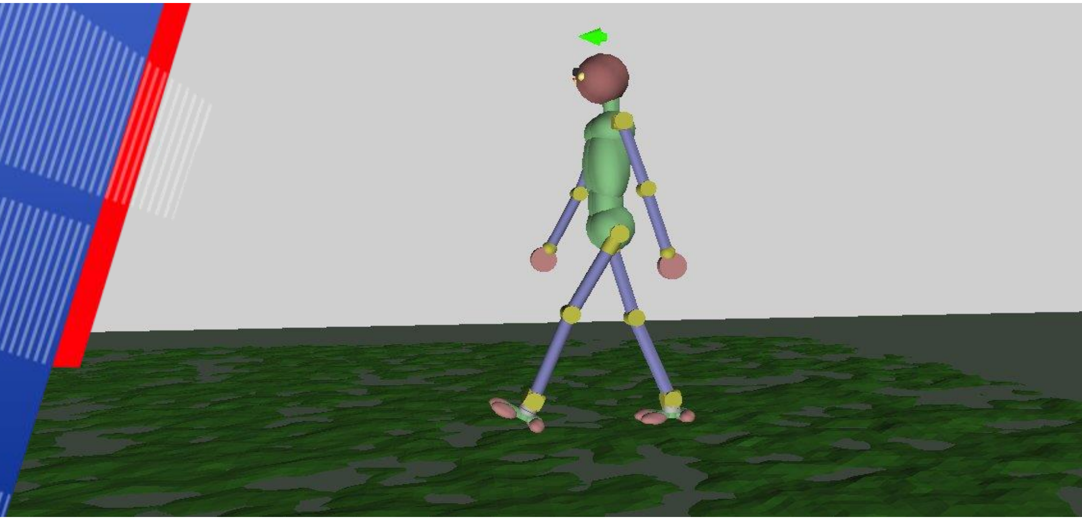
Advanced Behavior-based Control of Bipedal Locomotion



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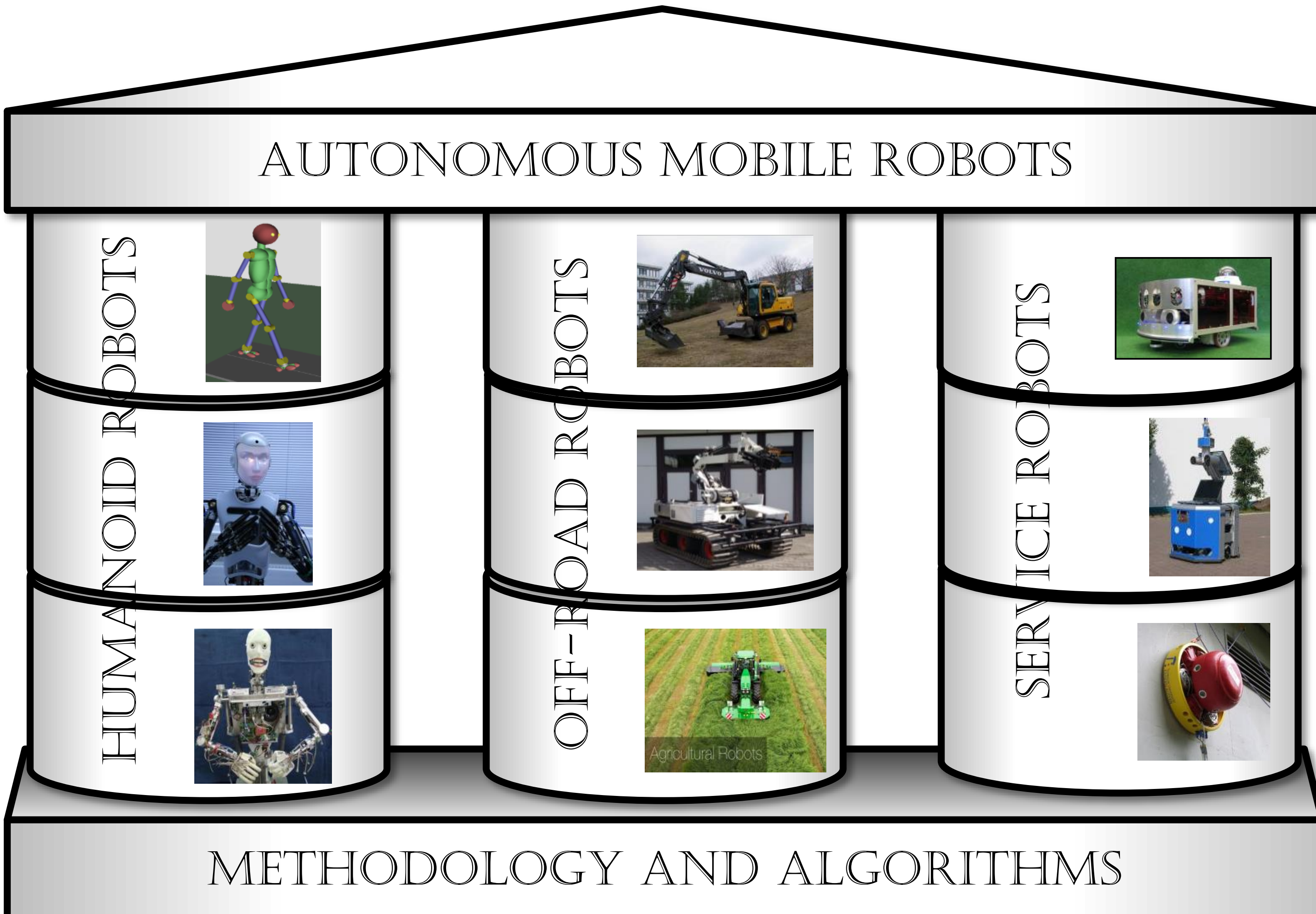
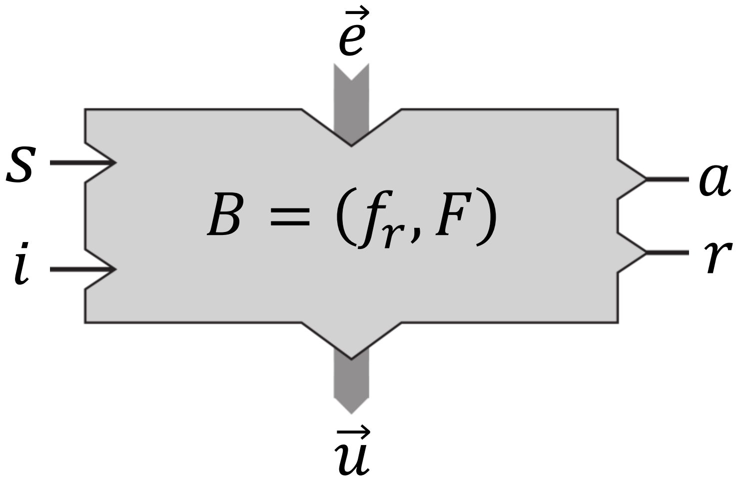
Research at Robotics Research Lab (RRLab)



Human Robot Interaction

Behavior-based Control (iB2C)

- Fundamental unit in iB2C: Control/Perception module
  $$B = (f_r, F)$$
- f_r: Target rating function
- F: Transfer function determines output vector

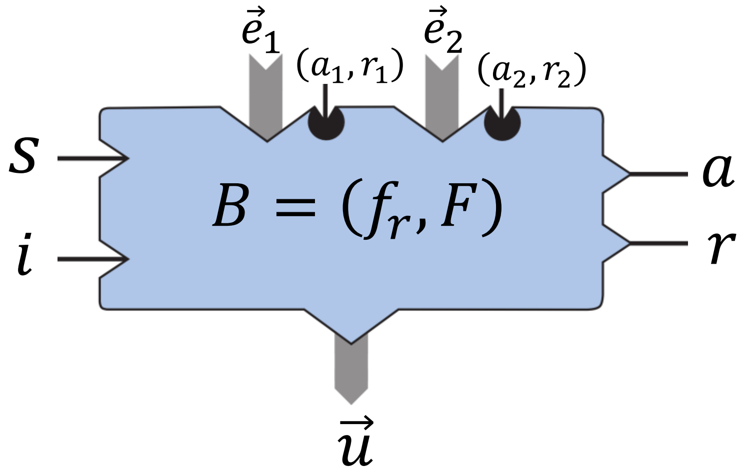


- $\vec{e} = \overrightarrow{(d, \sigma)} \in \mathbb{R}^{2^m}$: Input vector
- $\vec{u} = \overrightarrow{(d, \sigma)} \in \mathbb{R}^{2^n}$: Output vector
- $d \in \mathbb{R}$: Data value
- $\sigma \in \mathbb{R}^+$: Standard deviation of d
  - Percept: Uncertainty
  - Behavior: Error margin

- $s \in [0,1]$: Stimulation
- $i \in [0,1]$: Inhibition
- $a \in [0,1]$: Activity
- $r \in [0,1]$: Target rating

Fusion Behavior Module

- Common interface
- Coordinate p competing behaviors B_c
- F is the fusion function processing input values to a merged output control vector $\vec{u}$

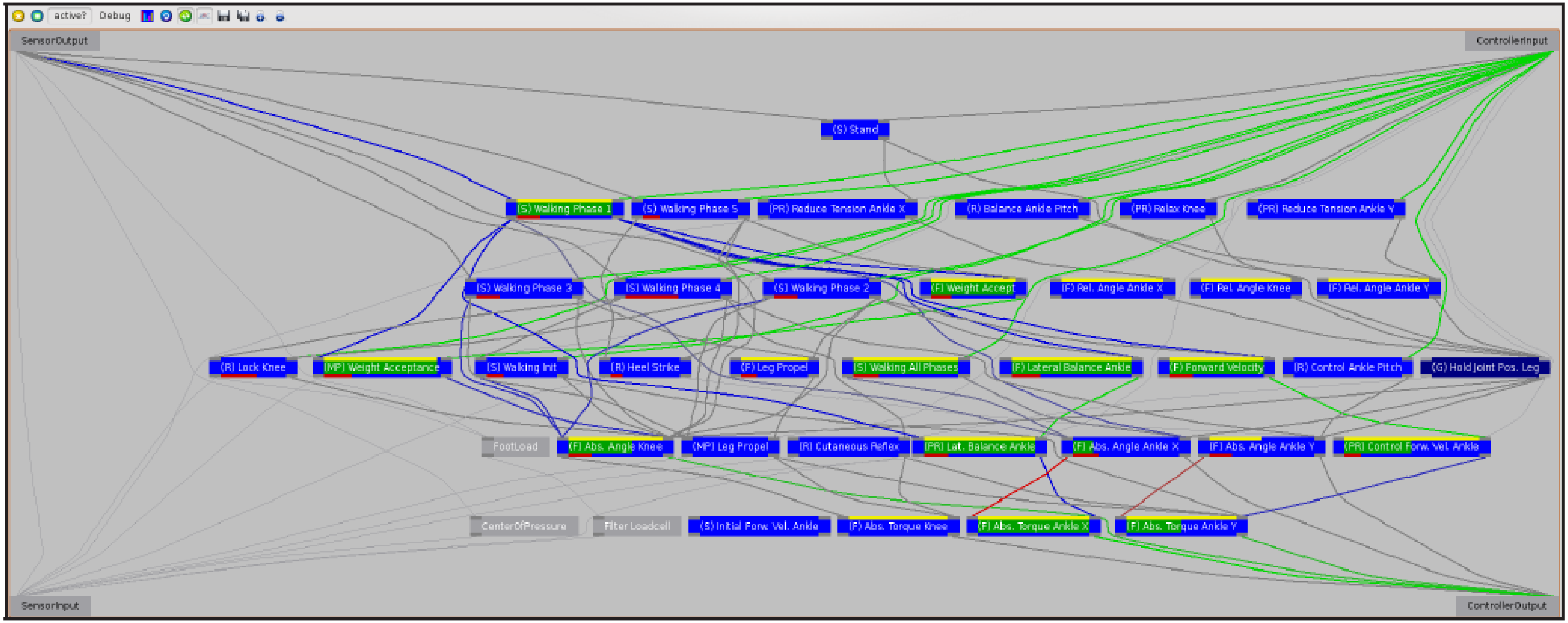


- Maximum fusion: $\vec{u} = \vec{u}_s$, $a = \max_c(a_c)$, $r = r_s$ where
  $$s = \operatorname{argmax}_c(a_c)$$

