Stable Dynamic Walking of the Quadruped Robot "Kotetsu" Using Phase Modulations Based on Leg Loading/Unloading against Lateral Perturbations

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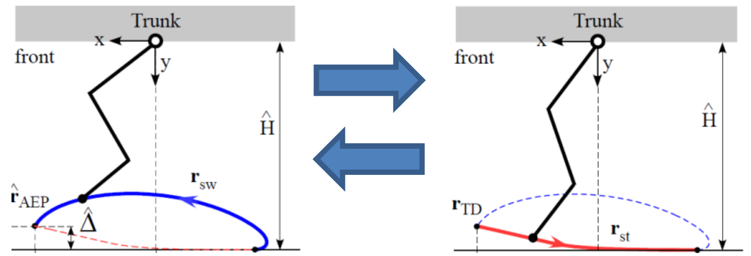
Simple quadruped controller as far as possible

At least, we need

- Motion of single leg

(by desired trajectory & PD control)



forward backward

- Leg phase transitions between swing and stance (using what kind of sensor information?)
- Explicit interleg coordination? (what kind of coordination?)
- Explicit posture (rolling motion) control?
- Reflexes to adapt to terrains of middle and high degree of irregularity [series of Tekken: 2001-2005]

While studying such basis of quadruped controller ….

We can while using no reflex

1. clear the meanings of phase modulations in the view points of
   - rhythmic motion control
   - interleg coordination
   - posture (rolling motion) control

   for adaptive walking and running.
2. make it decentralized and robust (in future)
3. investigate the roles of CPG of animals.

CPG : Central Pattern Generator [Orlovsky et al. Neural control of locomotion. 1999]

Biologically Inspired Approach

Sensor information for regulation of stance termination

In cats, the transition from stance to swing in the hind legs relies on signals related to :

- ankle extensor muscle force ⇔ leg unloading
  [Duysens and Pearson 1980]
  More important !
  [Ekeberg and Pearson 2005]

- hip extension ⇔ close to PEP (**P**osterior **E**xtreme **P**osition)
  [Grillner and Rossignol 1978, Hiebert et al. 1996]

Outlines

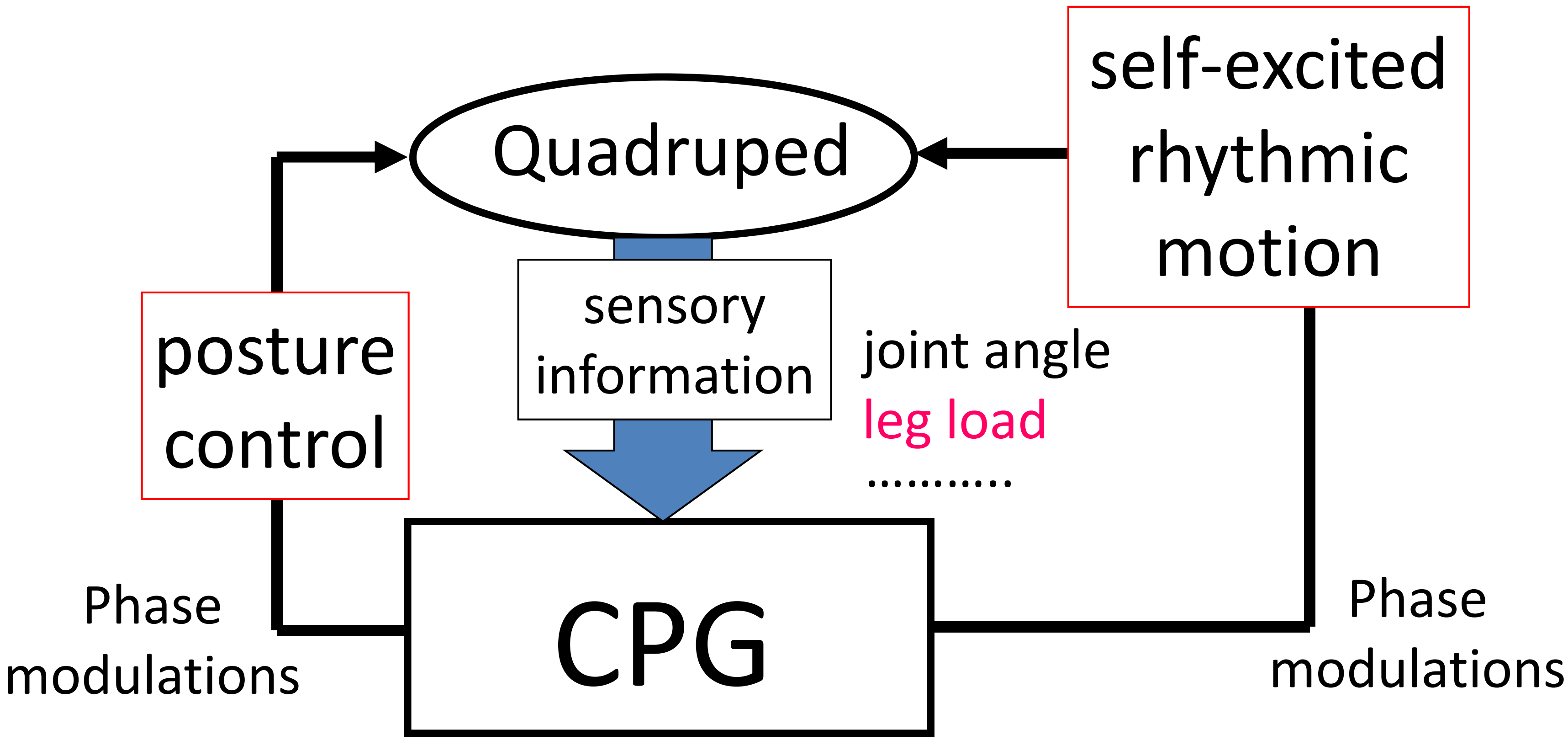
- Background & Motivation
- Leg controller
  - phase modulations based on leg loading/unloading
- Results of simulations & Interleg coordination
  - the ACM for lateral perturbations
- Results of experiments using Kotetsu
- Discussions & Conclusions

Idea

[Inspired by Ekeberg & Pearson, 2005]

Integration of

- sensor driven self-excited rhythmic motion control
- sensor dependent posture control



Singe Leg Controller (LC)

- Phase dynamics, phase reset and phase transition -

leg phase of LC

SWING	TRANSITIONS	STANCE
phase dynamics initial reset: $\phi = \hat{\phi}_{PEP}$ (1) $\dot{\phi} = \begin{cases} \hat{\omega} + \omega_{mod} & \text{if } \phi < \hat{\phi}_{AEP} \\ 0 & \text{if } \phi = \hat{\phi}_{AEP} \end{cases}$ (2)	$f_n > \hat{\chi}_{TD}$ → ← $f_n < \chi_{LO}$	**phase dynamics** initial reset: $\phi = \hat{\phi}_{AEP}$ (6) $\dot{\phi} = \begin{cases} \hat{\omega} & \text{if } \phi < 2\pi \\ 0 & \text{if } \phi = 2\pi \end{cases}$ (7)

ϕ phase of an oscillator

$\hat{\phi}_{PEP}$ $\hat{\phi}_{AEP}$ initial phase of swing and stance phase, respectively

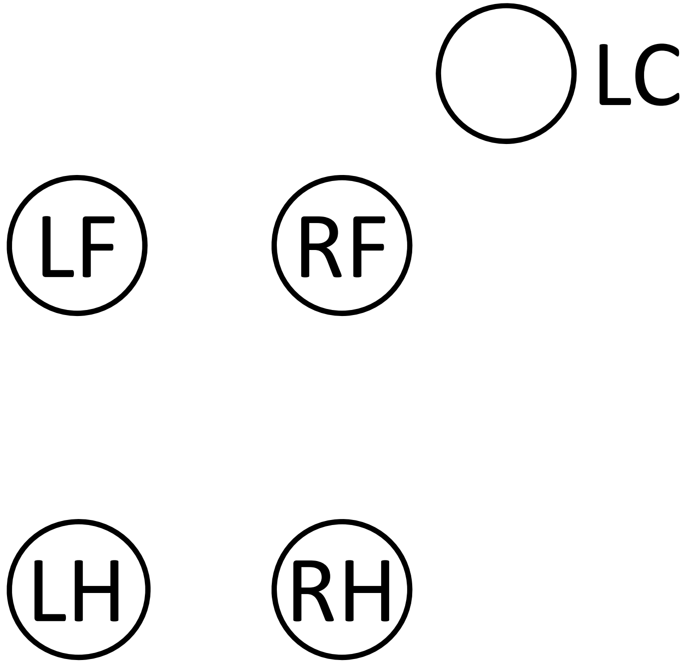
AEP: anterior extreme position
PEP: posterior extreme position

^ nominal value
- real value

3D Simulations for gait generation

Gait generation and posture (rolling motion) control
using phase modulations based on leg loading/unloading

