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Neuromorphic Eng. Workshop, *Telluride, 14 Jul. 2003*

Biological Inspired Legged Locomotion Control of a Robot

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Japan

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Outline

- Why we can/should learn from animals
- Common principles in robots and animals
- Applying biological concepts to a quadruped robot
- Energy consumption
- Discussions
- Future Works

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Recent Popular Legged Robots in Japan

Self-contained!

Adaptive?

Just following the pre-programmed motion pattern

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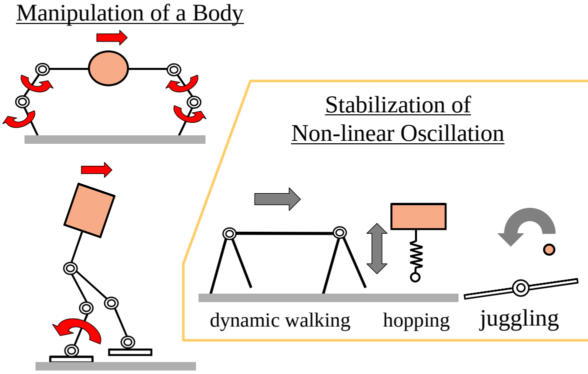
What is legged locomotion?

Manipulation of a Body



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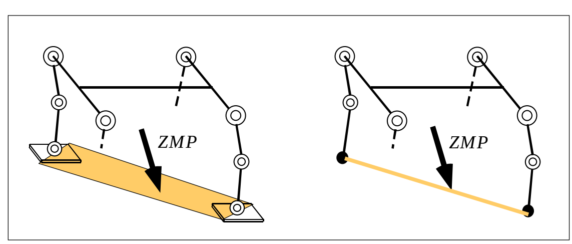
ZMP Based vs. Limit Cycle Based

Zero Moment Point



Stable Limit Cycle on Phase Plane

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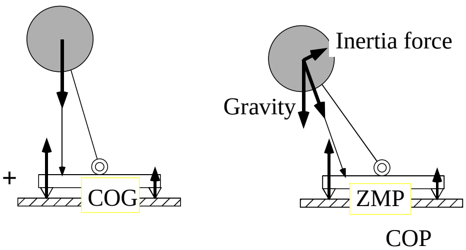
ZMP Based



In order to avoid falling down,
realize the given trajectory as precise as possible. ← Control of a arm

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ZMP-based Motion Generation and Control

Avis & Ashimo [Japan, Feb. 2003]

Johnnie [Germany, Jul. 2003]

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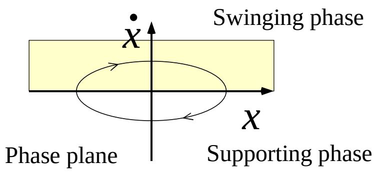
Limit Cycle Based



To keep the stable oscillation,

Switching supporting/swinging phases → non-linearity

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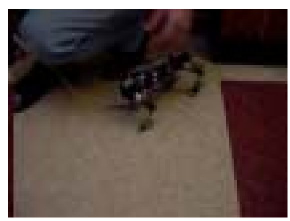
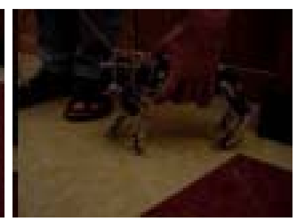
Limit Cycle based Motion Control





TomCat [Jul. 2003]

the upper bound of the cyclic period of walking

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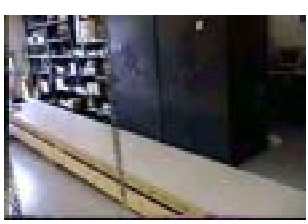
Passive Dynamic Walking

A walking machine can walk down the slope without actuation.

Is the control necessary?



