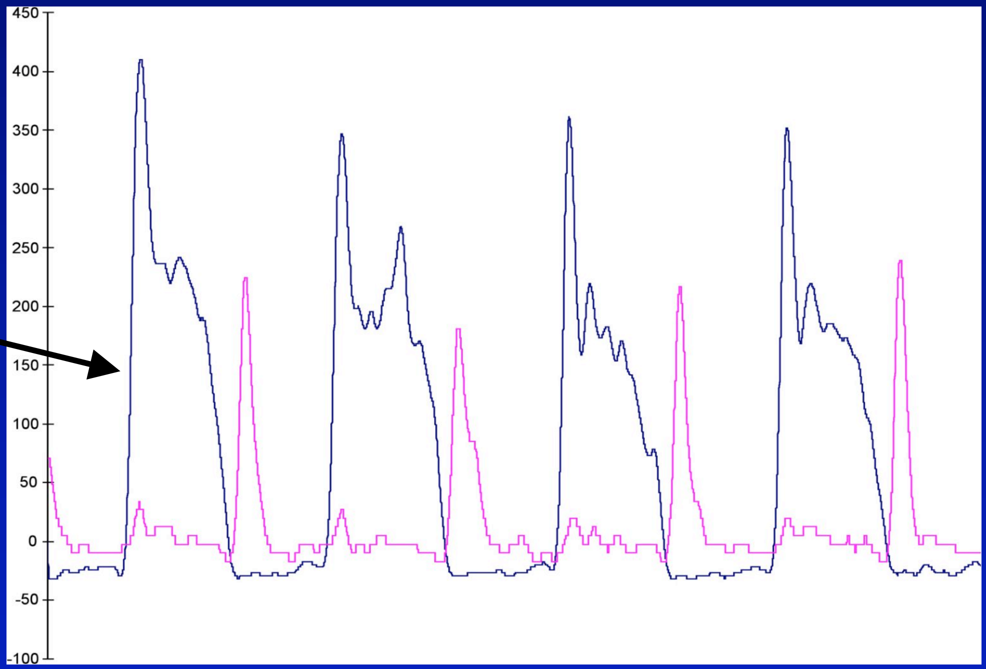
- Motor pattern in robot biped is strictly alternating – 180° degrees out of phase

- Motor pattern in cat limbs is more complex – range of phase relations
- Extensors are active prior to ground contact (Engberg and Lundberg, 1969)
- Antagonists are co-active



Muscle pattern in cats: co-activation of antagonists

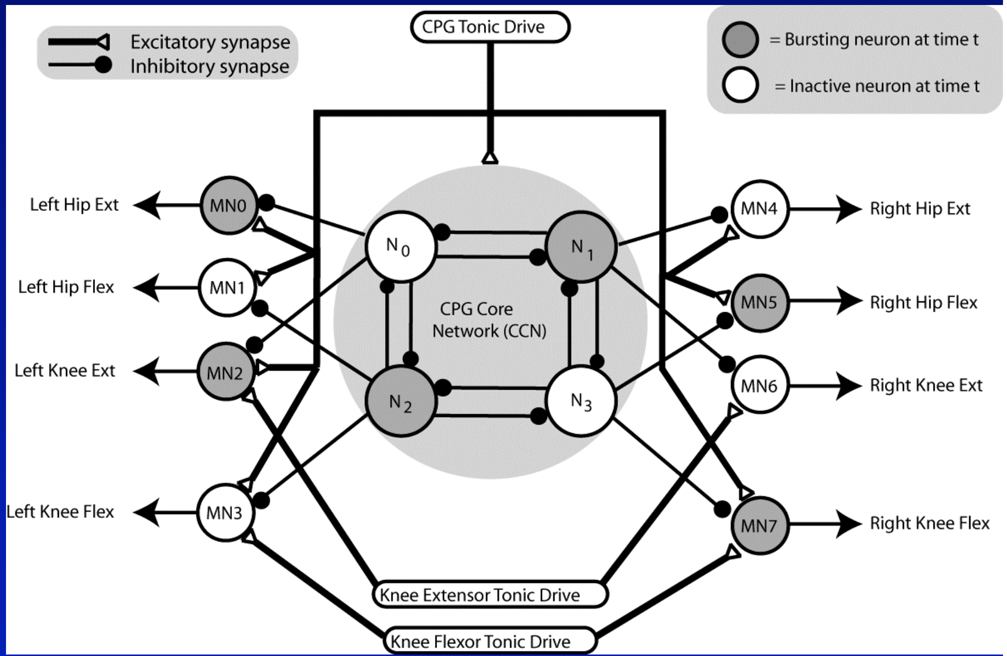
- Pattern in **fictive cat** – note the flexor activity during extension
- Complexity of pattern is seen in isolated spinal cord > product of CPG



