1

Adaptive Dynamic Walking of the Quadruped on Irregular Terrain

autonomous adaptation
using neural system model

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Decerebrated Cat

[1939]

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Current Staus in

- Legged Locomotion Studies in Robotics
- Neuro-Mechanics

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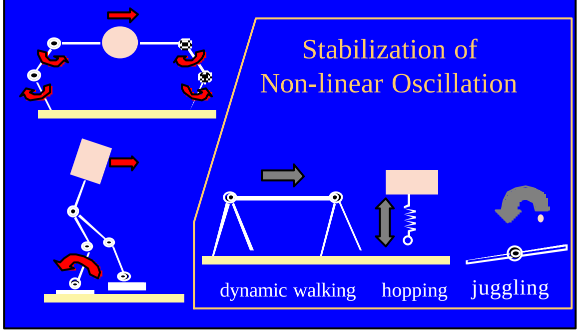
What is legged locomotion?



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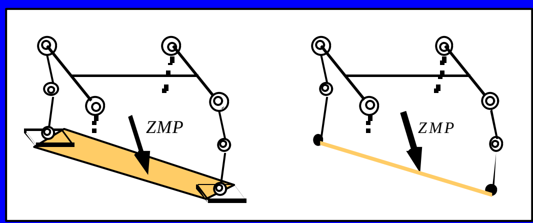
ZMP Based vs. Inverted Pendulum Based

<u>Z</u>ero <u>M</u>oment <u>P</u>oint



Stable Limit Cycle on Phase Plane

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Which is primitive?

Static (or Dynamic) Walking based on ZMP
position control of ZMP

model
trajectory based

Dynamic Walking based on Inverted Pendulum
limit cycle on a phase plane

Dynamic Walking using CPG + Reflexes
no explicit model
torque based

No passive static walking
Passive dynamic walking

Acquired by learning
Genetically programmed

Studies on Neuro-Mechanics

Dynamic Coupling between
Neural Controller and Musculoskeleton

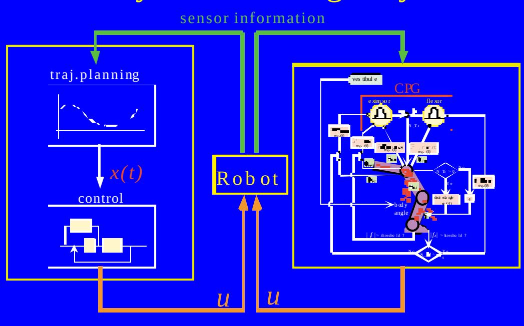
- Simulation   Taga, Ekeberg, Ijspeert, …..
- Manipulator
  - Miyakoshi   [TITECH]   juggling
  - Williamson   [MIT]   crank, sawing, ..
  - Kotosaka   [ERATO/JST]   drumming
- Legged Robot
  - Lewis   [USC]   salamander type
  - Kimura
  - Ilg
  - Miyakosi
  - …..

Why Matsuoka's Neural Oscillators?

What's the output of CPG?

- Torque
  - Directly output to actuators
  - Easily combined with reflexes
- Joint Angle/Velocities
  - Inverse dynamics is necessary to calcuate output torque

Dual System vs. Single System



$x(t)$: joint trajectory
u : joint torque

Sensory Feedback to CPGs

- Peripheral sensory input:
  - Somatic sensation (joint angle, torque, contact, …)
  - Vestibular sensation
- Directive signal from upper level:
  - Vision

Essential for Adaptation to Irregular Terrain

Dynamic Walking on Irregular Terrain

Conventional Method
precise model
trajectory planning
control

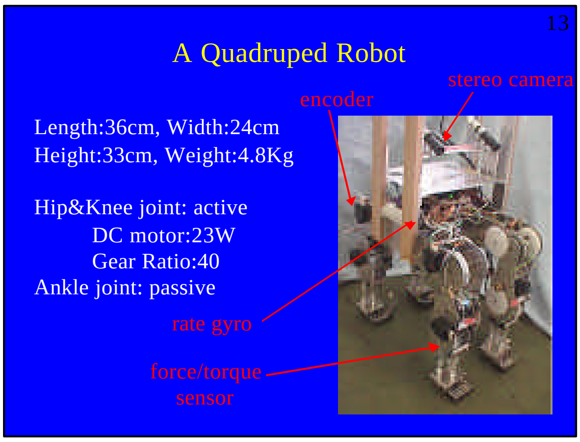
variety of irregularity

Problem
Autonomous Adaptation

?