(Cornel Univ：2000)

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Legged Locomotion on Irregular Terrain

Conventional Method
- precise model
- trajectory planning
- control

→ variety of irregularity →

Problem
Autonomous Adaptation

? ←

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How we can learn from animals

~~Functions of Animals → (mimicking) → Robots~~

Functions of Animals → (analysis) → Principles ↓ Robots

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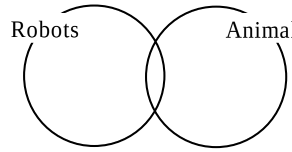
Hypothesis on Legged Locomotion
- principles of mechanism and motion -

low speed motion



A lot of alternatives
in mechanism, devices
and control methods

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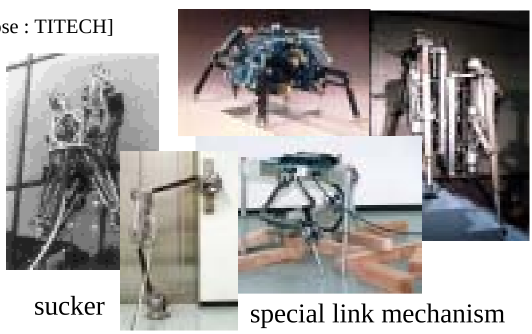
Examples of Not Mimicking Animals

[Hirose : TITECH]



sucker

wheel-leg

special link mechanism

pantograph, parallel, ….

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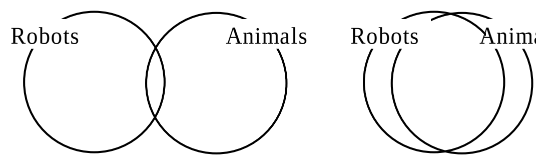
Hypothesis on Legged Locomotion
- principles of mechanism and motion -

low speed motion

high speed motion



A lot of alternatives
in mechanism, devices
and control methods

Only few alternatives
since dynamics is dominant

The differences
in the number of joints and actuators, etc.
become not so important.

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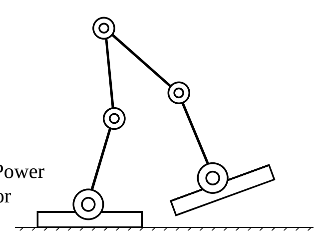
Not Good Mechanical Design

Energy consumption : Large

Adaptability to irregular terrain : Small

independent of the number of legs



Large Power Actuator

Large Foot

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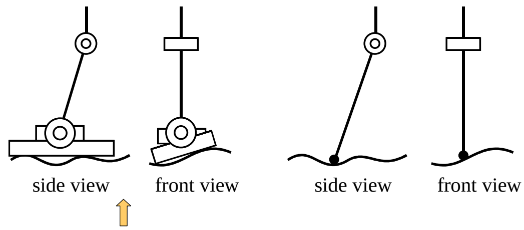
"Size of Foot" vs. "Adaptability to Irregular Terrain"



Influence of local shape of terrain : large

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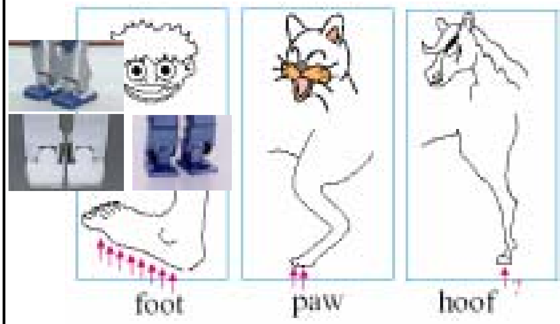
Size of Contacting Surface



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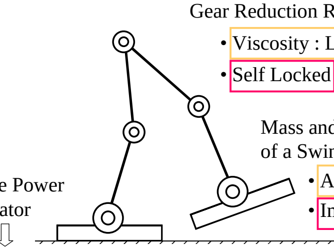
Not Good Mechanical Design

