Neurorobotics

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Telluride 2008

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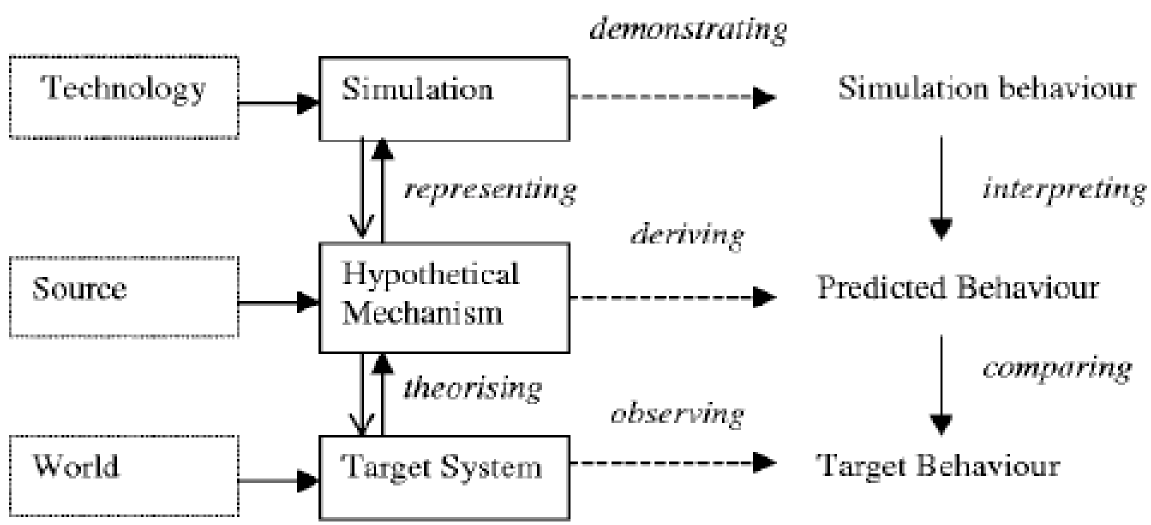
Neurobotics

- Biorobotics with emphasis on neural sources of model inspiration
- **Biologically Inspired Robots <> (BIO/Neurorobots)**
- Biologically inspired robots use biology as metaphors to solve practical problems in robotics (Brooks/Arkin)
- Bi/Neurorobots are simulation of biological systems

Simulation & the Scientific Method



Barbara Webb 2001

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Robots have been strongly inspired by biological systems.

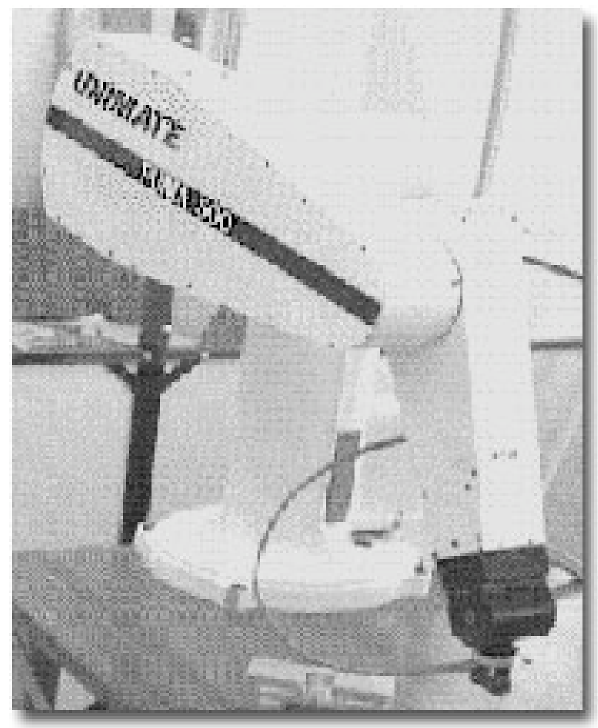
In a sense, all robots are “biologically inspired”

GE ELEKTRO & Sparko1937

- ELEKTRO
  - 7’ Tall 265 LBS
  - Could “walk” by “voice command”
  - Mouth coordinated with 78 RPM record
  - Eyes could distinguish Red vs Green
- Sparko
  - Walk
  - Move toward bright light
- Used to demonstrate automated controls
- Example of animatronic technology

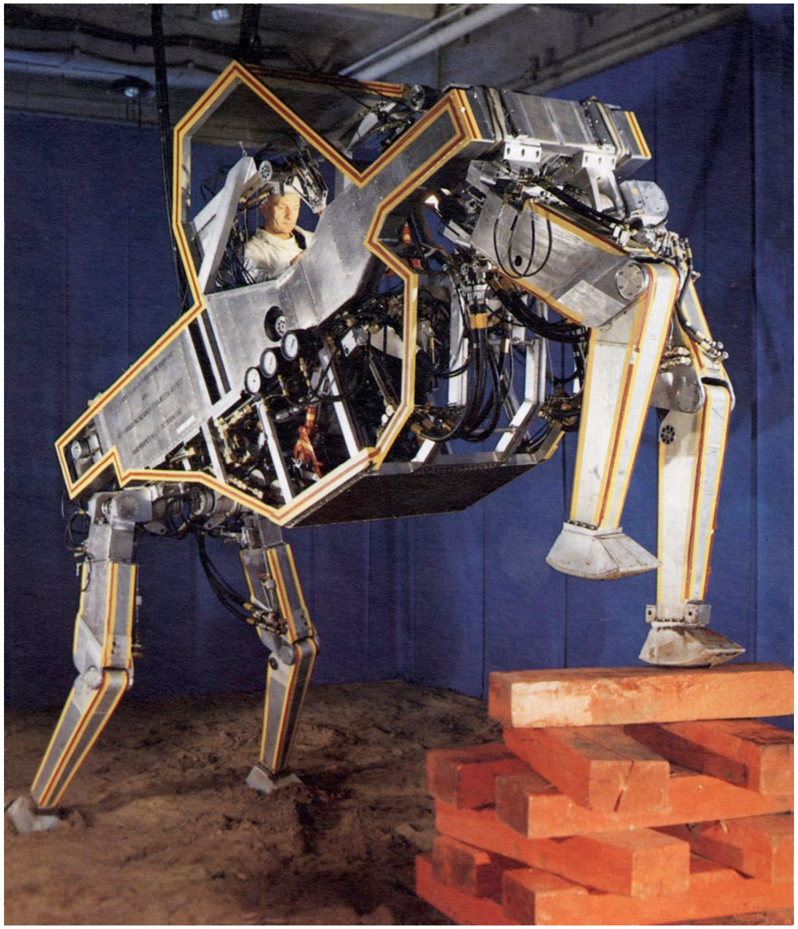
Unimation 1956-

- Unimation Founded by Engelberger
- George Devol writes patents
- Installs robots at GE
- Unimation is acquired by GE
- Billion Dollar industry Spawned



GE Walking Robot

- Ralph Mosher GE 1960’s
- Too complex to control without onboard computer



Significantly, biorobots were an early ‘simulation’ tool

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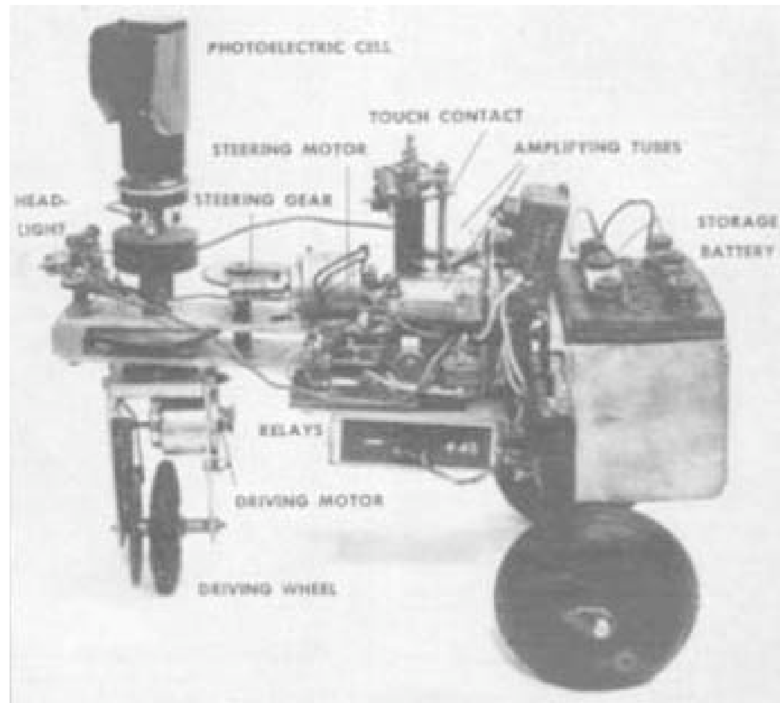
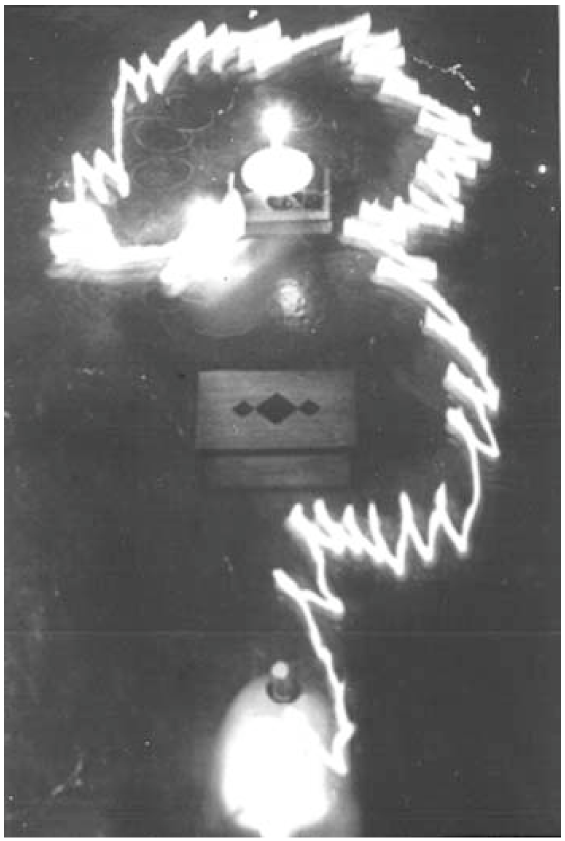
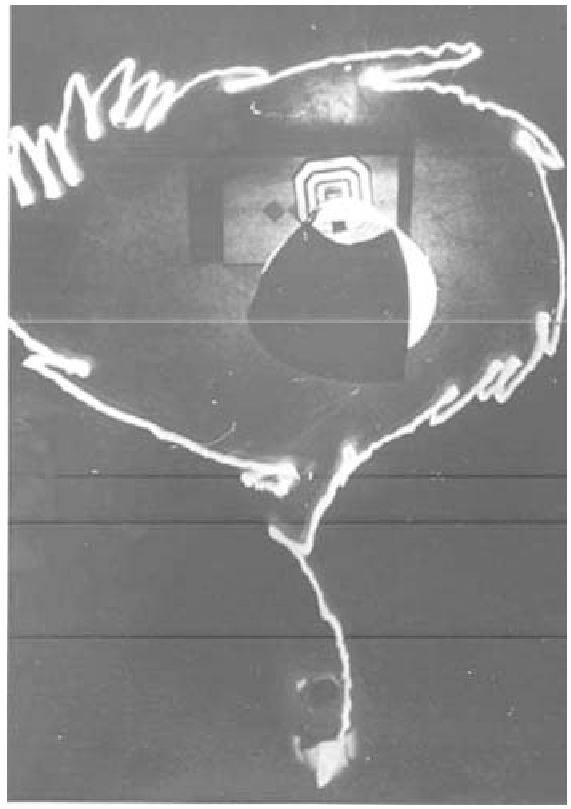
Grey Walter's Turtle 1950's

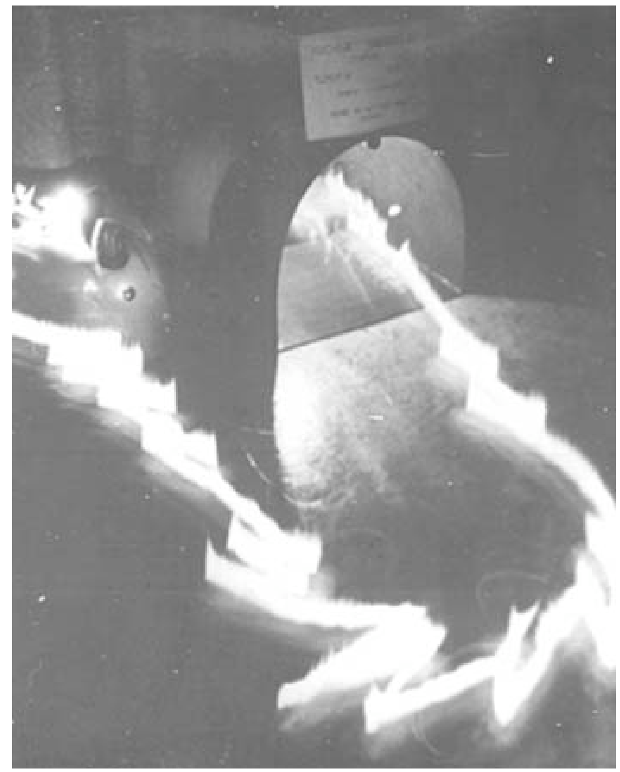
- Key feature was "decision" making capability
  - Seek Light
  - Recharge
- Interested in mechanistic explanations of psychological phenomena



Grey Walter's Turtle Elsie
Circa 1950







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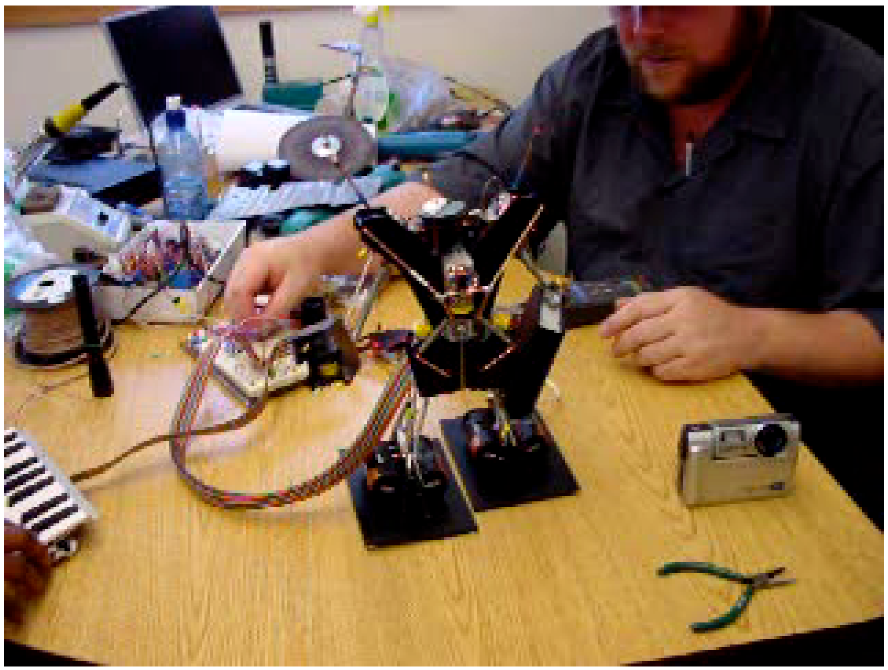
Telluride Historical Note



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Classical robotics

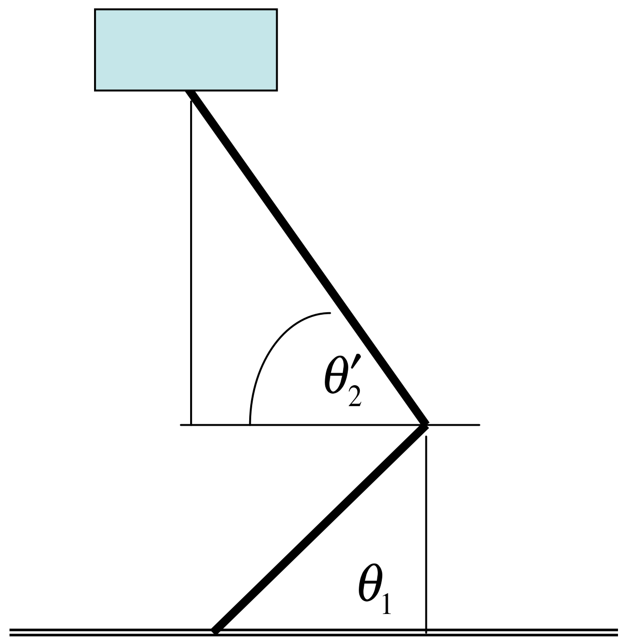
- Robotics requires a *rational basis for design*
  - Analytic geometry gives us great power in finding solutions
    - The Classic Elements of robotics are Kinematics, Inverse Kinematics, Statics, Dynamics and Trajectory
  - Bayesian probability has assumed a prominent role in the last 10 years

Example

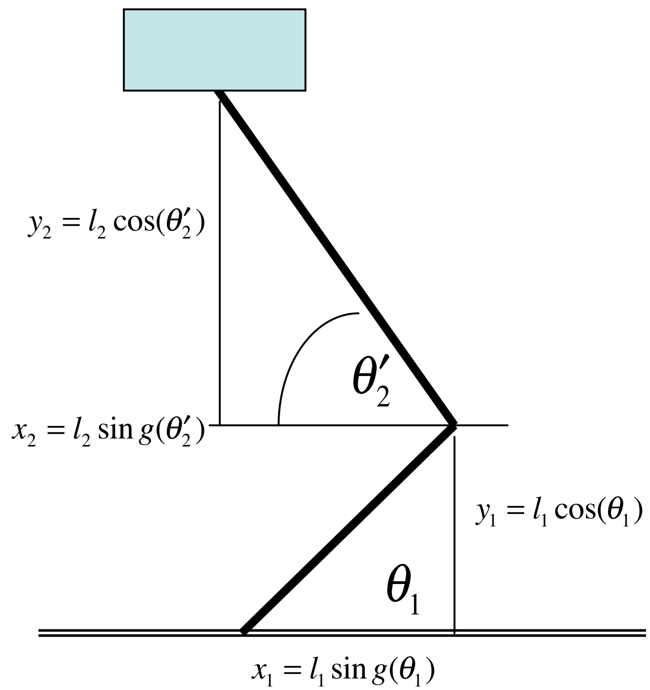
The position of the body can be described

joint angles: configuration space.