Data from J.-P. Gossard
Modeled by Boothe and Cohen

CPG Chip III Configuration

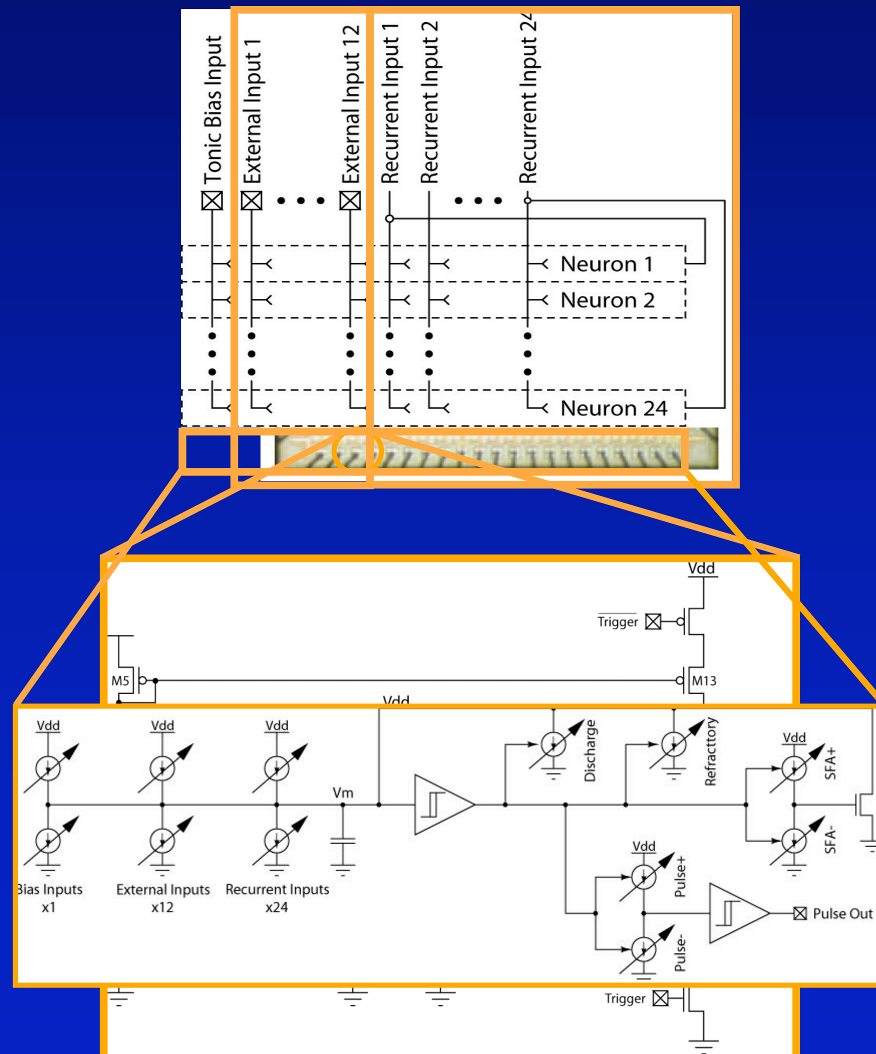
- Network of neurons
  - *Flexible configurations*
- Autonomously generate rhythmic outputs with specific phase relationships
- Will control walking with regular, periodic activity
- Record sensory feedback and adapt to perturbations or changing demands



Chip: Ralph Etienne-Cummings
Francesco Tenore: digital
Jacob Vogelstein: analog

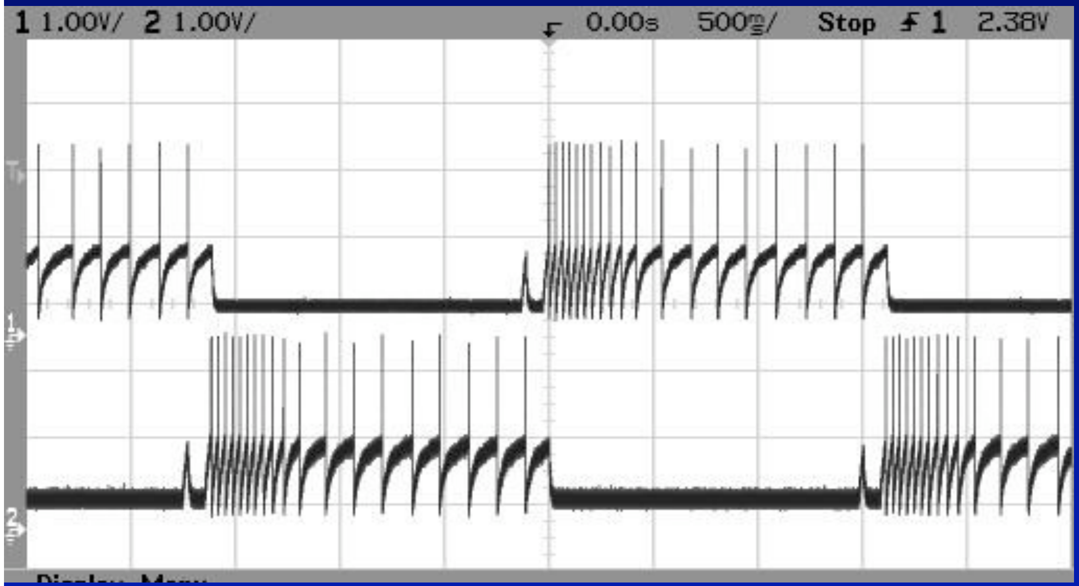
Silicon CPG Chip (SiCPG)

- **Designed specifically for CPG networks**
  - ***Intended to be standalone system after programming***
  - ***24 fully-interconnected (hardwired) silicon neurons***
  - ***Continuous-time external inputs for sensory feedback***
  - ***Programmable synapses based on floating gate transistors (FGT)***
  - ***Programmable cell properties: refractory period, SFA, pulse-width***



Source: Tenore et al., Proc IEEE ISCAS, 2005; Tenore et al., Proc IEEE ISCAS, 2006

Interesting bursts possible



- Flexible properties
  - *Spike frequency adaptation*
- Learning synapses
  - *Flexible connection strengths*
  - *Flexible frequencies*

Role of co-activation of antagonists

- Stabilize the joint
- Provide stiffness
- Brace limb for ground contact
- (new RedBot of A. Lewis)

Red-bot running with controller

Limbs by Anthony Lewis

Iguana robotics

CPG in vertebrates

- Summary: There are feedforward signals from spinal cord to muscle for locomotion in vertebrates

- The spinal cord is organized around the CPG:
  - *Integrates sensory feedback*
  - *Structures and coordinates movements*