Energy consumption : Large

Adaptability to irregular terrain : Small

independent of the number of legs

Gear Reduction Ratio : High
- Viscosity : Large
- Self Locked



Mass and Inertia Moment of a Swinging Leg : Large
- Ac/Deceleration Torque
- Impact Force at Landing

Large Power Actuator

Large Foot

High Gain Feedback at the Swinging Leg Joints

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Control Methods According to the Speed

[Blickhan & Full:1993], [Full & Koditschek:1999]

	ZMP-based	Limit-Cycle-based	
		Neural System	Musculoskeletal System
good for control of	posture	low / medium speed walking	high speed running
main controller	upper neural system (learning)	lower neural system (CPG + reflexes)	visco-elasticity of muscles (self stabilization)

role of sensor feedback: large ⟷ small

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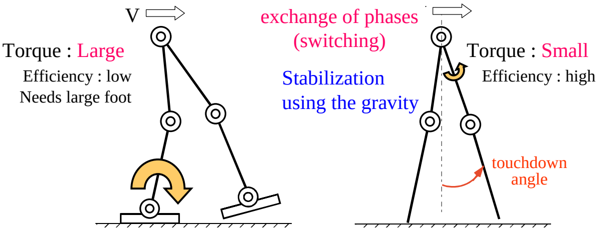
Why the role of sensor feedback becomes small in high speed locomotion?

- Kinetic energy is large and dominant.
- In the short cyclic period,
  - the influence of actuator output is small, problem!
  - motion cannot be stabilized by the direct actuation.
- In the short cyclic period,
  - the accumulation of errors is small, advantage!
  - motion can be stabilized by the exchange of stance/swing phases.
    non-linear switching control

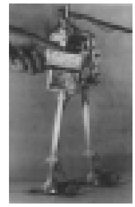
Stabilization of Forward Speed

independent of the number of legs

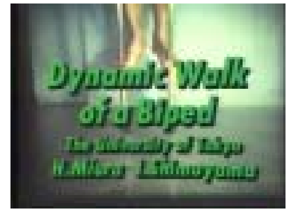
Angular Velocity Control around contact point	Touchdown Angle Control
by ankle joint torque, control the angular velocity of the supporting leg	by touchdown angle, control the forward speed of the next stance phase



Stabilization of Forward Speed - Touchdown Angle Control -

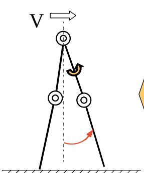


Biper3 [1981]
Miura &
Shimoyama
[IJRR:1984]

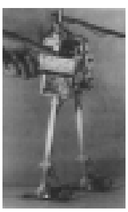


like walking on stilts

Stabilization of Forward Speed - Touchdown Angle Control -



in biological system
stepping reflex



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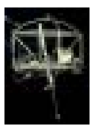
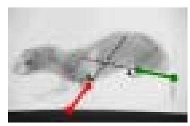


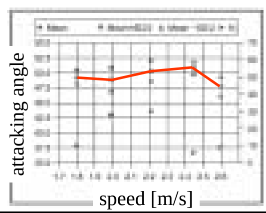
Raibert:1984
the neutral-point
foot-placement
algorithm

……

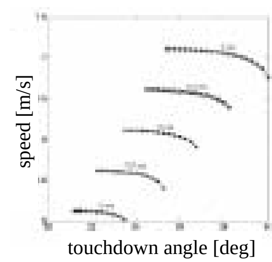
Touchdown (Attacking) Angle in Running

[Hackert, Witte & Fischer : AMAM2000]



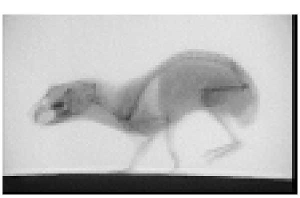


[Buehler, et al. : AMAM2003]



Half Bound Running

[Hackert, Witte & Fischer : AMAM2000]



[Buehler, et al. : AMAM2003]