Cartesian coordinates: world space



Example

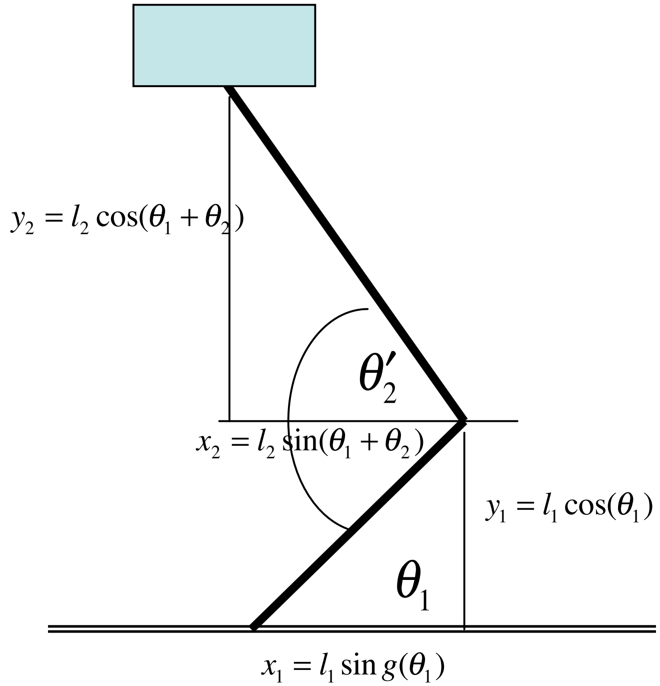


$y_2 = l_2 \cos(\theta_2')$
θ_2'
$x_2 = l_2 \sin g(\theta_2')$
$y_1 = l_1 \cos(\theta_1)$
θ_1
$x_1 = l_1 \sin g(\theta_1)$

Example

Kinematics:

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2)$$
$$y = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2)$$



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Inverse Kinematics

- Harder problem
  - Kinematics: Automatic solution
  - Inverse Kinematics: Use insight

Example

- Inverse Kinematics

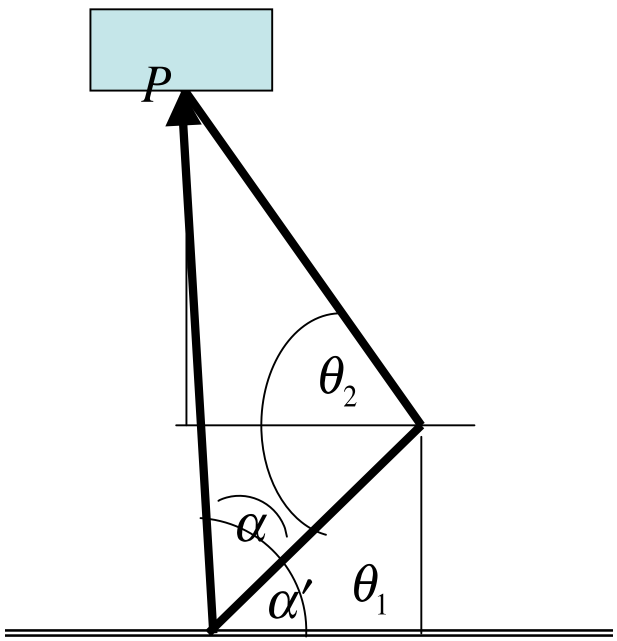
$$P = \sqrt{x^2 + y^2}$$

$$\theta_2 = \mathrm{acos}\left(\frac{l_1^2 + l_2^2 - p^2}{2 l_1 l_2}\right)$$

$$\alpha = \mathrm{acos}\left(\frac{l_1^2 + p^2 - l_2^2}{2 l_1 p}\right)$$

$$\alpha' = a\tan 2(y, x)$$

$$\theta_1 = \alpha' - \alpha$$



Differential motion

$$d\vec{x} = f(d\vec{\theta})$$

Vice Versa:

$$d\vec{\theta} = g(d\vec{x})$$

Differential motion

- Q:What is the relationship between small changes in ***configuration space*** and ***small changes*** in world coordinates?

$$\vec{x}_c + \Delta\vec{x} = F(\vec{\theta}_c) + J(\vec{\theta})\Delta\vec{\theta} + \ldots$$

- A: The Jacobian:

$$d\vec{x} = J(\vec{\theta})d\vec{\theta}$$

- Example :

$$\boxed{\begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{pmatrix} -l_1\sin(\theta_1) - L_2\sin(\theta_1+\theta_2) & -l_2\sin(\theta_1+\theta_2) \\ l_1\cos(\theta_1) + \mathrm{L}_2\cos(\theta_1+\theta_2) & l_2\cos(\theta_1+\theta_2) \end{pmatrix} \begin{bmatrix} d\theta_1 \\ d\theta_2 \end{bmatrix}}$$

Differential motion

- Q: What is there relationship between small changes in world coordinates and small changes in configuration space?

- A: The Jacobian Inverse:

$$\boxed{J^{-1}(\vec{\theta})d\vec{x} = d\vec{\theta}}$$

- Example cont:

$$\boxed{\begin{bmatrix} d\theta_1 \\ d\theta_2 \end{bmatrix} = \begin{pmatrix} -l_1\sin(\theta_1) - L_2\sin(\theta_1+\theta_2) & -l_2\sin(\theta_1+\theta_2) \\ l_1\cos(\theta_1) + \mathrm{L}_2\cos(\theta_1+\theta_2) & l_2\cos(\theta_1+\theta_2) \end{pmatrix}^{-1} \begin{pmatrix} dx \\ dy \end{pmatrix}}$$

Singularity

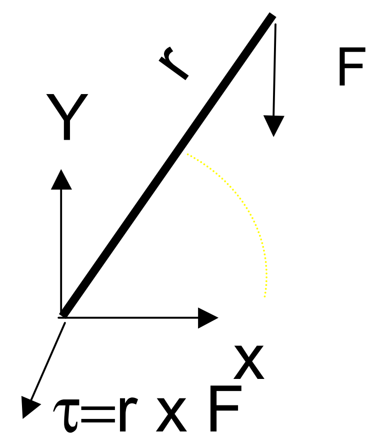
- Singular point exist, eg $\theta_2 = 0$ no inverse

$$\boxed{\det\left|J(\vec{\theta})\right| = 0}$$

$$0 = L_1 L_2 \left(\cos(\theta_1+\theta_2)\sin(\theta_1) - \sin(\theta_1+\theta_2)\cos(\theta_1)\right)$$

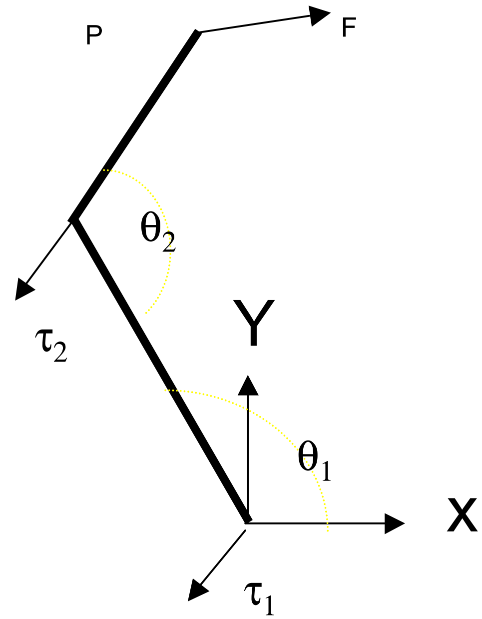
Statics

- Effect of torques and forces acting on a static structure
- Useful Preliminary Concepts
  - Generalized Force
    - Force
      - Newton
    - Torque
      - Newton-Meter
  - Work
    - Force x distance
    - Torque x angle
    - Joule=Newton*Meter
  - Power
    - Force x Velocity
    - Torque x angular velocity
    - Watt/sec



Statics

- What is the relationship between end-tip force and joint torques?
  - Work done at tip=Σjoint work!
  - Implies $J^T F$=tau!



$$\Delta\vec{W}^{tip} = \Delta\vec{X}^T\vec{F}$$
$$\Delta W_i^{joint} = \Delta\theta_i \bullet \tau_i$$
$$\Delta\vec{X}^T\vec{F} = \Delta\vec{\theta}^T\vec{\tau}$$

$$Jd\theta = dx \longrightarrow J\Delta\vec{\theta} \approx \Delta\vec{X}$$
$$\Rightarrow$$
$$\left(J\Delta\vec{\theta}\right)^T\vec{F} = \Delta\vec{\theta}^T\vec{\tau}$$
$$\Delta\vec{\theta}^T J^T\vec{F} = \Delta\vec{\theta}^T\vec{\tau}$$
$$\Rightarrow$$
$$\boxed{J^T\vec{F} = \vec{\tau}}$$

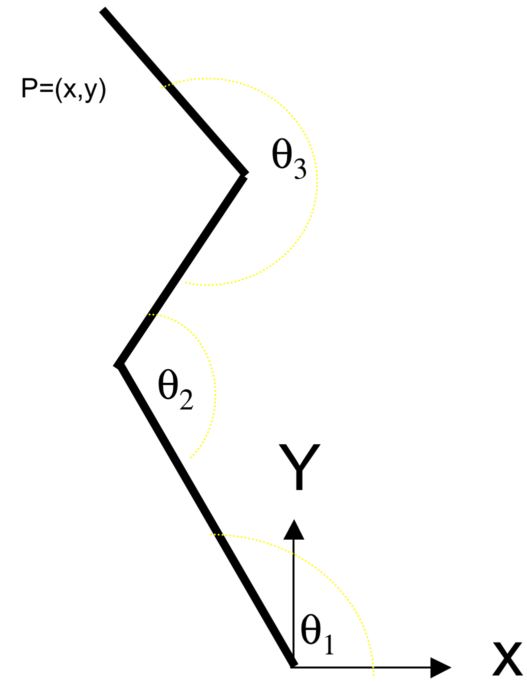
Redundancy

Forward Kinematics unique

$$f: Q \rightarrow X$$

Inverse Kinematics not unique

$$f^{-1}: X \rightarrow Q$$



Think of Posture and Balance Problems

Dynamics

- Real systems have mass and evolve through time
- Lagrangian summarizes the dynamics of a system
- Automatic Soln
- 3 dof practical limit of ability to do dynamics by hand

$$L = KE^{TOTAL} - PE^{TOTAL}$$

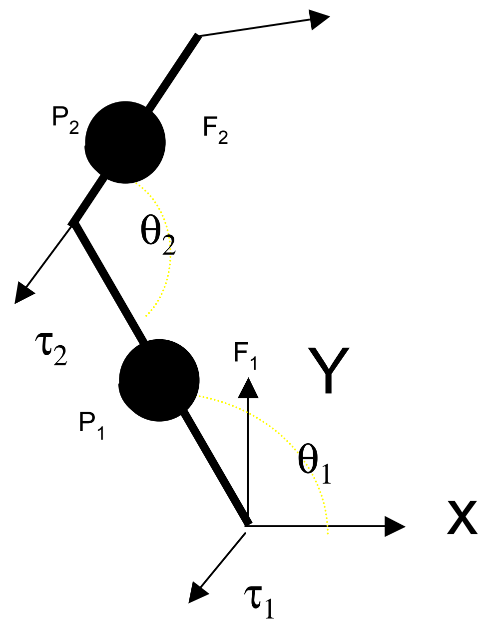
$$KE = \frac{1}{2}\dot{\vec{x}}^{*T} M \dot{\vec{x}}^{*}$$

$$KE = \frac{1}{2}\frac{d\vec{\theta}^{T}}{dt} J^{*}(\vec{\theta})^{T} M J^{*}(\vec{\theta}) \frac{d\vec{\theta}^{T}}{dt}$$

$$PE = g\sum_{i} height_i \bullet m_i$$

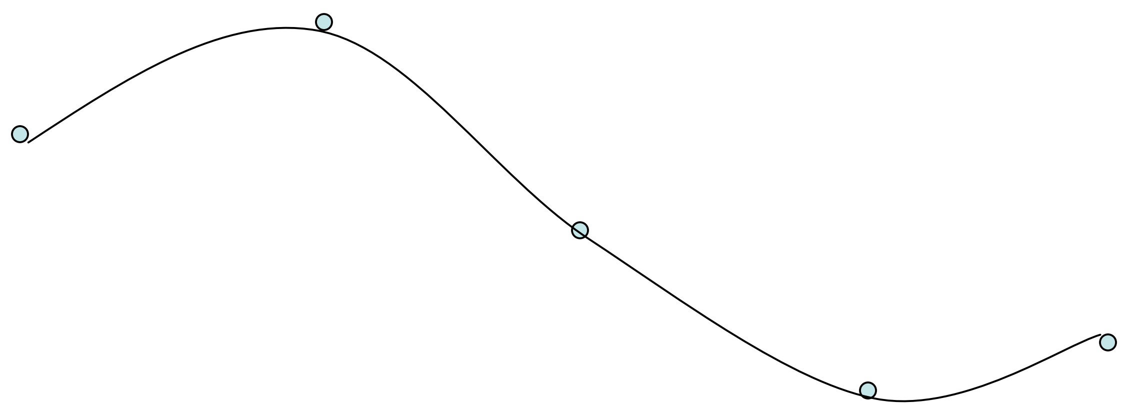
$$PE = \left[L^{*}_{1}\sin(\theta_1)\bullet m_1 + \left(L_1 \sin(\theta_1) + L^{*}_{2}\sin(\theta_1+\theta_2)\right)\bullet m_2 \ldots \right]\bullet g$$

$$\tau = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \left(\frac{\partial L}{\partial q}\right)$$



Trajectory Generation

- Basic idea: generate a spline from knot-points
- Spline satisfies endpoint, vel, and acc constraints
- Goal of robot is to track trajectory



Notions in Legged Locomotion

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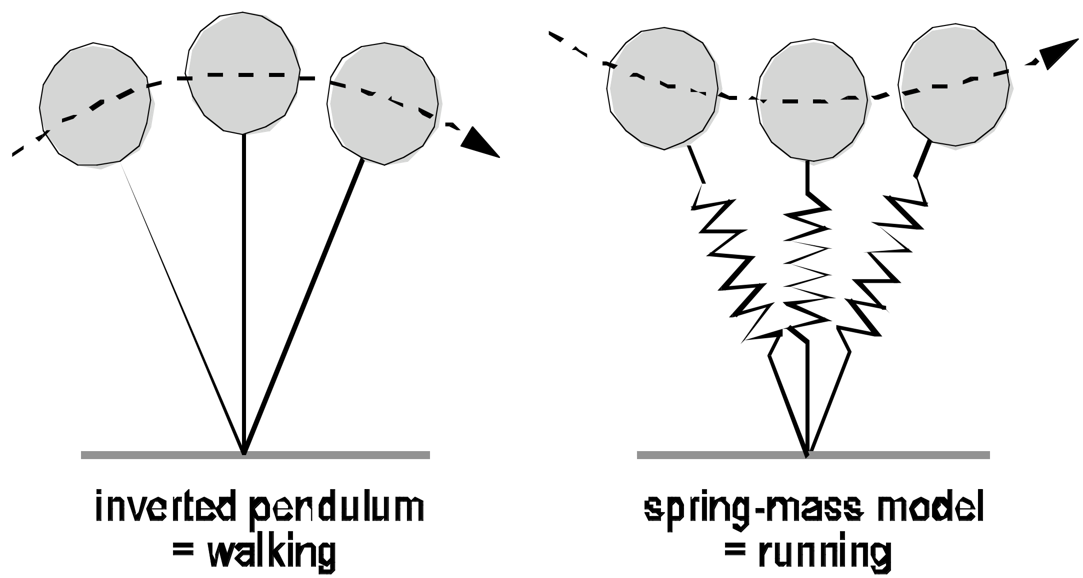
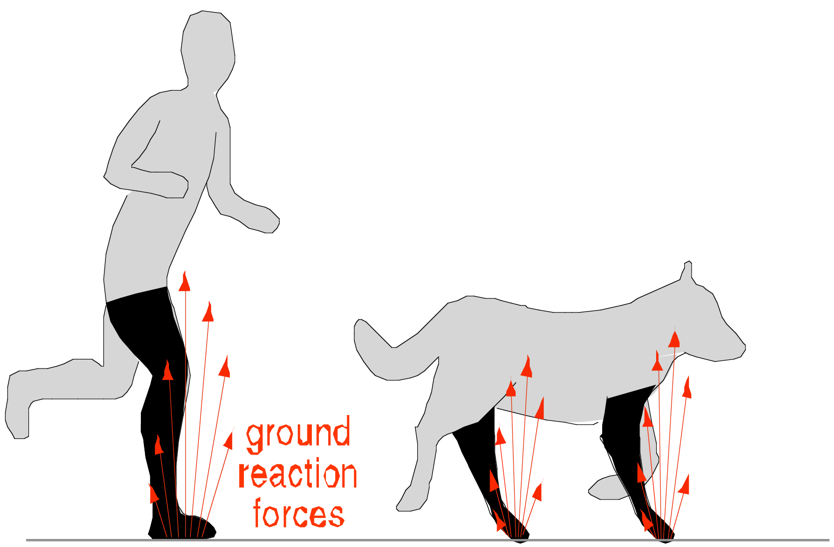
Models of Locomotion