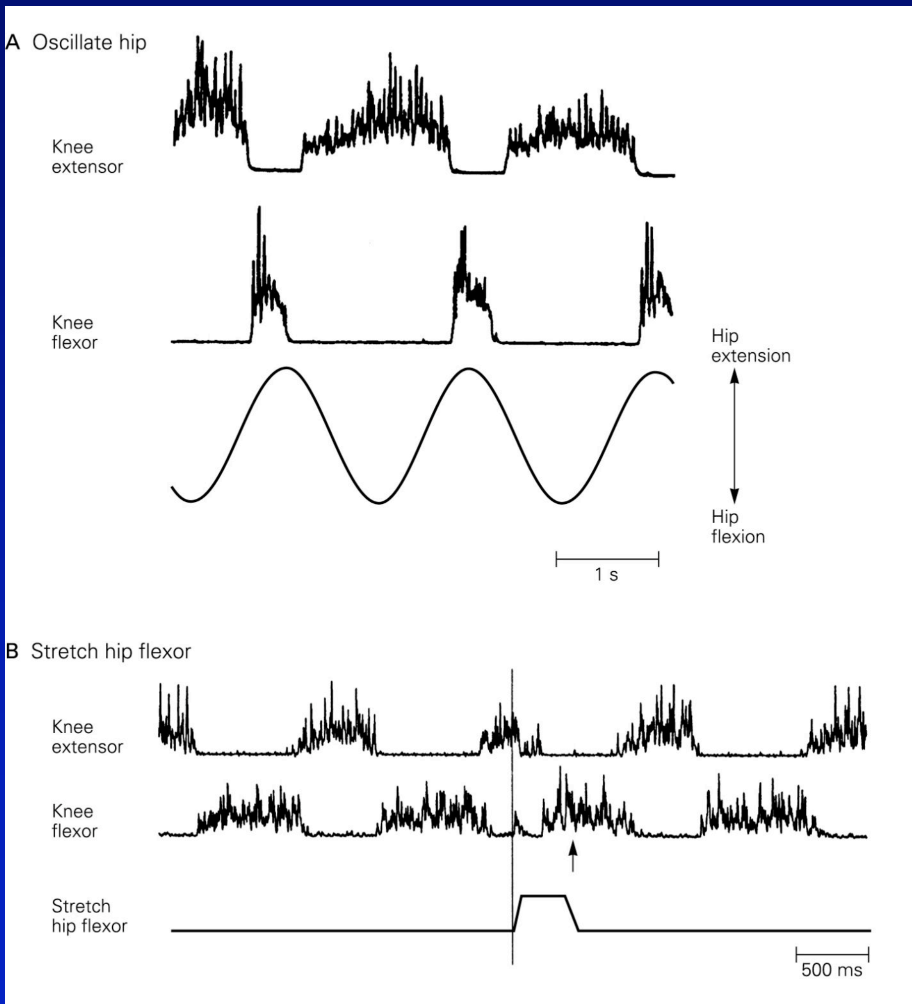
CPG + Sensory feedback

- CPG strongly interacts with sensory feedback
- CPG and spinal cord dynamically regulate responses to sensory inputs
- CPG requires sensory feedback for adaptive movement!

Another universal: adaptation of cycle by feedback

- All CPGs have some feedback signal(s) that resets the rhythm
- Serves to adapt the limbs to environmental conditions
- Sensor and CPG become mutually entrained (Note Kimura's Tekken for this)

Sensory entrainment in cats



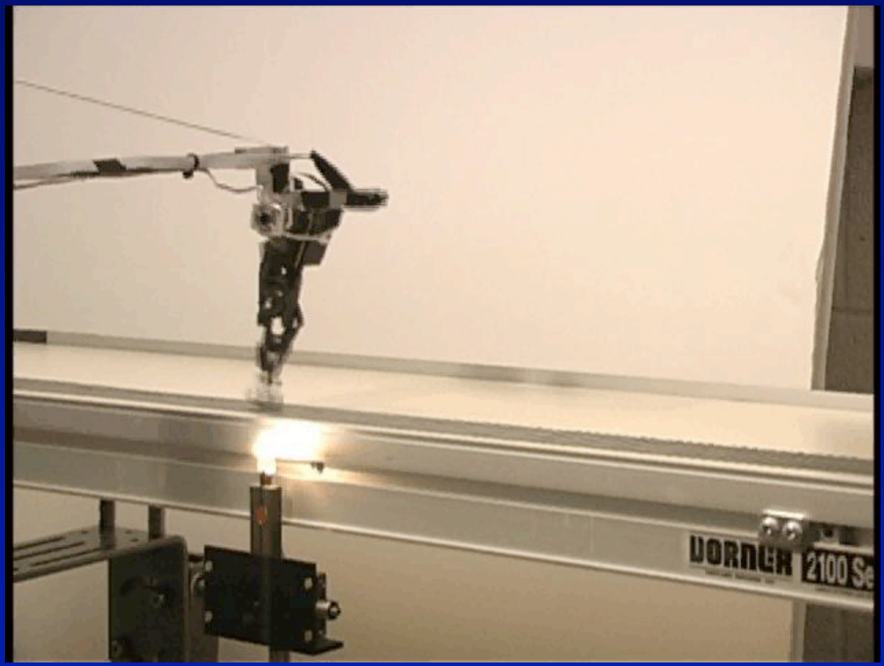
Data from Hiebert et al.

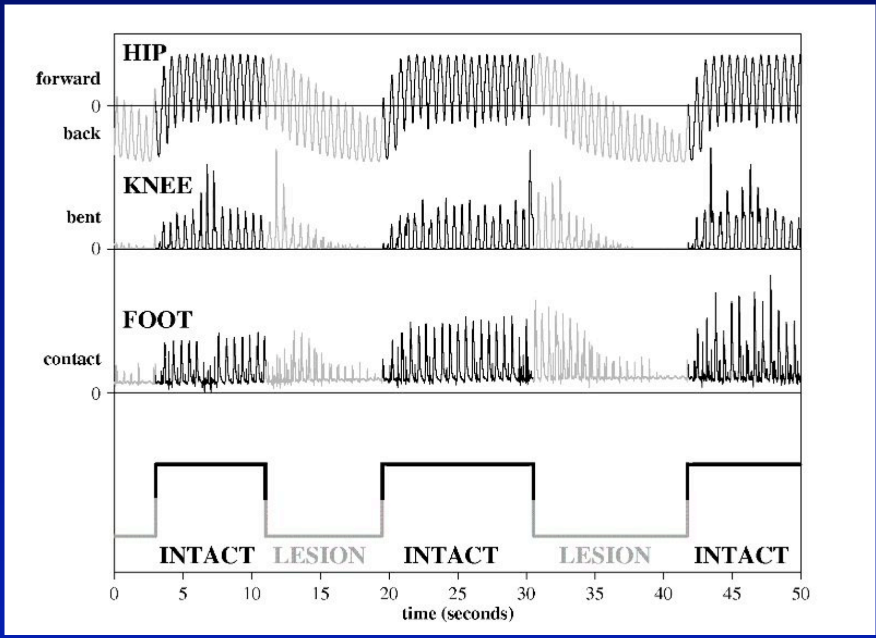
Hip sensors entrain the rhythm and can reset the cycle