Why Neural System Model?

- Animals show marvelous ability of autonomous dynamic adaptation.
- In spite of difference in sensors and actuators, there exist same principles as a physical phenomenon between animals and robots.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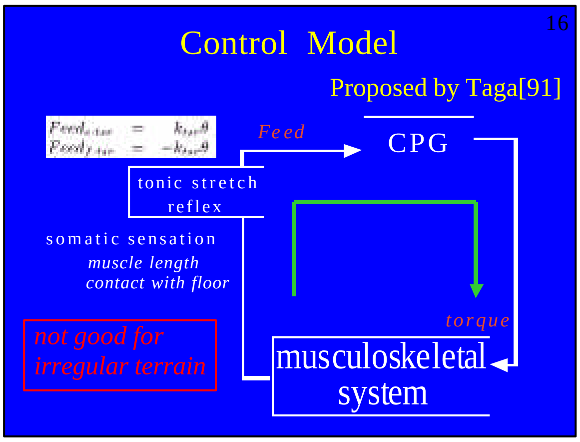
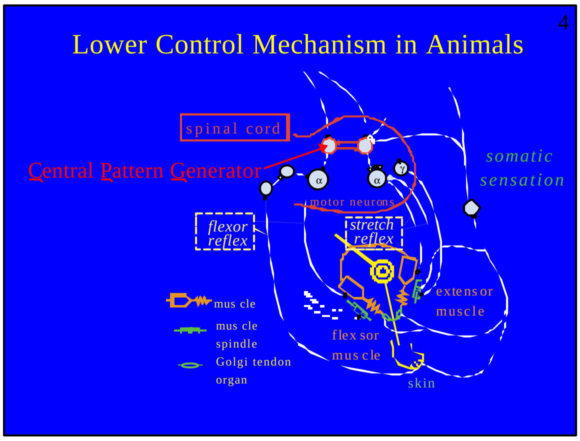
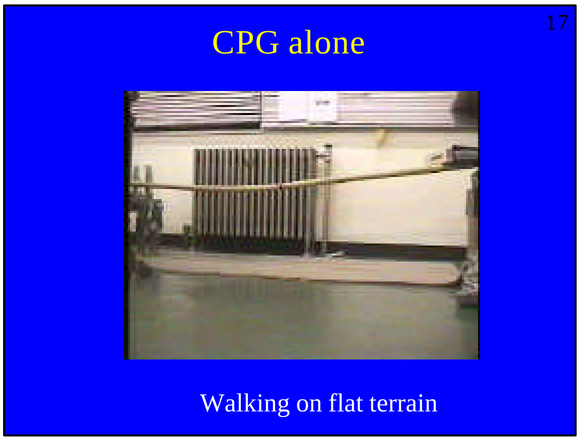
A Quadruped Robot
stereo camera
encoder
Length:36cm, Width:24cm
Height:33cm, Weight:4.8Kg
Hip&Knee joint: active
DC motor:23W
Gear Ratio:40
Ankle joint: passive
rate gyro
force/torque
sensor


16
Control Model
Proposed by Taga[91]
Feed
CPG
tonic stretch
reflex
somatic sensation
muscle length
contact with floor
torque
not good for
irregular terrain
musculoskeletal
system