- Inverted Pendulum Model
- Spring Model: Leg is modeled as a prismatic joint with spring in line



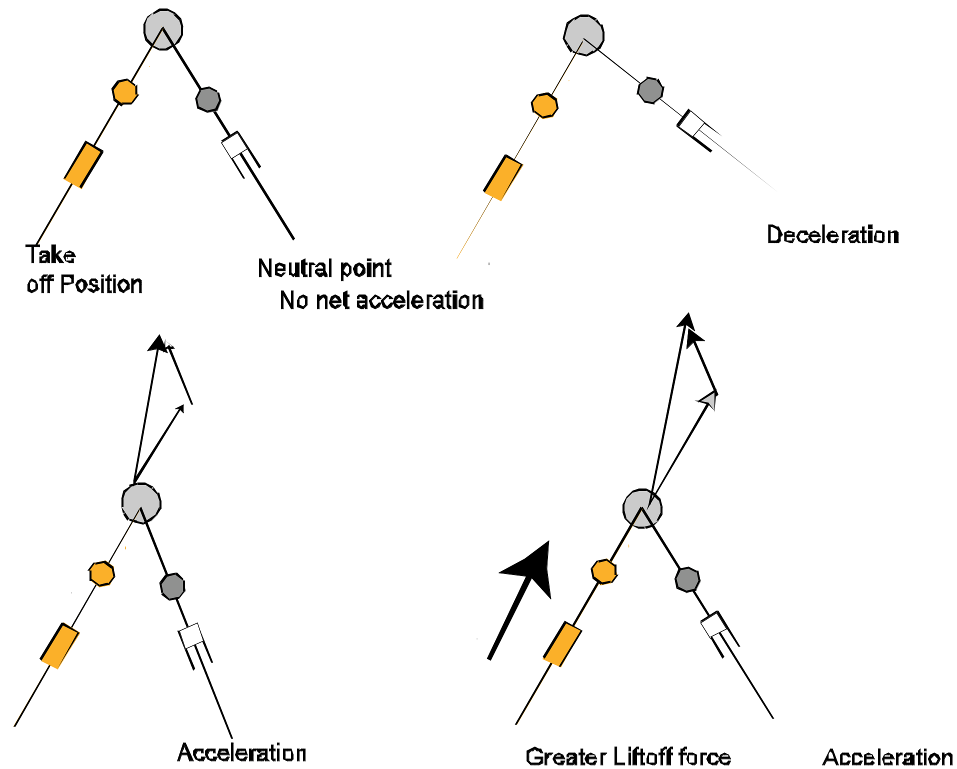
Models of Locomotion: SLIP model

- Spring loaded Inverted Pendulum (SLIP)



Speed Control in Hopping

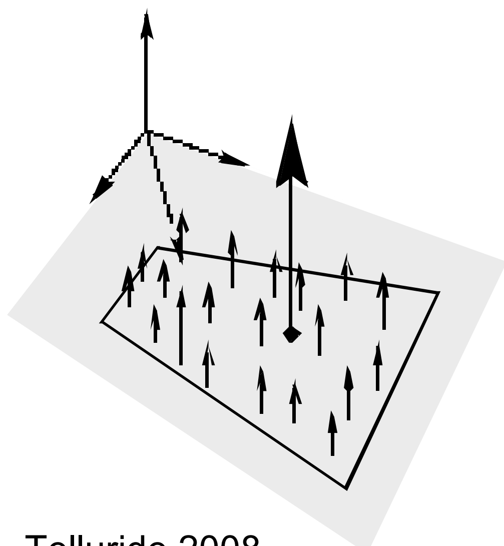
- Neutral point: landing point were no net acceleration occurs.
- Longer stride, same take off power: deceleration
- Shorter stride, same take off power: acceleration
- Greater takeoff power: Longer stride, flight phase: greater net speed.

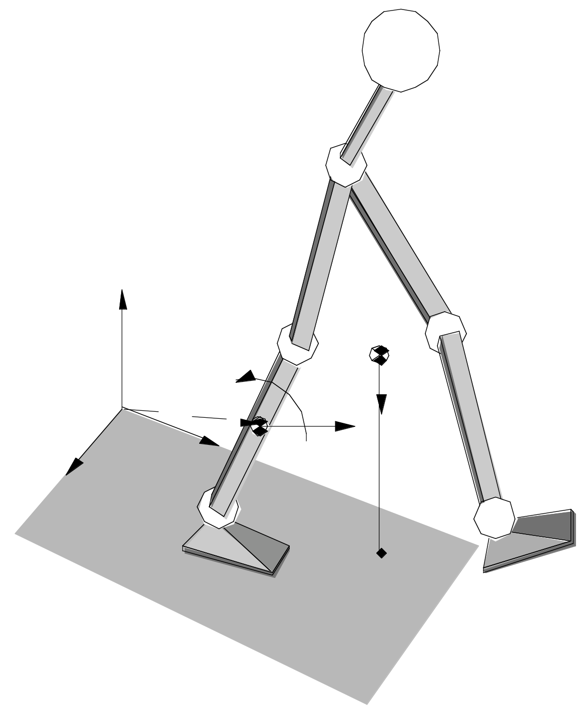


Hodgins Raibert 1991

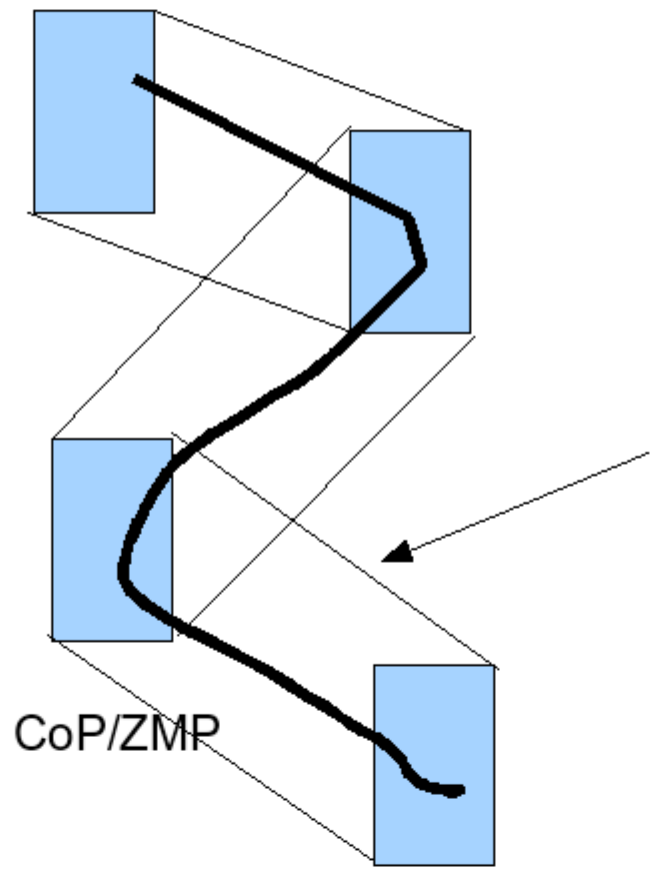
CoP

- COP: Center of the resulting foot forces
- ZMP: ZMP is the point where the vertical reaction force intersects the ground (Hemani and Golliday 1977).
- COP=ZMP (Goswami, 1999)





In conventional robots: CoP never touching edge of convex hull of support



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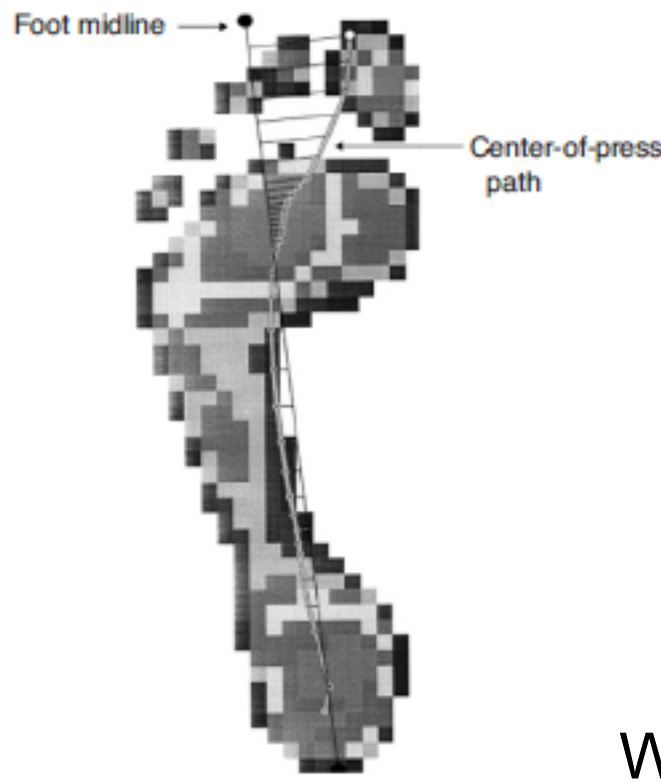
CoP Movement/Humans



Wong et al 2008

Limitations of the geometric approach

- Geometrics methods
  - Useful when simulating mechanical systems
  - Useful as a tool for understanding
  - Useful when analyzing biomechanical aspects
  - Useful as a *source* for certain biorobots
- Analytic Geometry is probably not the technology of the brain
  - Neurorobots requires a different source: *Neurons*

Neural building blocks

- ANN have been shown to be universal approximators
- Therefore functions can be created using classic ANN
  - Kinematics
  - IK
  - Dynamics
  - Inverse dynamics
  - Statics
  - Trajectory tracking
- Subsumes part of the functionality of geometrical methods

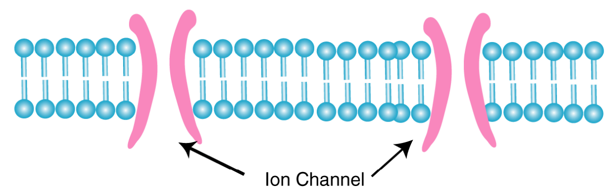
Neurons

- Cells are the building blocks multi-cellular organisms.
- Special cells exists which are electrically excititable
  - these include muscle cells
  - and neural cells (neurons)

Cell construction

Extracellular Space

- The cell membrane is the bag which contains the cellular machinery
- we do not care about dna, mitochondria, cell nuclei etc. (computationally)



Cytoplasm

- We care that:
  - cells are bags of electrolytes
  - the cell membrane has a very high resistance
  - ION channels penetrate the bilipid membrane and are highly selective to ion species

Capacitor

- The membrane/electrolyte system forms a capacitor
- The electrical model of an ideal capacitor is:

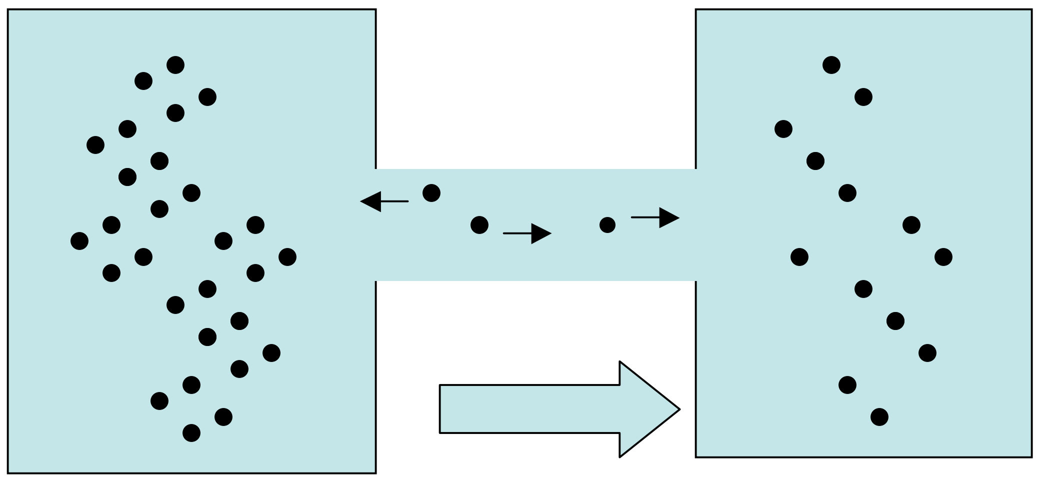
$$C\frac{dV}{dt} = i$$

- were C is the capacitance, i is a current flow, v is the voltage potential measured relative to the inside

Ion Flow

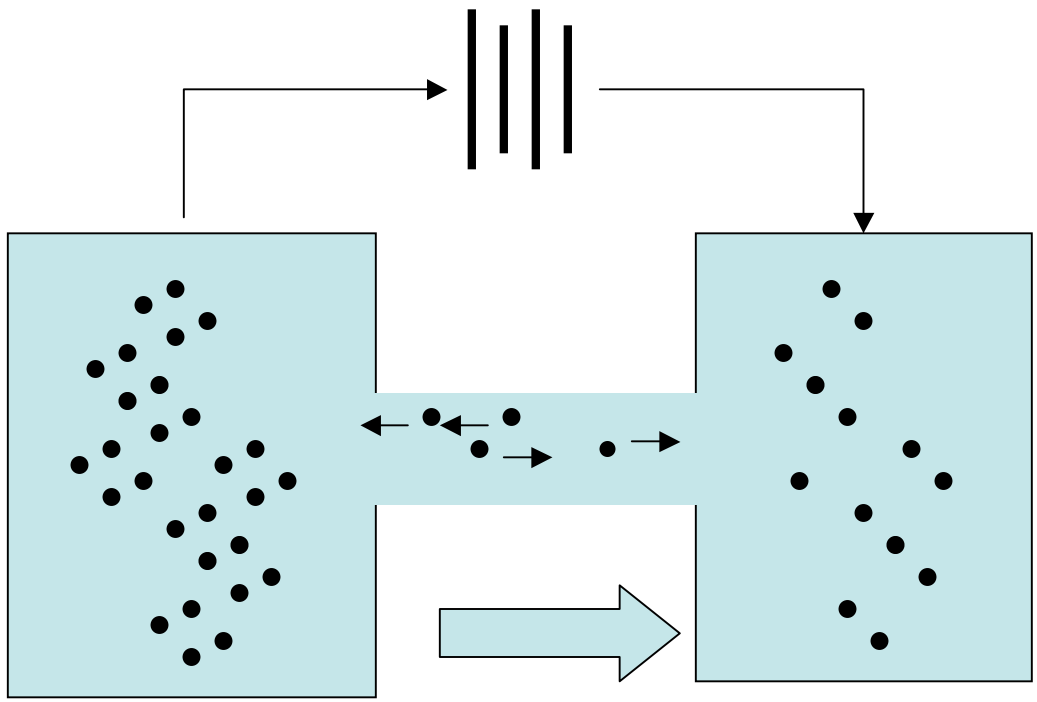
- Driven by **diffusion** and **voltage**
- Ion pumps maintain concentrations
- Ion channels allow current flow

Current Flow



Net flow of particles from higher to lower concentration
If the particles are charged, a current is generated

Balancing Current Flow



Zero net flow at proper potential

Nernst potential

$$E = \frac{RT}{zF} \ln\left(\frac{[outside]}{[inside]} \right)$$

- where E is the potential, z the the particle charge [] indicate concentration of an ion species

For real cells..

$$E_K = [-70 \ldots -90\,mv]$$

$$E_{Na} = [50\,mv]$$

$$E_{Ca^{2+}} = [150\,mv]$$

Models of I

$$C\frac{dV}{dt} = i$$

Hodgkin Huxley

$$i_m = \overline{g}_L(V - E_L) + \overline{g}_k n^4(V - E_K) + \overline{g}_{Na} m^4 h(V - E_{Na})$$

- n,m,h evolve according to complex equations
- Difficult to integrate-> Not practical in real-time simulations

Integrate and Fire

$$c_m \frac{dV}{dt} = -g_l(V - E_L) + \frac{I}{A}$$

$$if\,(V > V_{thres}) - > V = V_{reset}$$

- Insufficient for motor models

Integrate and Fire With Adaptation

$$c_m \frac{dV}{dt} = -g_l (V - E_L) + r_m g_{sra} (V - E_k) + I$$

$$\tau_{sra} \frac{dg_{sra}}{dt} = -g_{sra}$$

$$if (V > V_{thres}) -> V = V_{reset}, g_{sra} -> g_{sra} + \Delta g_{sra}$$

Leaky Integrator

$$\tau \frac{dv}{dt} = -v_i + \sum w_{i,j} x_j$$

$$x_j = f(v)$$

- x represents the average short-term firing rate
- f(v) is a sigmoidal function
- τ is C and $1/g_L$

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Matsuoka Oscillator

$$\tau_i \dot{u}_i = -u_i - \beta f(v_i) + \sum_{j \neq i} w_{ij} f(u_j) + u_0,$$

$$\dot{\tau}_i \dot{v}_i = -v_i + f(u_i),$$

$$(f(u) = \max(0, u)), \quad (i = 1, 2)$$

- Popular in CPG modes controlling robots

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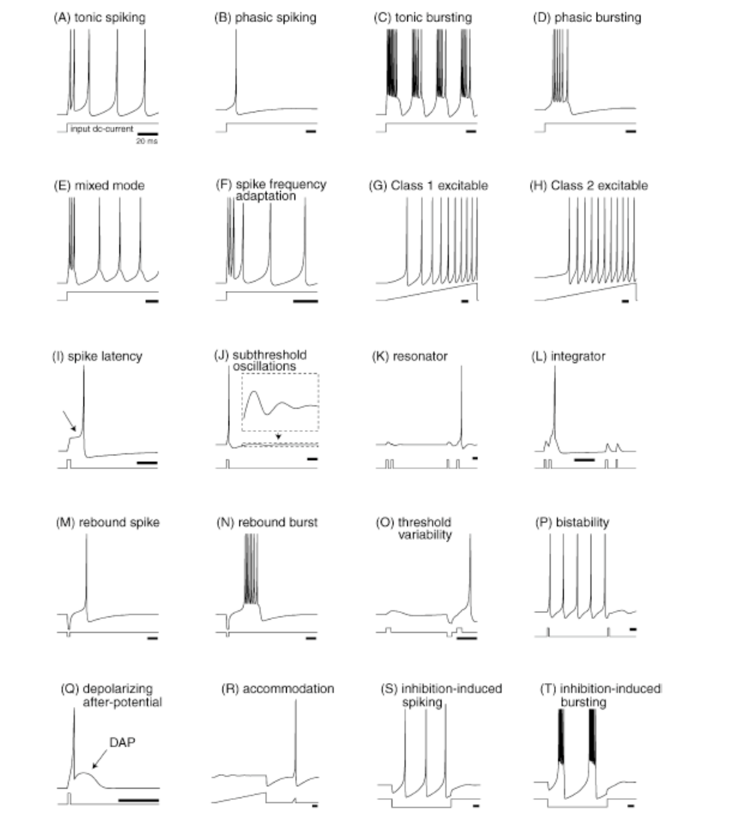
Izhikevich Model