- **Force sensors**
- **Muscle stretch receptors***
- **Joint receptors**

Now: principle in CPG chip>>>>

Lesion Experiment





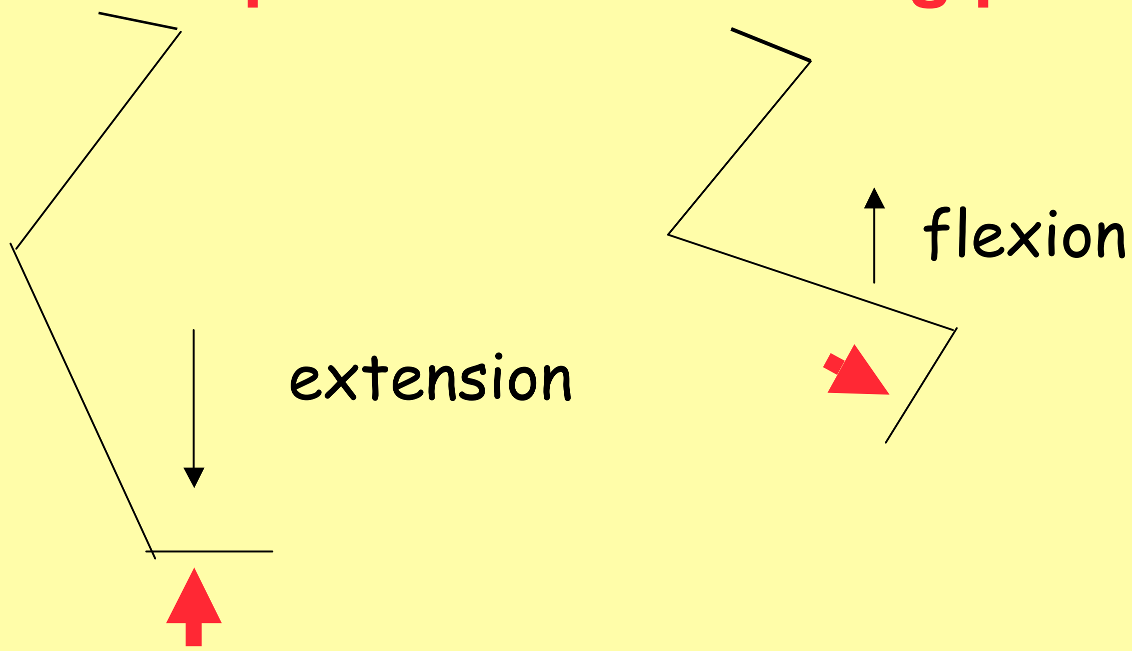
- **Sensory feedback is lesioned**
  - ***Light ON: Intact***
  - ***Light OFF:Lesion***

Joint angle changes

CPG response to perturbations

Response depends on phase of stimulus

Stance phase swing phase



Sensory feedback and CPG: principles found in all vertebrates

- Sensory feedback is integrated at the level of the spinal cord – does not require the brain
- CPG gates reflexes to make them adaptive
- Spinal cord is generally organized around the CPG for locomotion – reflexes are never displayed in direct form during locomotion
- Input from the brain is coordinated with and by the CPG

Successful Embodiment of Biological Principles: Fukuoka and Kimura, "Tekken"

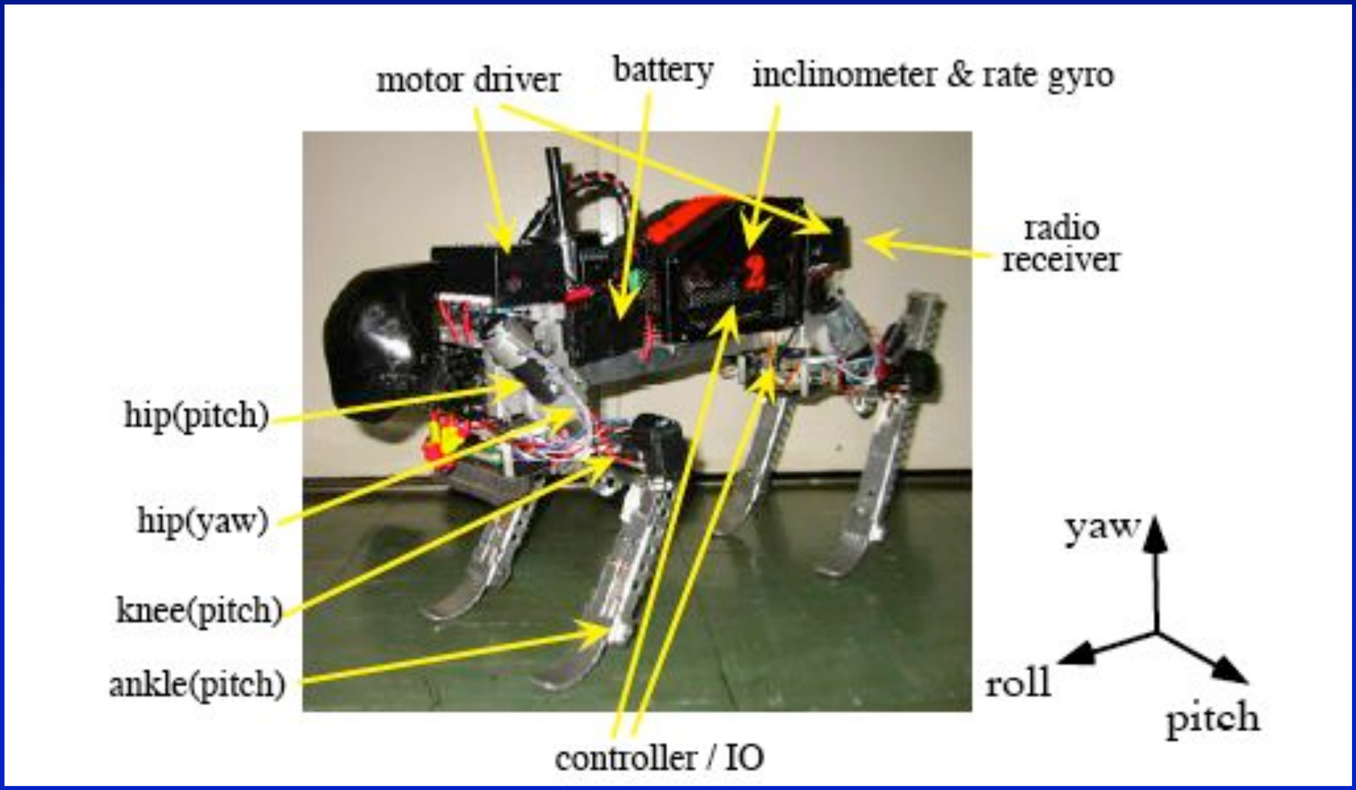
- Uses differential equations for oscillator
- Uses mutual entrainment of oscillator and feedback
- Uses reflexes gated by CPG to be phase dependent
- Uses "tonic vestibular reflex" for adjustment of role and pitch