the walk gait in various speed



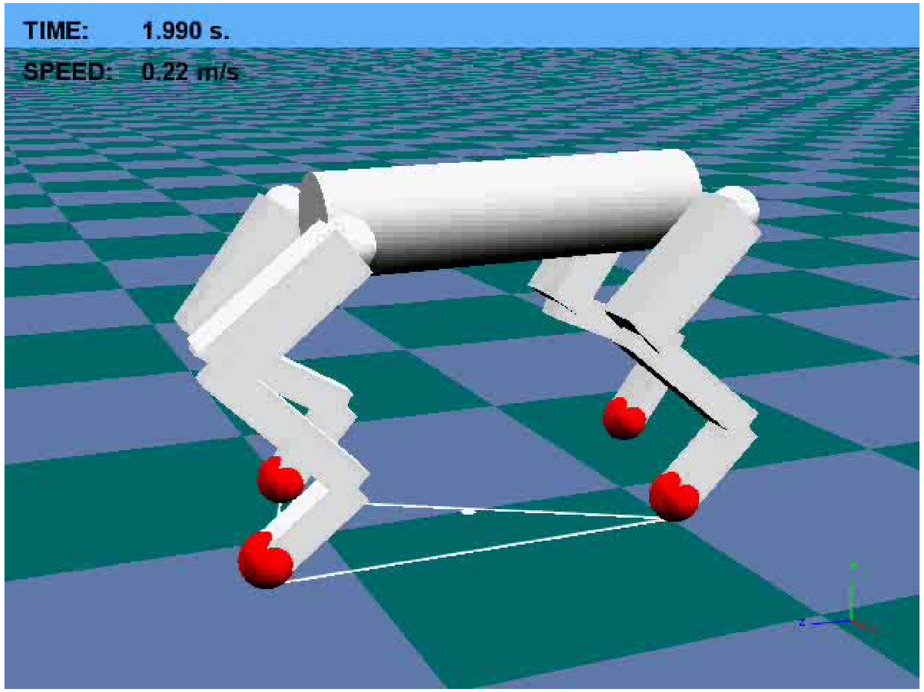
without explicit
interleg coordination

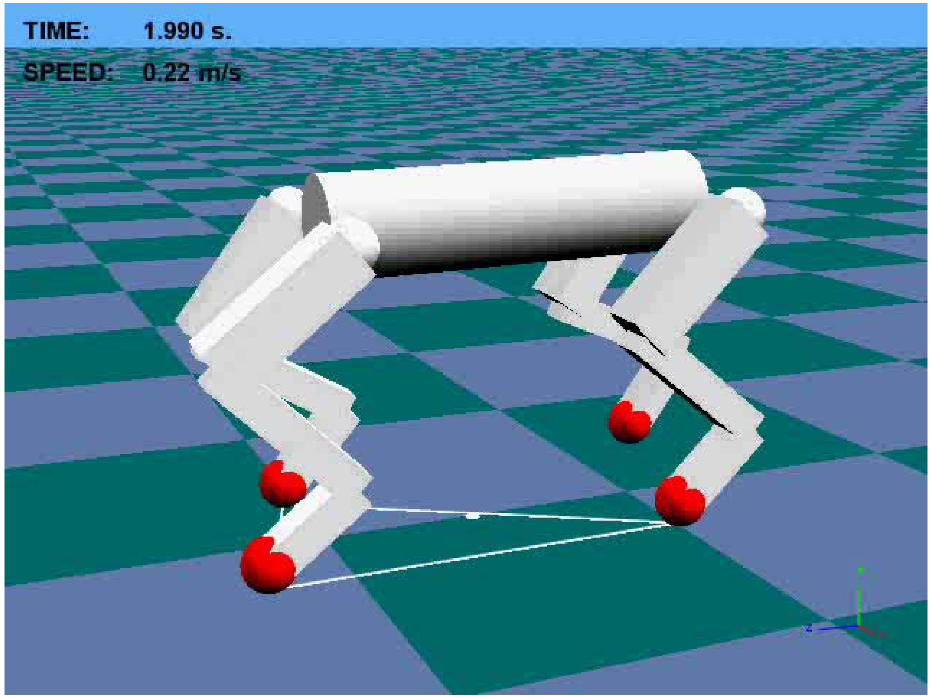
[Maufroy, Kimura and Takase, Auto. Robots, 2010]

3D Simulations for lateral perturbation

θroll : body roll angle

increasing $|\dot{\theta}roll|$ decreasing $|\dot{\theta}roll|$

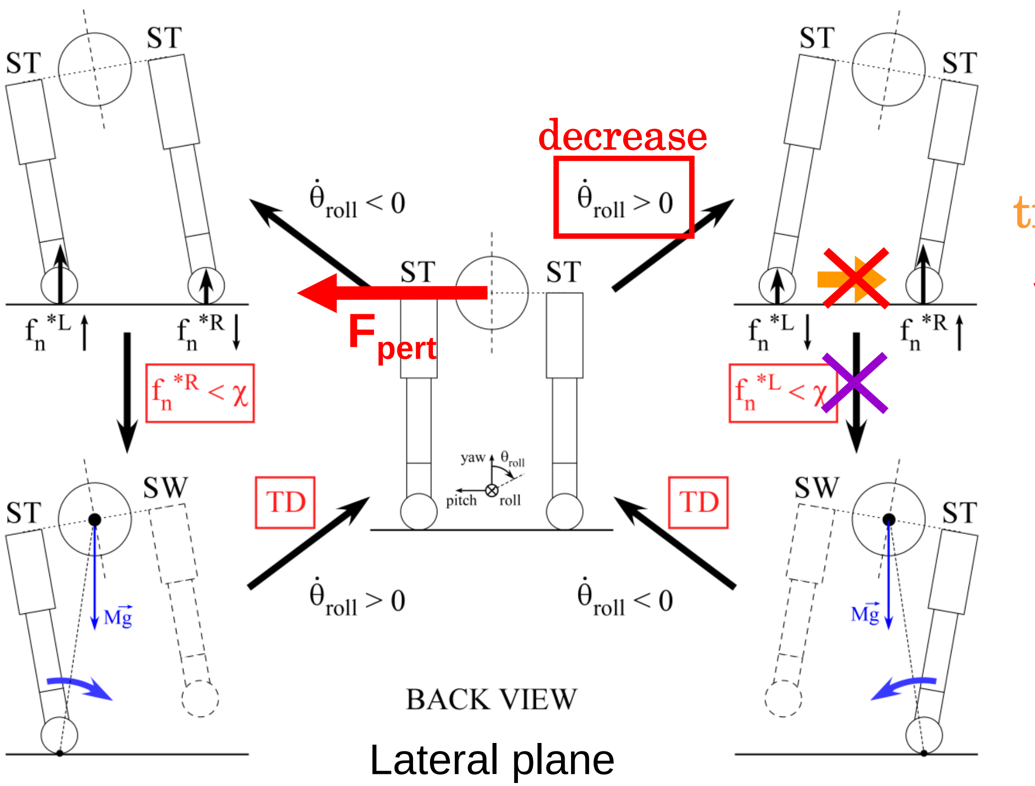




without explicit interleg coordination

[Maufroy, Kimura, et al. Auto. Robots. 2010]

Perturbation decreasing $|\dot{\theta}_{roll}|$ (Simulation)



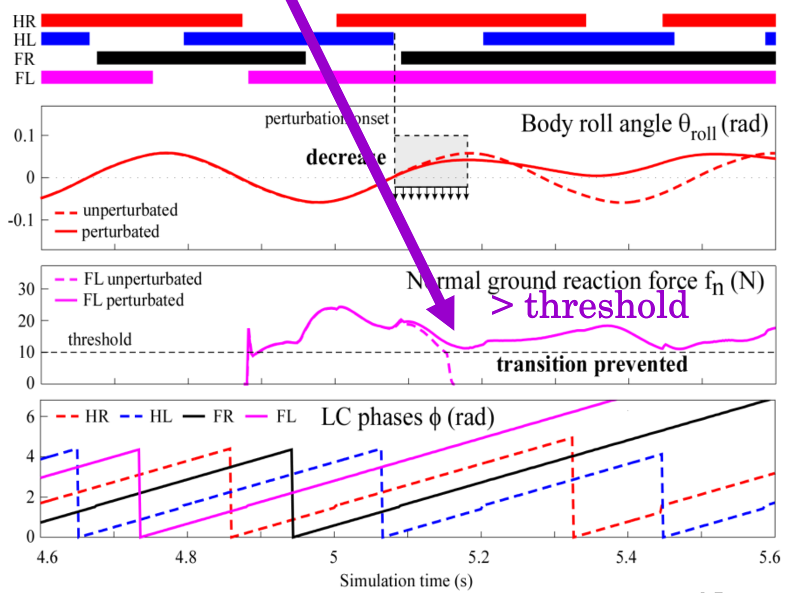
conflict between rhythmic motion control and posture control

we need to introduce an additional mechanism to solve it

Application at swing onset in HL (F_{pert} = 3 N)

~~tra... loading~~ **impaired**

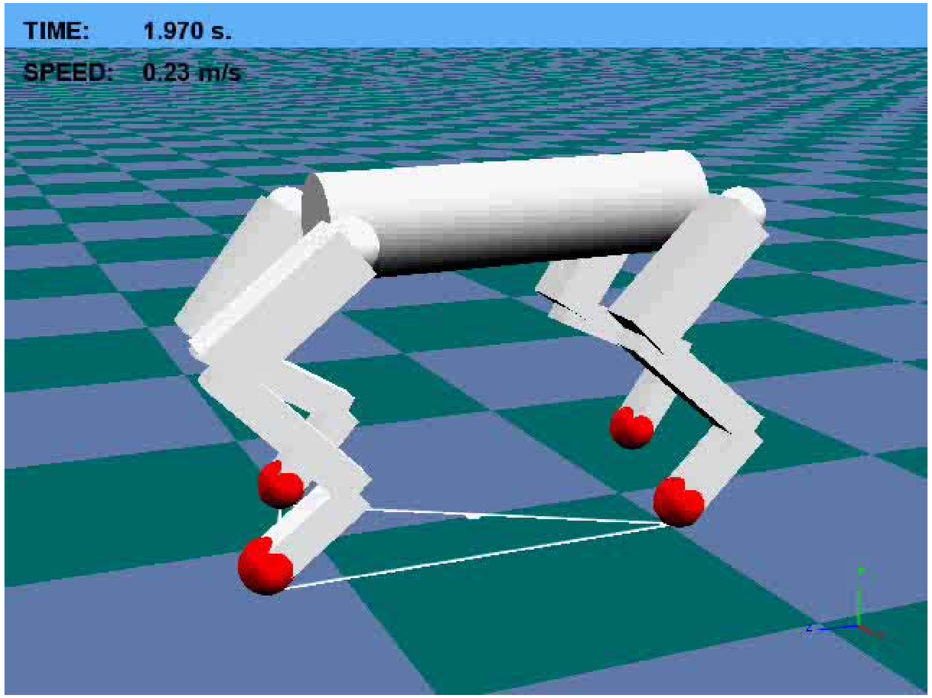
On the more loaded side :
➔ unloading due to rolling motion is reduced
➔ the foreleg cannot swing