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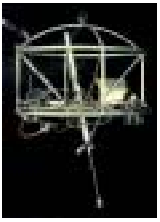
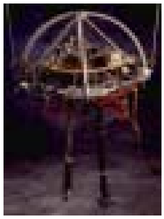
Hopping Robots

by Raibert [1983-1992]


- Point contact
- Air spring
- Light weight leg and the body of large inertia moment
- Touchdown angle control, others

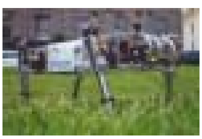
Hopping Robots

by Raibert [1983-1992]

Touchdown angle control


Running on irregular terrain

Quadruped & Hexapod Robots



[SCOUT-II]

[RHex]

[Sprawlita]

- Point contact
- (Passive) compliant and light weight leg
- Analysis of self stabilization

Hexapod Robots

RHex (2000-)

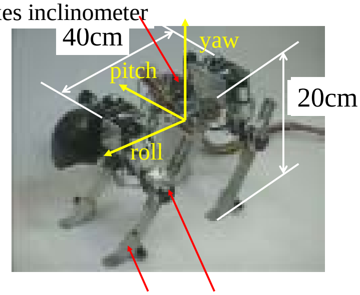
Sprawlita, … (2000-)

Self stabilization

to stabilize the forward speed without measuring it

Quadruped Robot: ‘Tekken’

- Weight:3Kg
- Pitch Axis (3 joints)
  - Hip & Knee joints: active
  - Ankle joint: passive
- Yaw Axis (1 joint)
- Light weight leg
- Small foot
- Small gear ratio: ~16
  - viscosity: small
  - compliant joint



Sensor based adaptive walking on irregular terrain

Over an Obstacle of 20% Relative Height to a Leg

Over an obstacle 4.0cm in height

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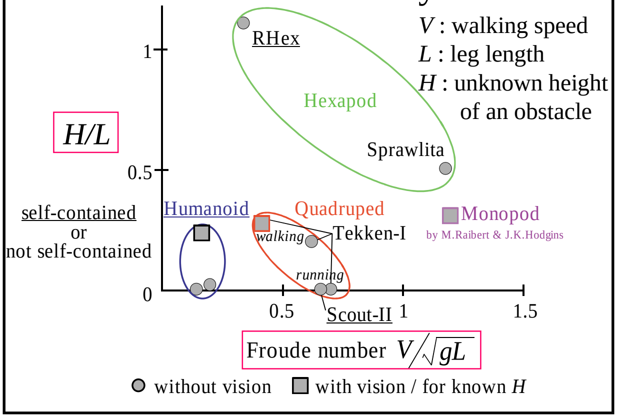
Maneuverability



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Characteristics of Legged Robots based on Dynamics and Biological Concepts

- Mechanical design good for
  - medium & high speed locomotion
  - adaptation to irregular terrain
- Short cyclic period : rhythmic motion
- Complicated trajectory planning and control are not necessary.

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[Blickhan & Full:1993], [Full & Koditschek:1999]

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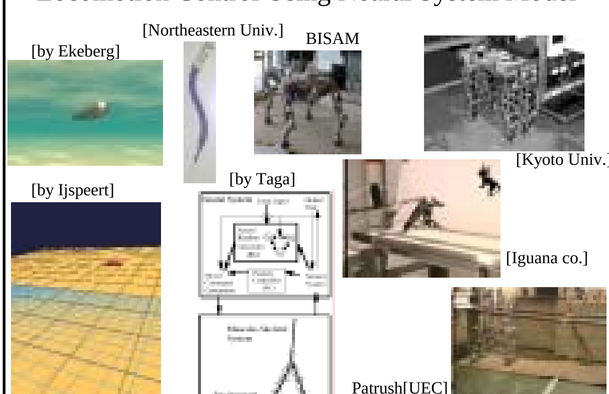
Locomotion Control Using Neural System Model



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Physiology

- CPG (Central Pattern Generator)
  - Entrainment among neurons of CPGs
  - Entrainment with musculoskeleton
- Reflexes
  - Negative feedback
  - Positive feedback
- Higher Level

By Grillner, Cohen, Pearson, Prochazka, Mori, Drew, et al.