All components present

- Second generation robot

Fukuoka and Kimura's robot

- Mechanical and "reflexive" control mechanisms



Takes principles from biology

- Joints and muscles have compliance
- There is easy mutual entrainment between the CPG and the properties of the limbs

- See work of Full and colleagues for principles of this construction:
  - *Shows self stabilization of movement with these principles*

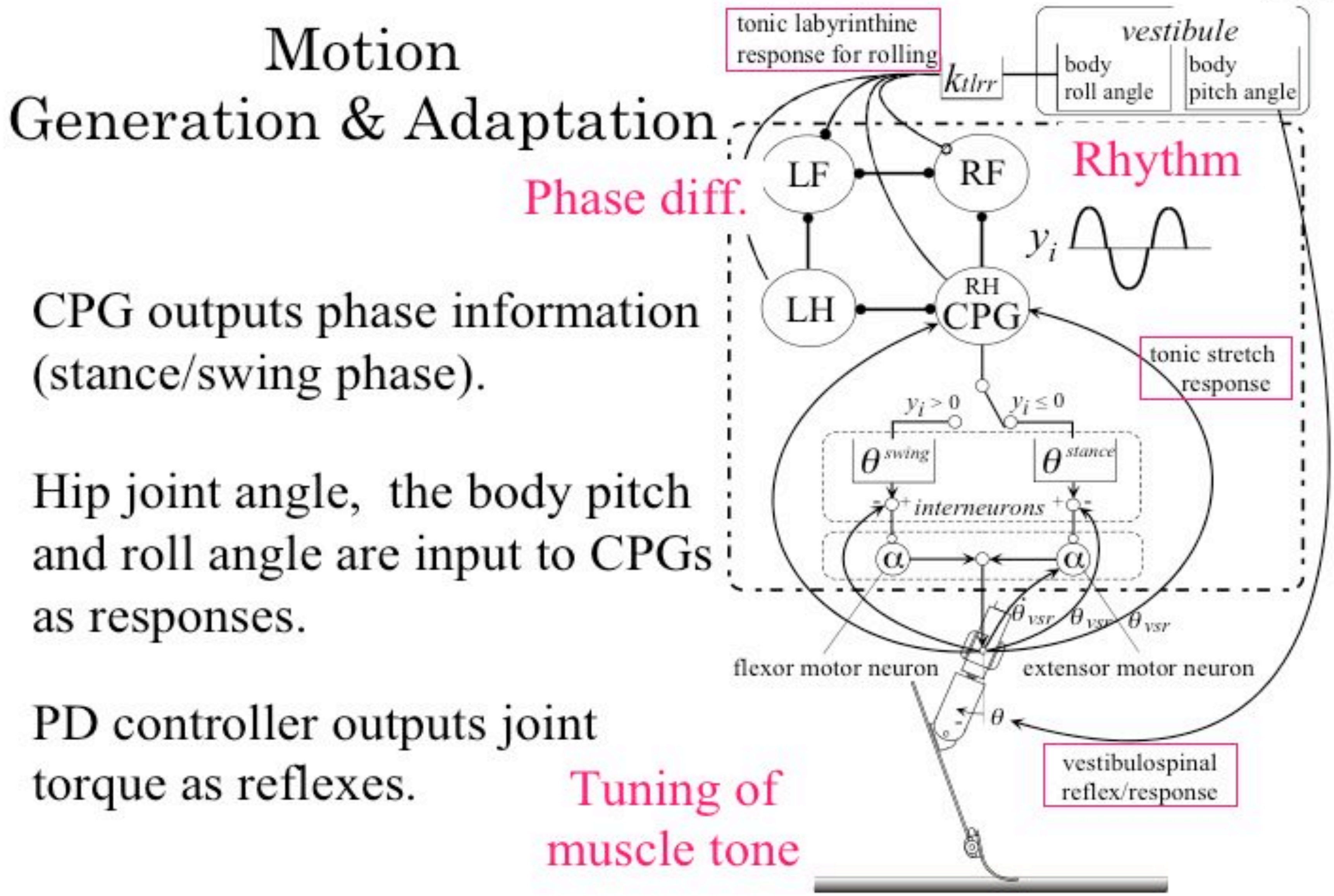
Limb motion principles

- Joints and actuators are built to provide compliance – actuators are near optimal for backdrivability
- PD controller with lookup table to provide appropriate force given position when “muscle” activated

THEN:

- Sensory feedback via reflexes mutually entrain with joint motion to provide adaptable limb motion over irregular terrain

Diagram of Tekken's robot control



CPG outputs phase information (stance/swing phase).