4
Lower Control Mechanism in Animals
spinal cord
Central Pattern Generator
somatic
sensation
motor neurons
flexor
reflex
stretch
reflex
muscle
muscle
spindle
Golgi tendon
organ
extensor
muscle
flexsor
muscle
skin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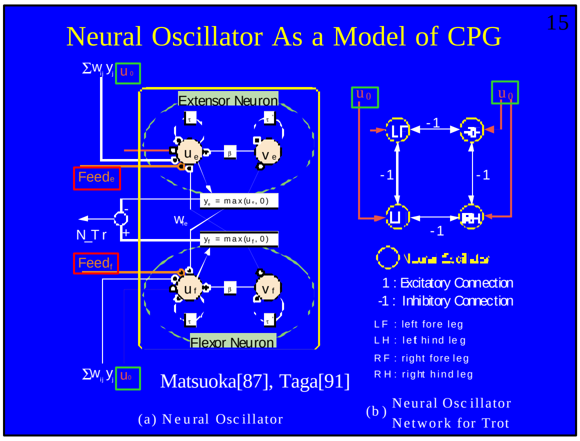
CPG alone
Walking on flat terrain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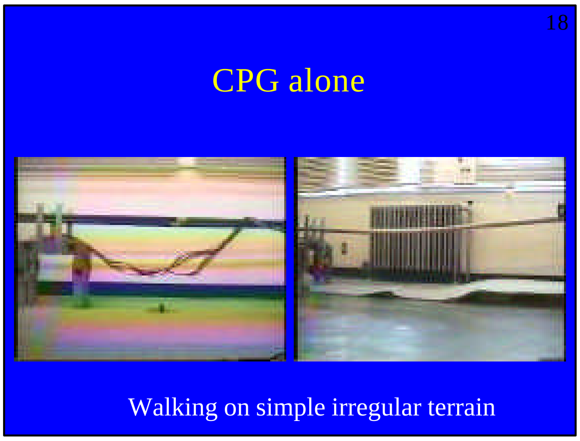
Neural Oscillator As a Model of CPG
Extensor Neuron
Feed
N_Tr
Feed
Flexor Neuron
Matsuoka[87], Taga[91]
(a) Neural Oscillator
-1
-1
-1
-1
1 : Excitatory Connection
-1 : Inhibitory Connection
LF : left fore leg
LH : left hind leg
RF : right fore leg
RH : right hind leg
(b) Neural Oscillator
Network for Trot


18
CPG alone
Walking on simple irregular terrain

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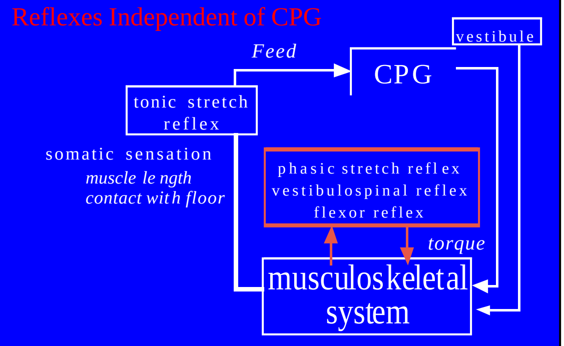
Control Model



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CPG + Reflexes Independent of CPG

Walking over an obstacle by using flexor reflex

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CPG + Reflexes Independent of CPG

Walking up a slope by using vestibulospinal reflex

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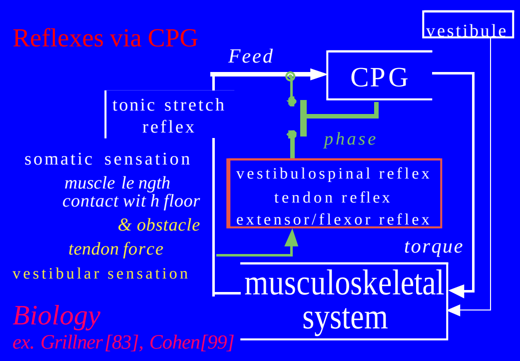
New Control Model



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Neural Oscillator

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

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Sensor Feedback to CPG

vestibuolospinal reflex:

$$\theta_{vsr} = \theta - \text{(body angle)}$$

$$Feed_{\{e,f\}\cdot tsr\cdot vsr} = \pm k_{vsr}\theta_{vsr}$$

tendon reflex:

$$Feed_{e\cdot tr} = \begin{cases} k_{tr}(\dot{\theta} + 1) & (\dot{\theta} \geq -1) \\ 0 & (\dot{\theta} < -1) \end{cases}$$

extensor reflex:

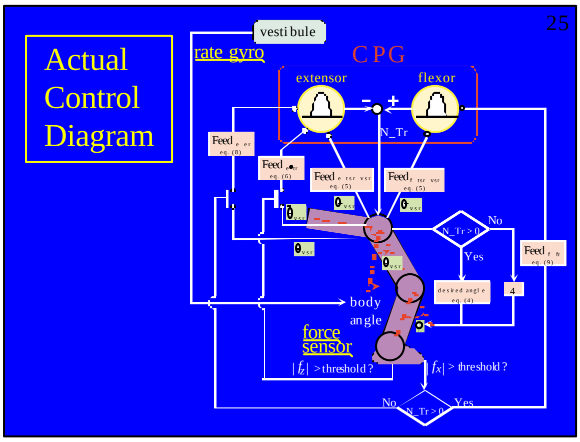
$$Feed_{e\cdot er} = \begin{cases} k_{er}\theta_{vsr} & (\theta_{vsr} \geq 0) \\ 0 & (\theta_{vsr} < 0) \end{cases}$$

flexor reflex:

$$Feed_{f\cdot fr} = (k_{fr}/0.12)(0.12 - t)$$

extensor: $Feed_e = Feed_{e\cdot tsr\cdot vsr} + Feed_{e\cdot tr} + Feed_{e\cdot er}$

flexor: $Feed_f = Feed_{f\cdot tsr\cdot vsr} + Feed_{f\cdot fr}$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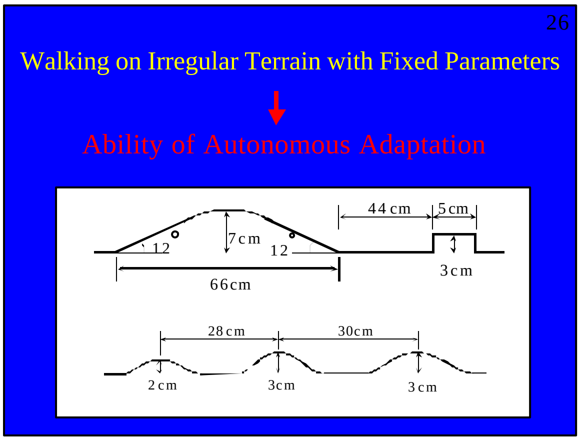
Actual Control Diagram
vestibule
rate gyro
CPG
extensor
flexor
N_Tr
No
Yes
body angle
force sensor
|fz| > threshold ?
|fx| > threshold ?
No
Yes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Walking on Irregular Terrain with Fixed Parameters
Ability of Autonomous Adaptation
44 cm
5 cm
7 cm
12
12
3 cm
66cm
28 cm
30cm
2 cm
3cm
3 cm