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What is Neural System Model Control?

- Rhythm
- Phase Difference between Legs

CPGs

- Tuning of Muscle Tone

Reflexes

Physiological Experiments Using Cats :

………..
S. Mori [1973]
………..

Computer Simulation & Robot Experiments

………………
Kimura [1994-]
………………

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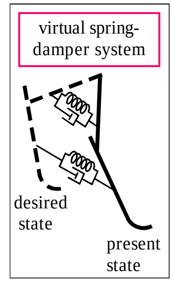
Tuning of Muscle Tone

Joint PD Control as a Tonic Stretch Reflex

$$trq_{jnt} = -K1_{jnt}\,(\theta^{*}_{jnt} - \theta_{jnt}) - K2\,\dot{\theta}_{jnt}$$

$$\theta^{*}_{jnt} = \begin{cases} \theta^{stance}_{jnt} \\ \theta^{swing}_{jnt} \end{cases}$$

$$K1_{jnt} = \begin{cases} K1^{stance}_{jnt} \\ K1^{swing}_{jnt} \end{cases}$$



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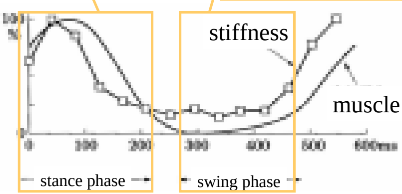
Change of Stiffness in Stance/Swing Phases

Tekken[2001-] & Collie-2[1987]

large in the stance phase
- against the gravity

small in the swing phase
- for irregular terrain
- reduce the impact force



Muscle tone and stiffness of walking cats [Akazawa:1982]

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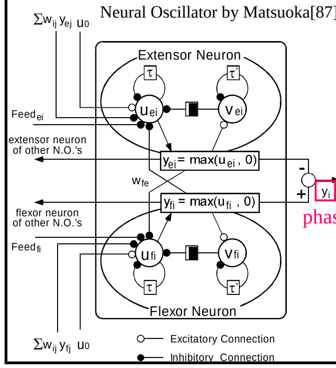
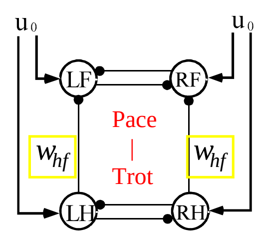
CPG (Central Pattern Generator)

Neural Oscillator by Matsuoka[87] & Taga[91]





$-1 < w_{hf} < -0.1$

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Neural Oscillator

Matsuoka[87], Taga[91]

time constant

$$\tau \dot{u}_{\{e,f\}i} = -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} + u_{0i} + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_j$$

$$y_{\{e,f\}i} = \max(0, u_{\{e,f\}i})$$

$$\tau' \dot{v}_{\{e,f\}i} = -v_{\{e,f\}i} + y_{\{e,f\}i}$$

joint angle, body roll angle, etc.

$u_{\{e,f\}i}$: inner state of the neuron $y_{\{e,f\}i}$: output of the neuron

$v_{\{e,f\}i}$: variable representing the self inhibition

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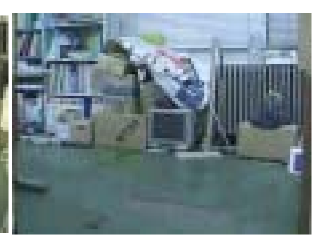
Gaits



Trot: $v = 0.6m/s$, $T = 0.35s$ Walk: $v = 0.3m/s$, $T = 0.6s$

-0.7 ⟷ w_{hf} ⟷ -0.3

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Other Mobility

Running in a bound gait

Changing the direction

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Motion Generation & Adaptation