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I$$

$$\frac{du}{dt} = a(bv - u)$$

$$if\,(v > 30mv) : v \leftarrow c, u \leftarrow u + d$$

Izhikevich Model



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Izhikevich Model

Models	biophysically meaningful	tonic spiking	phasic spiking	tonic bursting	phasic bursting	mixed mode	spike frequency adaptation	class 1 excitable	class 2 excitable	spike latency	subthreshold oscillations	resonator	integrator	rebound spike	rebound burst	threshold variability	bistability	DAP	accommodation	inhibition-induced spiking	inhibition-induced bursting	chaos	# of FLOPS
integrate-and-fire	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-	-	5
integrate-and-fire with adapt.	-	+	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	+	-	-	-	-	10
integrate-and-fire-or-burst	-	+	+		+	-	+	+	-	-	-	-	+	+	+	-	+	+	-	-	-		13
resonate-and-fire	-	+	+	-	-	-	-	+	+	-	+	+	+	+	-	-	+	+	+	-	-	+	10
quadratic integrate-and-fire	-	+	-	-	-	-	-	+	-	+	-	-	+	-	-	+	+	-	-	-	-	-	7
Izhikevich (2003)	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	13
FitzHugh-Nagumo	-	+	+	-		-	-	+	-	+	+	+	-	+	-	+	+	-	+	+	-	-	72
Hindmarsh-Rose	-	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	120
Morris-Lecar	+	+	+	-		-	-	+	+	+	+	+	+	+		+	+	-	+	+	-	-	600
Wilson	-	+	+	+			+	+	+	+	+	+	+	+	+	+		+	+				180
Hodgkin-Huxley	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	1200

Solving via Euler Integration

$$\frac{dx}{dt} = f(x)$$

$$dx = f(x) \bullet dt$$

$$\Delta x \approx f(x) \bullet \Delta t$$

$$x_{n+1} = x_n + f(x) \bullet \Delta t$$

$$x_0 = x(0)$$

Better Integrators Exist

- Runge-Kutta>>Euler for many problems despite greater number of evaluations per time step
- Time steps can be much greater
- Time can be ignored in may problems...

$$\frac{dx}{dt} = f(t, x)$$

$$x_{n+1} = x_n + \frac{h}{6}\left(a + 2b + 2c + d\right)$$

$$a = f(t_n, x_n)$$

$$b = f(t_n + \frac{h}{2}, x_n + \frac{h}{2}a)$$

$$c = f(t_n + \frac{h}{2}, x_n + \frac{h}{2}b)$$

$$d = f(t_n + h, x_n + hc)$$

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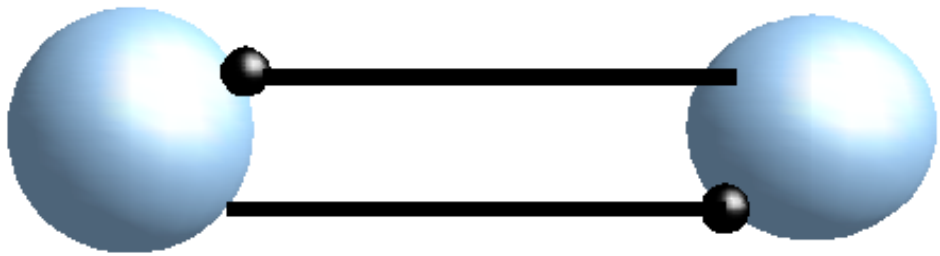
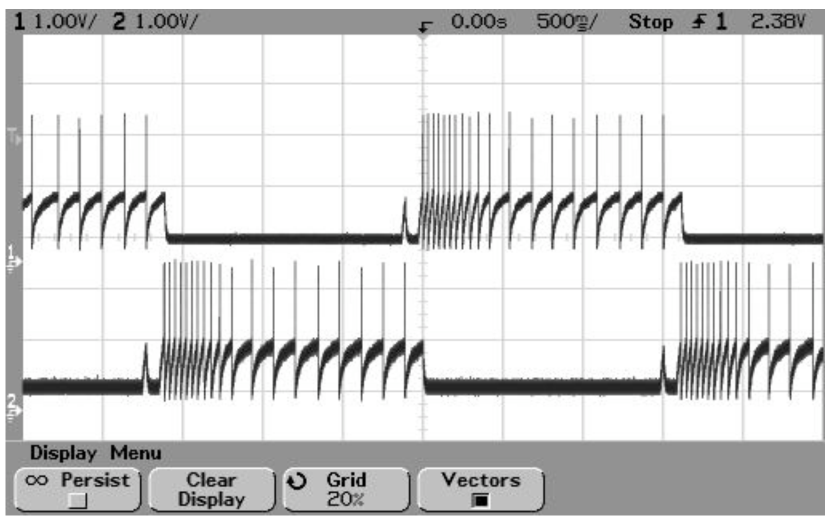
Building Oscillators: Brown Half-Centered Oscillator





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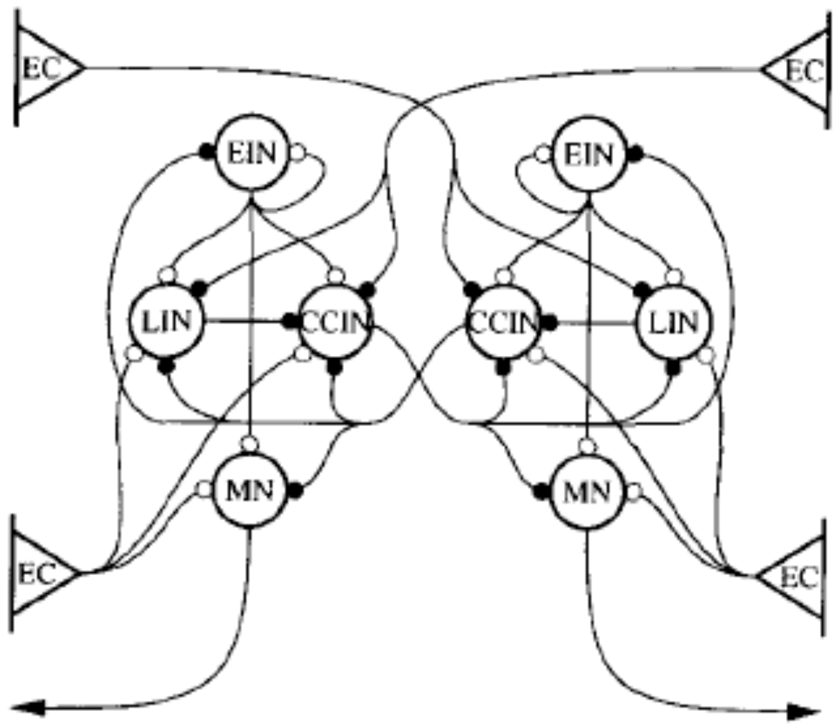
Lamprey example



Ekeberg 1993

CASE Group Hexapod 1

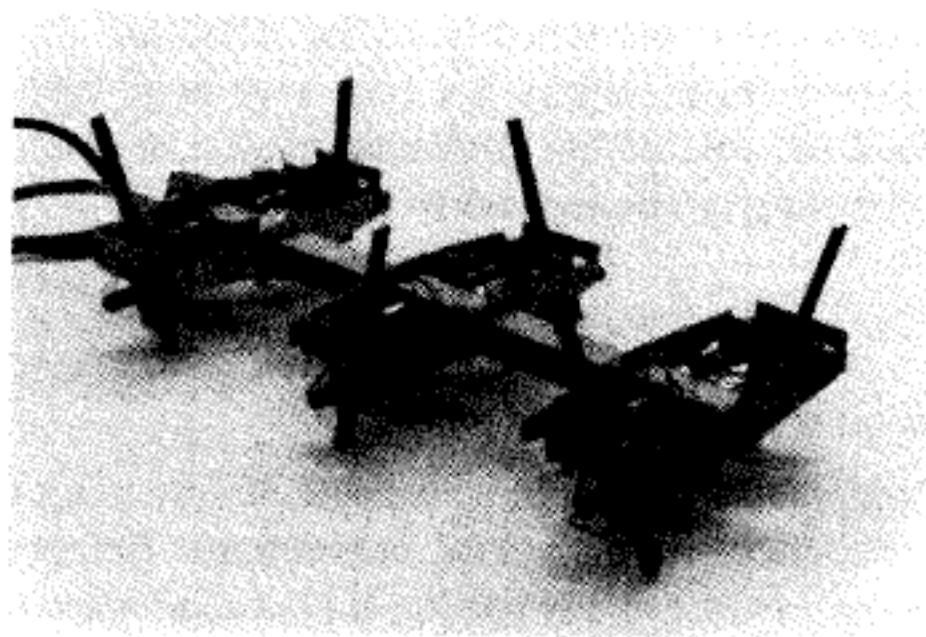


Fig. 2. Photograph of the robot.

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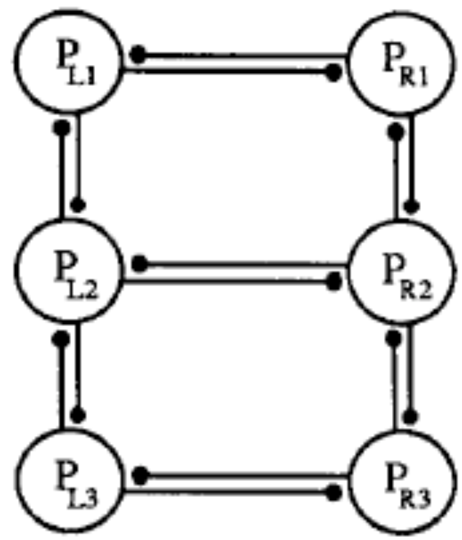


Fig. 4. Pacemaker coordination. Legs controlled by each pacemaker are indicated by subscripts.

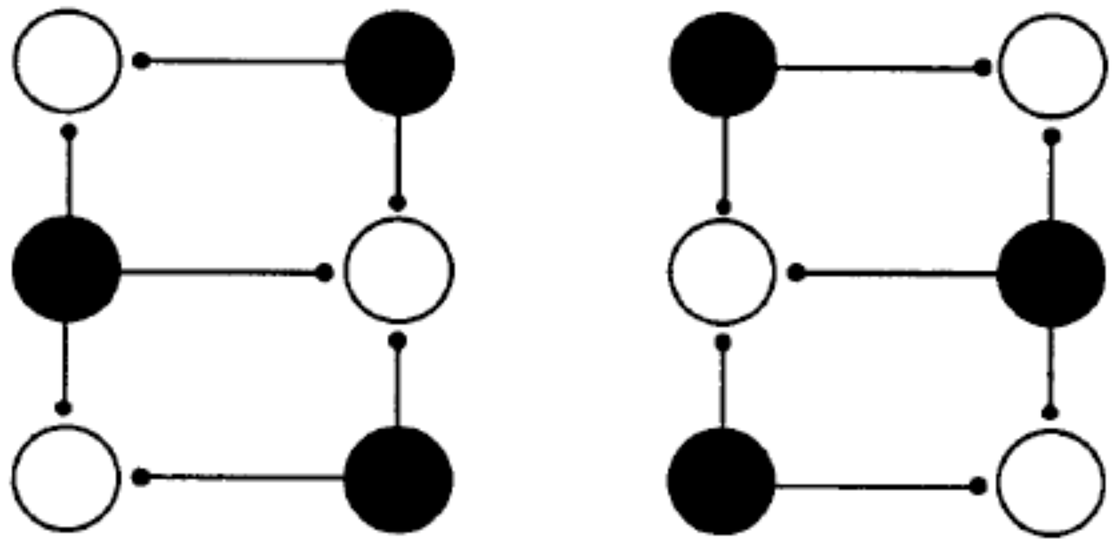
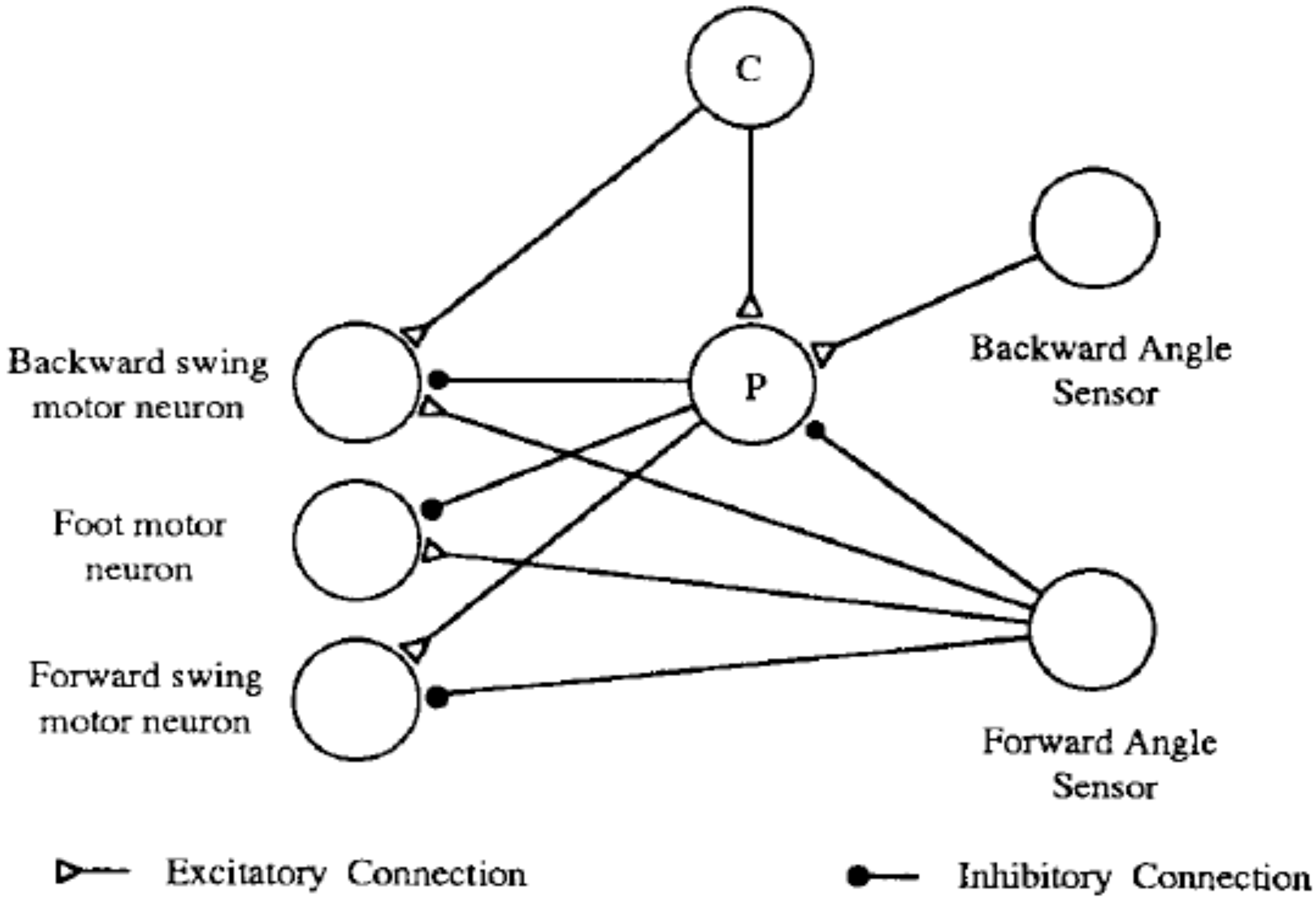


Fig. 10. Generation of the tripod gait. The two stable configurations of the central network during the tripod gait are shown. Neurons that are active are filled, inhibited neurons are white.