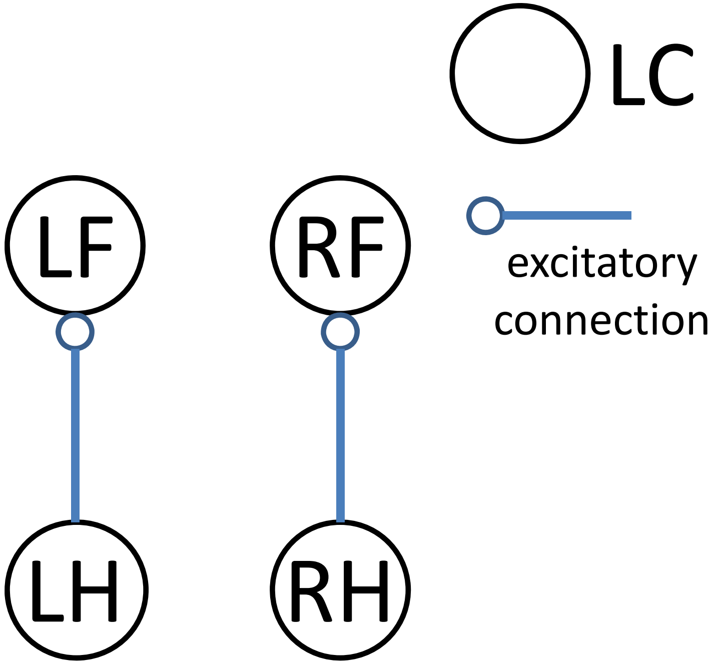


➔ the model falls forward

3D Simulations for lateral perturbation

decreasing $|\dot{\theta}roll|$





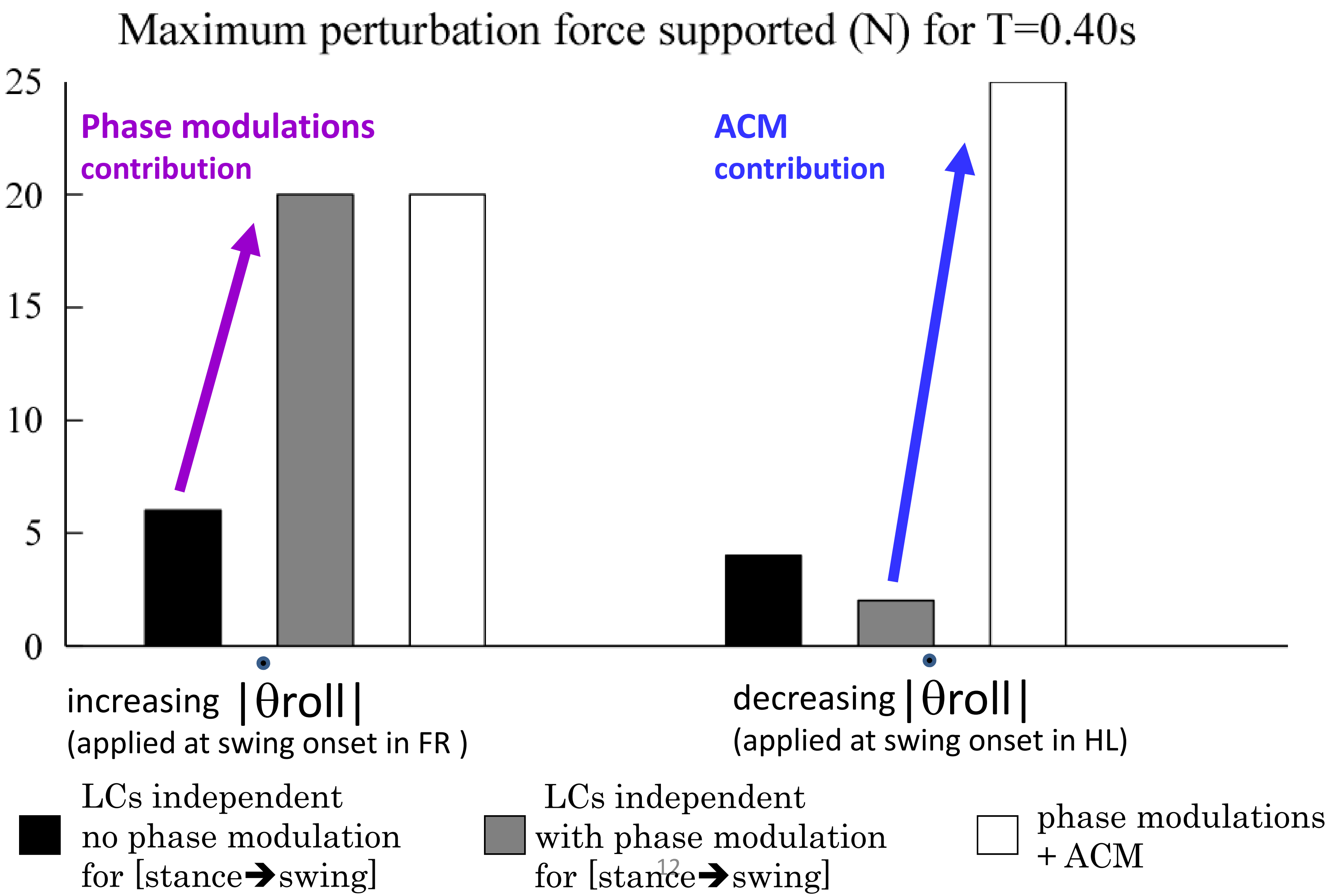
With Ascending Coordination Mechanism (ACM)

to modify χ_{LO} of a fore leg
according to the phase of the ipsilateral hind leg

χ_{LO} : the force threshold to liftoff

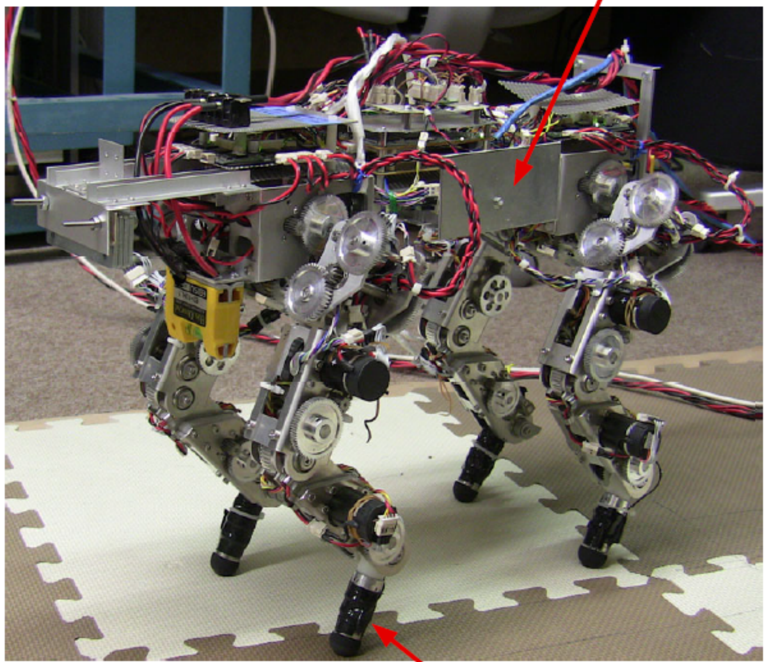
[Maufroy, Kimura, et al. Auto. Robots. 2010]

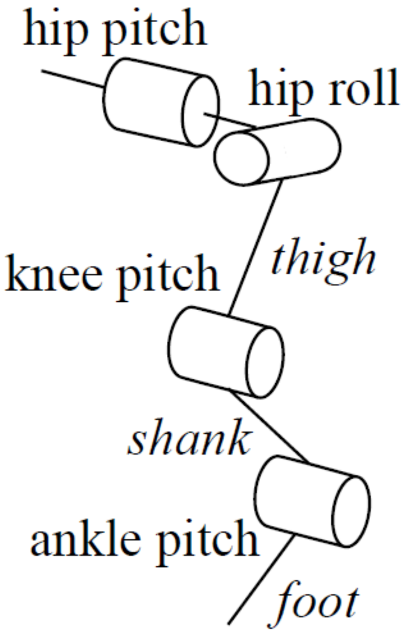
Performances against lateral perturbations (in simulations)



Quadruped Robot "Kotetsu"

plate struck by mass of a pendulum
in lateral perturbation experiments



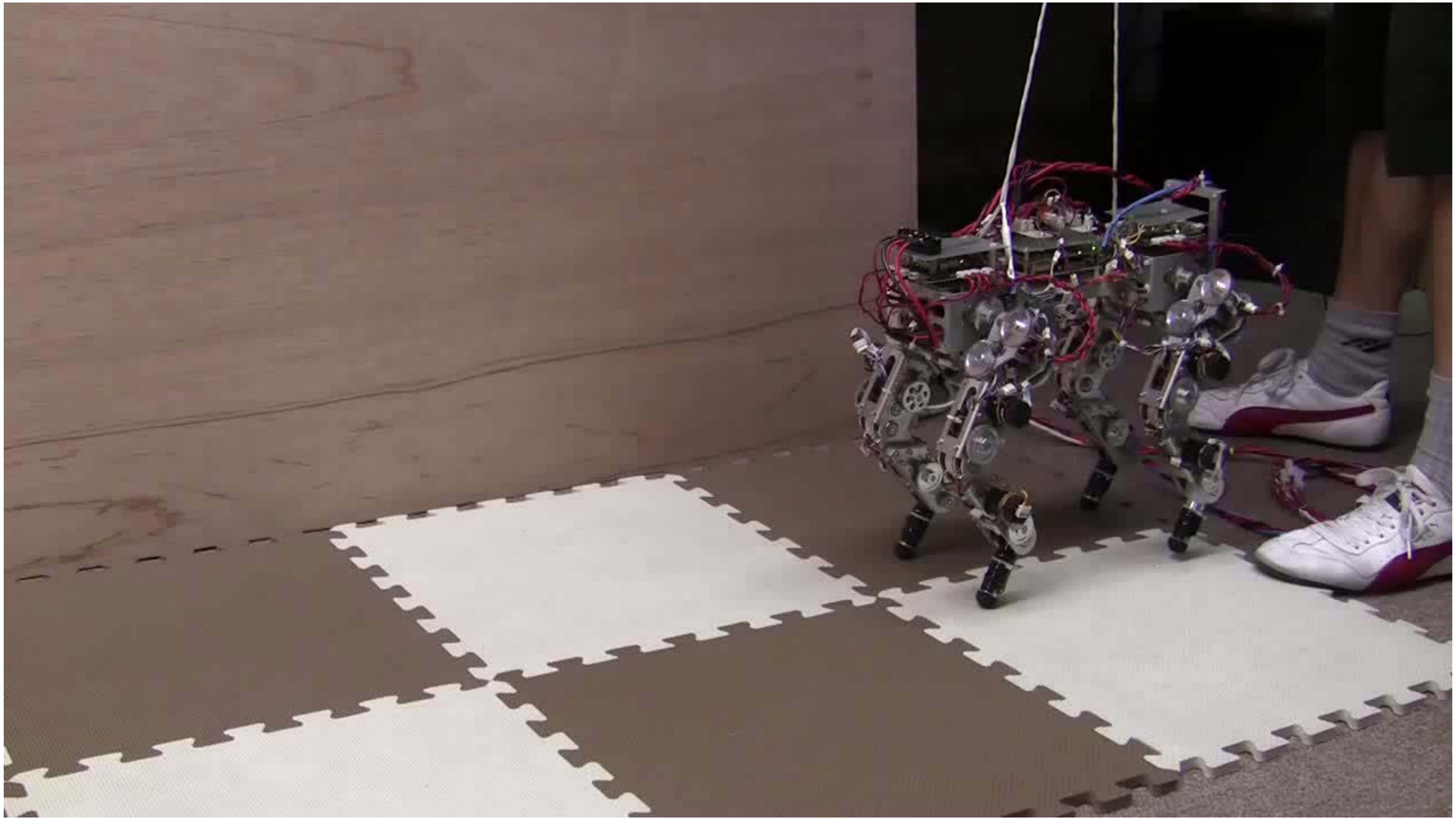


3 axes force/torque sensor

back-drivability &
compliance by software (P-gain)

whole size	length: 34, width: 19∼25, height: 35 (cm)
mass	5.2 (Kg)
DC motors	hip, knee, ankle pitch:20, hip roll:11 (W)
sensors	encoder, rate gyro (pitch&roll), 3 axes accelerometer 3 axes (force: 1 axis, torque: 2 axes) sensor