- Tuning of Muscle Tone
  - •torque output
  - •sensory feedback → reflex
- Rhythm Generation (CPG: Central Pattern Generator)
  - •phase (stance/swing) output
  - •sensory feedback → response

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Motion Adaptation & Sensory Feedback

[Tekken:2001]

- the legs should be free to move forward during the first period of the swing phase, Passive ankle joint & Flexor reflex

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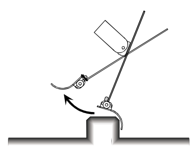
Passive Ankle & Flexor Reflex



- spring and lock mechanism
- contact & collision detect sensor

Over an obstacle 2.0cm in height

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Motion Adaptation & Sensory Feedback

[Tekken:2001]

- the legs should be free to move forward during the first period of the swing phase, Passive ankle joint & Flexor reflex

- the legs should land reliably on the ground during the second period of the swing phase, Tonic labyrinthine response for rolling
- the phase difference between rolling motion of the body and pitching motion of legs should be maintained,

Stepping reflex & Vestibulospinal reflex/response for pitching

- the average of the forward speed be kept constant,

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Vestibulospinal reflex/response for pitching

Slope of 10 degree inclination

Motion Adaptation & Sensory Feedback

[Tekken:2001]

- the legs should be free to move forward during the first period of the swing phase, — Passive ankle joint & Flexor reflex
- the legs should land reliably on the ground during the second period of the swing phase, — Tonic labyrinthine response for rolling
- the phase difference between rolling motion of the body and pitching motion of legs should be maintained, — Stepping reflex & Vestibulospinal reflex/response for pitching
- the average of the forward speed be kept constant, — CPG network
- phase difference between legs be kept appropriately.

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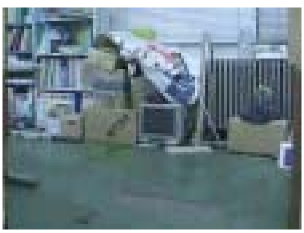
Waking in a long cyclic period is difficult to stabilize.

Trot *T = 0.35s*, *easy*



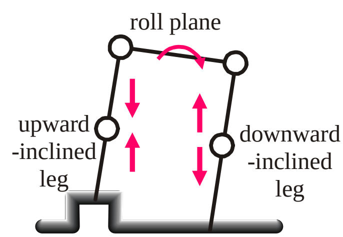
Walk *T = 0.6s*, *difficult*

Large rolling motion naturally generated disturbs pitching motion. → Rolling motion feedback to CPG

Nanzando's Medical Dic. 18th edn.

Tonic Labyrinthine Reflex for Rolling or Vestibular Reflex

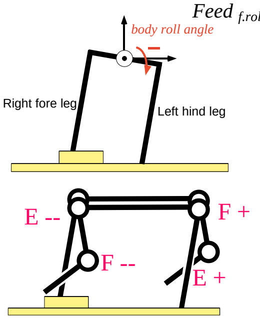
Principles of Neuro Science, 3rd edn.



Roll Motion Feedback to CPG

$$Feed_{e.roll} = \delta(leg) \times k_{roll} \times (body\ roll\ angle)$$

$$Feed_{f.roll} = -Feed_{e.roll} \quad < 0$$



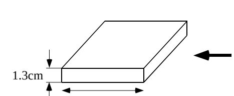
Right fore leg	E -- F +	Right hind leg	E -- F +
Left fore leg	E + F --	Left Hind leg	E + F --

Roll Motion Feedback to CPG

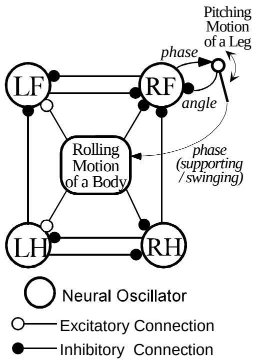
Without

With

T = 0.3 sec.