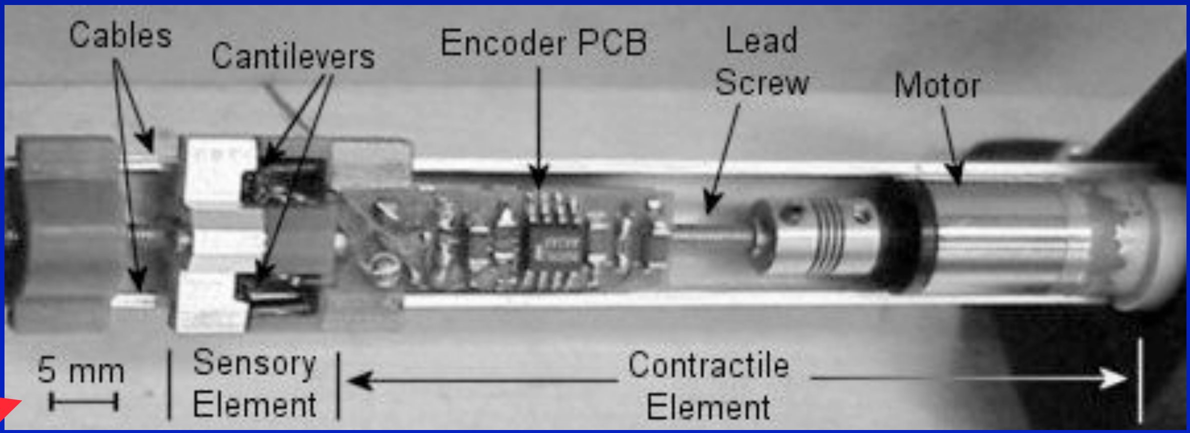
Hip joint angle, the body pitch and roll angle are input to CPGs as responses.

PD controller outputs joint torque as reflexes.

Over irregular terrain

A sophisticated sensor

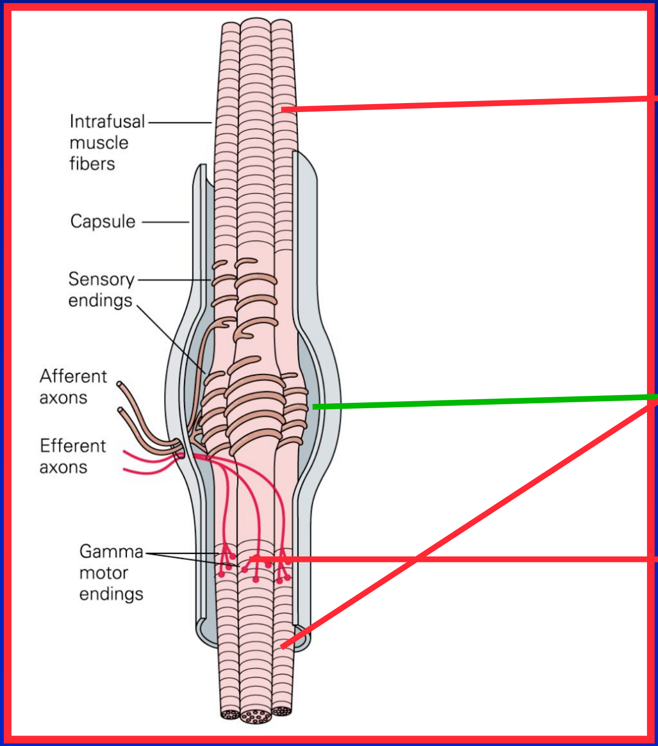
- Muscle stretch receptor of mammals: the spindle organ
- Now been implemented by Jaax and Hannaford, 2002



Note size!

Muscle spindle organ

- A highly non-linear sensor of muscle stretch
  - *Used for regulation as well as feedback*