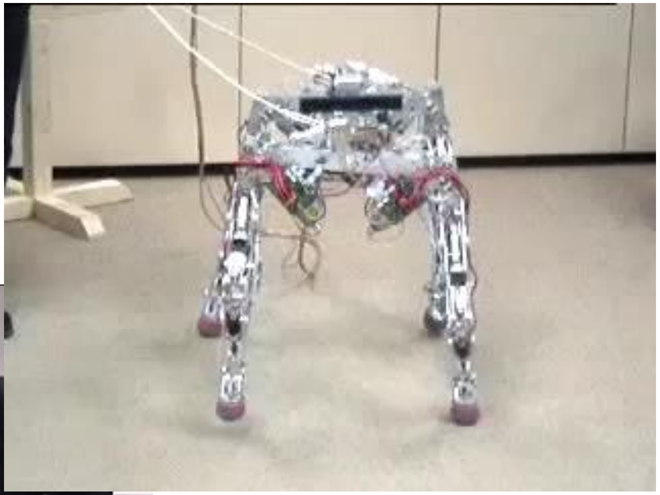
- Weighted average fusion: if $(1 = \max_c(r_c))$ then maximum fusion else

$$\vec{u} = \frac{\sum_{j=0}^{p-1} a_j \cdot \vec{u}_j}{\sum_{k=0}^{p-1} a_k} \quad a = \frac{\sum_{j=0}^{p-1} a_j^2}{\sum_{k=0}^{p-1} a_k} \quad r = \frac{\sum_{j=0}^{n-1} a_j \cdot r_j}{\sum_{k=0}^{n-1} a_k}$$

Behavior Networks



Background Biological inspired Robots (FZI)



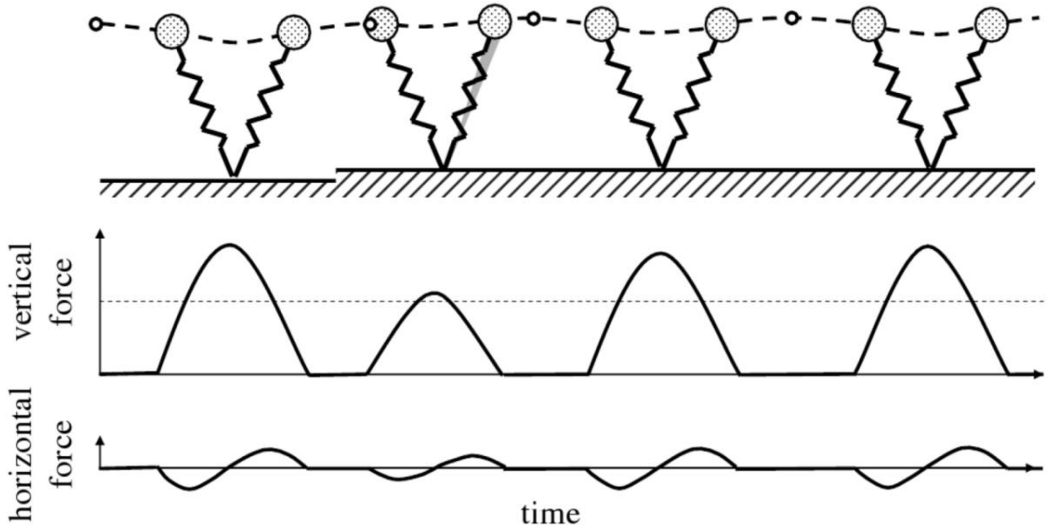
Challenges in Bipedal Locomotion Control

- Low energy consumption
- Control of stiffness, complaint
- Locomotion capability in rough environments
- Sensitive to any external disturbances

=> What principles can be transferred from nature

Mechanical System – Functional Morphology

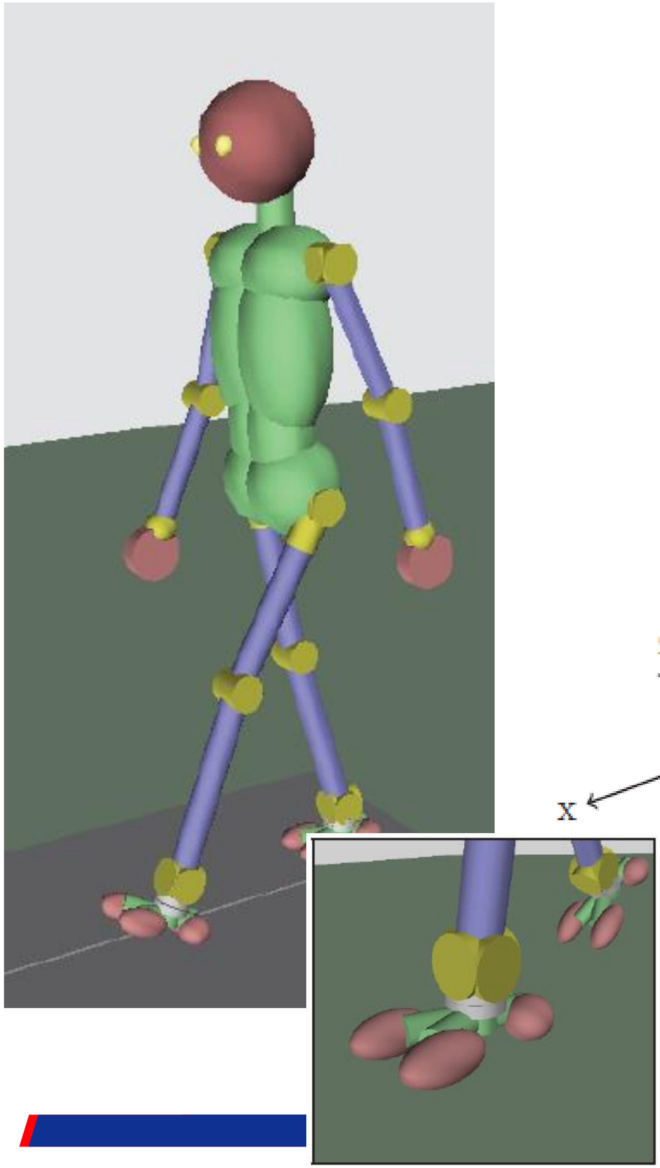
Elastic operation of the leg can passively stabilize running in the presence of external disturbances without changing the angle of attack or the stiffness [Blickhan 07].

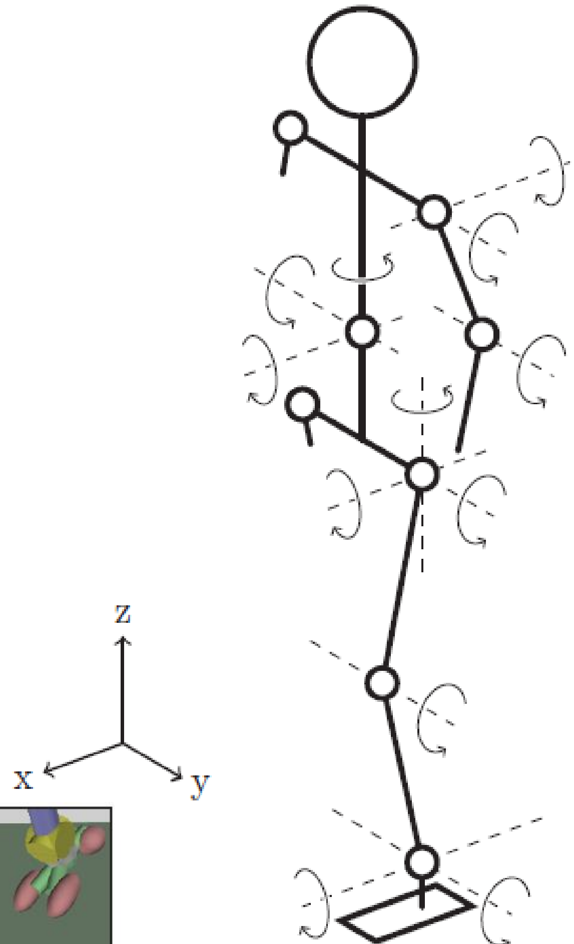


Functional morphology
- Mass distribution
- Geometry of trunk and extremities
- Low resistant elastic actuator

Exploitation of inherent dynamics

Mechanical Model of the Bipedal Robot





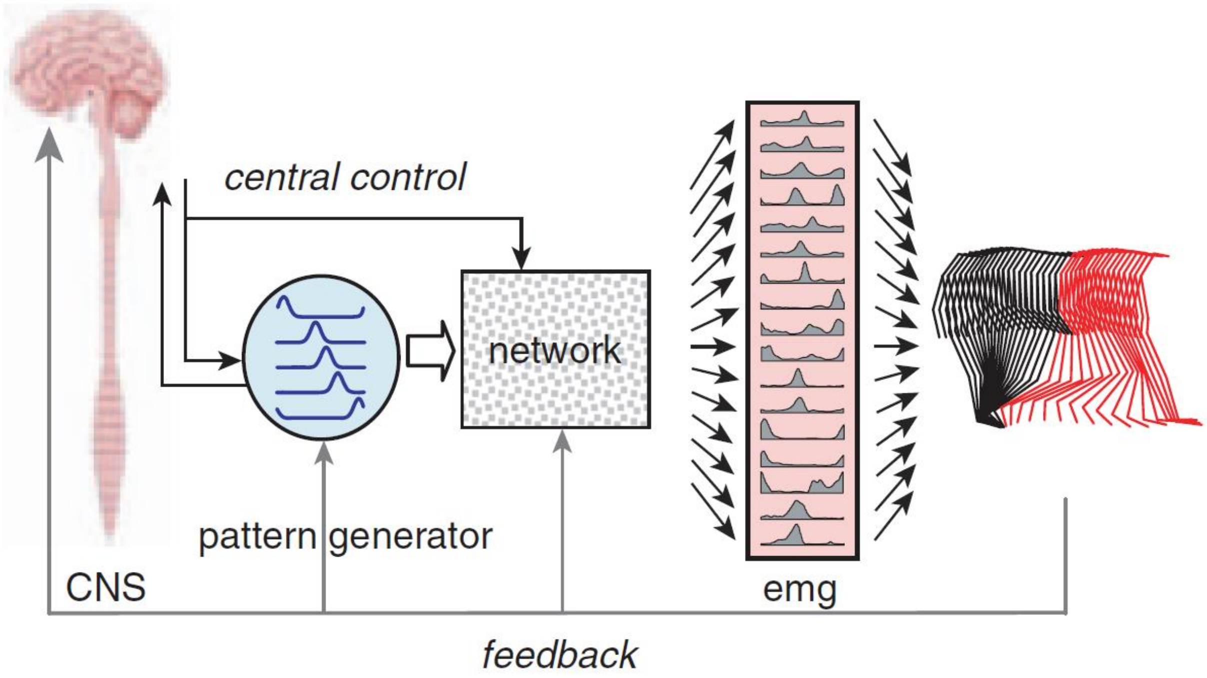
- Anthropomorphic biped
  - mass distribution
  - segment length
- Weight 76kg
- Height 1.8m
- DOF 21
  - 6 DoF per leg
  - 3 DoF spine
  - 3 DoF per arm
- Physics simulation environment - Newton