Rolling Motion as Standard of Rhythm



Rolling motion feedback to CPG

↓

Stabilizing a gait

Adjusting phases of CPGs

Roll Motion Feedback to CPG

Slope of 5 & 3 degree inclination

Walking over Pebbles

The values of all parameters are fixed for unknown terrain of medium degree of irregularity.

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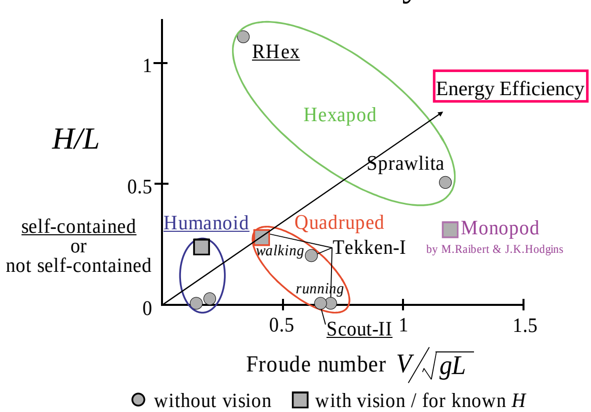
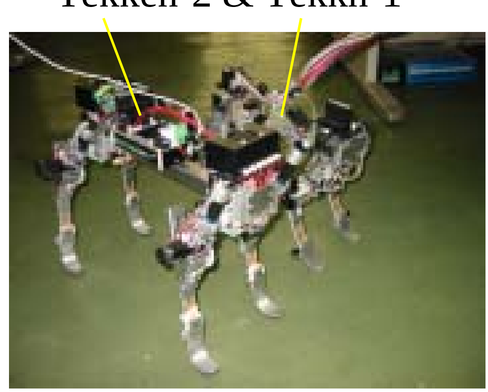
- Future Works

Maneuverability



Tekken-2 & Tekkn-1



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Mechanically Variable Stiffness of Knee Joints

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Tekken-2

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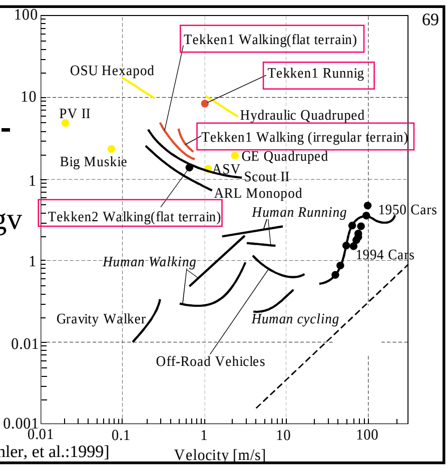
Energy Consumption

-

$\boldsymbol{\varepsilon}$ = P/mgv



modified from [Buehler, et al.:1999]

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Outline

- Why we can/should learn from animals
- Common principles in robots and animals
- Applying biological concepts to a quadruped robot
- Energy consumption
- Discussions
- Future Works

Discussion #1

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What is Neural System Model Control?

ZMP Based

Limit Cycle Based

Equivalent?

CPG
(Central Pattern Generator)

Interaction

Reflexes

Real Mechanism?

Feedforward
compensation of gravity and inertia force

Feedback
correction of errors using sensor information

Discussion #1

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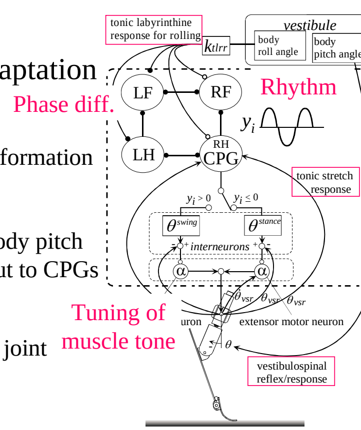
Motion Generation & Adaptation

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 responses.