Gait Generation



$T=0.64s$, $\beta=0.71$, $\gamma_{ipsi}=0.21$, $V=0.2m/s$

ACM to modify χ_{LO} of forelegs

stance to swing of forelegs

$$f_n < \chi_{LO}^{sF}$$

sF : a foreleg

sH : the ipsilateral hind leg

ACMinh

ACMexc

$$\chi_{LO}^{sF} = \begin{cases} \tau_{acm} \cdot \hat{\chi}_{LO} & \text{if } \phi^{sH} < \hat{\phi}_{acm} \\ \hat{\chi}_{LO} + \chi_{mod} & \text{if } \phi^{sH} \in [\hat{\phi}_{acm}; \hat{\phi}_{AEP}] \\ -5(N) & \text{if } \phi^{sH} > \hat{\phi}_{AEP} \end{cases}$$

$$\hat{\phi}_{acm} = 0.5 \cdot \hat{\phi}_{AEP} \qquad \tau_{acm} = \phi^{sH} / \hat{\phi}_{acm}$$

$$\chi_{mod} = \tau_{mod}(\phi^{sH}) \cdot \hat{\chi}_{ampl}$$

$$\tau_{mod}(\phi) = (\phi - \hat{\phi}_{acm})/(\hat{\phi}_{AEP} - \hat{\phi}_{acm})$$

ACM to shorten the swing phase duration of forelegs

increasing angular velocity of an oscillator

$$\omega^{sF} = \hat{\omega} + \omega^{sF}_{mod}$$

ACM$_\omega$

sF : a foreleg

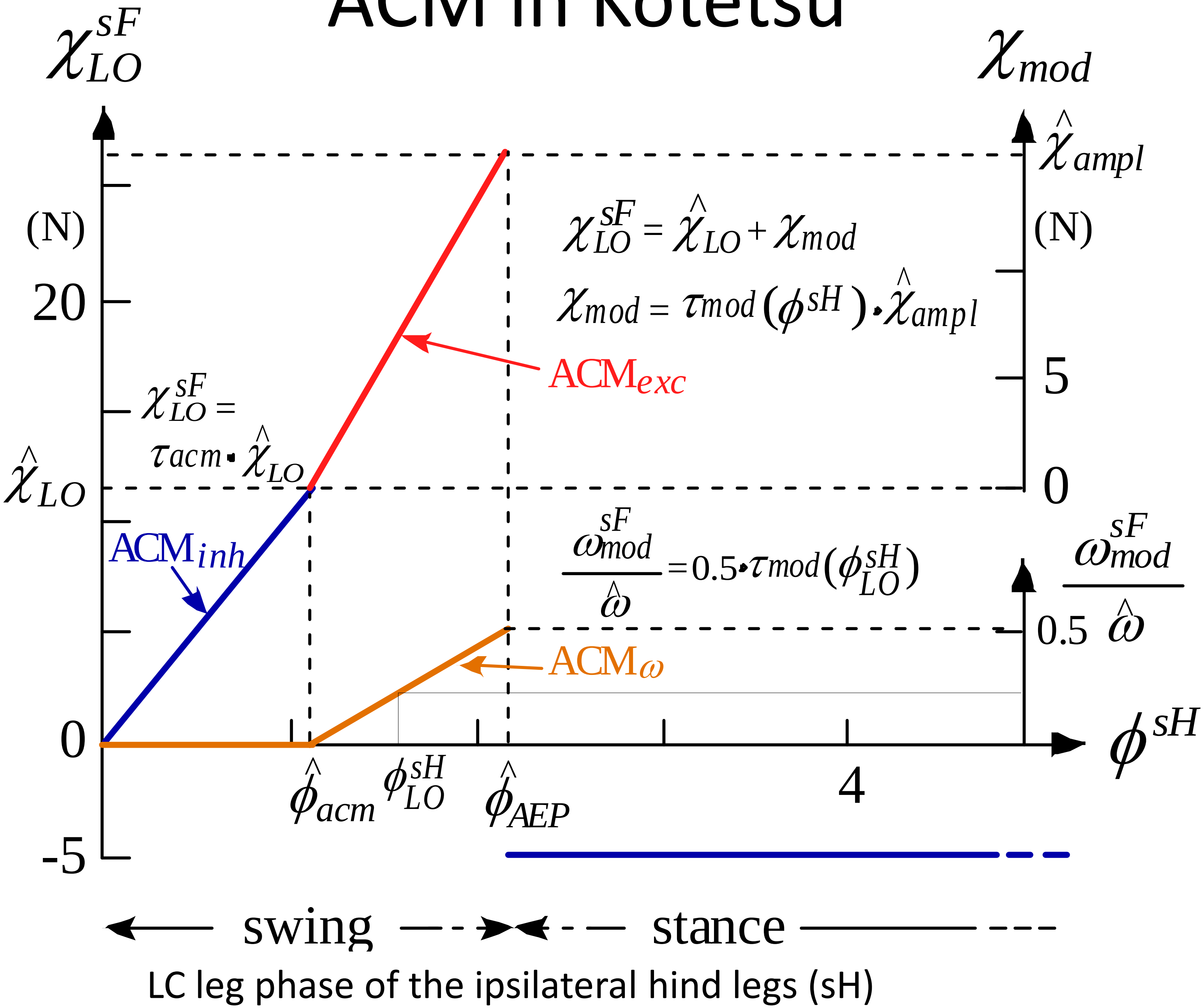
sH : the ipsilateral hind leg

$$\omega^{sF}_{mod} = \begin{cases} 0.5 \cdot \tau_{mod}(\phi^{sH}_{LO}) \cdot \hat{\omega} & \text{if } \phi^{sH}_{LO} \in [\hat{\phi}_{acm}; \hat{\phi}_{AEP}] \\ 0 & \text{otherwise} \end{cases}$$

ϕ^{sH}_{LO} the LC phase of the hind leg at the moment when the foreleg transits to the swing phase.

$$\tau_{mod}(\phi) = (\phi - \hat{\phi}_{acm})/(\hat{\phi}_{AEP} - \hat{\phi}_{acm})$$

ACM in Kotetsu



Role of each ACM

ACM_{inh} (always being employed in Kotetsu)

to avoid disorder of phase transitions caused by the slightly backward location of the center of mass of the body.

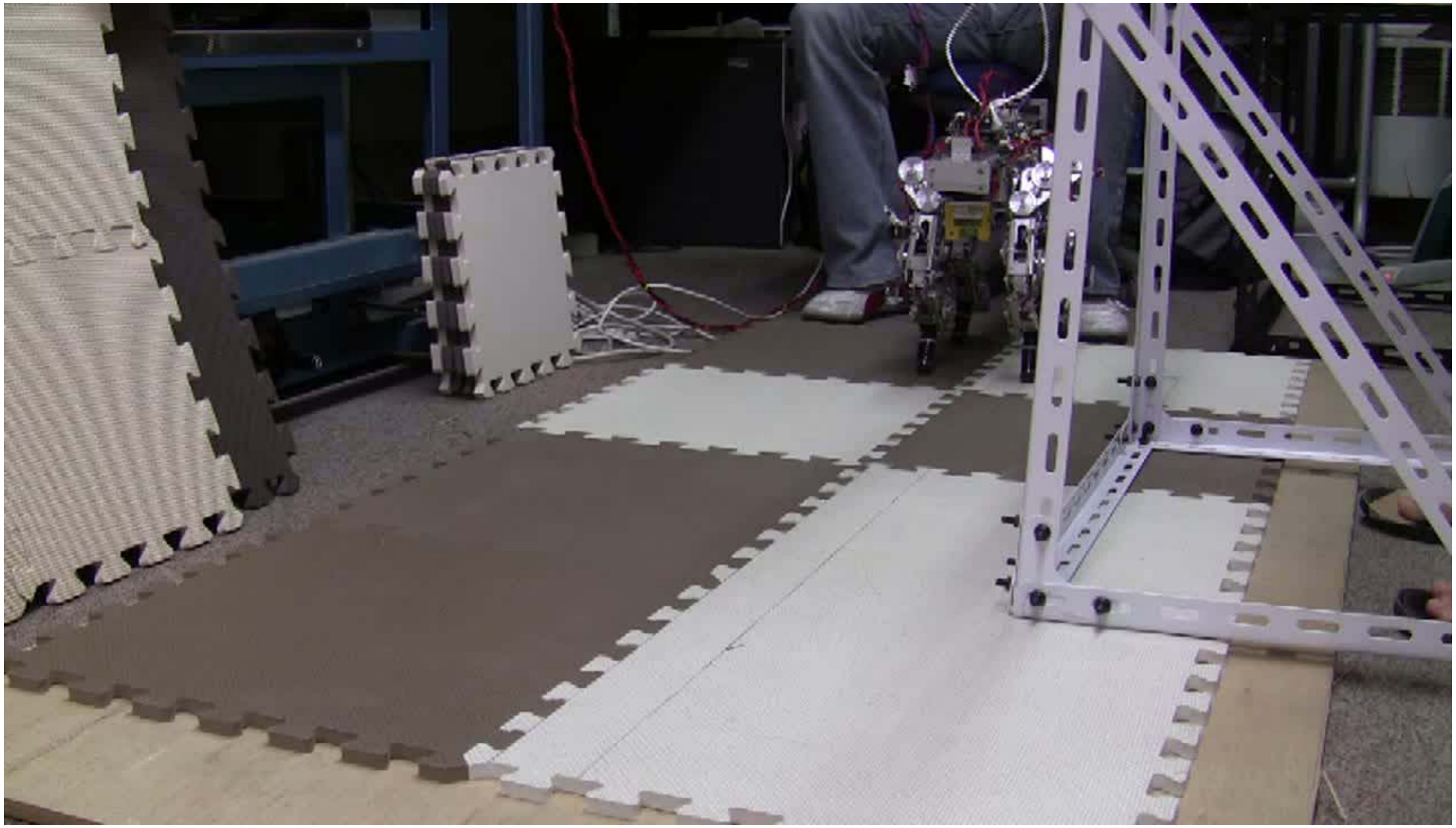
ACM_{exc}

to promote the stance-to-swing phase transition of a foreleg by increasing the force threshold. As a result, a robot can keep stepping of correct order after a lateral perturbation.