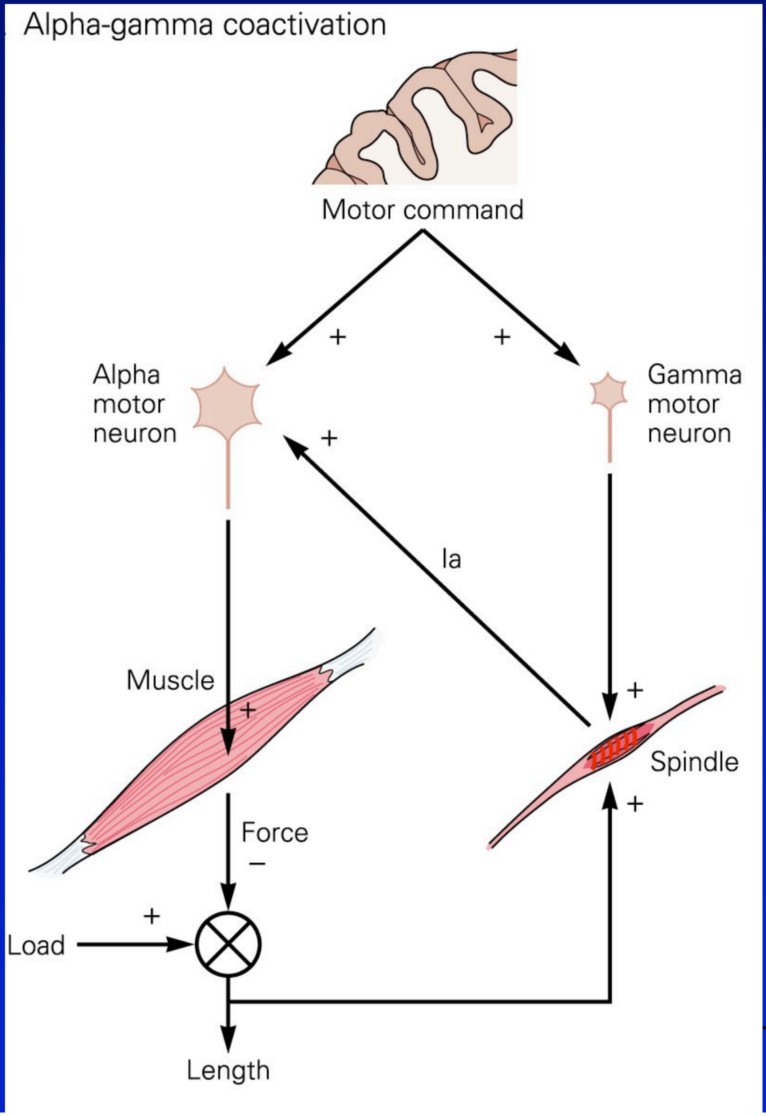


Muscle controller regions

Sensor region

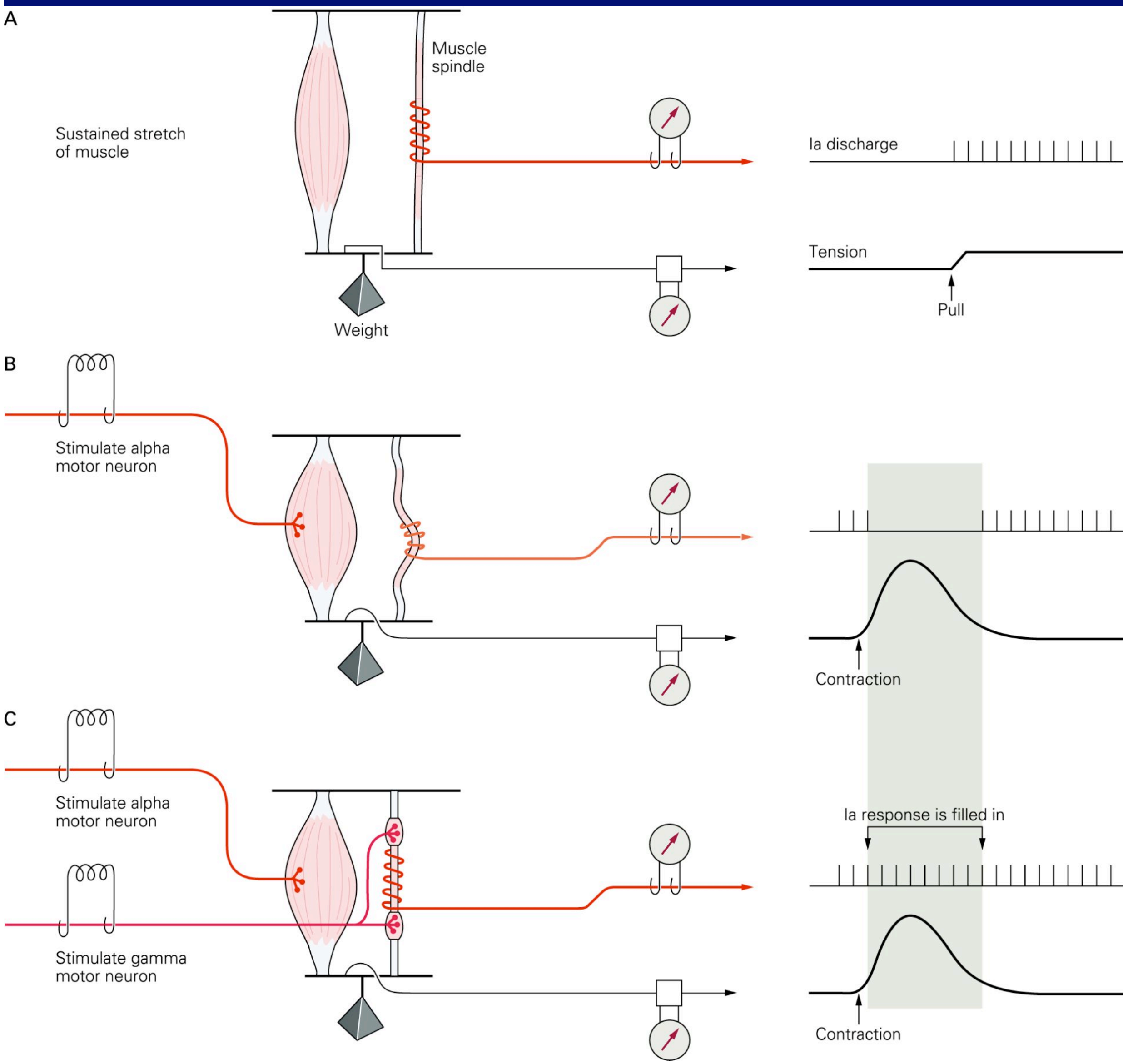
γ–motor neuron Innervation to Intrafusal fibers