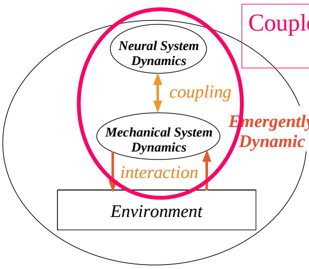


Discussion #2

Autonomous Adaptive Walking

by Taga[1991]

Coupled Dynamic based Motion Generation



For desirable adaptation, we must construct neural system carefully.

dynamic walking on irregular terrain

physics,
biology,
physiology,
…

Discussion #2

How dynamics of mechanism is encoded into parameters of the neural system

- Relation between the leg length or the stiffness and the time constant of CPG!
  - Choose the original cyclic period of CPG as

$$T_{CPG}^{O} \propto \sqrt{length\ of\ a\ leg} \propto \sqrt{mass / stiffness}$$

- Reflexes / Responses ?

Discussion #3

CPG Models

Cruse , Ekeberg
- •more sensor dependent & more decentralized
- •more general
- •cyclic period is determined by speed of the body and legs

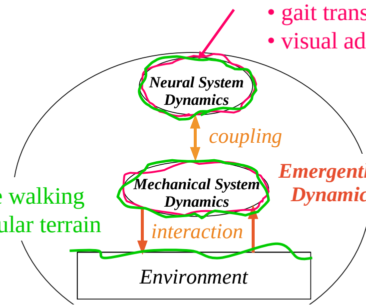
Taga, Kimura , Lewis, Tsujita&Tsuchiya , Ilg, …
- •non-linear oscillator
- •time constant or standard cyclic period
- •dynamics of mechanism is encoded into parameters of the neural system

argument (BC:2002)

essential for dynamic walking by Kimura (IJRR2003)

Coupled Dynamics based Motion Generation

- gait transition
- visual adaptation



adaptive walking on irregular terrain

Emergently Adaptive Dynamic Walking

autonomous adaptation at levels from the lower spring-damper system to the higher vision system

Outline

- Why we can/should learn from animals
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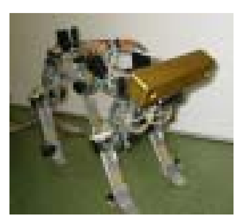
- Future Works

Future Works

- Self-contained System & Outdoor Experiments
- Visual Adaptation
- Behavior
- Gait Transition
- Bipedal Locomotion



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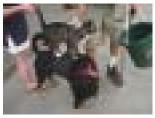
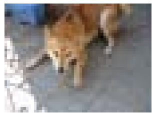
Future Works

- Self-contained System & Outdoor Experiments
- Visual Adaptation
- Behavior
- Gait Transition
- Bipedal Locomotion


[in Telluride, 2001]


[of Kimura]

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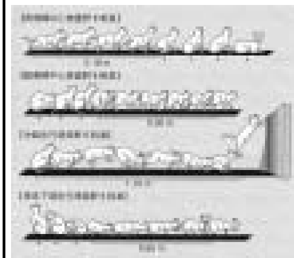
Behavior and Tuning of Muscle Tone


[S. Mori:1996]


[Prochazka:1988]

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Future Works

- Self-contained System & Outdoor Experiments
- Visual Adaptation
- Behavior
- Gait Transition
- Bipedal Locomotion

By Tsujita-san

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2nd AMAM

Int. Conf. on Adaptive Motion of Animals and Machines
March 4-8 2003, Kyoto

Supported by Japan Science Promotion Society

Biology,
Physiology,
Biomechanics,
Robotics,
…….

3rd AMAM in Germany on Sep. 2005

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Acknowledgment

- Ph.D Student
  Yasuhiro Fukuoka

- TEPCO
- AVICE & ……
- JST
- JSPS

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http://www.kimura.is.uec.ac.jp

Y. Fukuoka, H. Kimura & A.H. Cohen
Int. J. of Robotics Research, 2003

continued …

END