Case Neuron model

$$C_i dV_i/dt = -V_i/Ri + \sum w_{ij} f_j(V_j) + INT_i + EXT_i$$



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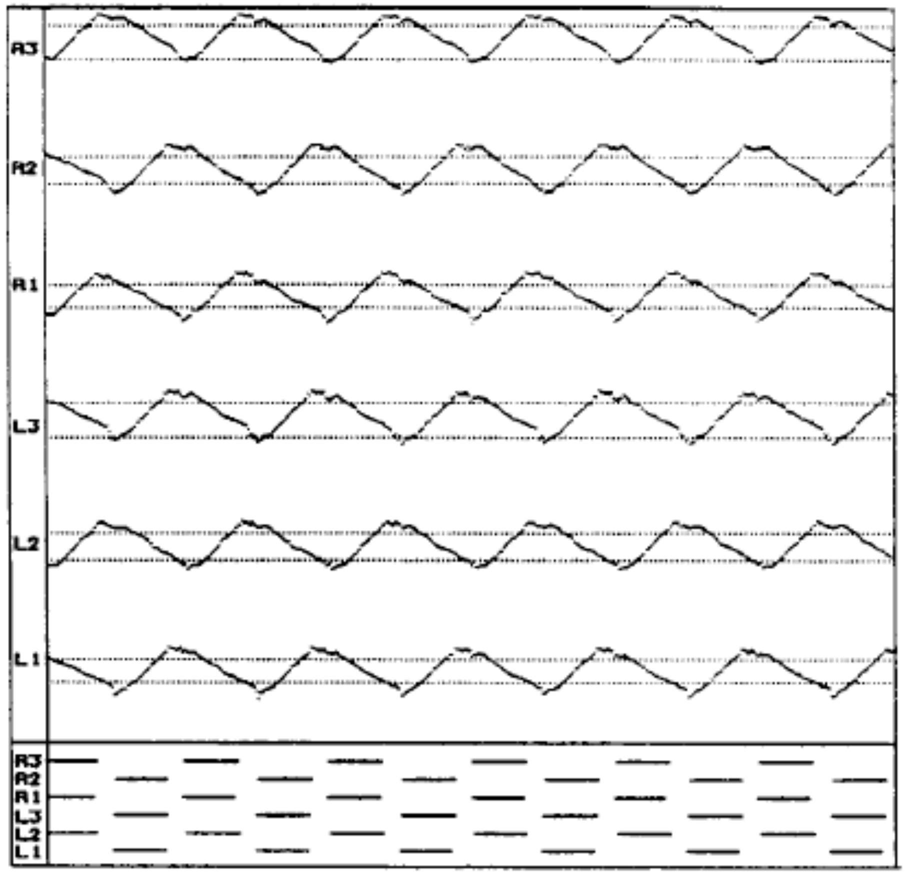
high speed gait



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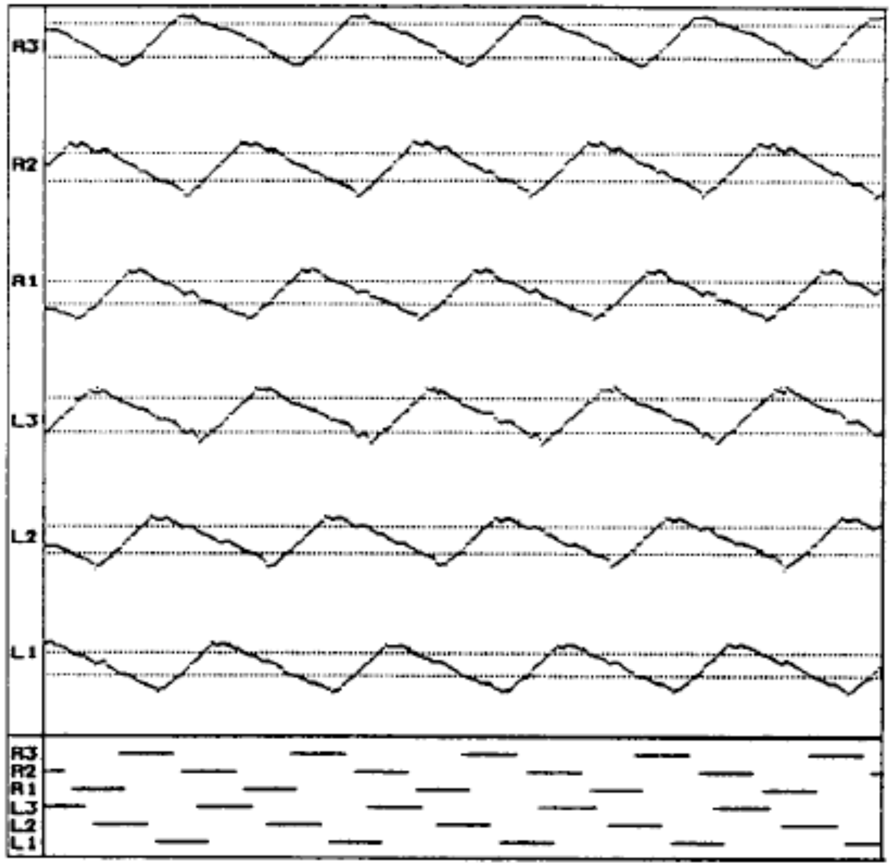
Medium Speed



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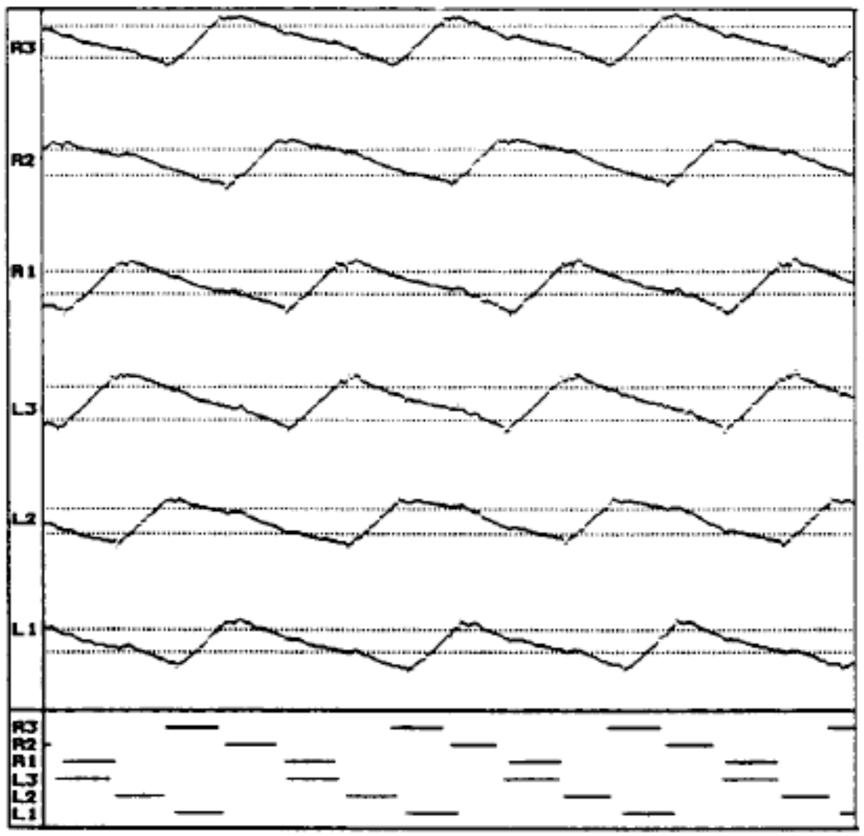
Low Speed



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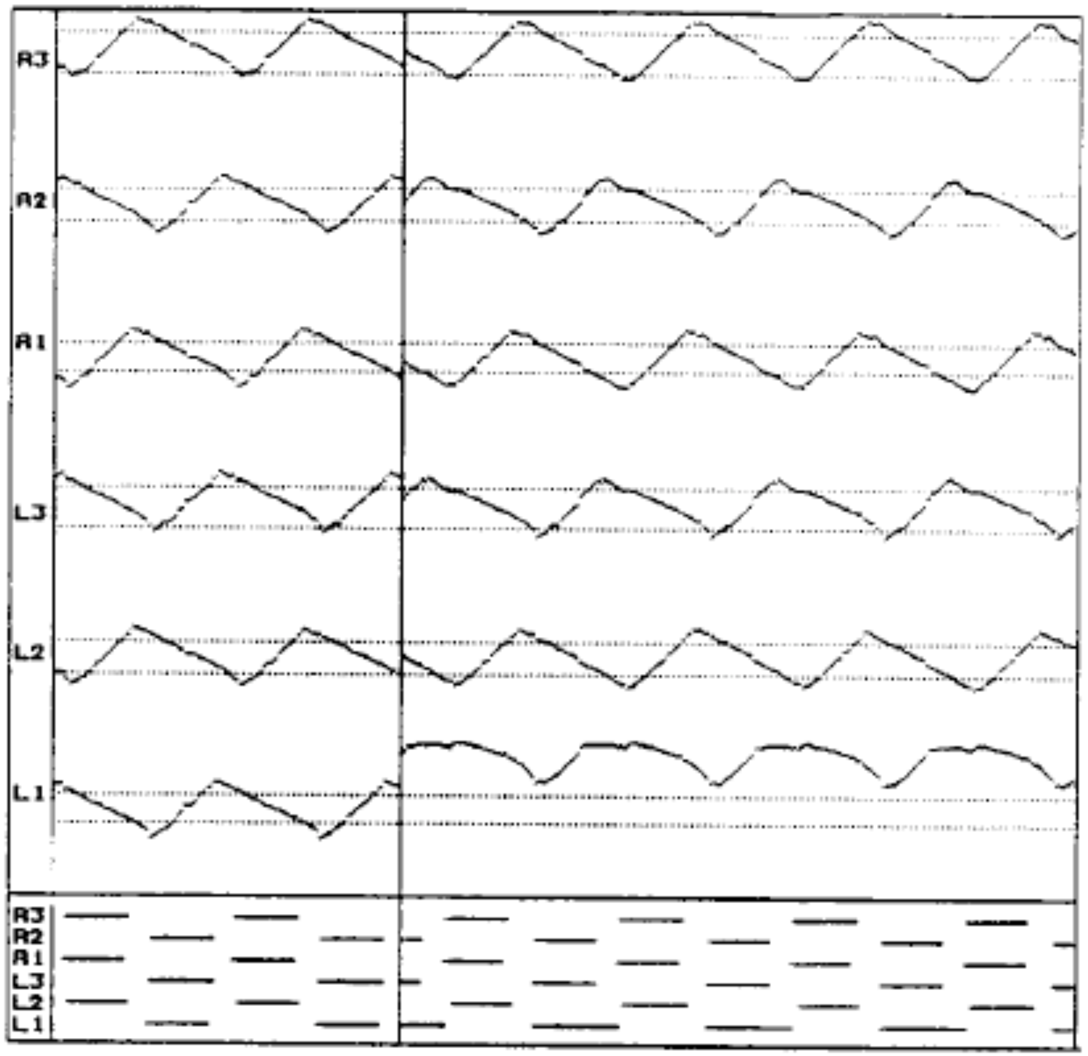
Lesion Experiments

Forward swing L1 Sensor



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Taga, 1995

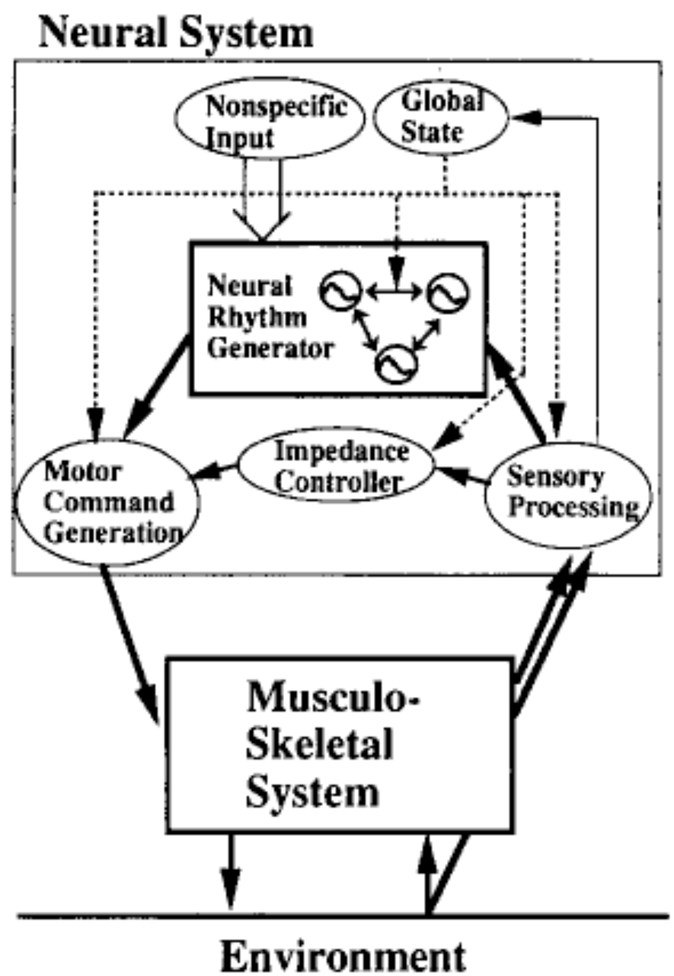

Fig. 1. Model for human locomotion

Taga dynamic model

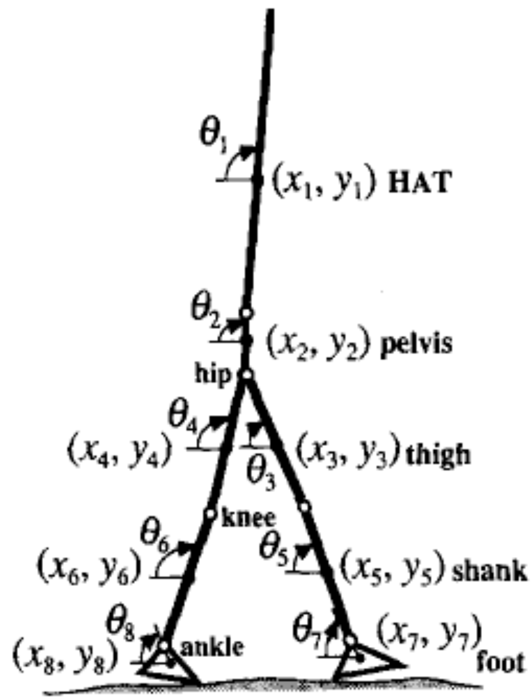

Fig. 2. The model of the human body, composed of the *HAT* (head, arms, and trunk), pelvis, thigh, shank, and foot. There are seven joints, two each at the hips, knees, and ankles, and one at the trunk

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Matsuoka Oscillator

$$
\begin{aligned}
\tau_i \dot{u}_i &= -u_i - \beta f(v_i) + \sum_{j \neq i} w_{ij} f(u_j) + u_0, \\
\dot{\tau}_i \dot{v}_i &= -v_i + f(u_i), \qquad (4) \\
(f(u) &= \max(0, u)), \quad (i = 1, 2)
\end{aligned}
$$

Global State

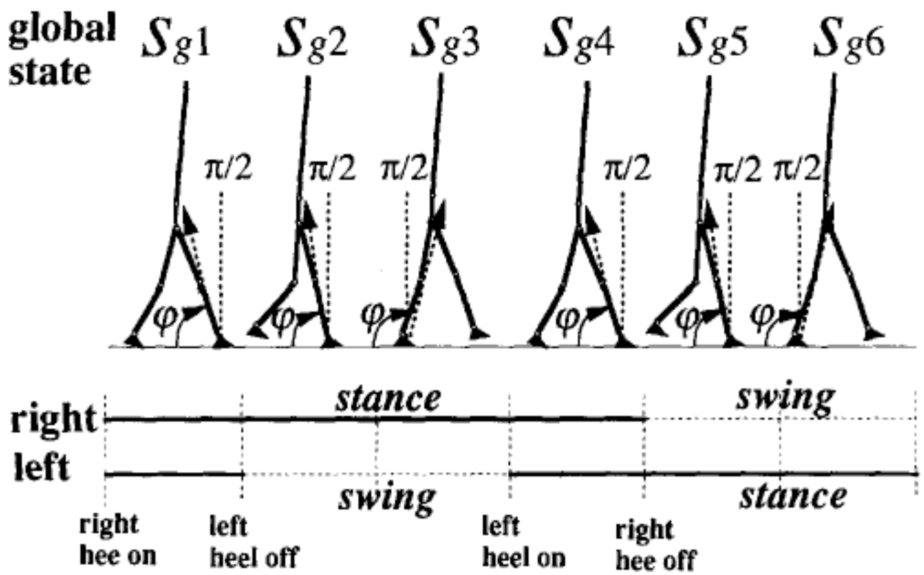


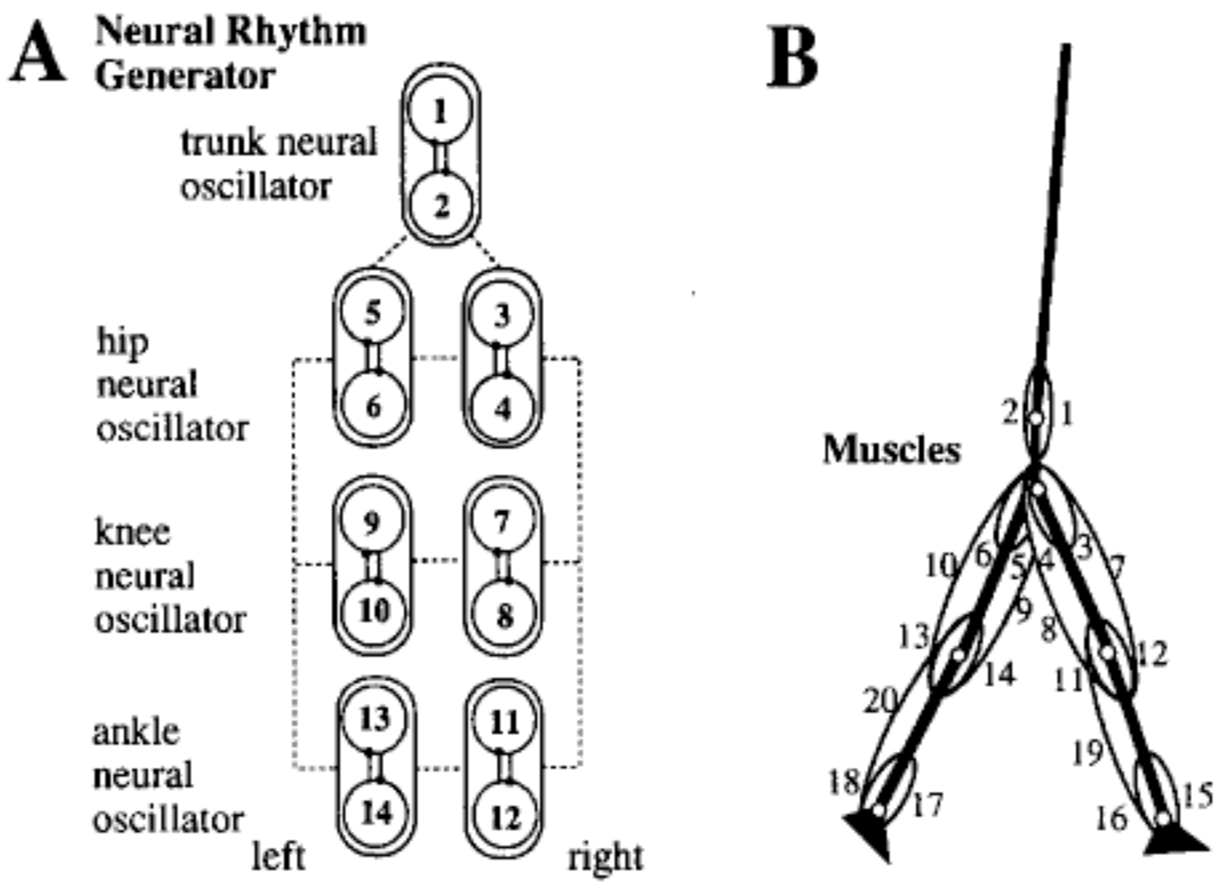
Fig. 3. Global pattern of movement within a gait cycle represented by a cyclic sequence of the global states. A gait cycle is defined as the time interval between successive instances of initial foot-to-floor contact with the same foot. s_{gk} is determined by the global angle φ and the position of the foot contacting the ground. The single-support phase is divided into two periods: the first half, when the global angle is less than $\pi/2$, and the second half, when the global angle exceeds $\pi/2$