Co-activation of sensor and force producing muscle



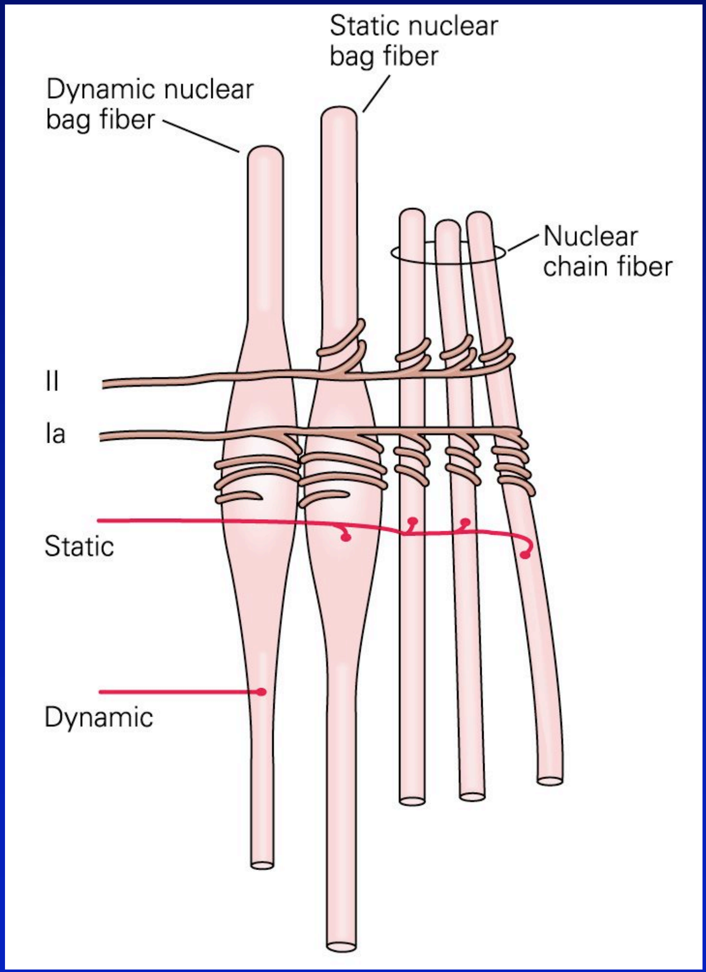
- Force producing muscle: extra-fusal muscle with α-motor neuron innervation
- Control muscle: intrafusal muscle with γ–motor neuron innervation
- Co-activated with force producing muscle

Spindle function



- Passive stretch > excites receptor
- Activated muscle > no response
- Active controller muscle + activated muscle > full response

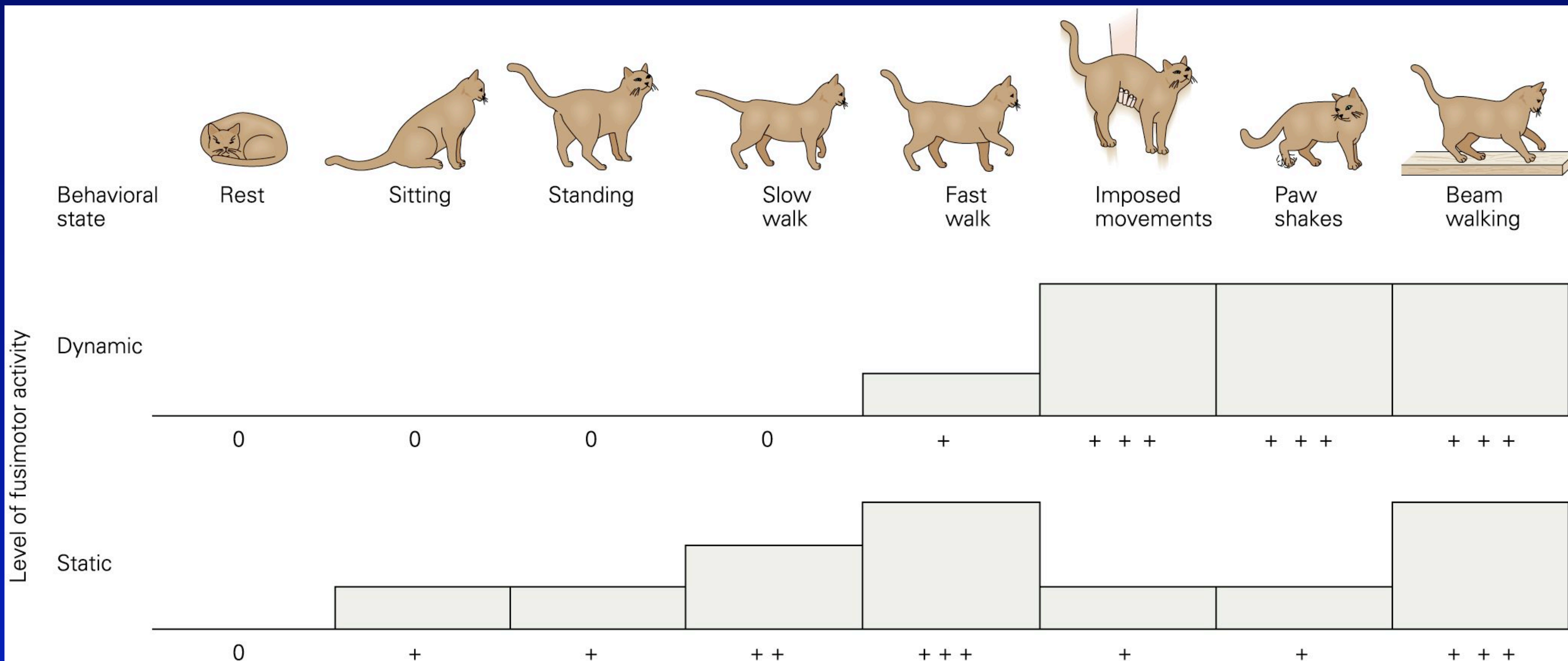
Spindle function



- Spindles and spindle controller muscles come in a variety of types – dynamic and static γ's, primary and secondary spindle fibers
- Thus: functional relationship to muscle length is highly complex and non-linear

- Spindle organ
  - *monitors stretch*
  - *controls force producing muscle*
- Maintains muscle contraction for as long as needed

Co-activation during behaviors



- +: level of dynamic/static activity with force producing muscle activity

(data from Prochazka et al., 1988)

Spindle function

- Spindle activity is highly complex
  - *Conveys length information*
  - *Regulates activity of muscle*
  - *Interacts with force sensors*

- Use in robotics (in less complex form!)
  - *Non-linear regulation of actuators*
    - Length control
    - Force control
    - Regulation at transitions
  - *Perhaps combined to produce more subtle control strategies*

Summary and conclusions

- Biology offers some universal principles that can be applied to robots
  - *Efficient if non-linear*
  - *Control is easier to implement*
  - *More robust*
- Other features may offer some interesting opportunities to build more flexible and sophisticated robots

Bye now!

Figure compliments of Philip Holmes and Lex Smits, Princeton