Mechanical Parameters of the Simulated Biped

Joint	min. angle [rad]	max. angle [rad]	max. torque [Nm]
Spine X	-1.0	1.0	180
Spine Y	-1.0	1.0	180
Spine Z	-1.0	1.0	100
Shoulder X left	0.0	2.0	80
Shoulder X right	-2.0	0.0	80
Shoulder Y	-1.0	1.0	80
Elbow Y	-2.0	0.0	30
Hip X	-1.0	1.0	220
Hip Y	-0.85	0.15	220
Hip Z	-1.0	1.0	150
Knee Y	0.0	2.0	150
Ankle X	-0.5	0.5	80
Ankle Y	-0.5	0.5	150

Hierarchical Layout of Motion Control

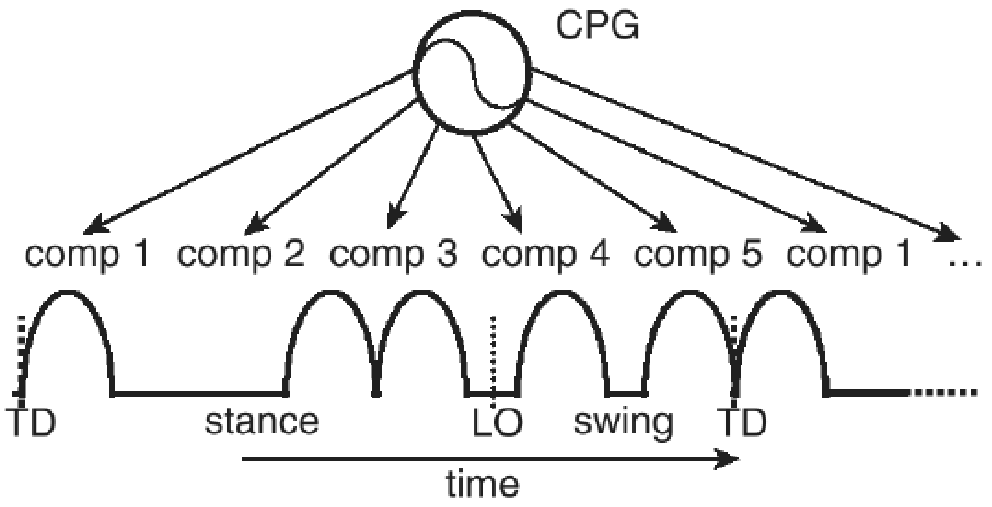
[Y.P. Ivanenko et al., Motor control programs and walking, The Neuroscientist, 12(4), 339–348, 2006]



- Hierachical control concept
- Movement based on synergies and
- Refelexes (modulated by intensity of stimulus)

Phases of Walking

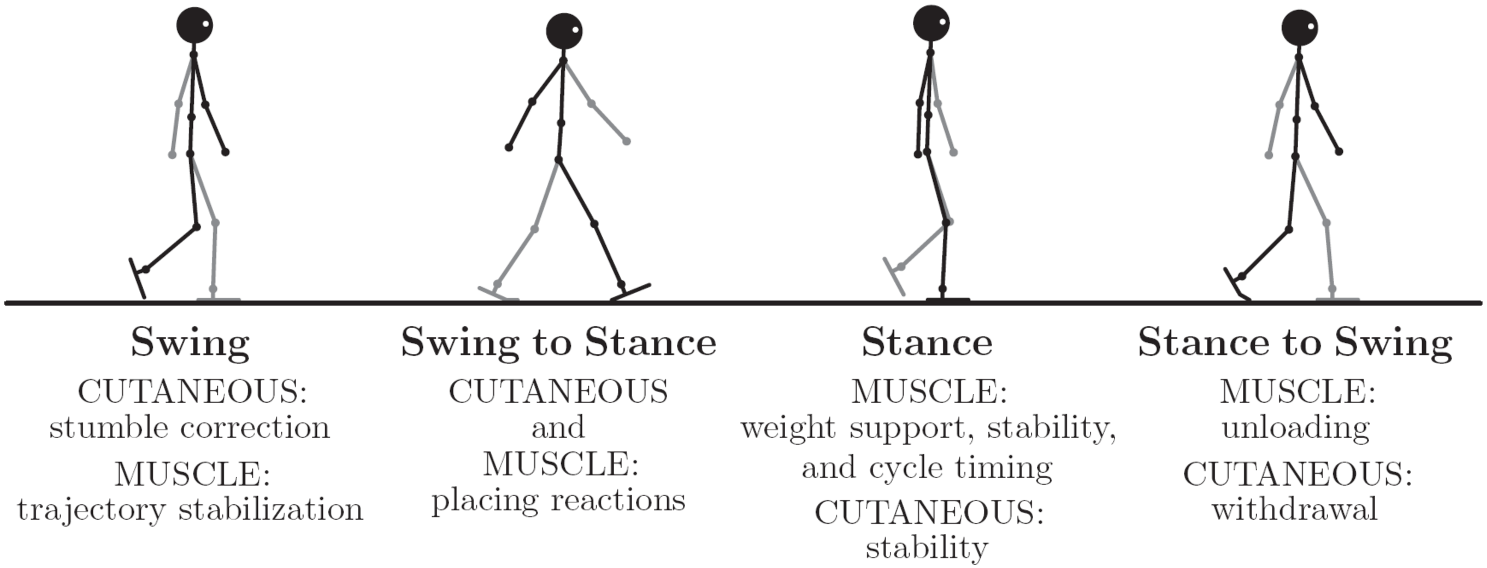
(1) weight acceptance
(2) loading or propulsion
(3) trunk stabilization
during double support
(4) toe lift-off
(5) heel strike



- Fixed sequence of walking phases
- Weighting and scaling dependent on walking speed

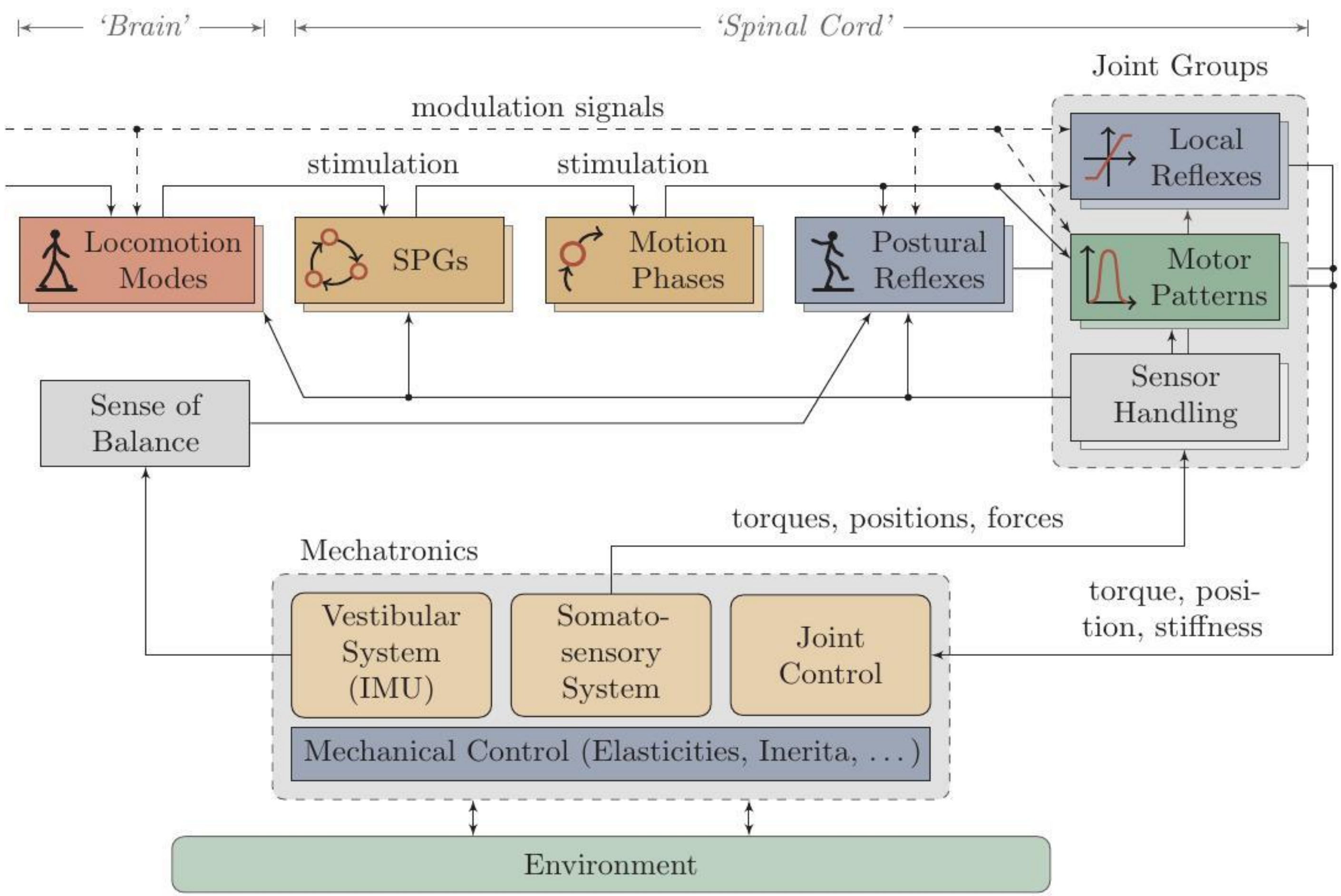
Reflex Function during Walking

Function of stretch reflex, load receptor reflexes and cutaneous reflexes during locomotion [Zehr 99].