Global Angle

- Between CoG and COP

$$\phi = \cos^{-1}\left[(x_{cp} - x_{cg}) / \{(x_{cp} - x_{cg})^2 + (y_{cg} - y_{cp})^2\}^{\frac{1}{2}}\right] \quad (5)$$

Oscillation



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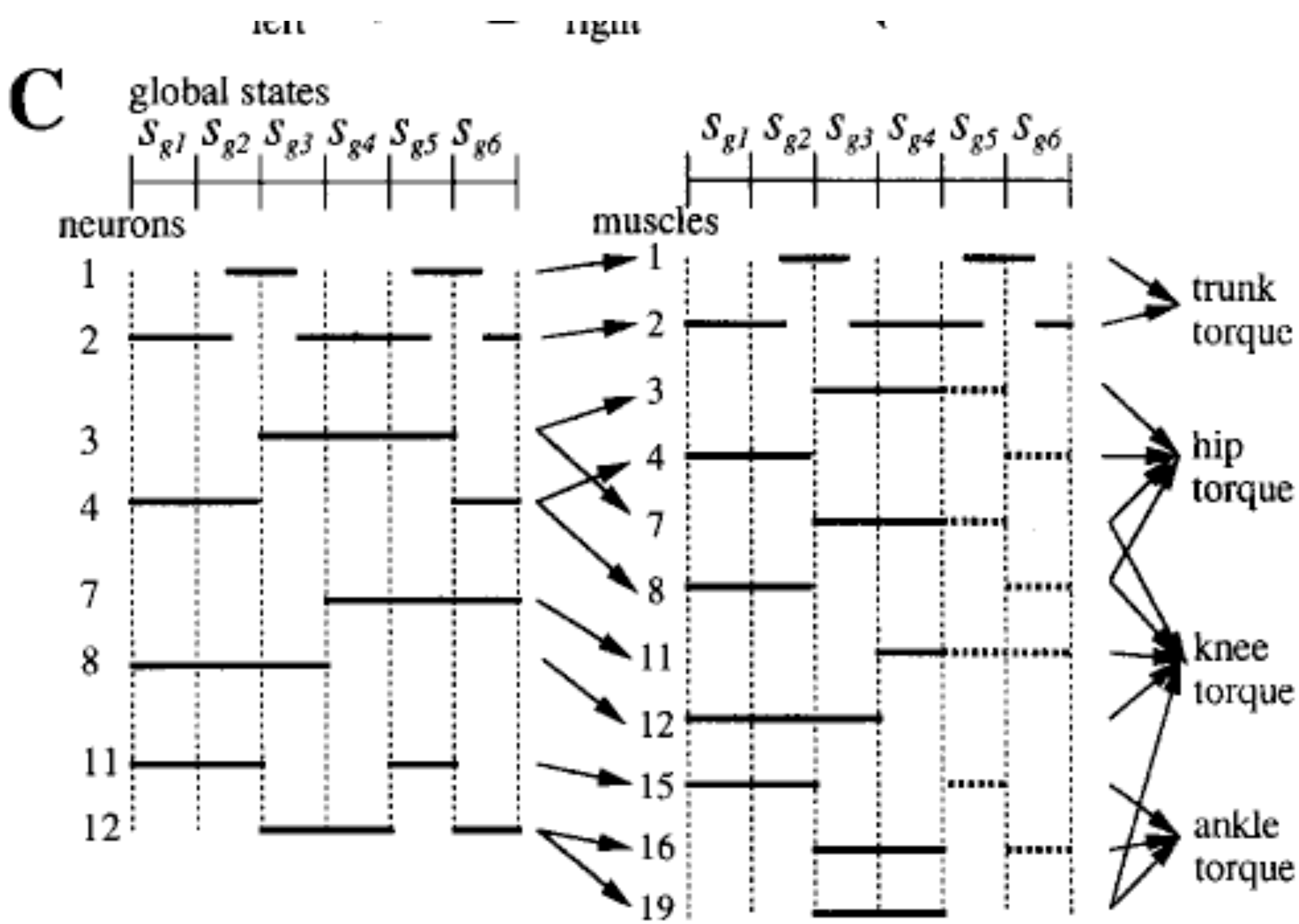
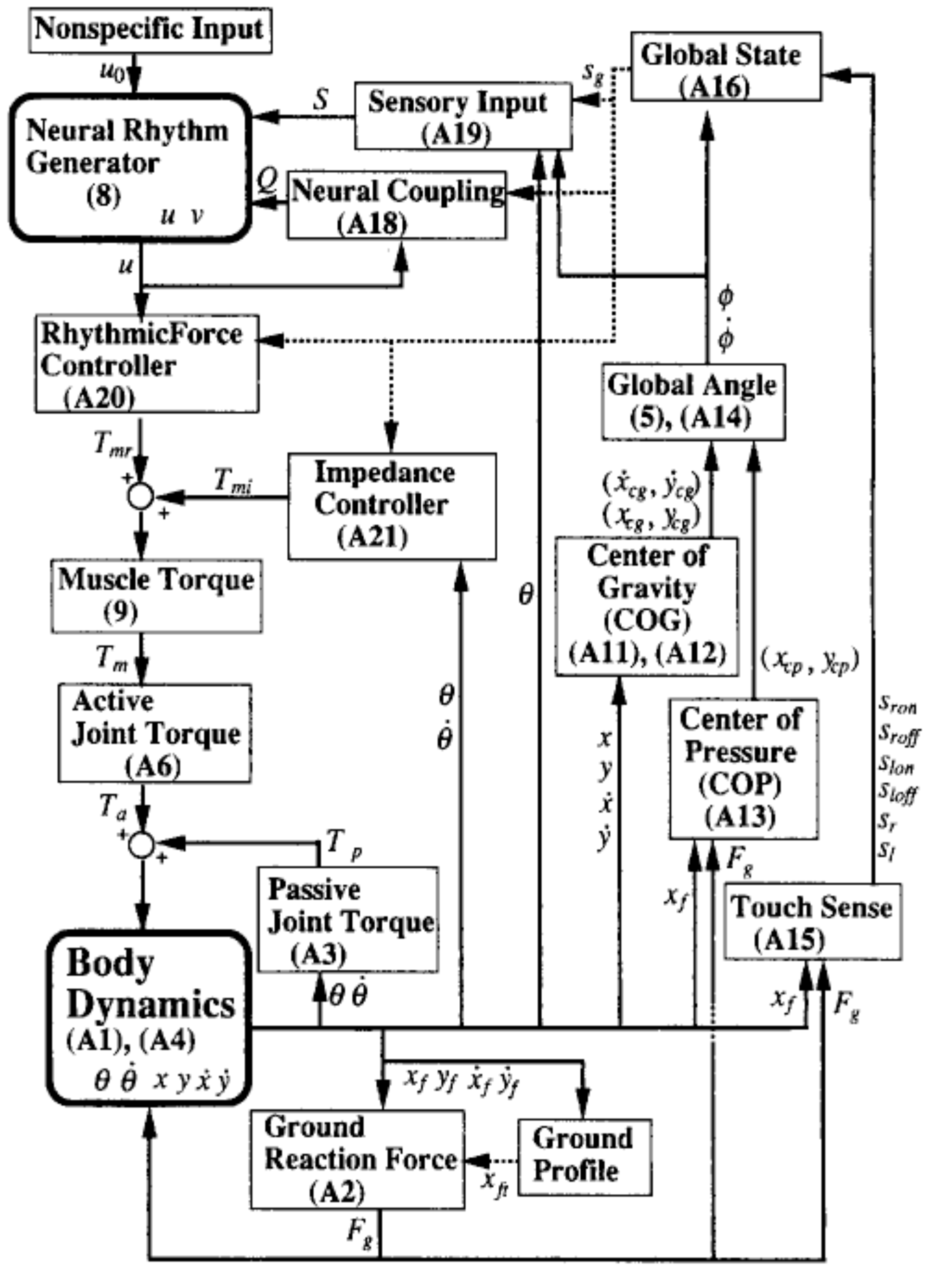
Correlation of muscle and neural activations





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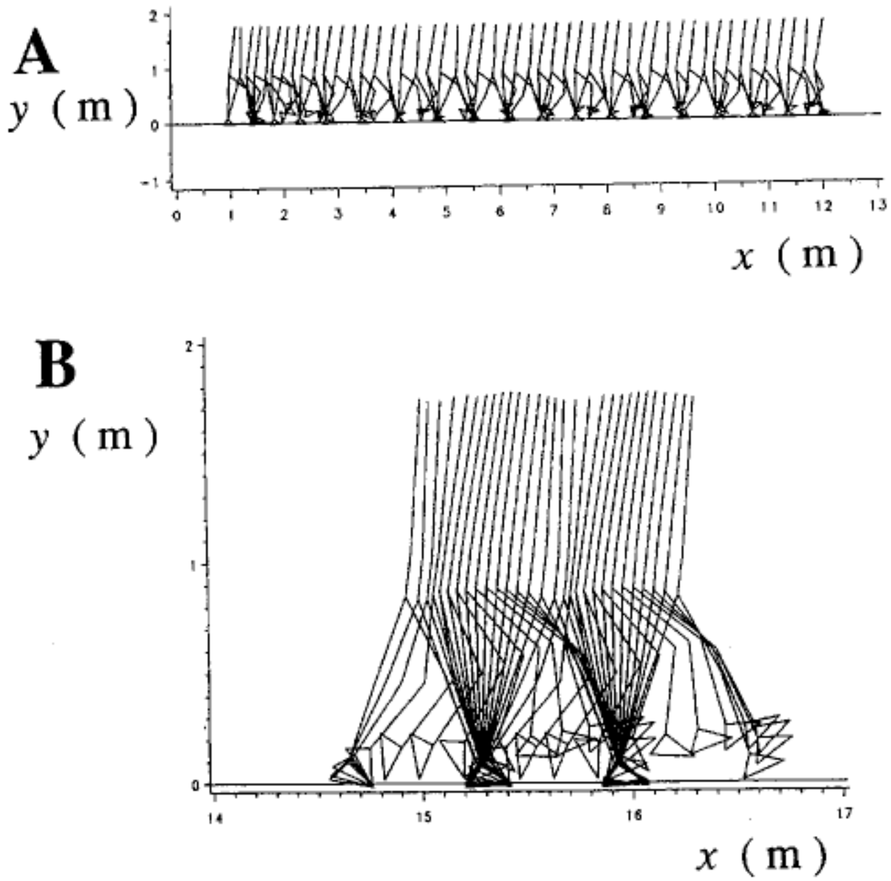

Fig. 6. A Stick figure of walking movement. Given a set of initial conditions, the walking movement converged to a steady state. The stick figure was traced every 0.2 s. **B** Stick figure of walking movement in the steady state within a gait cycle. The stick figure was traced every 0.01 s

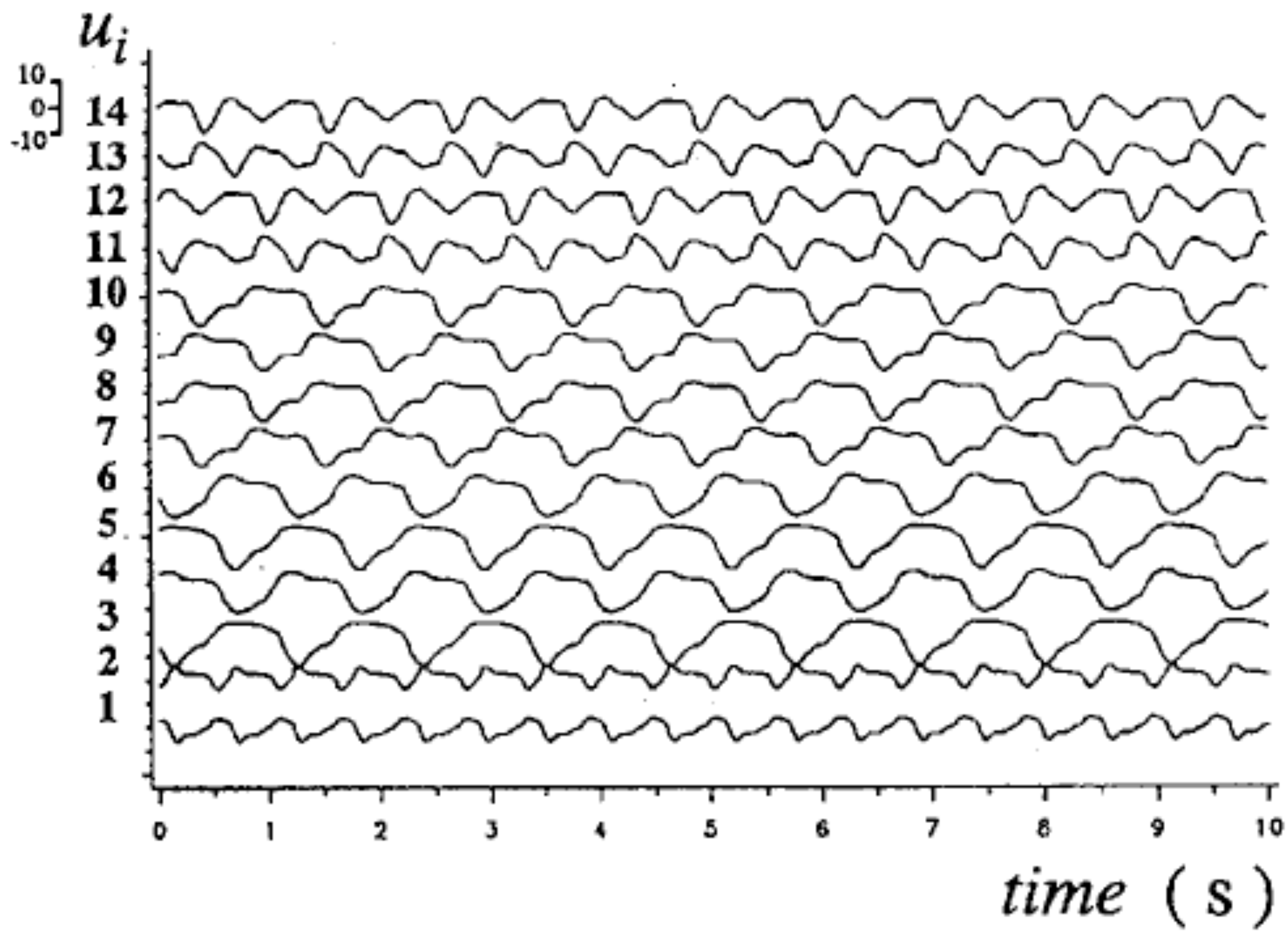

Fig. 7. Activities of the neural oscillators. The time courses of the state variables of each neuron are shown