ACM_{ω}

to increase the speed of a foreleg when the stance-to-swing phase transition is delayed. As a result, a robot can keep the enough step length after a lateral perturbation.

Without ACMexc and ACM$\dot{\omega}$
lateral perturbation decreasing $|\theta_{roll}|$

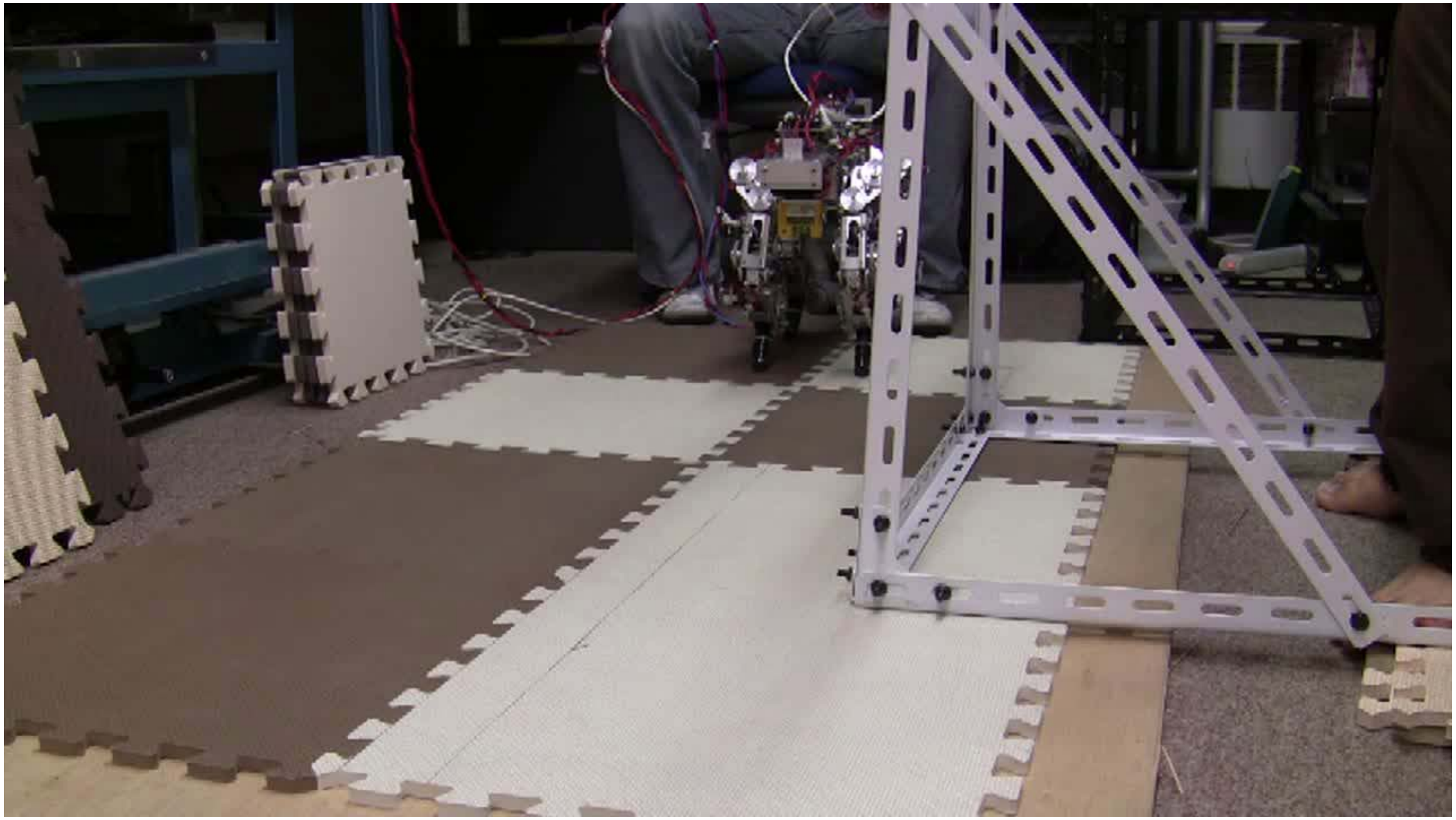


Impact: LF-sw

Afterwards: LF-st→RH-sw→RF-sw ….. RF-st→LH-sw ✗→ LF-sw

With ACMexc and ACMω

lateral perturbation decreasing $|\dot{\theta}roll|$



Impact: LF-st

Afterwards: LH-sw→LH-st→LF-sw→LF-st→RH-sw→RF-sw...

How to defined the value of $\hat{\chi}_{LO}$

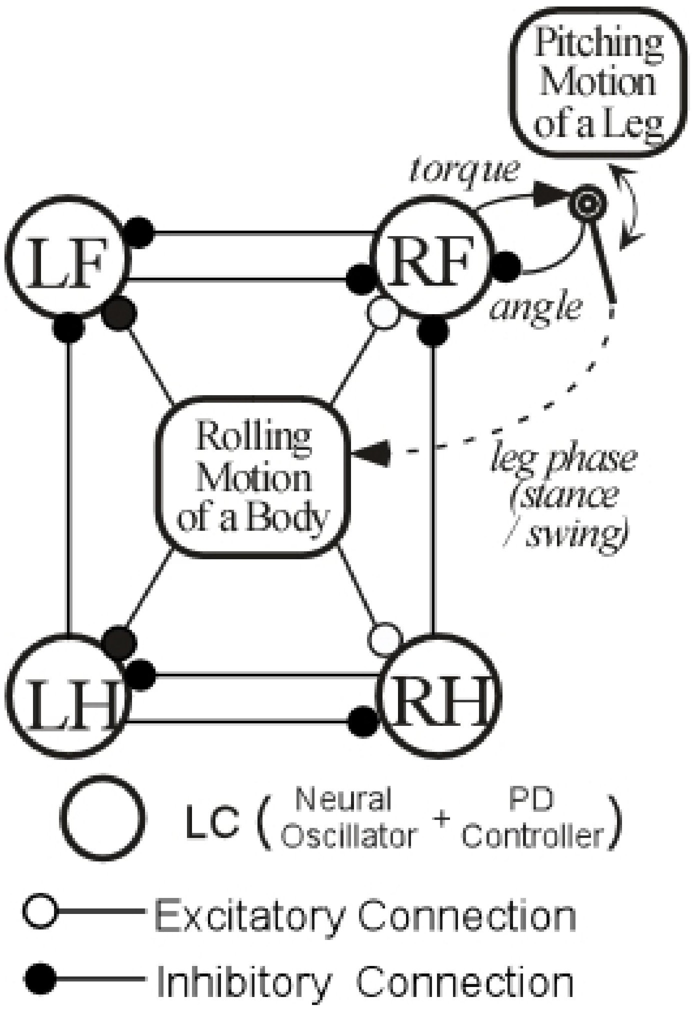
nominal threshold to liftoff

- $\hat{\chi}_{LO}$ is an important parameter to defines when a leg is considered as unloaded.

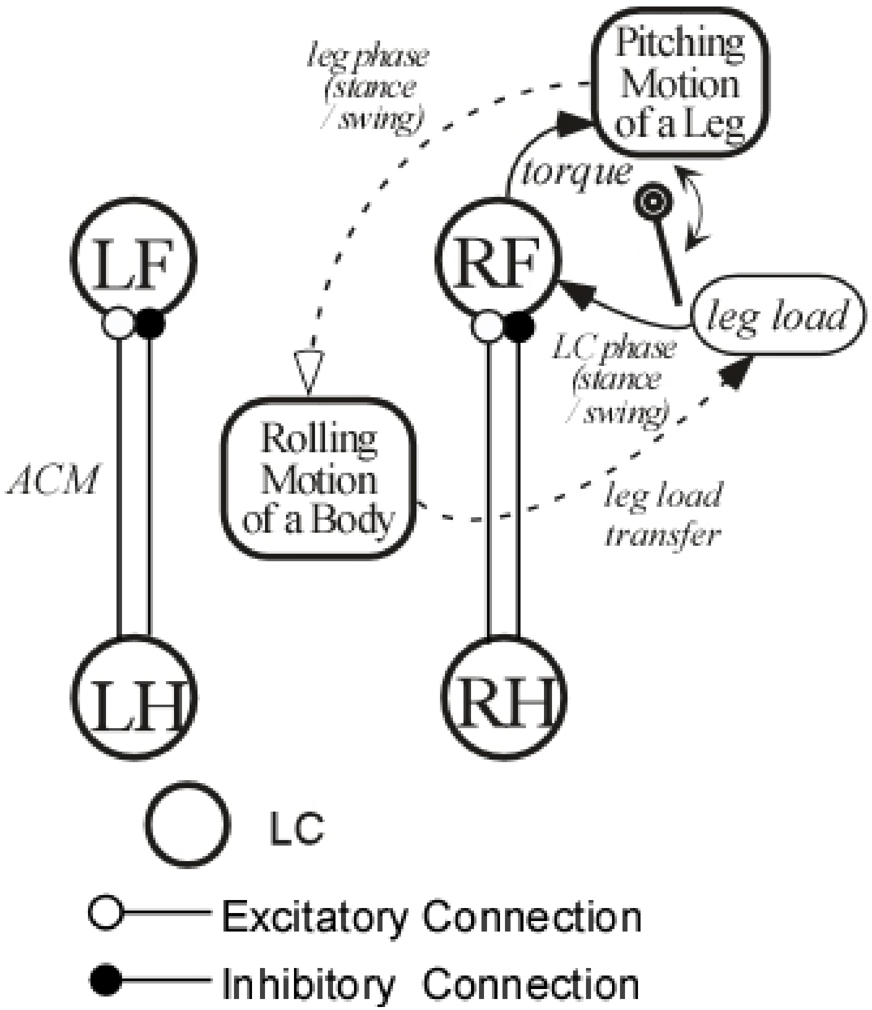
- Too much high or small values prevent stable leg load transfer between contralateral legs.
  - high : too small walking cyclic period
    less robustness against force sensor noises
  - small : difficult to initiate and sustain the lateral rolling motion

- ACM makes the selection of $\hat{\chi}_{LO}$ value be less critical.