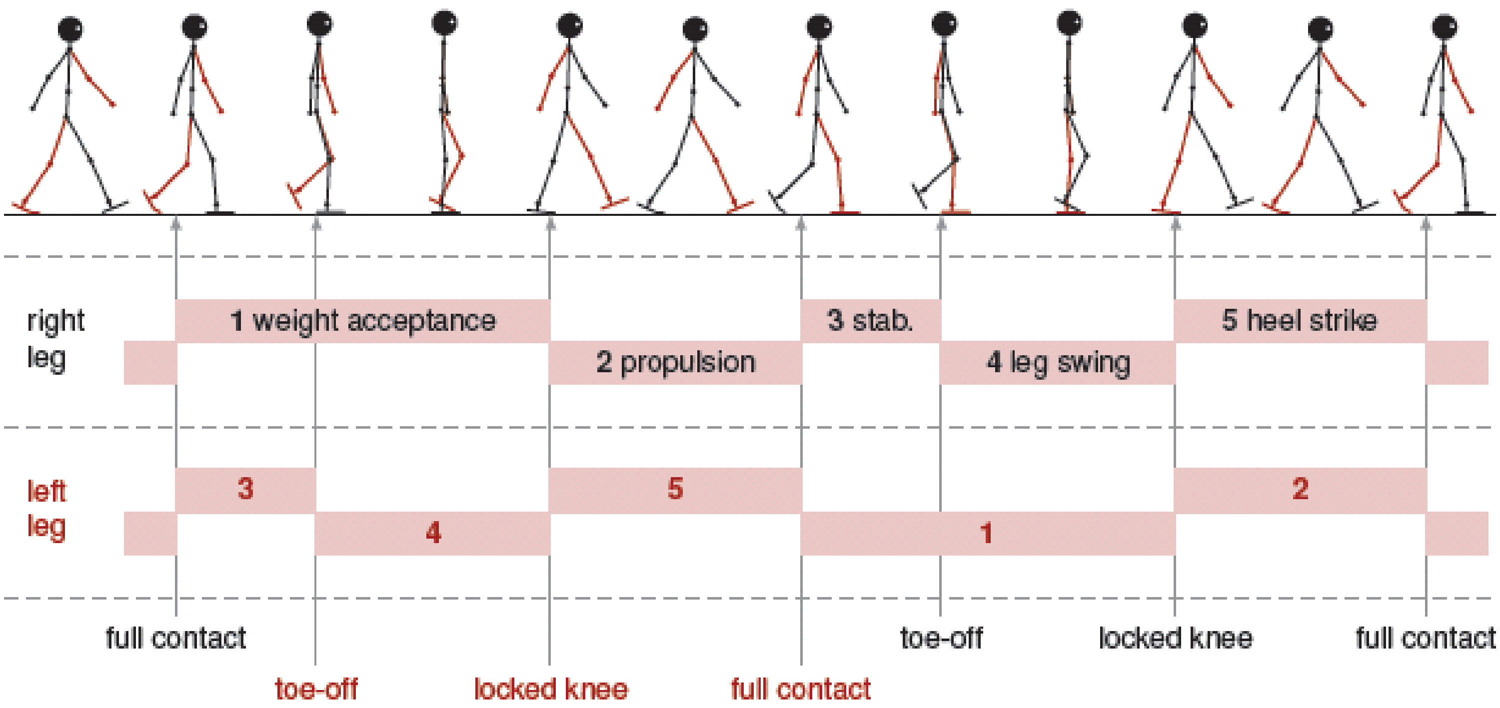
Stabilisation of Walking based on reflexes in different phases

Behavior-Based Bio-inspired Bipedal Locomotion

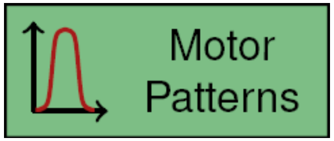


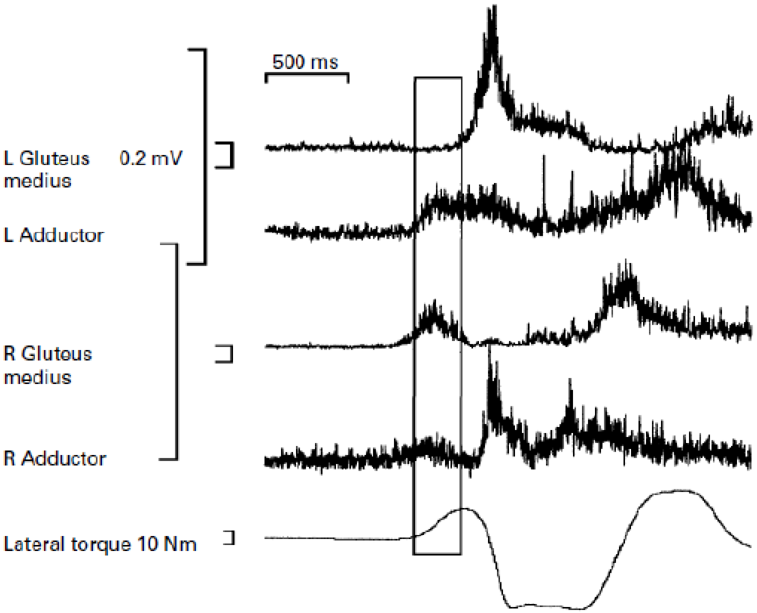
Human-like Walking Phases

- Five walking phases (see Lacquaniti et al.)
- Transitions triggered by sensor events
- Bilateral synchronization → robust state switches



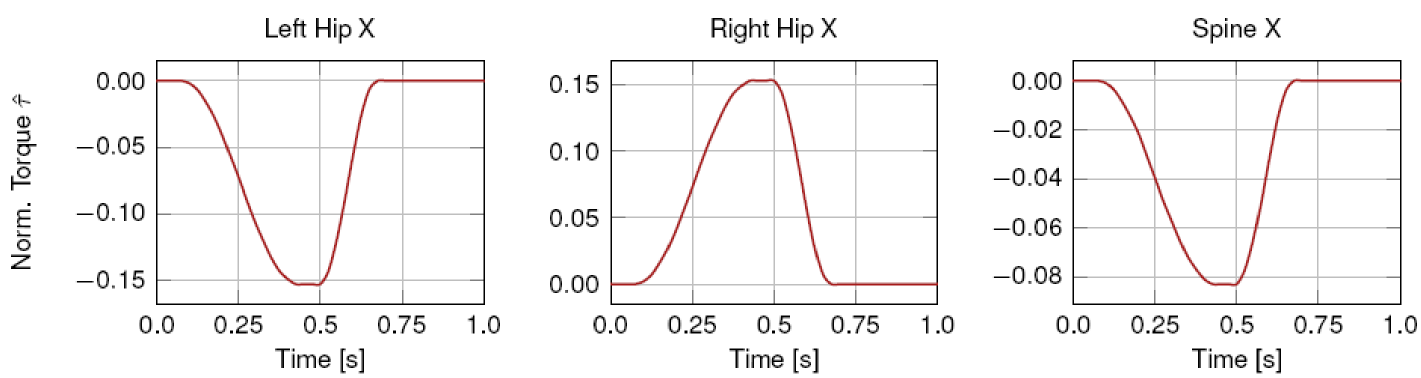
Example: Initiation of Walking





- How to take weight from swing leg?
- Analyse EMG from walking initiation
- Introduce new motor pattern and trigger it during initiation phase
- Let passive dynamics do the rest
- Ground reaction forces and angles comparable to human data

[S.G.B. Kirker et al., *Stepping before standing*, J. Neur

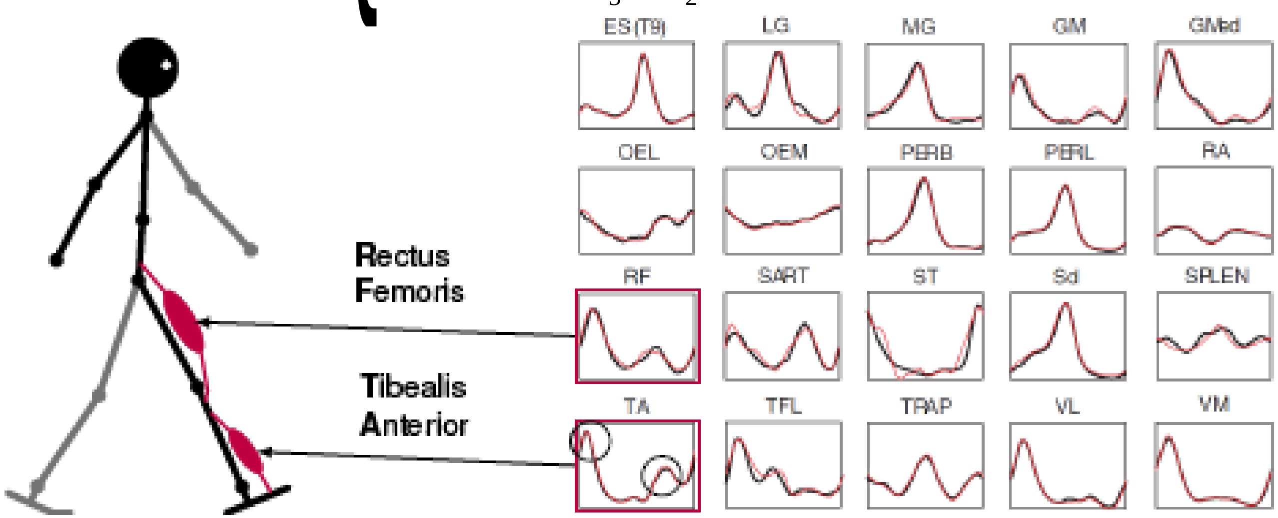


Design of Motor Patterns

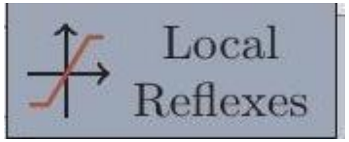
Motor Patterns

- Motor patterns shape passive dynamics (feed-forward control)
- Analysis of muscle activities, kinematical, and kinetic data: derive motor patterns (and other control units)
- Same parametrized equation for all motor patterns:

$$\hat{\tau} = \tau_{max} \begin{cases} \frac{1}{2} + \frac{1}{2}\sin\left(\pi\left(\frac{t}{T_1} - \frac{1}{2}\right)\right) & 0 \leq t < T_1 \\ 1 & T_1 \leq t < T_2 \\ \frac{1}{2} - \frac{1}{2}\sin\left(\pi\left(\frac{t-T_2}{T_3 - T_2} - \frac{1}{2}\right)\right) & T_2 \leq t \leq T_3 \end{cases}$$