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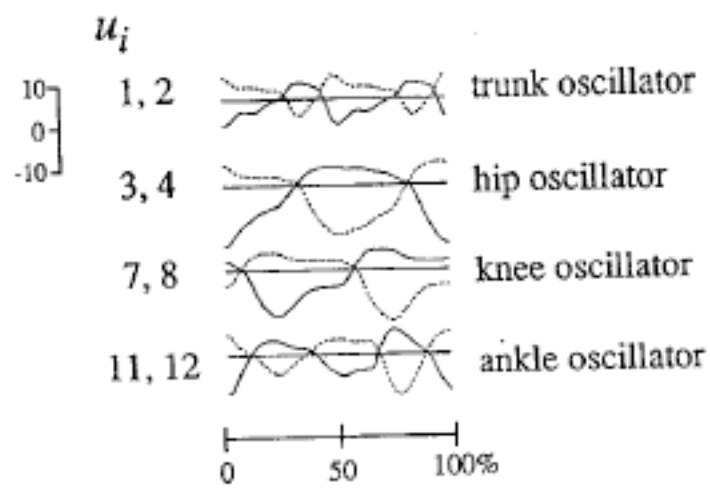
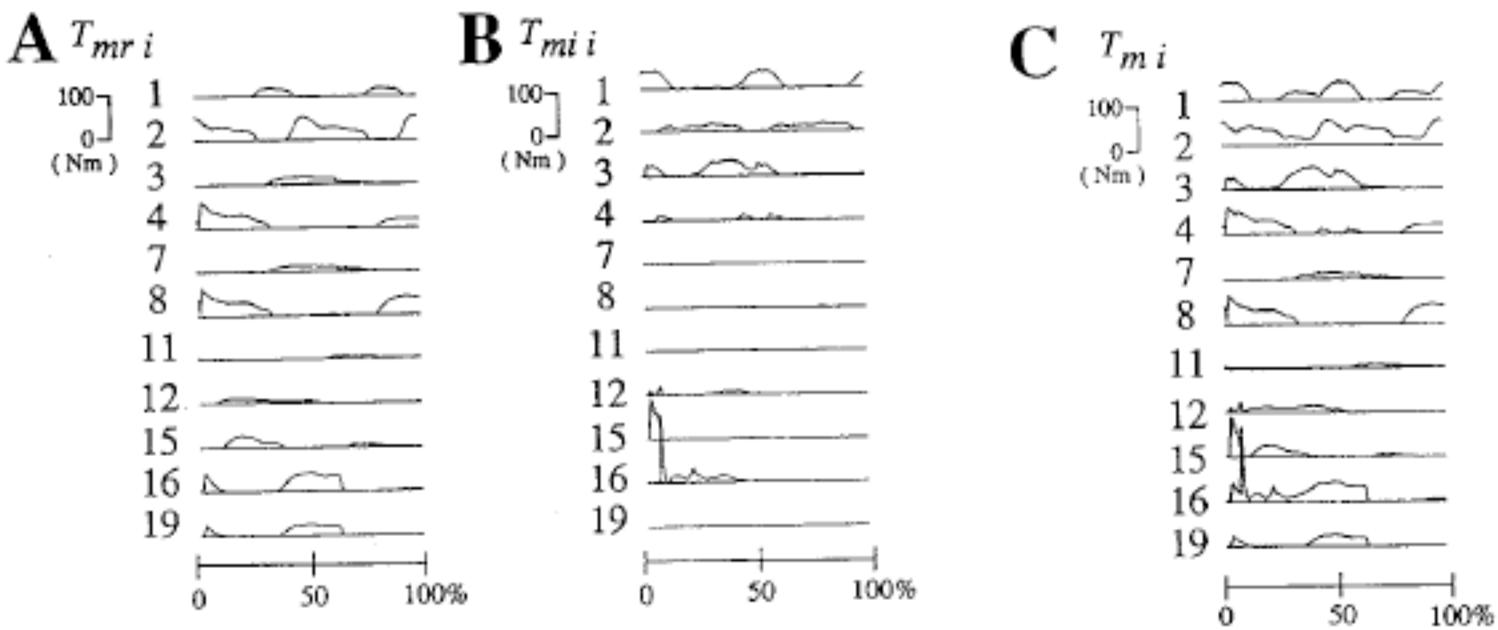
Neural Activities



Muscle Torques



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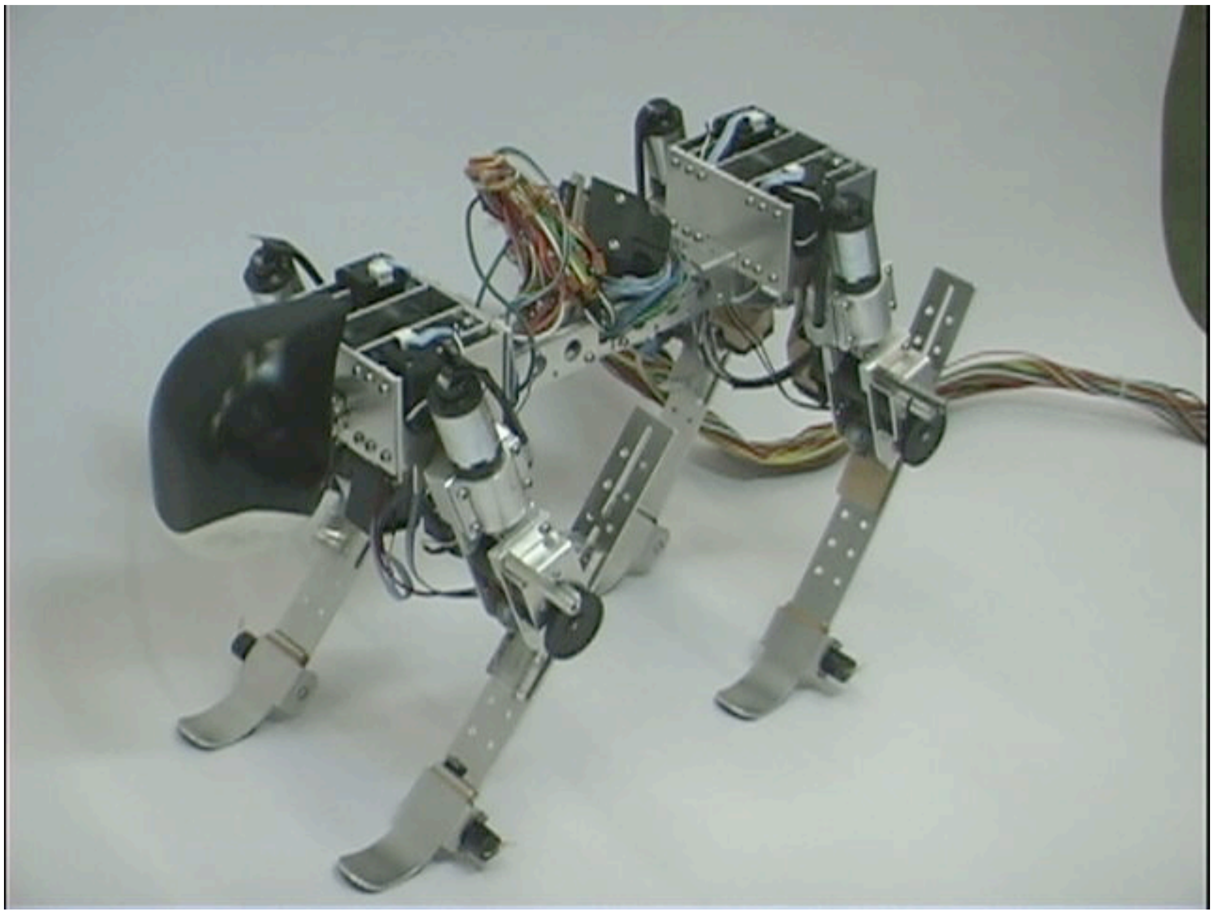
TEKKEN



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Oscillators network

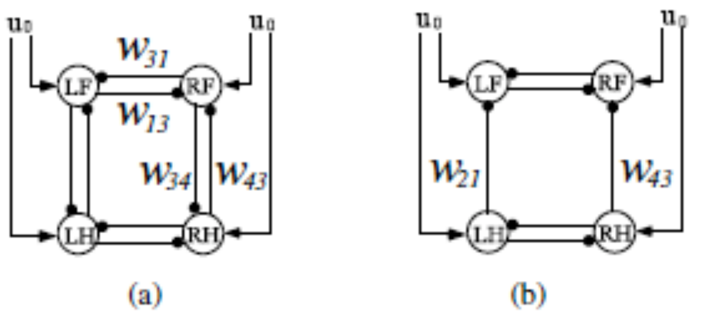
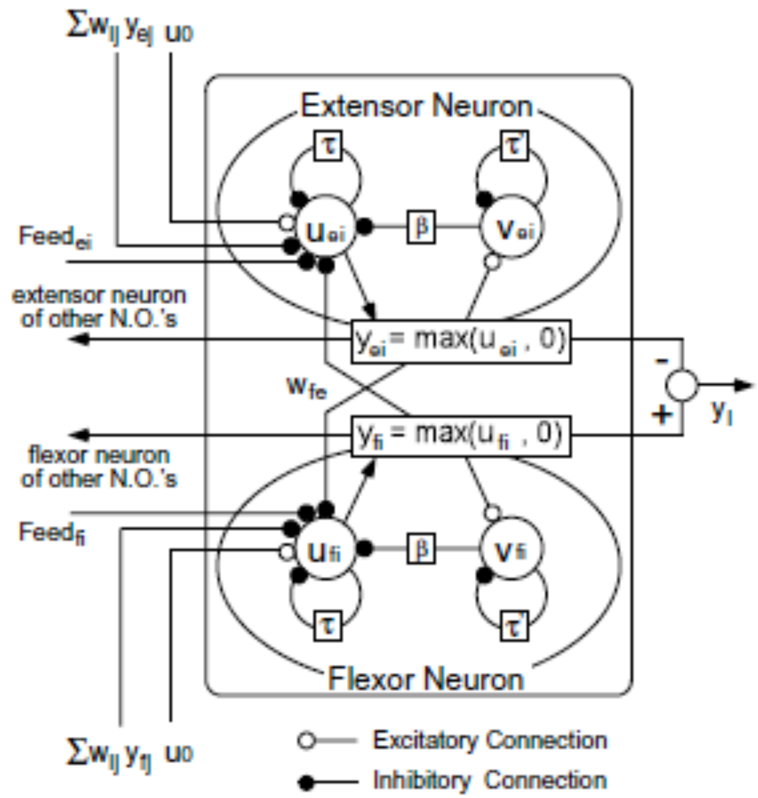


Fig. 3. CPG network for (a) Patrush and (b) Tekken. The subscripts i, j = 1, 2, 3, 4 correspond to LF, LH, RF, RH. L, R, F and H denote the left, right, fore or hind legs, respectively.



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Equations

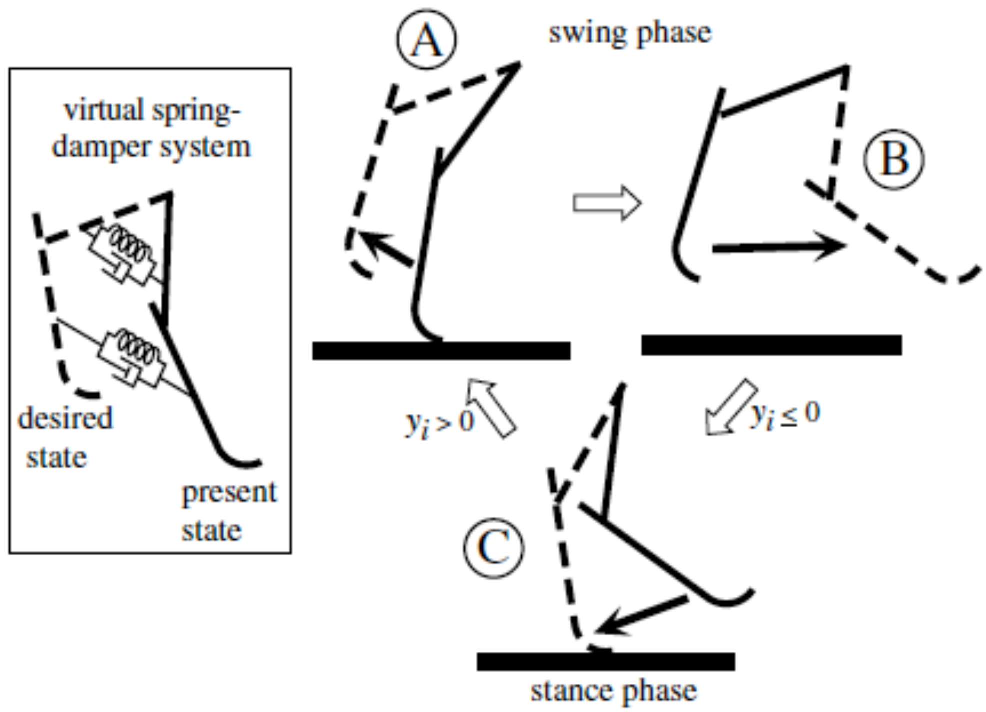
$$
\begin{aligned}
\tau \dot{u}_{\{e,f\}i} &= -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} \\
&\quad + u_0 + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_{\{e,f\}j} \\
y_{\{e,f\}i} &= \max\ (u_{\{e,f\}i}, 0) \qquad (1) \\
\tau' \dot{v}_{\{e,f\}i} &= -v_{\{e,f\}i} + y_{\{e,f\}i}.
\end{aligned}
$$

$$Feed_{e \cdot tsr} = k_{tsr}(\theta - \theta_0), \quad Feed_{f \cdot tsr} = -Feed_{e \cdot tsr}$$

- Matsuoka oscillator
- e: Extensor
- f: flexor
- Feedback: joint angles and sensors

Tekken using spring/damper system

- implemented electronically
- varies depending on state



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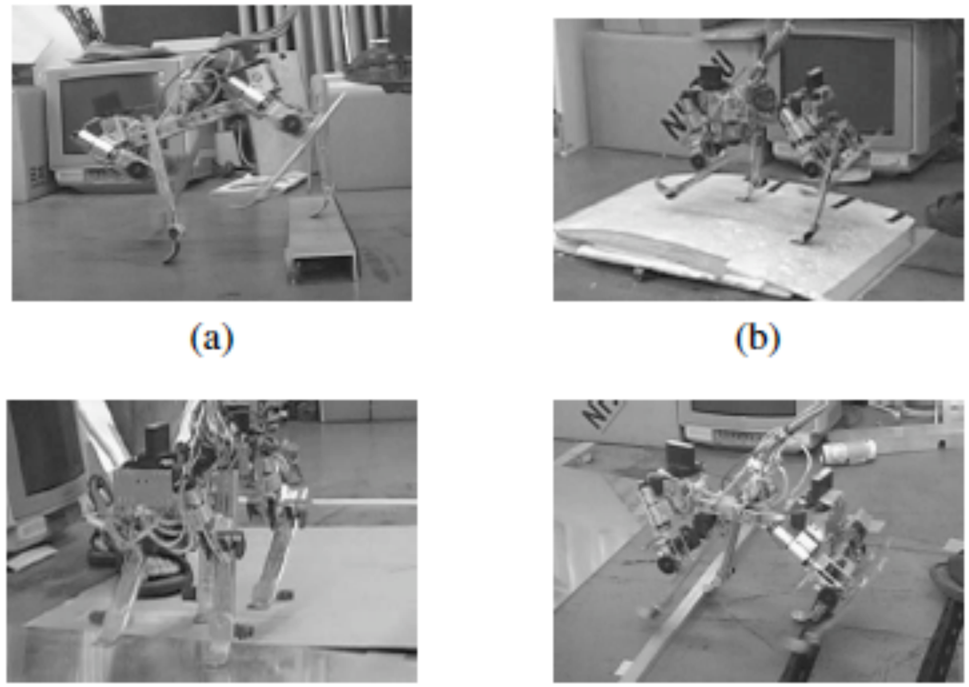

(a) (b) (c) (d)

ght

Fig. 18. Photographs of walking on irregular terrain: (a) walking over a step 4 cm in height; (b) walking up and down a slope of 10° in a forward direction; (c) walking over slopes of 3 and 5° in a sideways direction; (d) walking over a series of obstacles 2 cm in height.

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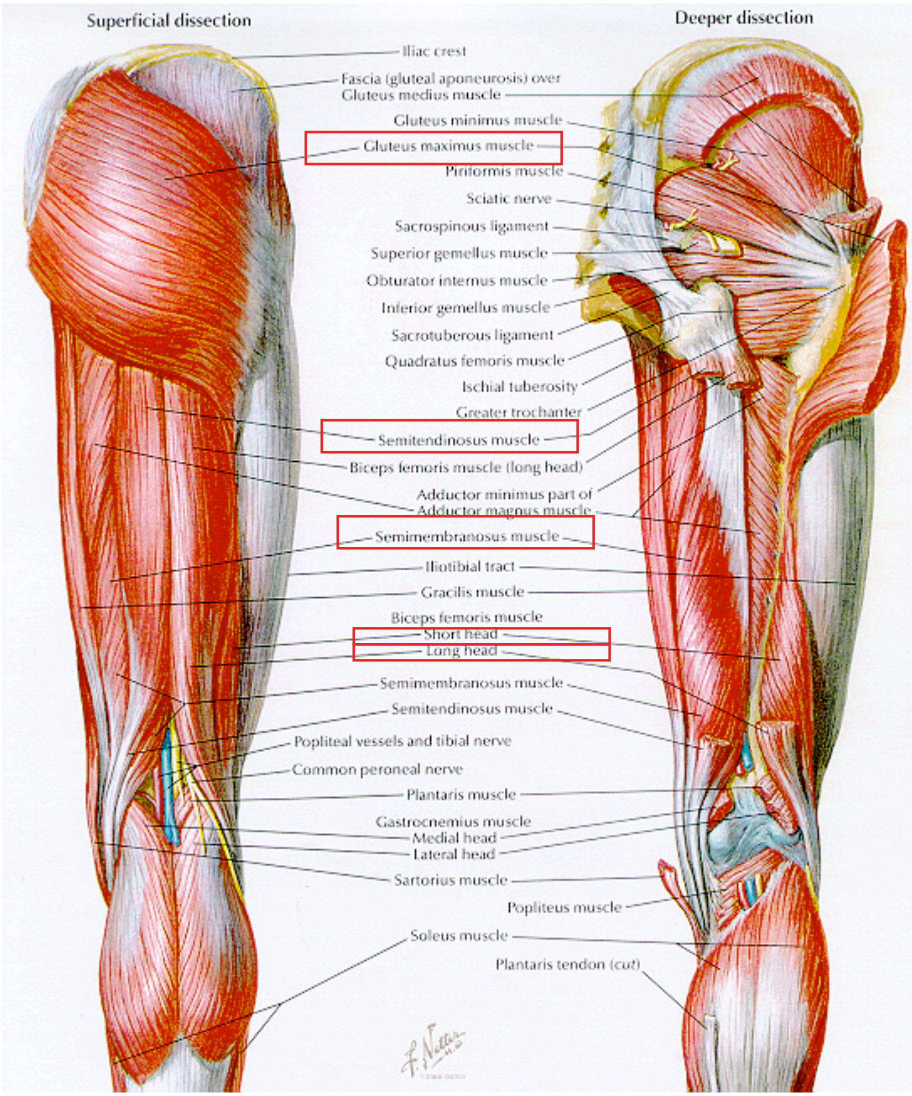
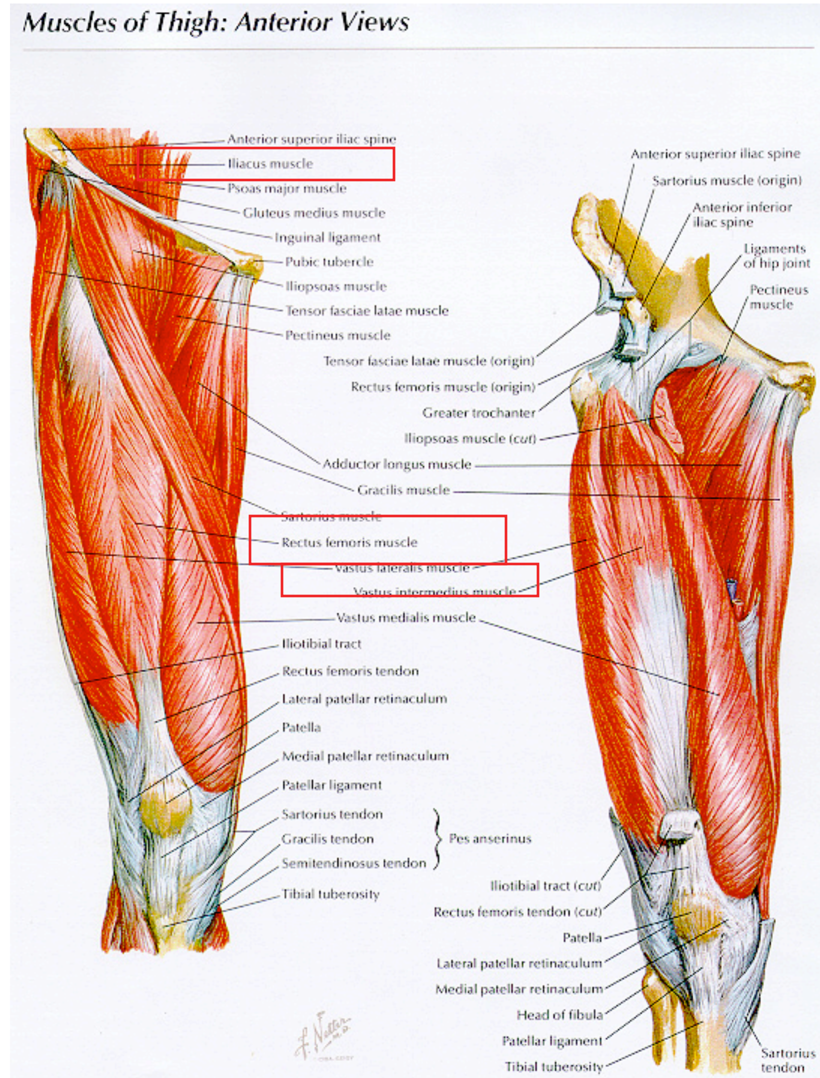
Building Biologically Realistic Legs