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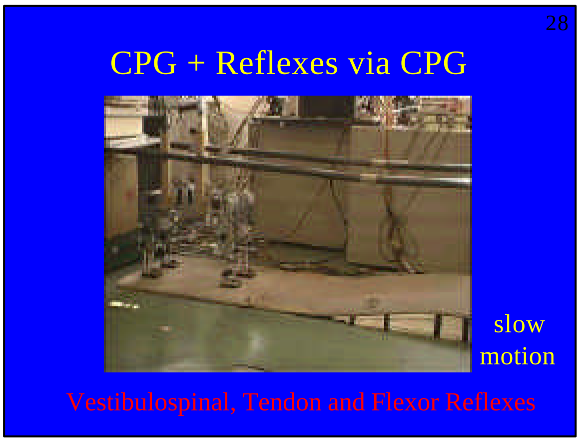
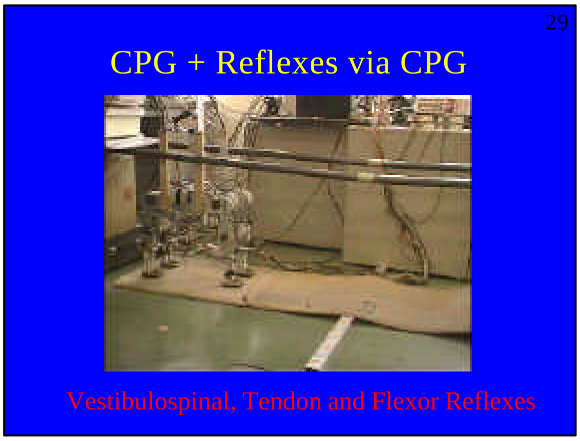
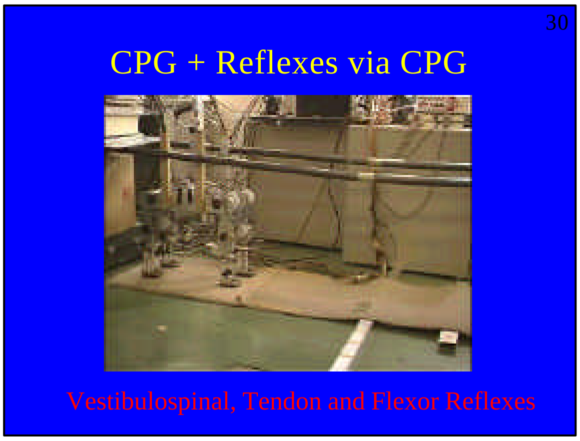
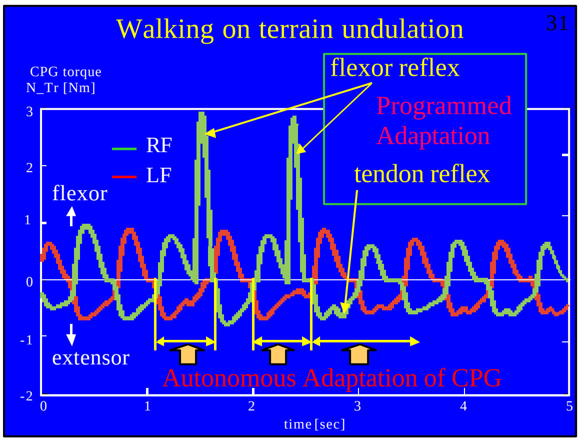
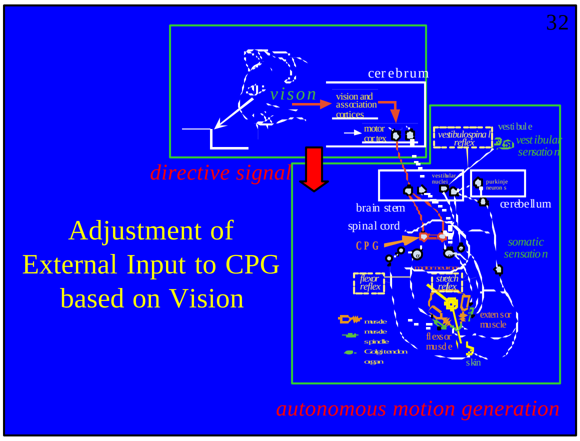
CPG + Reflexes via CPG
Vestibulospinal, Tendon and Flexor Reflexes