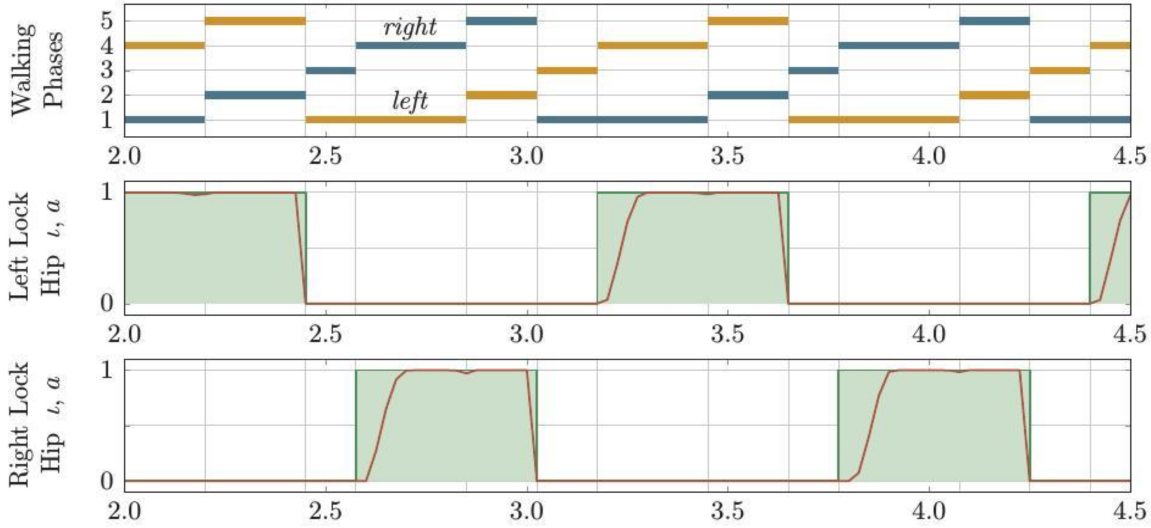
Feedback Local Reflexes



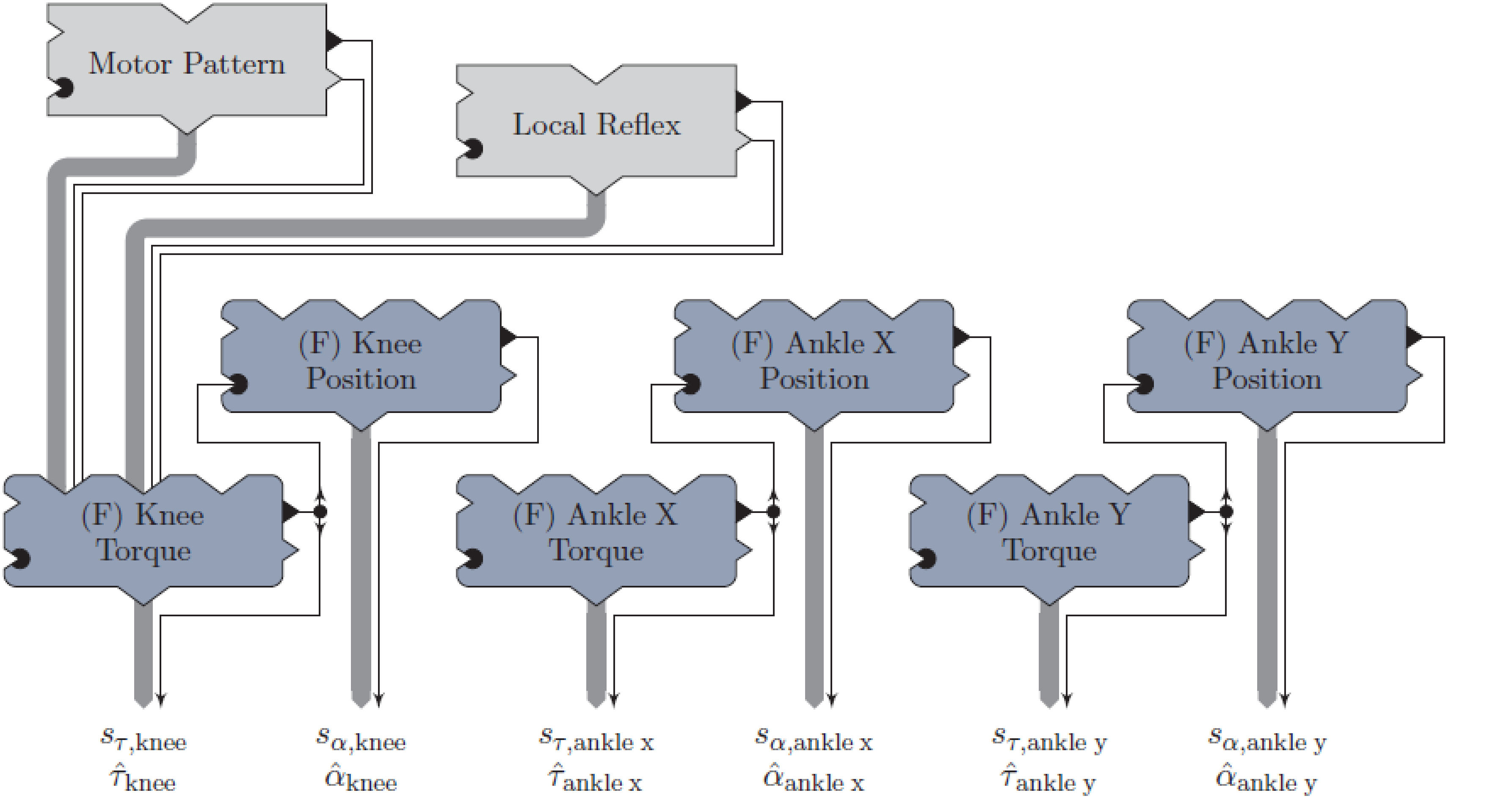
- Tight coupling between sensor information and motor action
- Linear/nonlinear relation between sensor data and control output
- Event-based control
- Example: Lock Hip
  - Active when hip angle approaches target position, generate braking torque

$$\hat{\tau}_{lp} = -\omega_{leg} \cdot K_{torque}$$

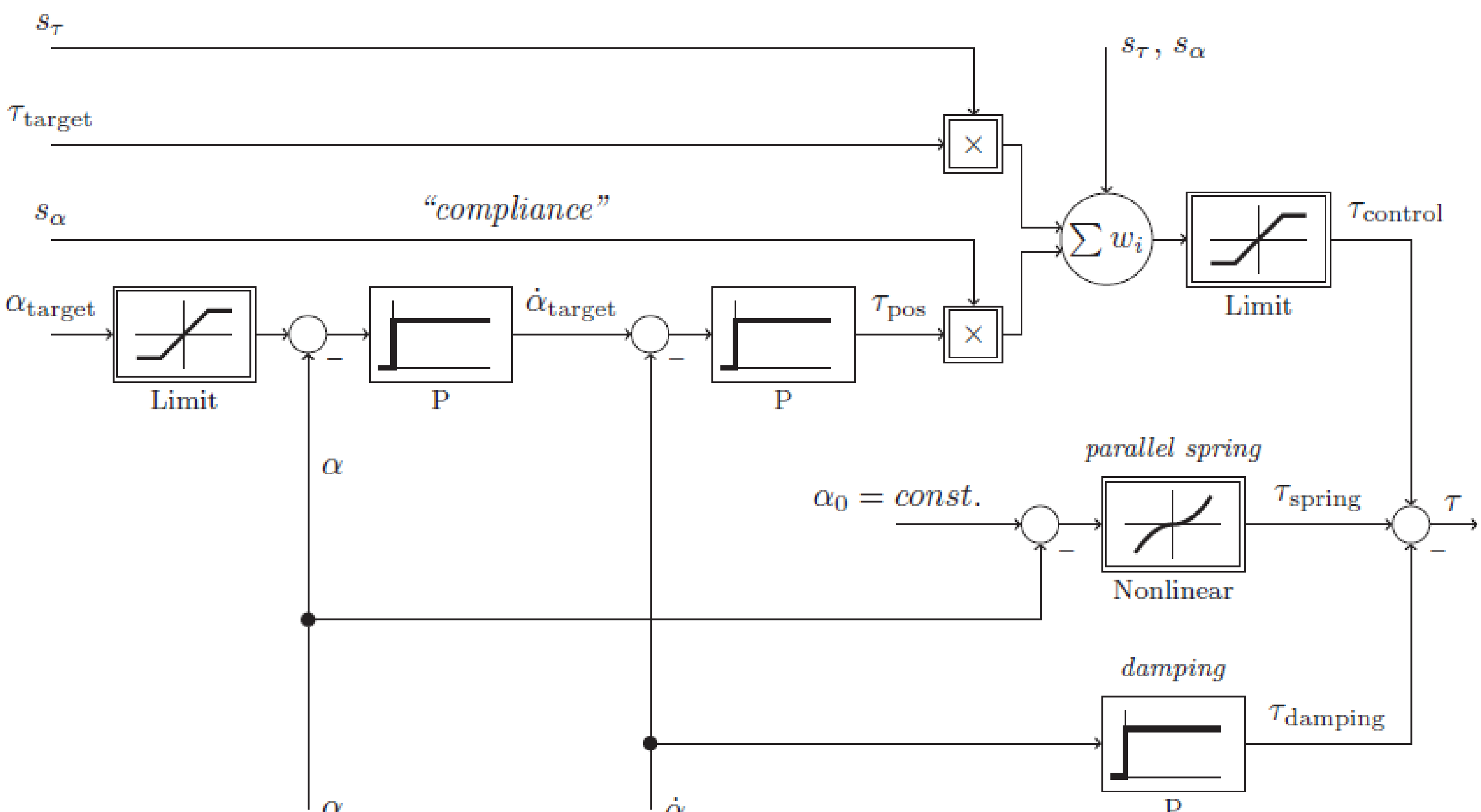
  - Until rotation velocity is 0, hold leg in target position $\hat{\alpha}_{lp}$ for preparation of heel strike



Implementation of lowest Level of Control



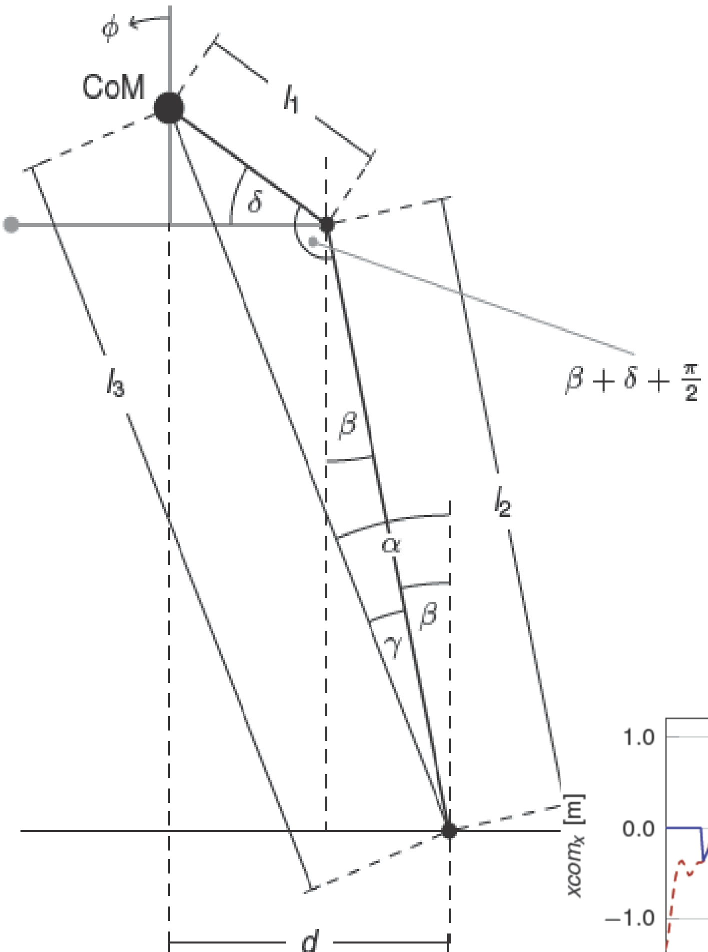
Control Block Diagram



$$\tau_{\text{control}} = \frac{s_\tau(\tau_{\text{target}} s_\tau) + s_\alpha(\tau_{\text{pos}} s_\alpha)}{s_\tau + s_\alpha}$$

$$\tau_{\text{spring}} = \operatorname{sgn}(\alpha_0 - \alpha) \cdot K_{\text{spring}} \cdot (\alpha_0 - \alpha)^2.$$

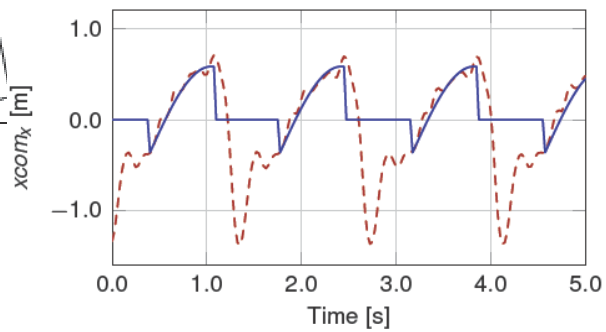
Postural Control is Supraspinal

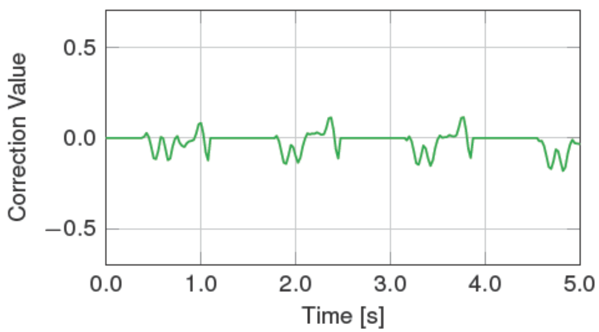


- [Hof 08]: postural control based on extended center of mass (XcoM)