Emergent Motion Generation

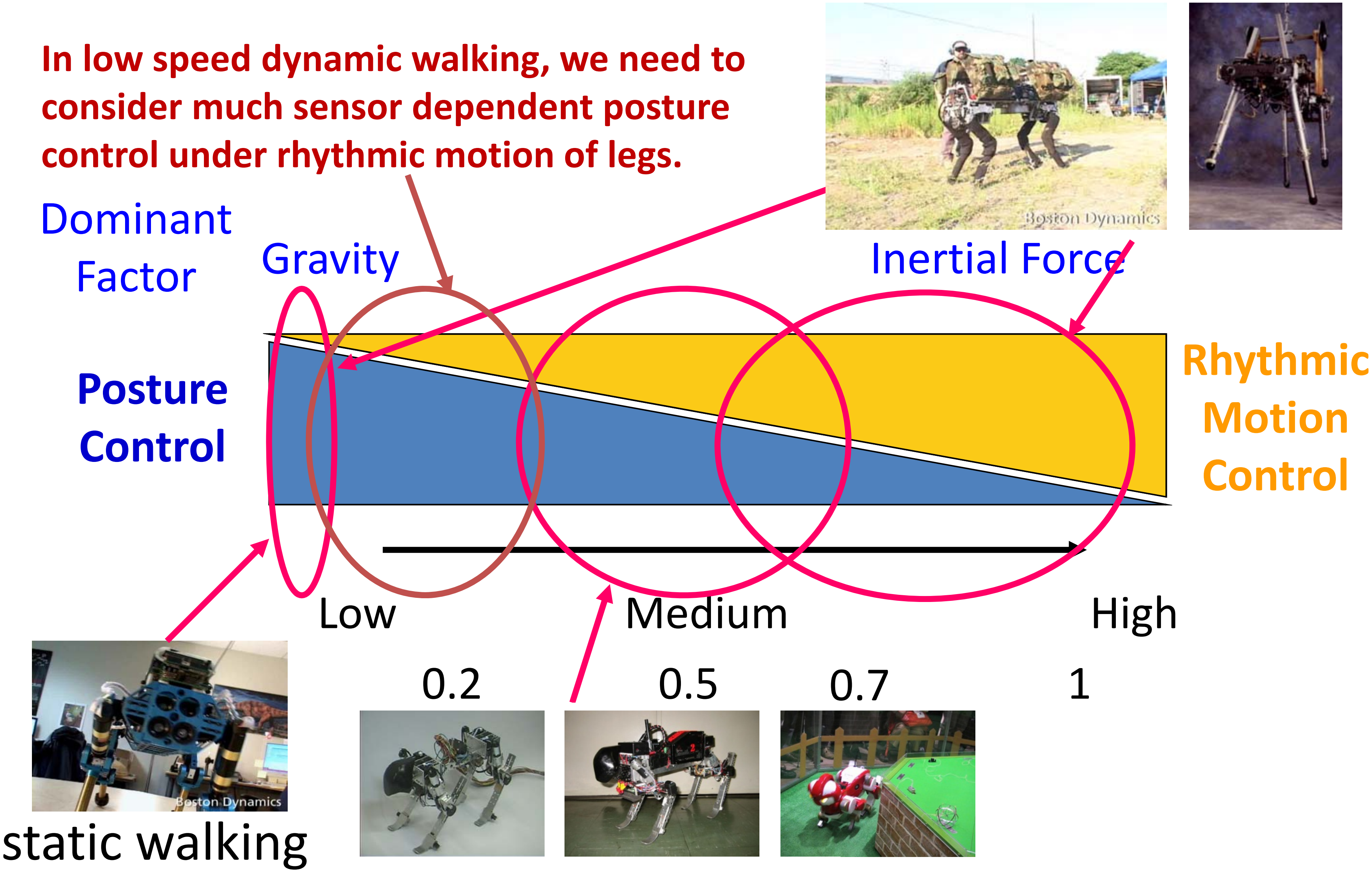


Tekken



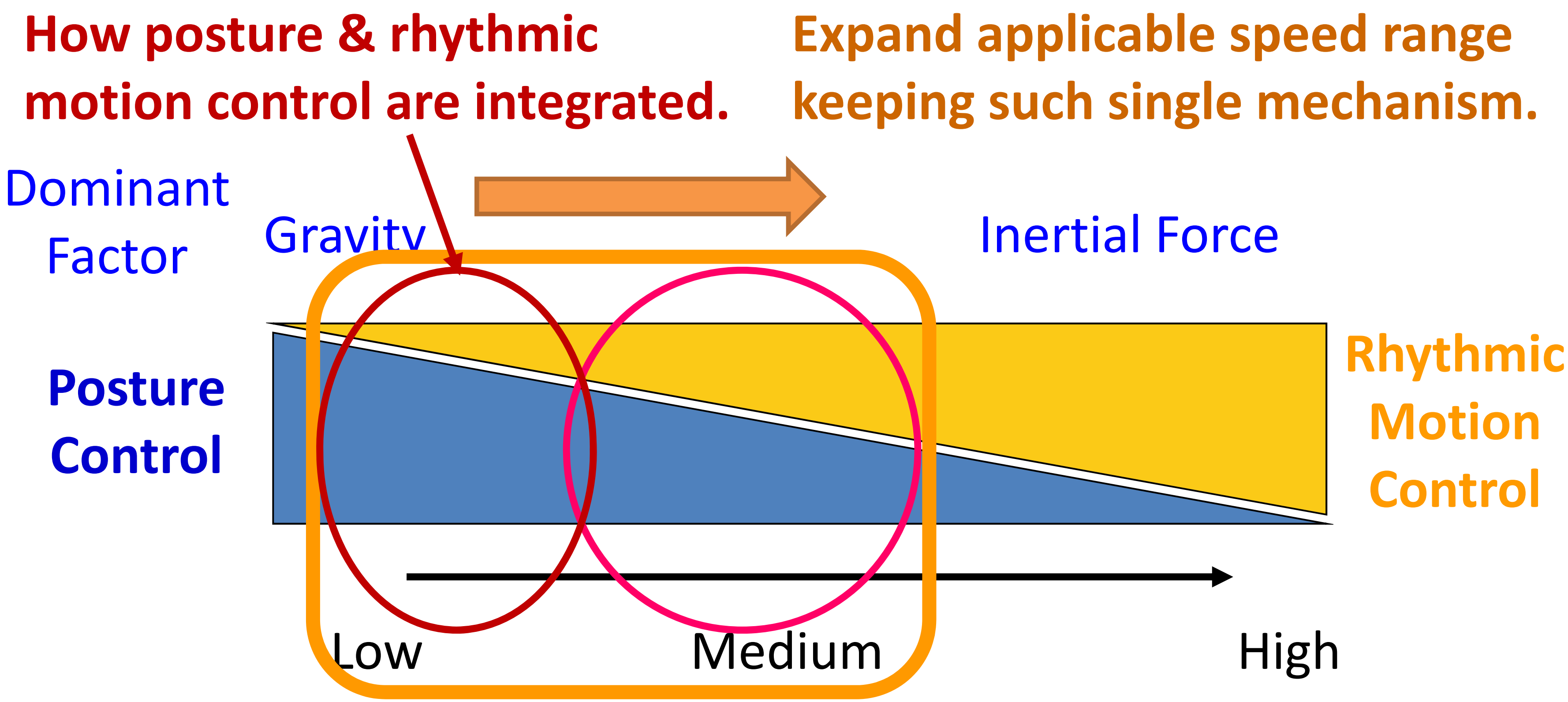
Kotetsu

Locomotion speed & control



Series of Tekken [2001-2005]

Objectives of this study



Realization of low- & medium-speed dynamic walking with using **single mechanism integrating posture and rhythmic motion control**

Conclusions
- perturbations on lateral motion -

- Phase modulations based on leg loading/unloading:
  - basic but **powerful mechanism**
  - greatly contribute to leg coordinations and rolling motion stabilization
  - LCs independent but for the ascending coordination mechanism (ACM)
- As the ACM, we implemented
  - ACMinh : newly employed for experiments using “Kotetsu”
  - ACMexc and ACMω : exactly identical to the ones used in simulations
- We confirmed the validity of simulation results by experiments

Thank you for your attention !

http://robotics.mech.kit.ac.jp/kotetsu/

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from MEXT in Japan.

Why low speed dynamic walking with long cyclic period is difficult to realize.

- It means that frequency of switching phase or touch down of legs decreases. As a result, posture control via
  - switching phase &
  - touchdown angle control (used in Biper, Raibert's hopping machines, Tekken, ASHIMO, BigDog)

  is not so effective.

- The increased amplitude of rolling motion makes walking unstable. [Kimura, Shimoyama and Miura 1990]

Comparison between Simulations and Experiments

Excluding ACMinh, results are exactly corresponding.

	perturbation	ACM_{inh}	ACM_{exc}	ACM_{ω}	result
sim.	no (*Fig.6*)	×	×	×	success
sim.	↑ (*Fig.12*)	×	×	×	success
sim.	↓ (*Fig.13*)	×	×	×	fail
sim.	↓ (*Fig.14*)	×	○	○	success
exp.	no	×	×	×	disorder
exp.	no	○	×	×	success
exp.	↑ (Fig. 4)	○	×	×	success
exp.	↓ (Fig. 5)	○	×	×	fail
exp.	↓ (Fig. 6)	○	○	○	success