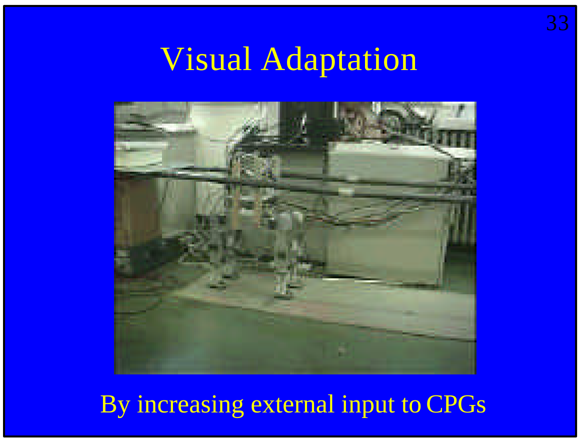

28
CPG + Reflexes via CPG
slow motion
Vestibulospinal, Tendon and Flexor Reflexes

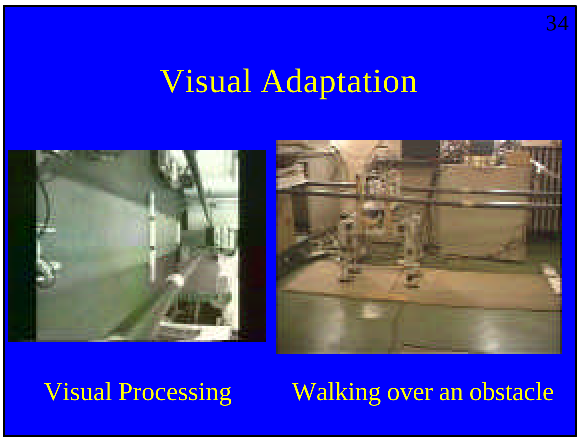

29
CPG + Reflexes via CPG
Vestibulospinal, Tendon and Flexor Reflexes

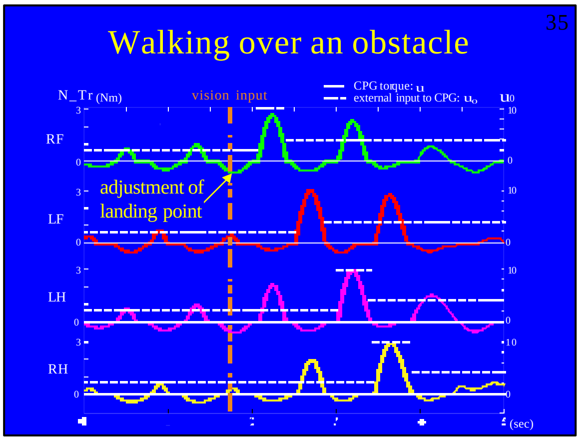

30
CPG + Reflexes via CPG
Vestibulospinal, Tendon and Flexor Reflexes











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Adjustment of CPG

- Period
  Adjusted by reflexes
- Amplitude
  Adjusted by an external input
- Phase
  Adjusted autonomously
  on a CPG network

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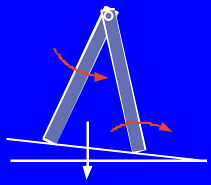
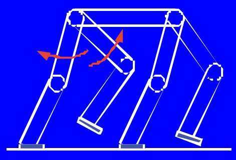
What is Dynamic Walking?

Mechanism itself has ability of dynamic walking.

Dynamic walking is generated by

external force : gravity   internal force : CPG torque





Passive Dynamic Walking (PDW)   Neural System Model (NSM)

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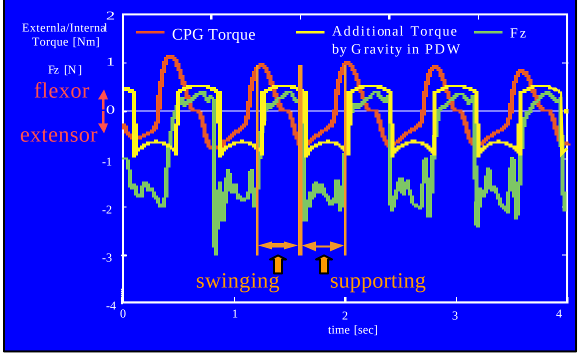
PDW vs. NSM



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Mechanical Design & Coupling with a Neural System

- Small gear ratio & Large torque motor
  - Backdrivability of a joint for passive adaptation
  - Quick motion
- Dynamics of mechanical system is encoded into parameters of neural system
  - Relation between the leg length and the frequency of CPG

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Conclusion & Future Work

- Autonomous adaptive dynamic walking on terrain of medium degree of irregularity by using reflexes via CPG
- Effectiveness
- Well coordinated system by centering CPG

- 3D dynamic walking on 3D irregular terrain

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END