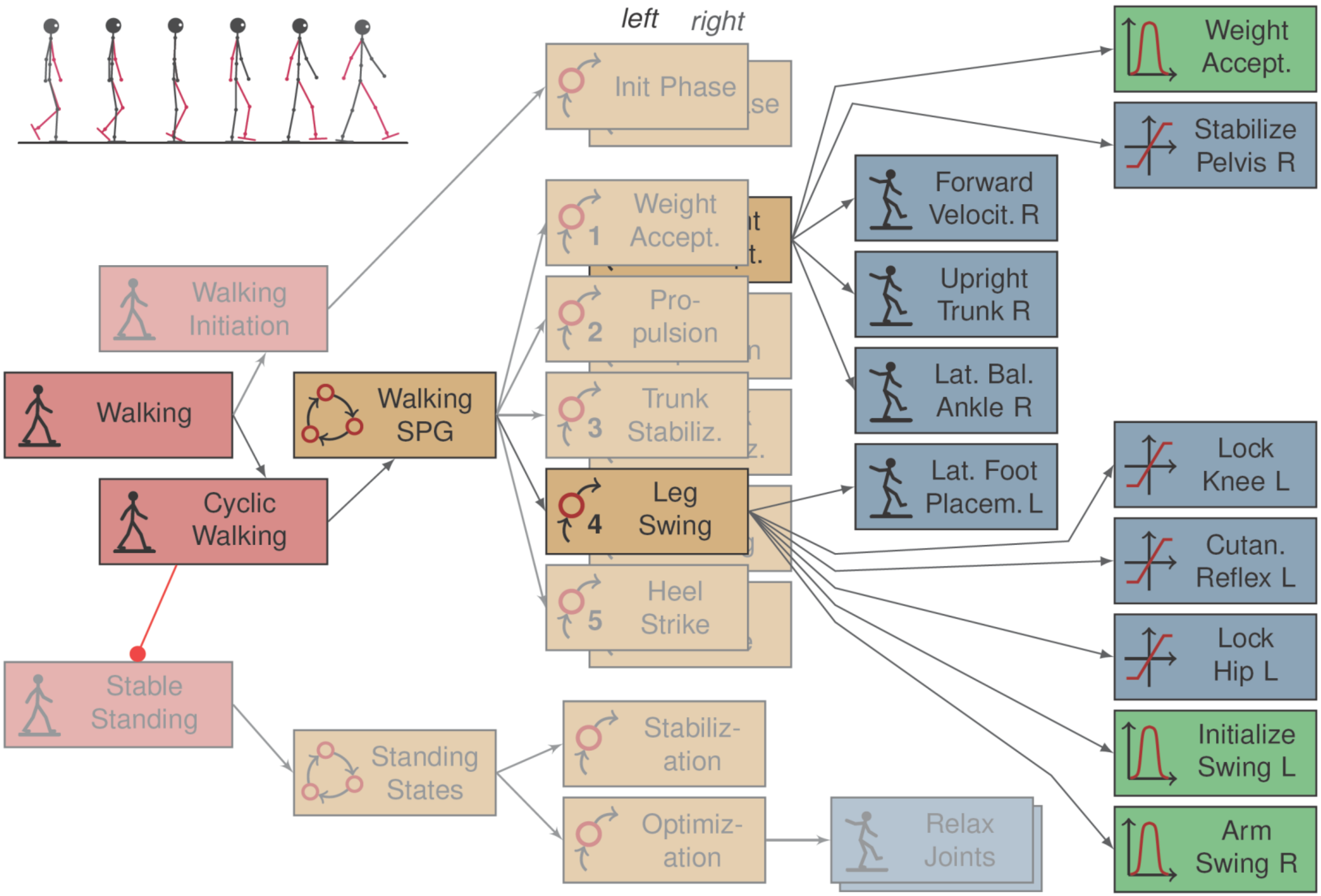
$$Xcom = d + \frac{\dot{d}}{\omega_0}$$

- For each leg and each direction (frontal and sagittal plane)
- Postural reflexes: Upright Trunk, Forward Velocity, Lateral Balance Ankle, Lateral Foot Placement
- Approximation of XcoM trajectory
- Derivation results in reflex action

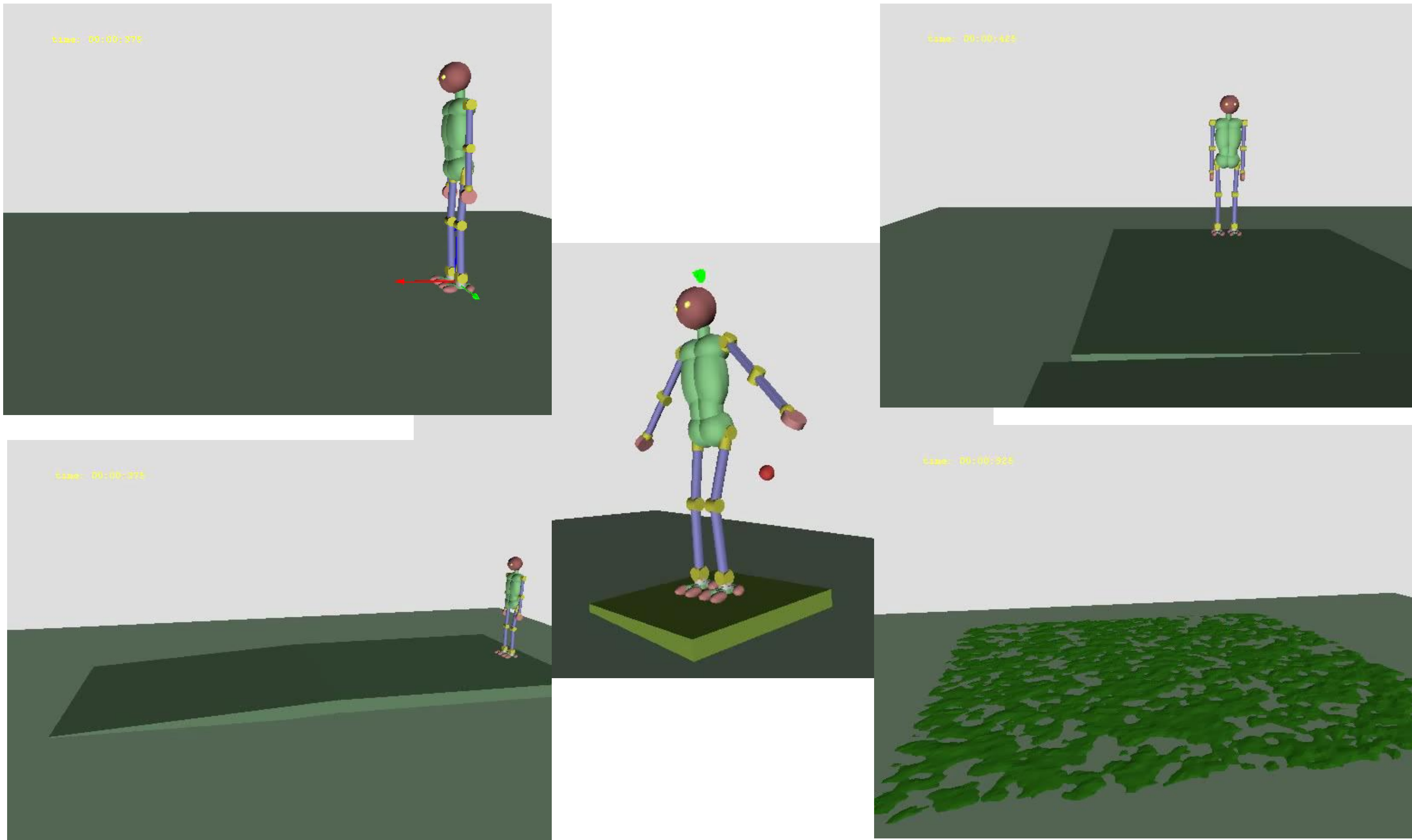




Example: Network during Walking Phases 4/1

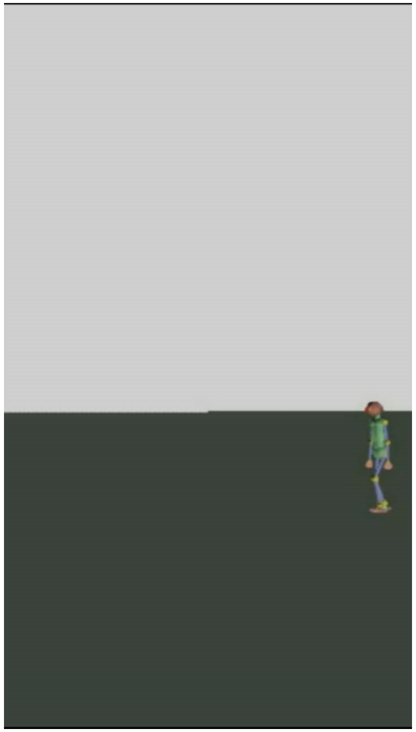


First Results

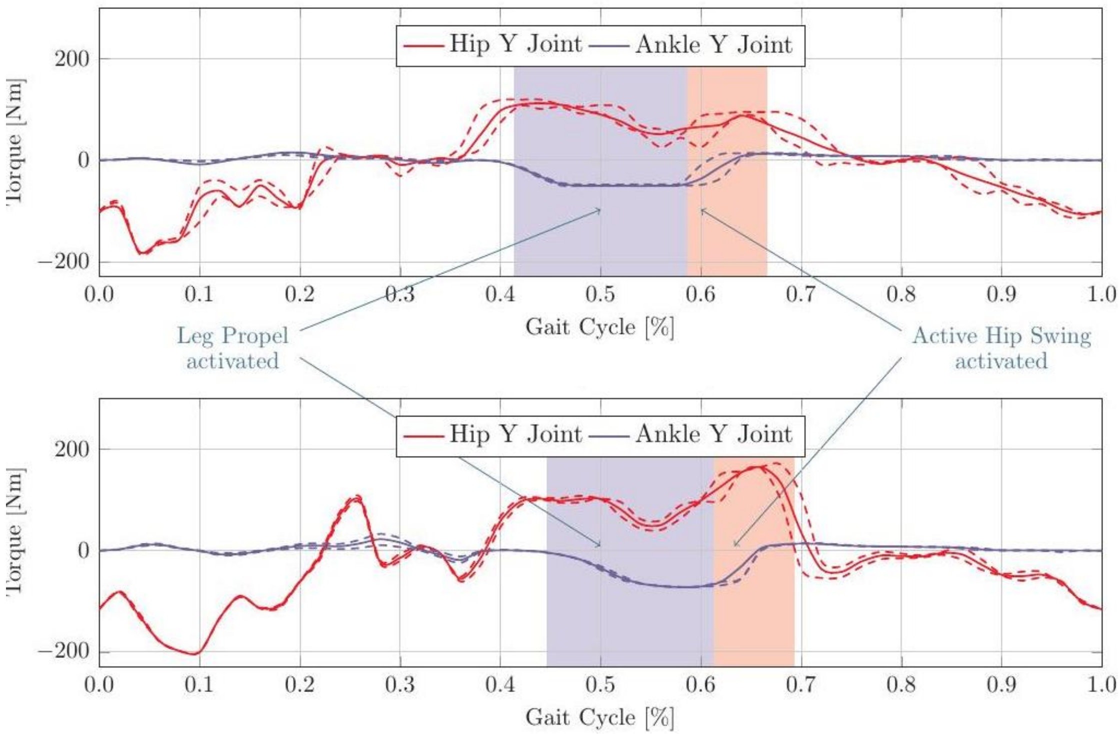


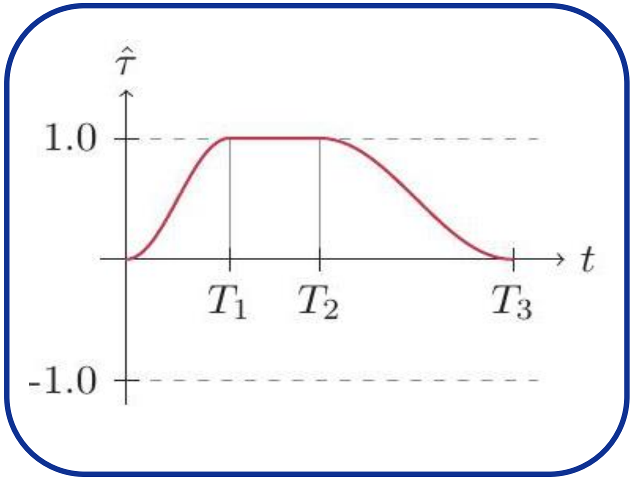
Problems of B4LC System

- Not optimized in current locomotion skills
  - Energy consumption
  - Velocity control
  - Stability
- Not adaptive to more challenging disturbances
  - Rough terrains
  - Large obstacles
  - Stairs
  - Slopes