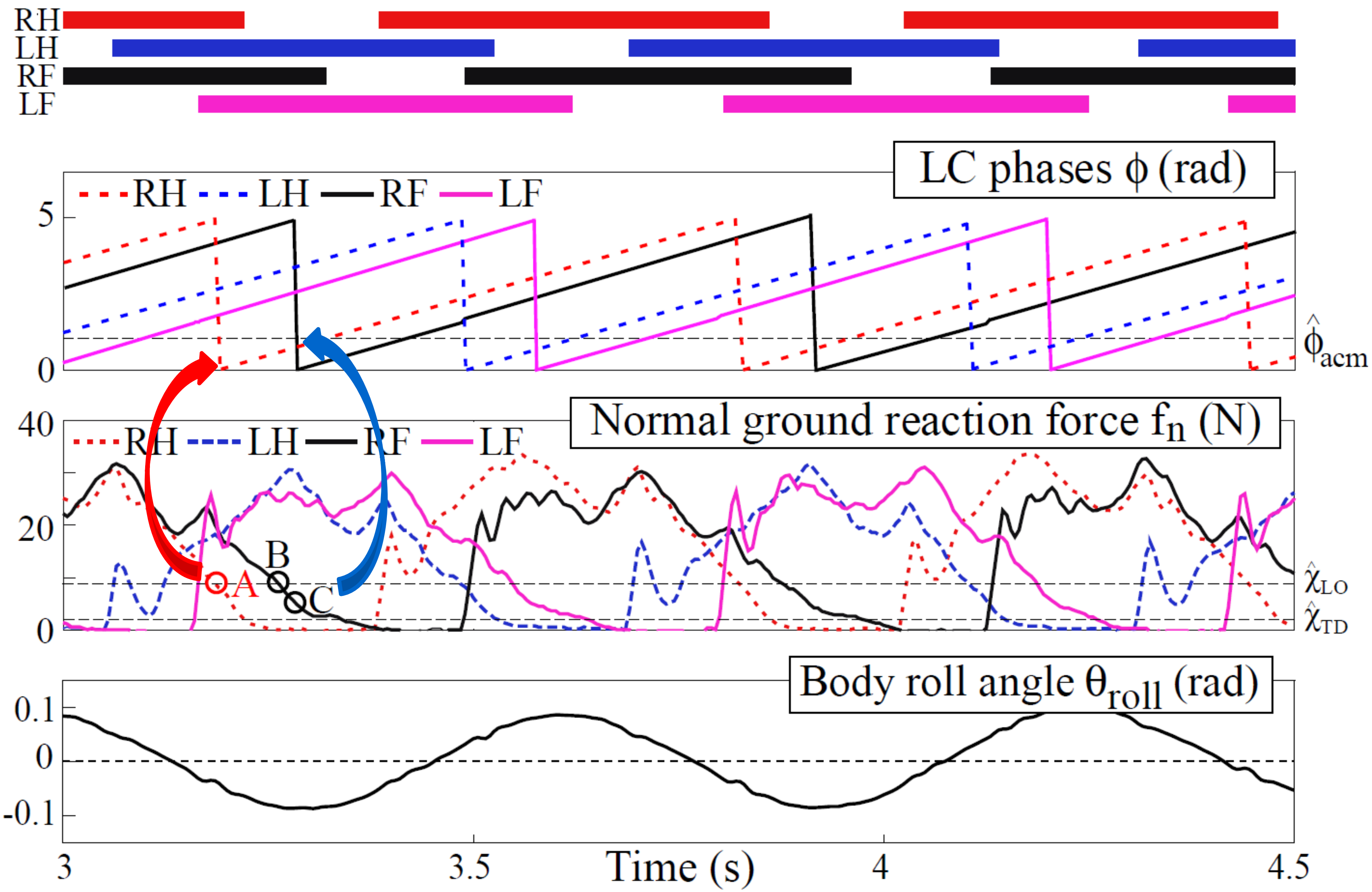
↑ increasing

↓ decreasing

$|\dot{\theta}roll|$

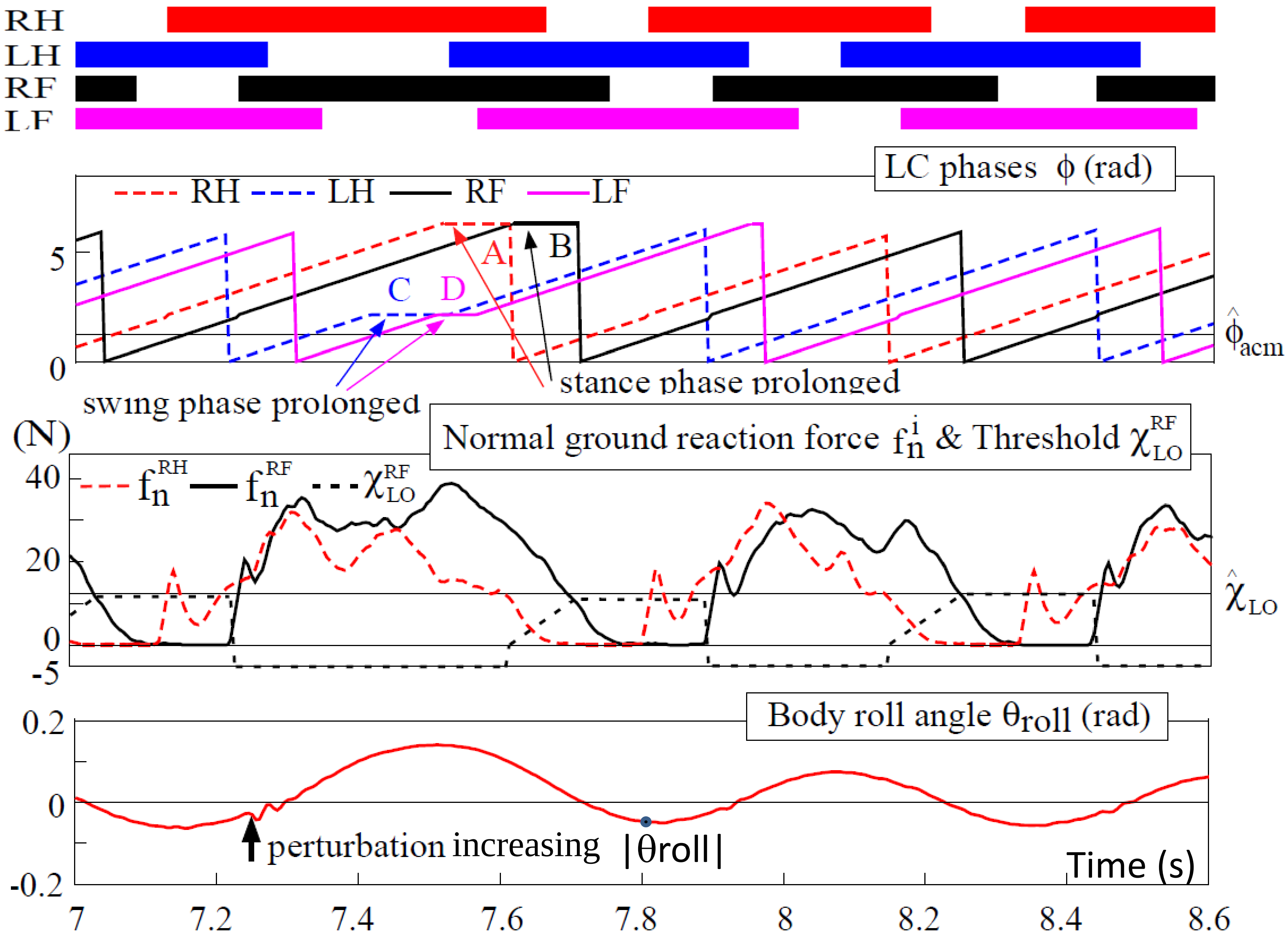
Gait Generation Result (Experiment)