- Human body has 244 Kinematics DOFs and ~660 muscles
- more muscles than are needed(!)
- Biarticulate muscles are ubiquitous.





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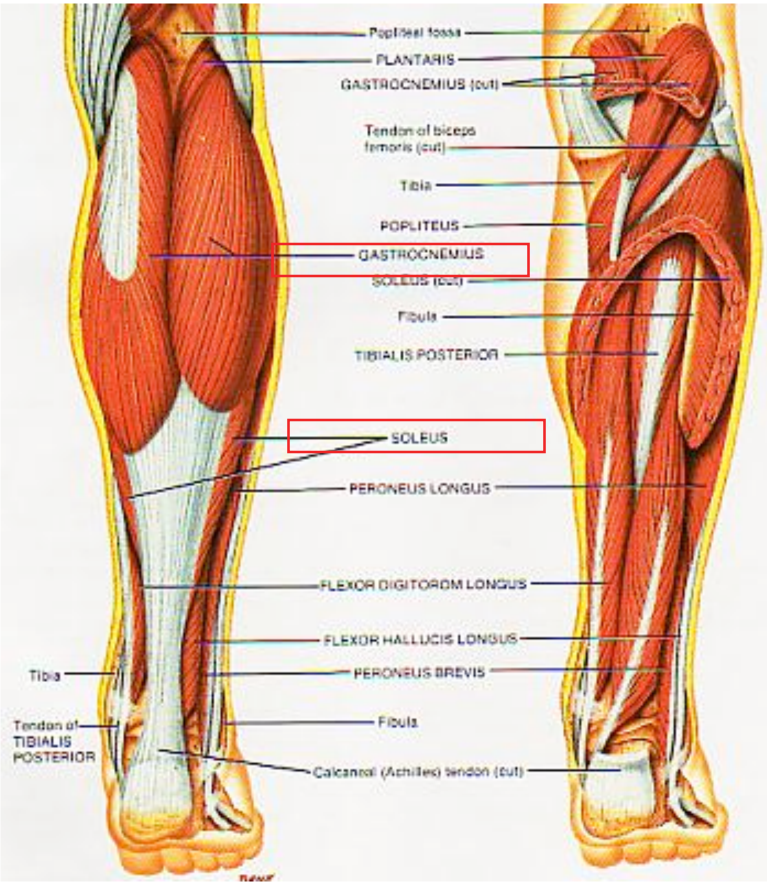
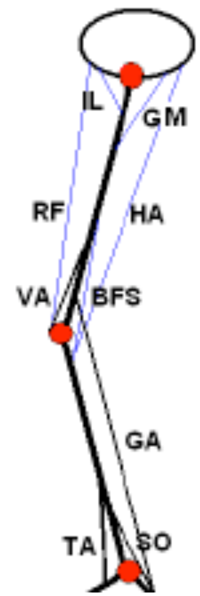
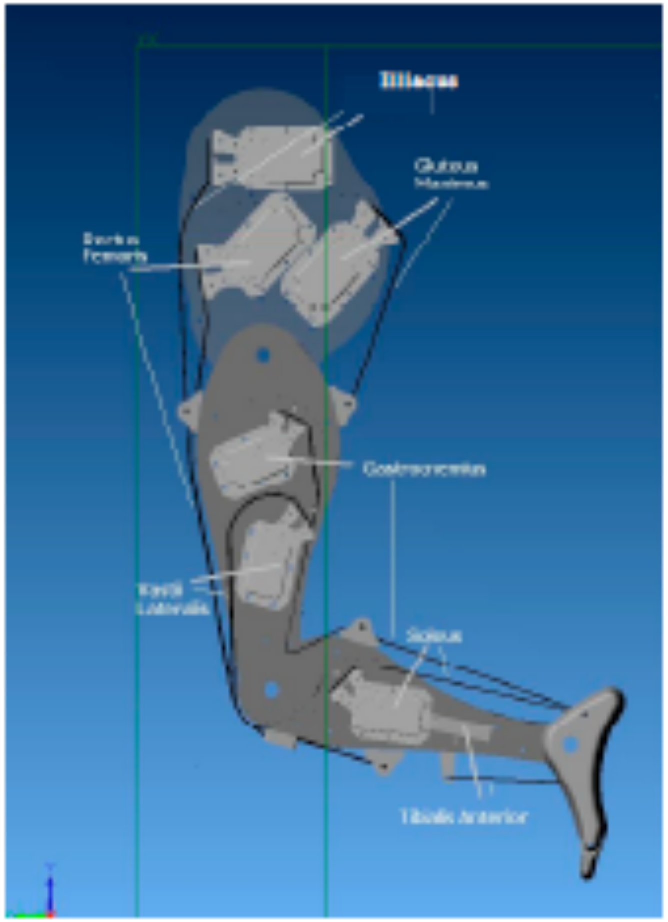
Leg Muscle



Popliteal fossa
PLANTARIS
GASTROCNEMIUS (cut)
Tendon of biceps femoris (cut)
Tibia
POPLITEUS
GASTROCNEMIUS
SOLEUS (cut)
Fibula
TIBIALIS POSTERIOR
SOLEUS
PERONEUS LONGUS
FLEXOR DIGITORUM LONGUS
FLEXOR HALLUCIS LONGUS
PERONEUS BREVIS
Tibia
Tendon of TIBIALIS POSTERIOR
Fibula
Calcaneal (Achilles) tendon (cut)



Redrawn from Prilutsky and Zatsiorsky 2002



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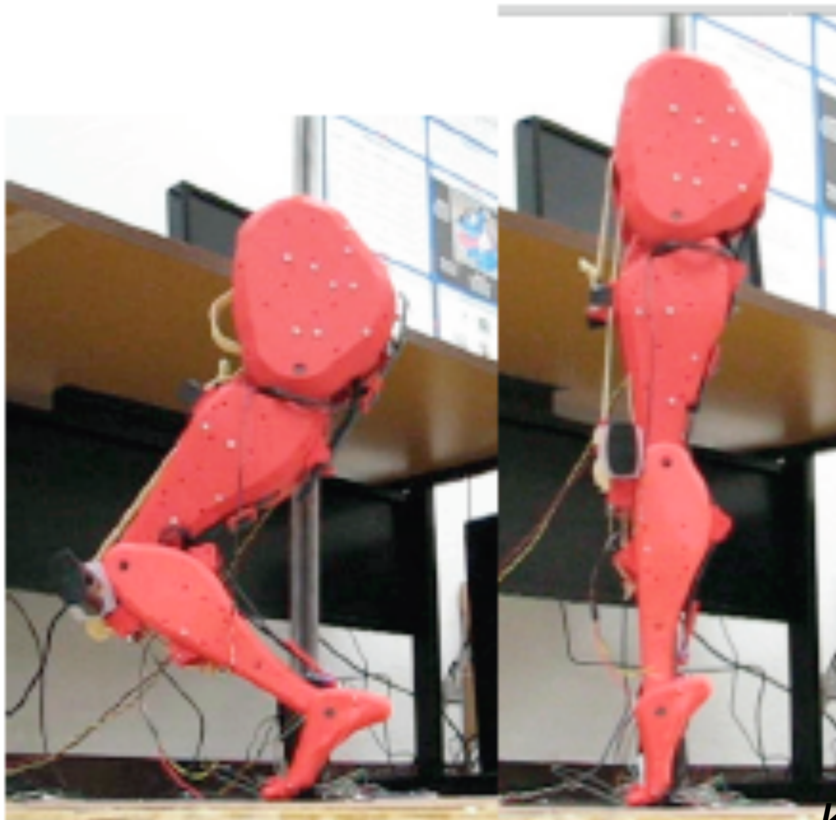
Transfer of power via Gastrocnemius



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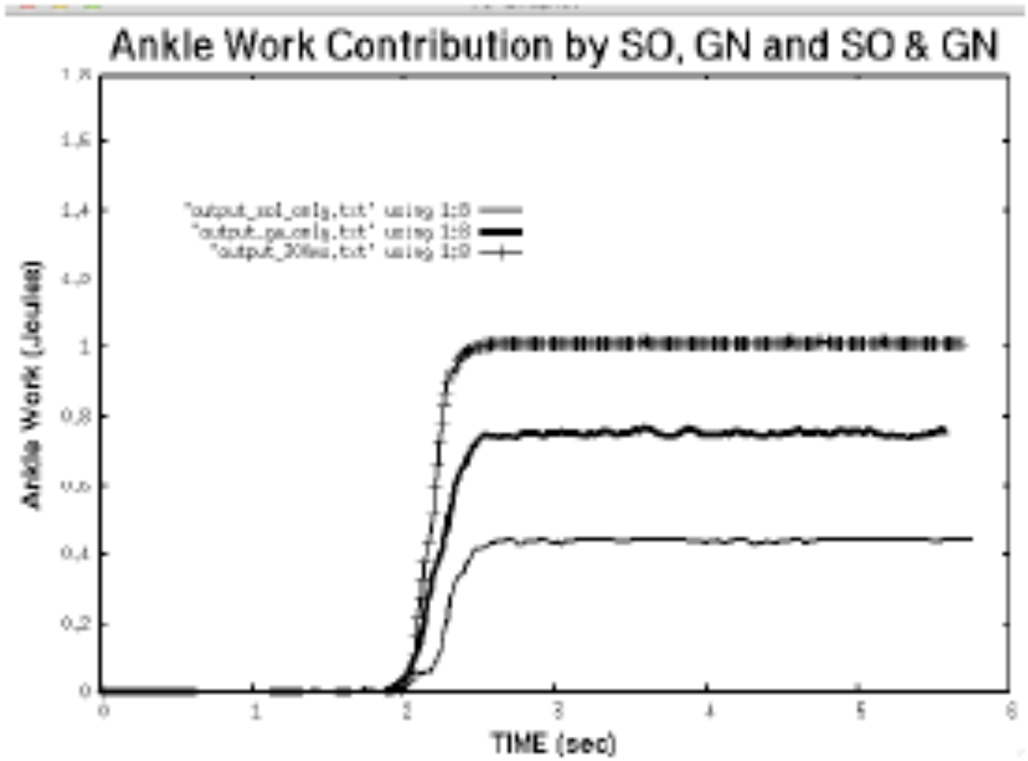

Figure 4. Ankle work done by SO, GA and both SO and GA together during return from squat.

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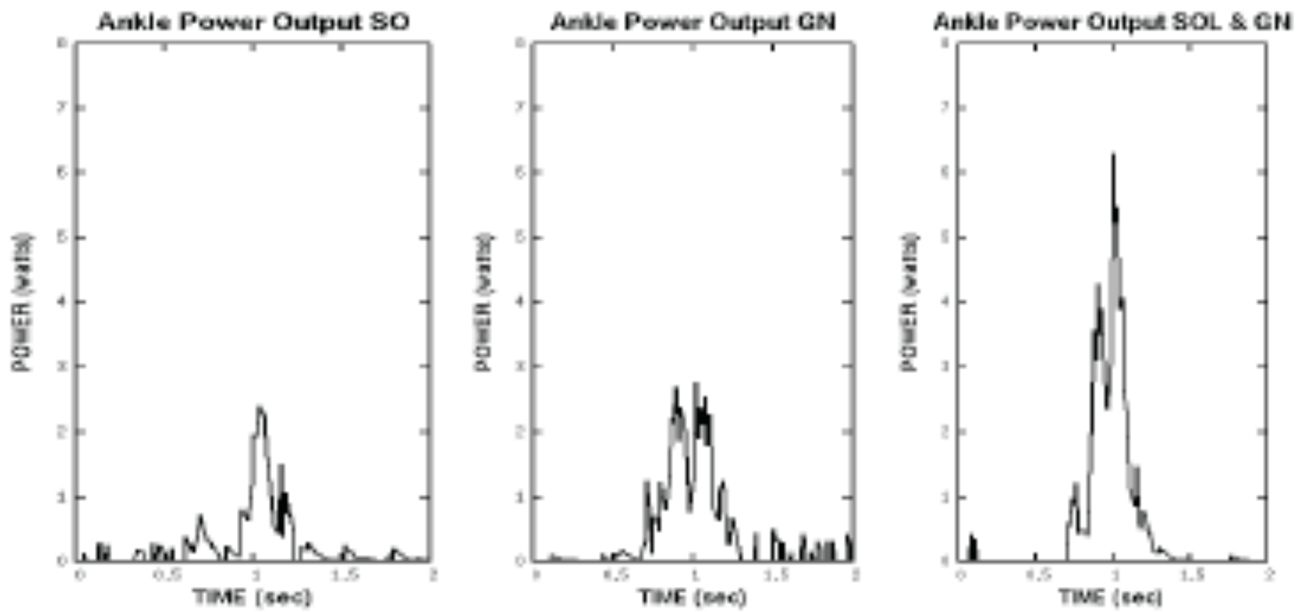

Figure 5. Power versus time at ankle during return from squat. (A) SO alone, (B) GA alone (C) Sol and GA.

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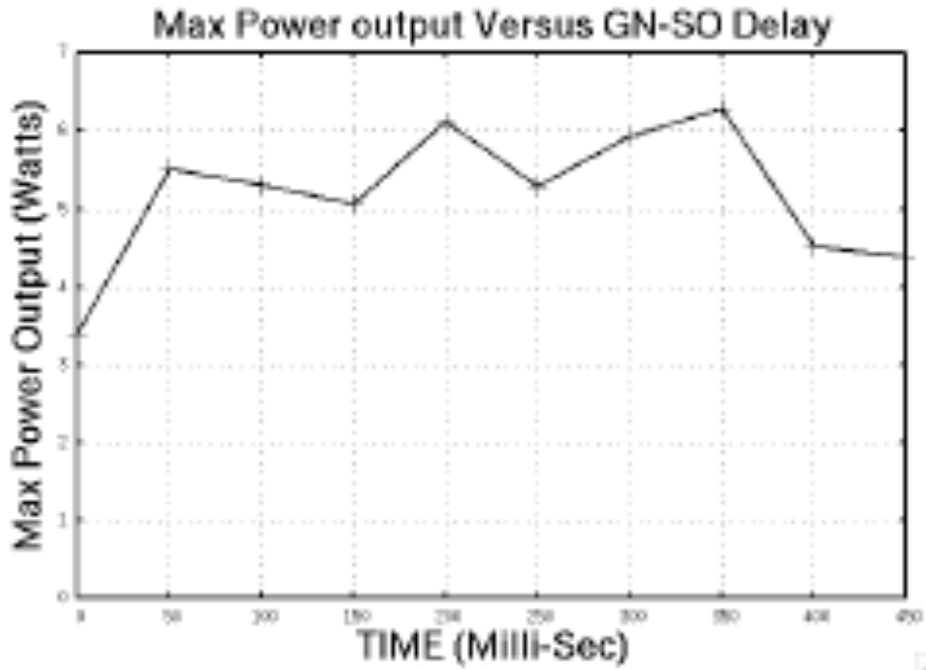

Figure 6. Max power at ankle versus delay between GA activation and SO activation.

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END

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