With ACMinh & Without ACMexc and ACMω

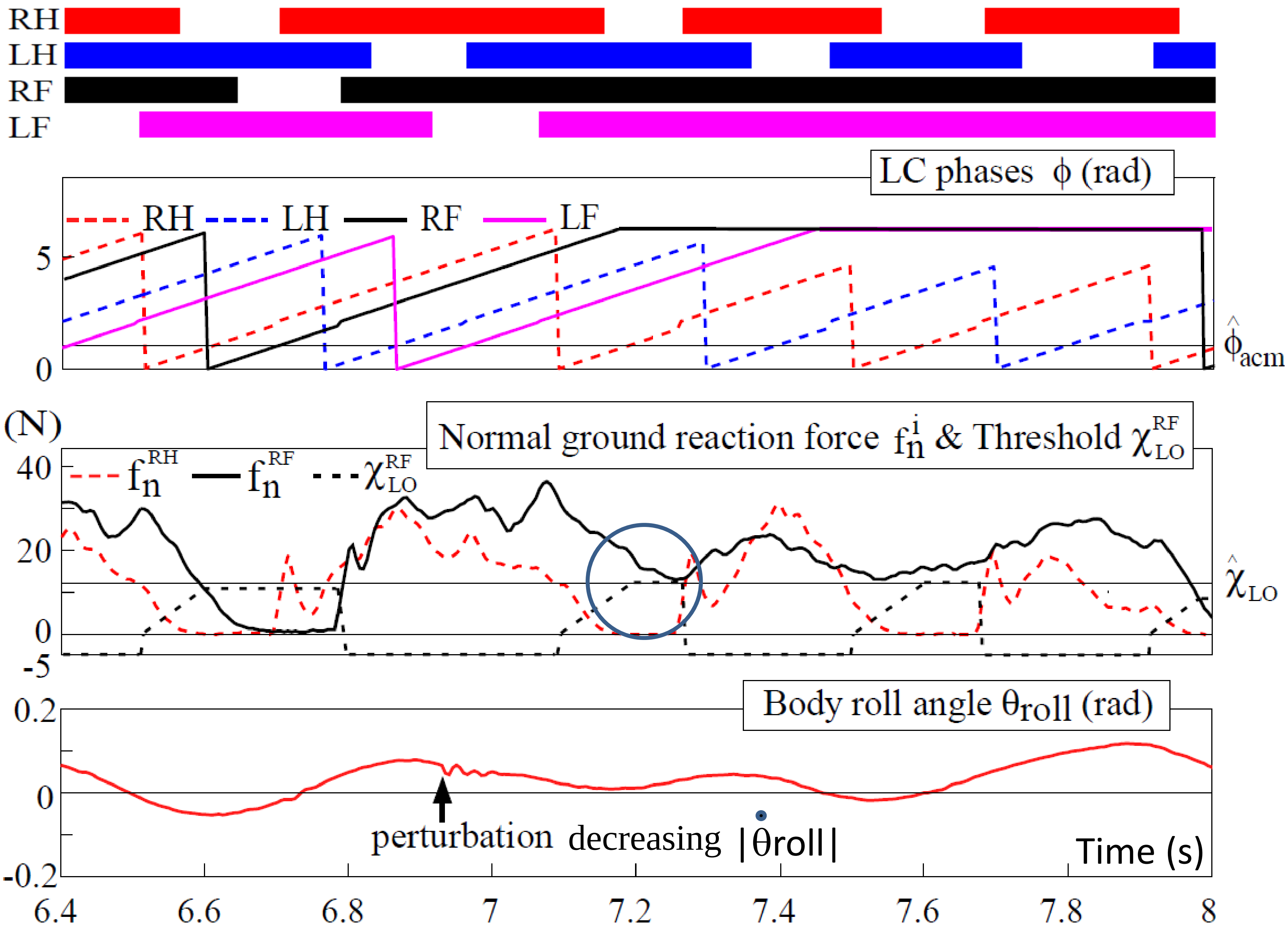


T=0.64s, β=0.71, γ_{ipsi}=0.21, V=0.2m/s

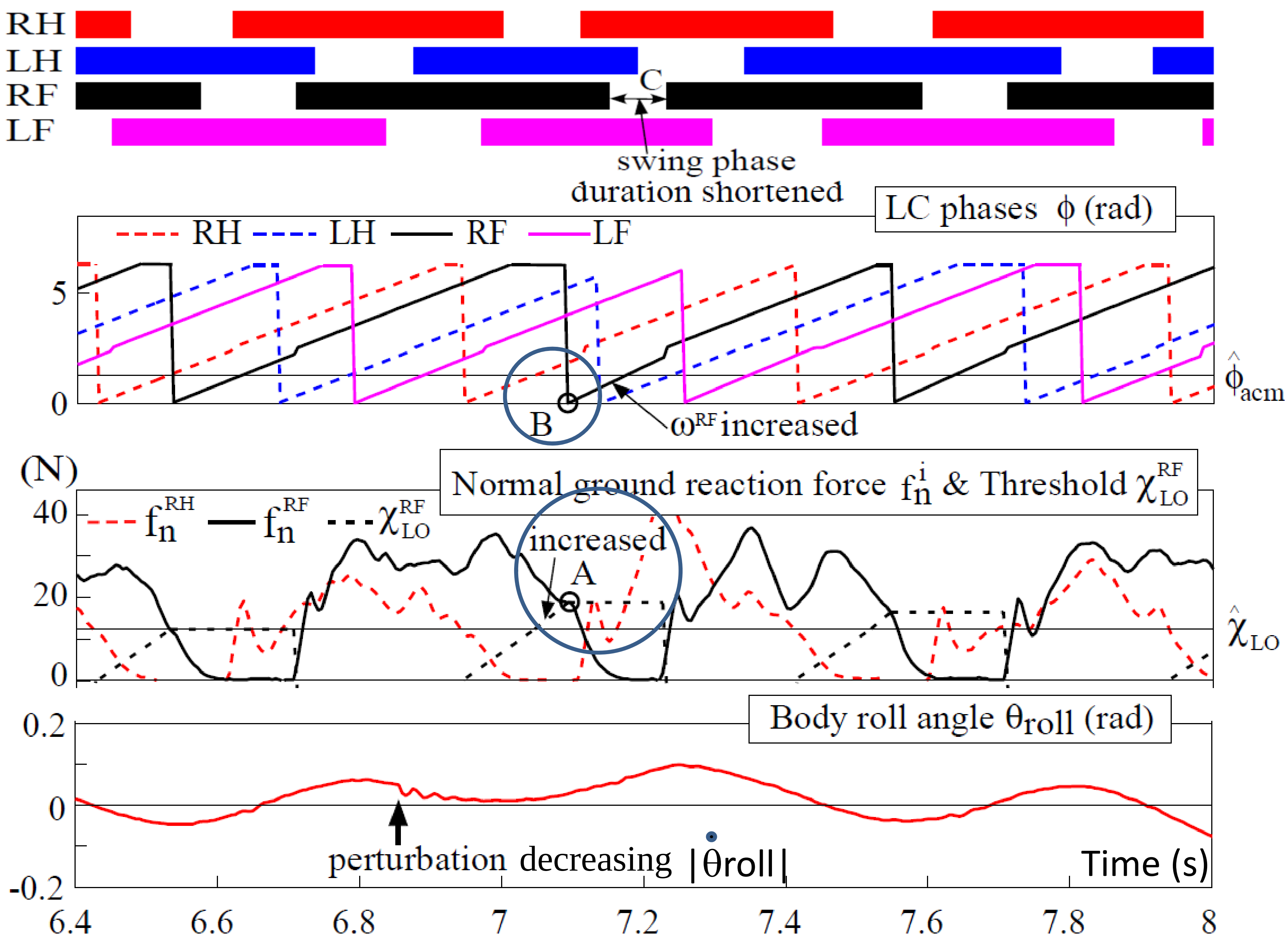
increasing |$\dot{\theta}$roll| without ACMexc and ACMω



decreasing $|\dot{\theta}_{roll}|$ without ACMexc and ACMω

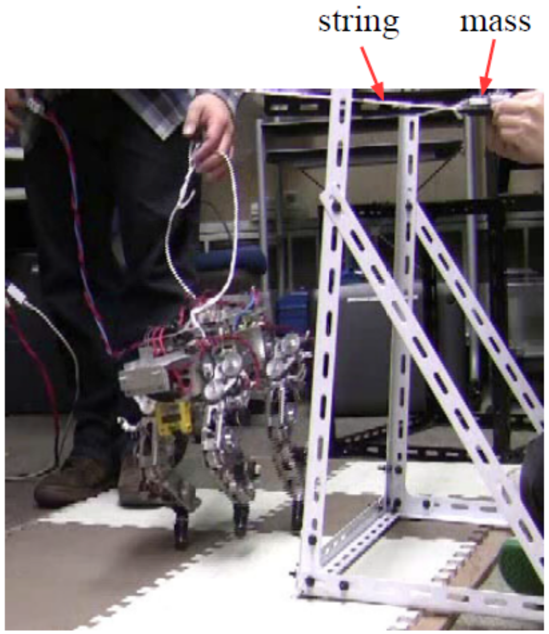


decreasing $|\dot{\theta}roll|$ with ACMexc and ACMω

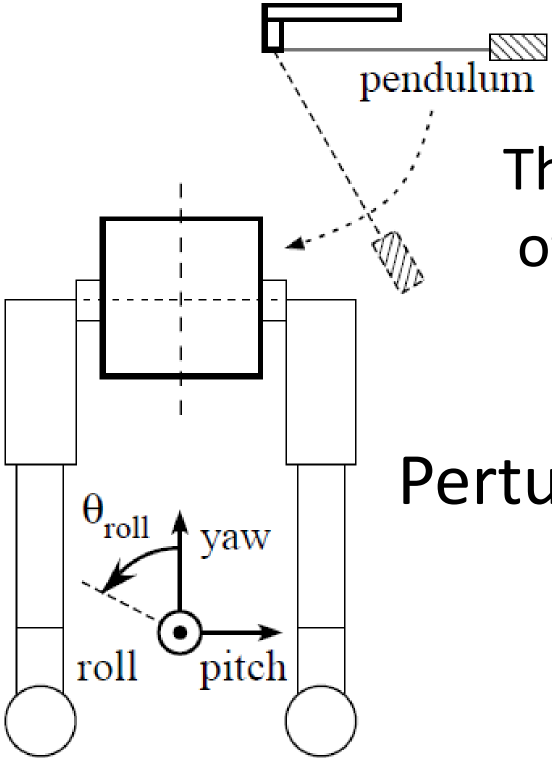


Lateral Perturbation Setup

mass 200g, string length 0.35m



just before
releasing the mass



frontal view

The mass hits the center of the body to the right.

Perturbation Timing

increasing $|\dot{\theta}roll|$

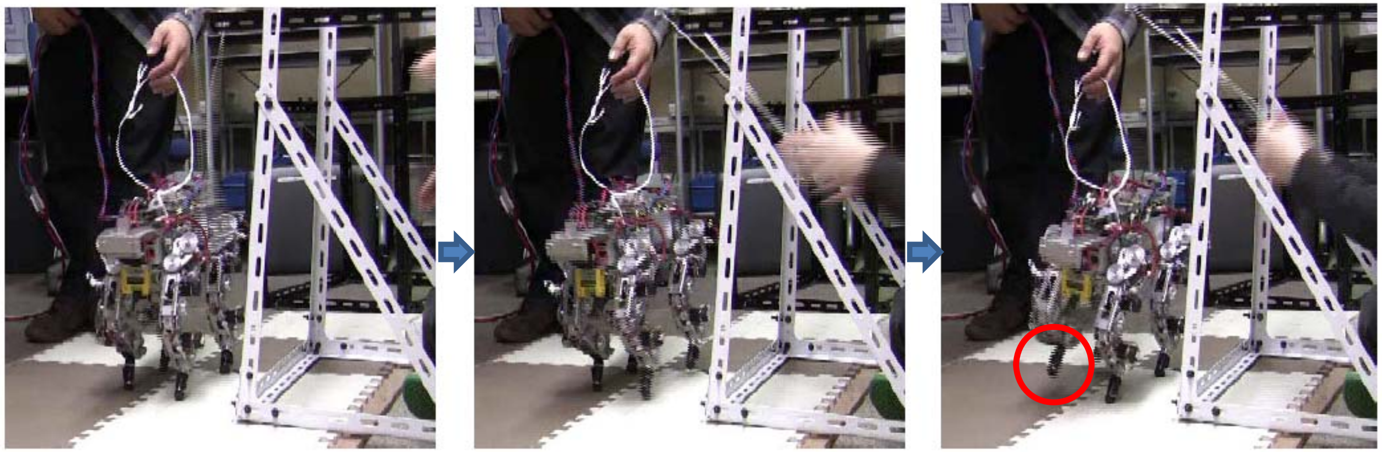
or

decreasing $|\dot{\theta}roll|$

more serious

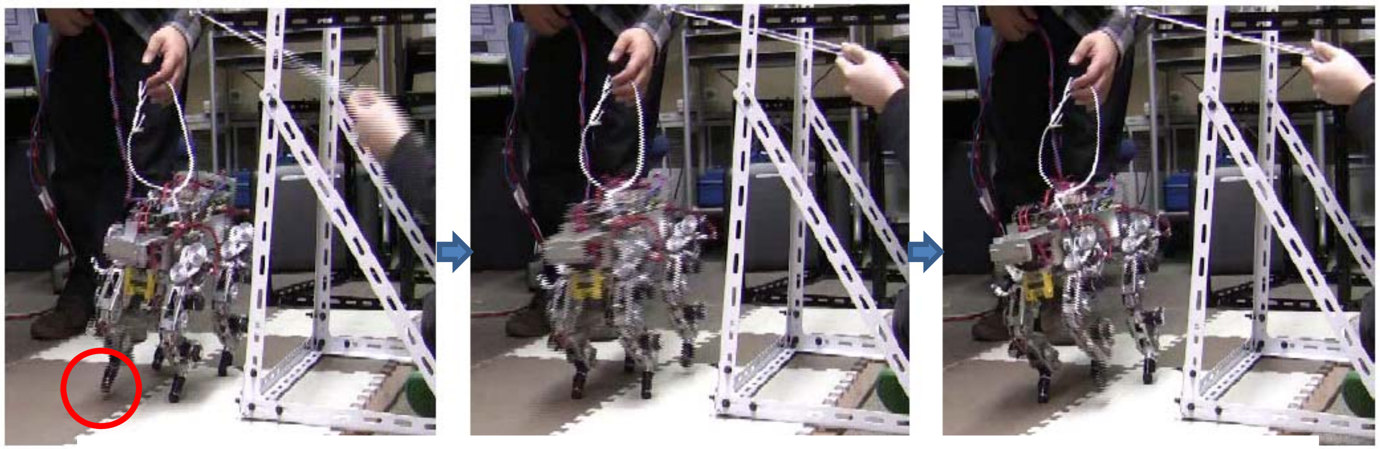
With ACMexc and ACMω

lateral perturbation decreasing $|\dot{\theta}_{roll}|$



at impact — just after impact — 0.3s after impact

RF lifted off



RF touched down

afterwards