Optimization of Motor Patterns





$$\hat{\tau} = A * \begin{cases} \frac{1}{2} + \frac{1}{2}\sin\left(\pi\left(\frac{t}{T_1} + \frac{1}{2}\right)\right) & 0 \le t \le T_2 \\ 1 & T_1 \le t \le T_2 \\ \frac{1}{2} - \frac{1}{2}\sin\left(\pi\left(\frac{t-T_2}{T_3-T_2} - \frac{1}{2}\right)\right) & T_2 \le t \le T_3 \end{cases}$$

T_1 the starting time of maximum torque
T_2 the ending time of maximum torque
T_3 the total time of torque command

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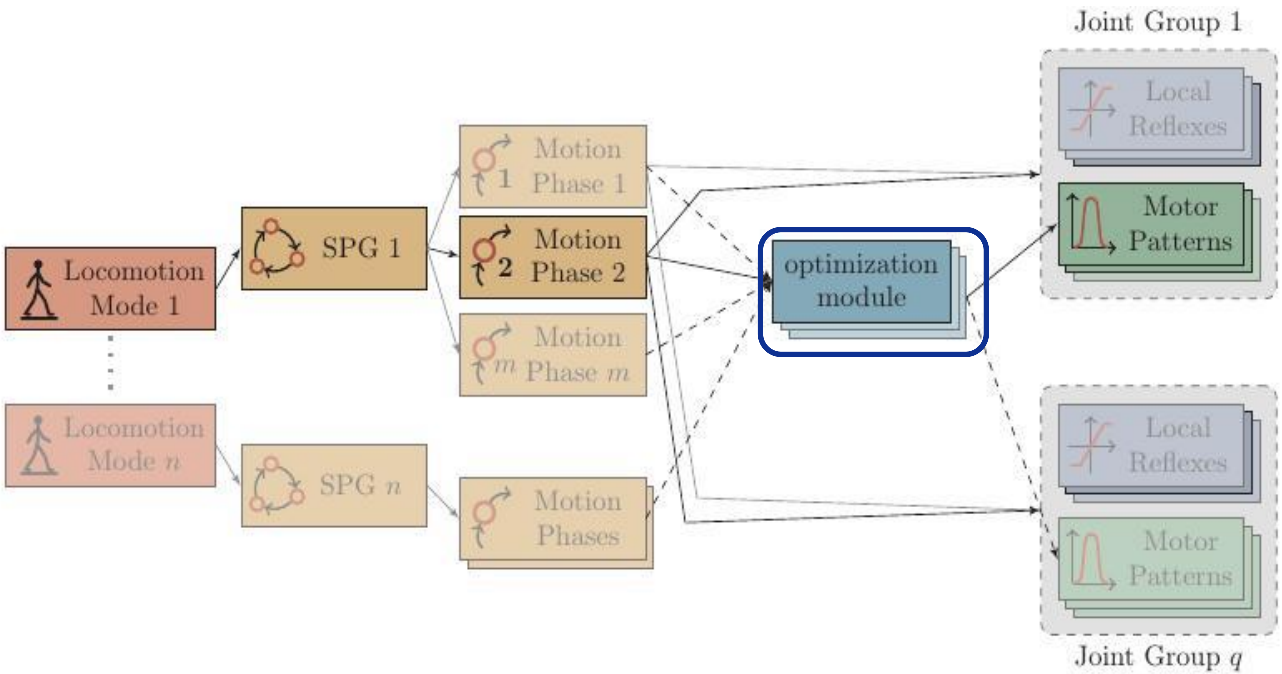
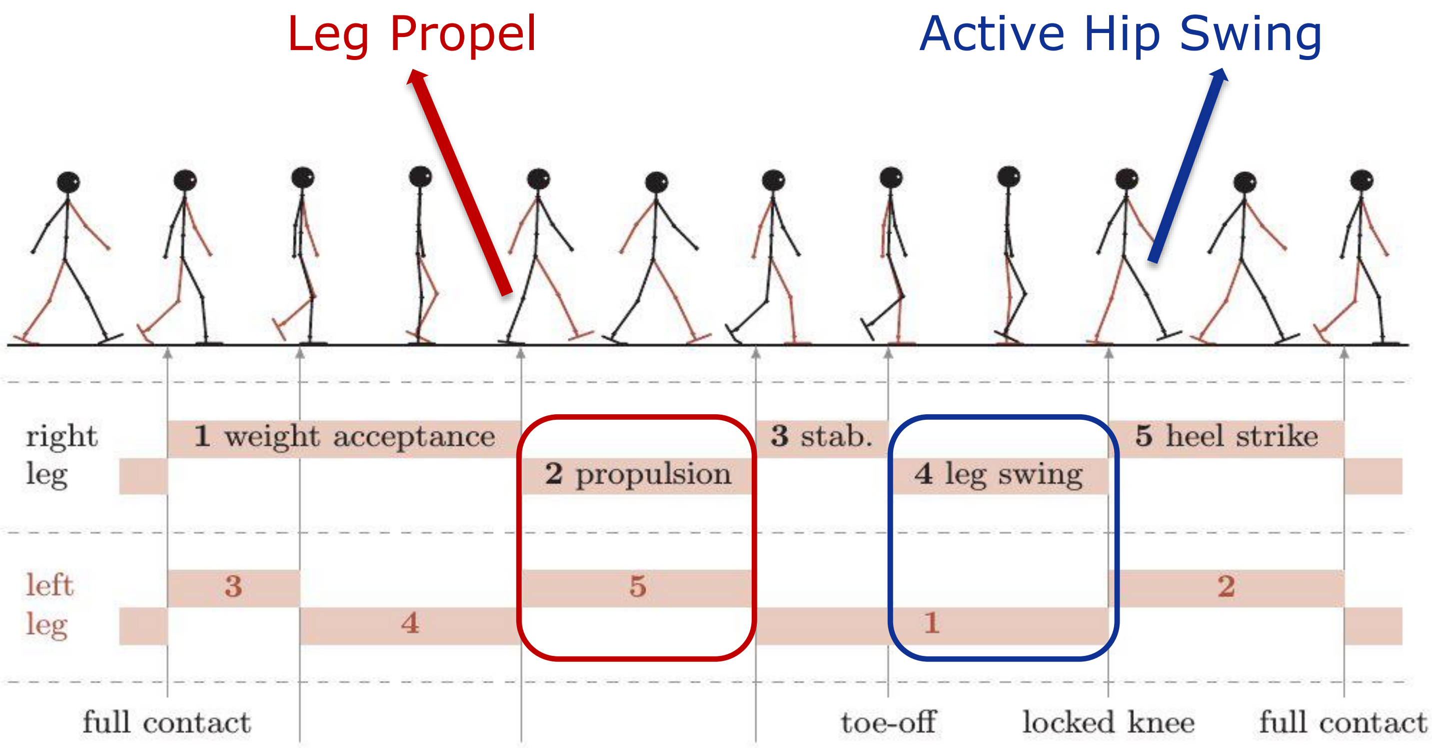
Optimization Methodology

- Optimization module using Particle Swarm Optimization
- Parameter values are calculated until the desired fitness functions are obtained



Example: Optimization on Even Ground

- Optimization for **energy consumption, locomotion stability, and walking speed**



Example: Optimization on Even Ground

- Fitness functions:

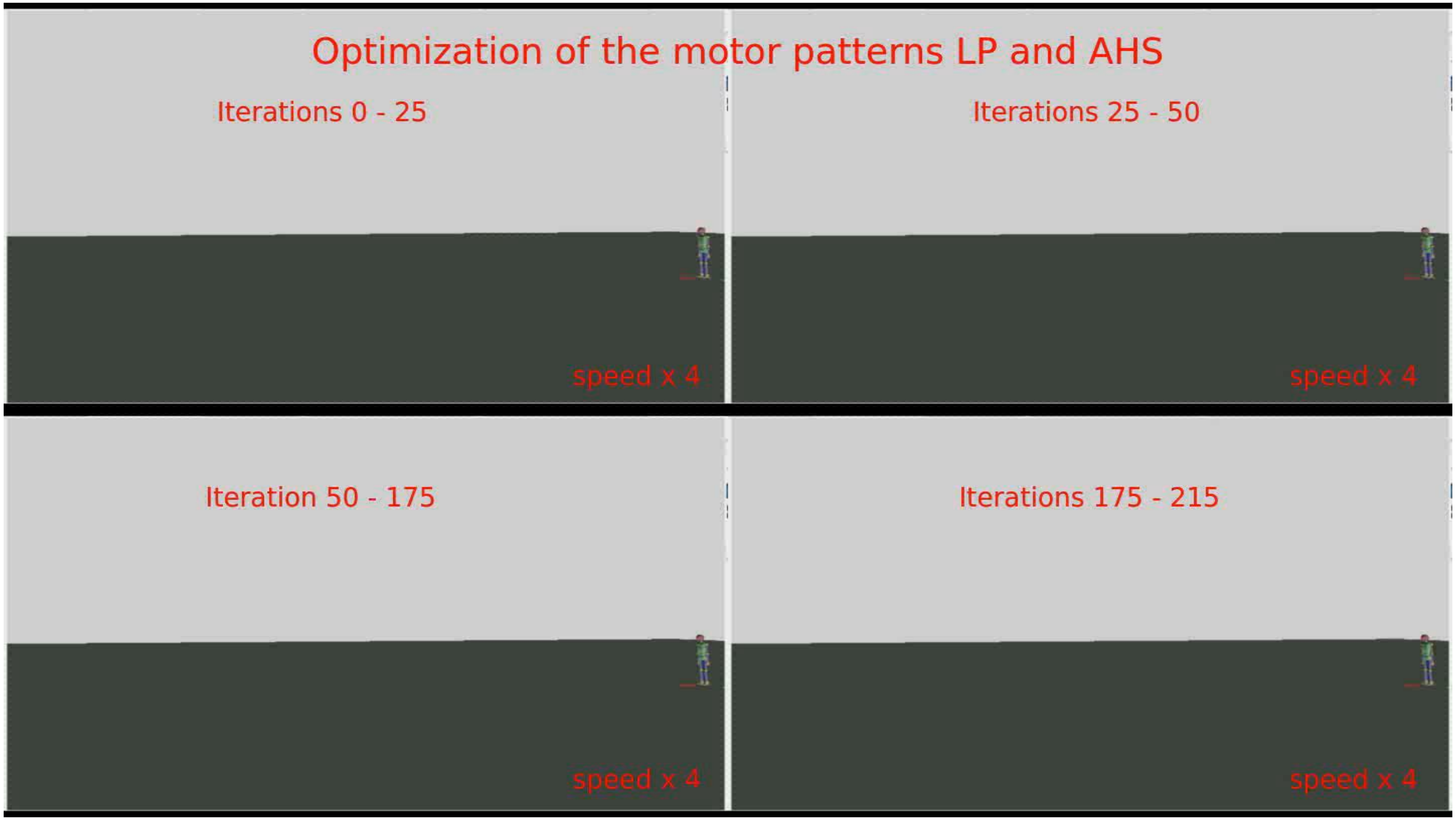
$$f_1 = s_w$$ ← Robustness

$$f_2 = \sum_{i=0}^{T} \Delta Xcom_i / s_w$$ ← Stability

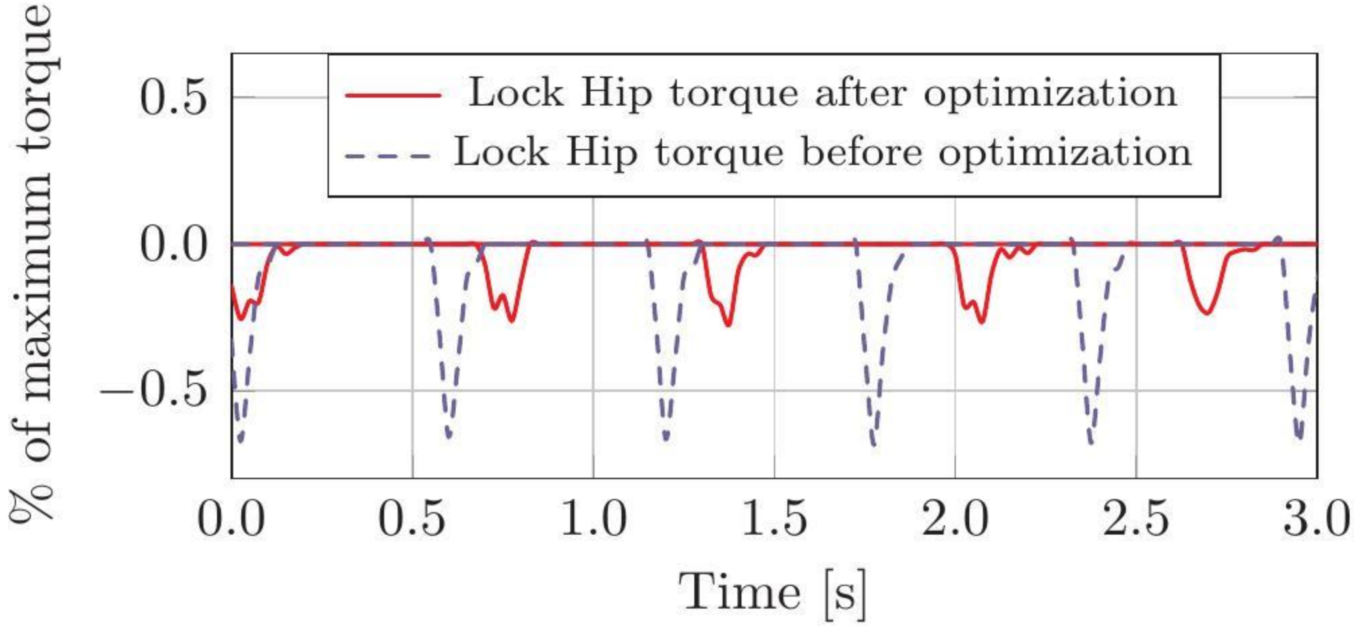
$$f_3 = \sum_{i=0}^{T} |(V_{ref} - V_i)|^2 / T$$ ← walking speed control

$$f_4 = \sum_{i=0}^{T} \tau_i^h / T$$ ← energy consumption

Example: Optimization on Even Ground



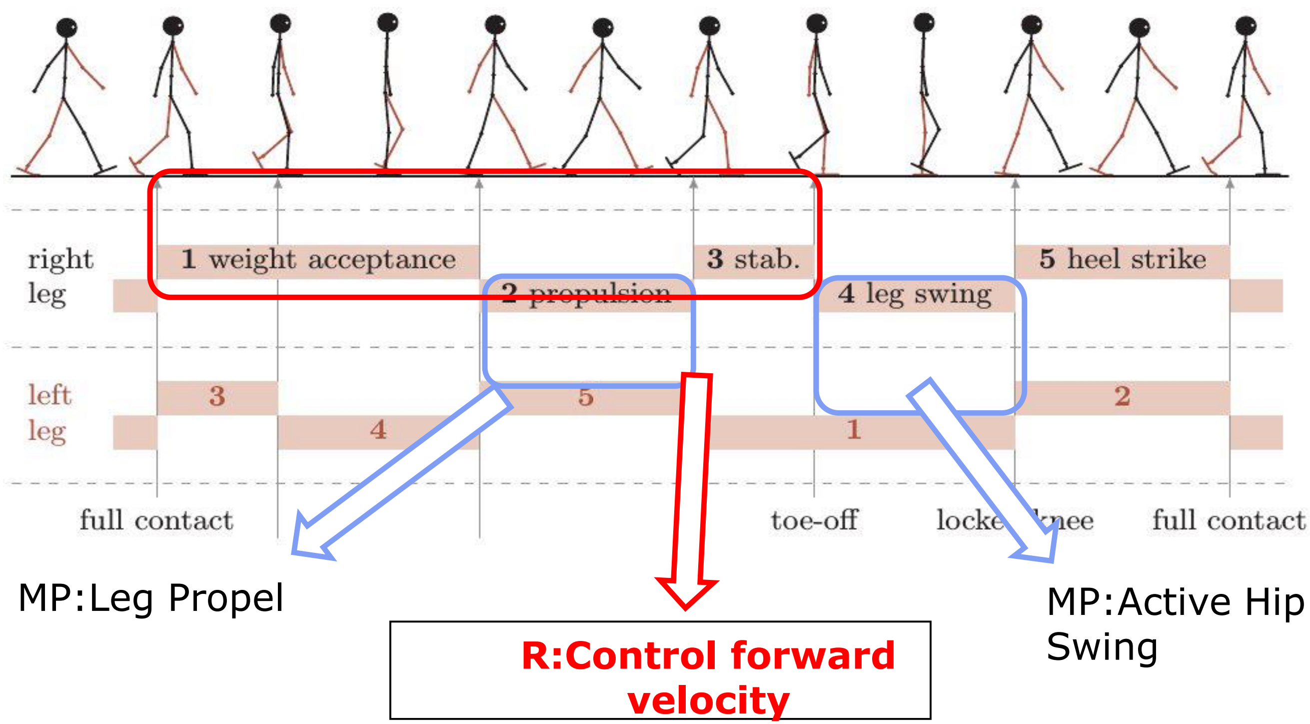
Example: Optimization on Even Ground



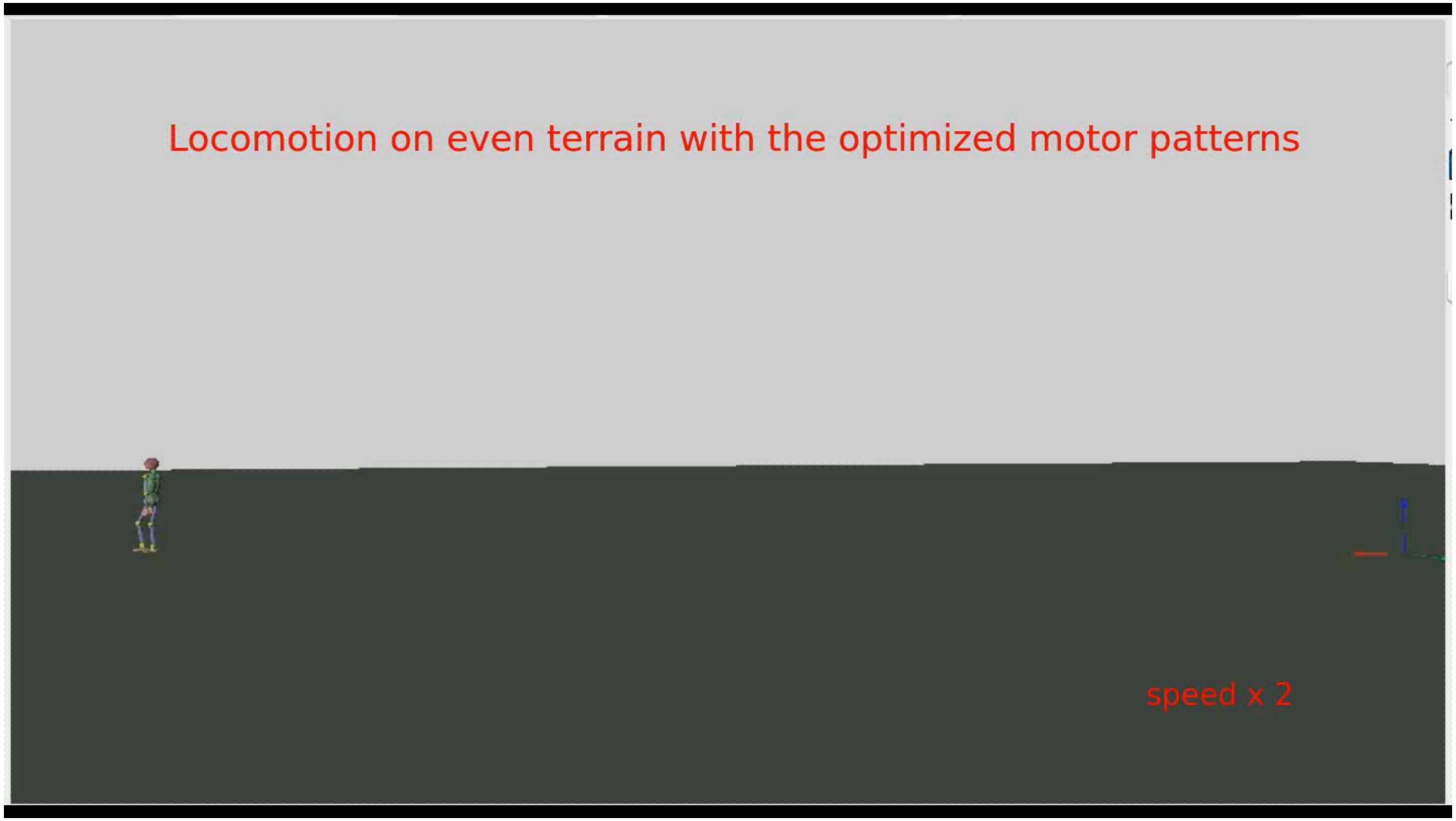
	Accumulated joint torques during one cycle		Velocity deviation during 10 seconds (%)	Accumulated $\Delta Xcom$ during one cycle(m)
	ankle (Nm)	hip (Nm)		
Before	3842.2	746.3	8.3	2.721
After	3142.1	657.9	0.04	1.232
Improvement	18.22%	11.83%	8.26	1.489

RL for Reflexes - Locomotion on Uneven Ground

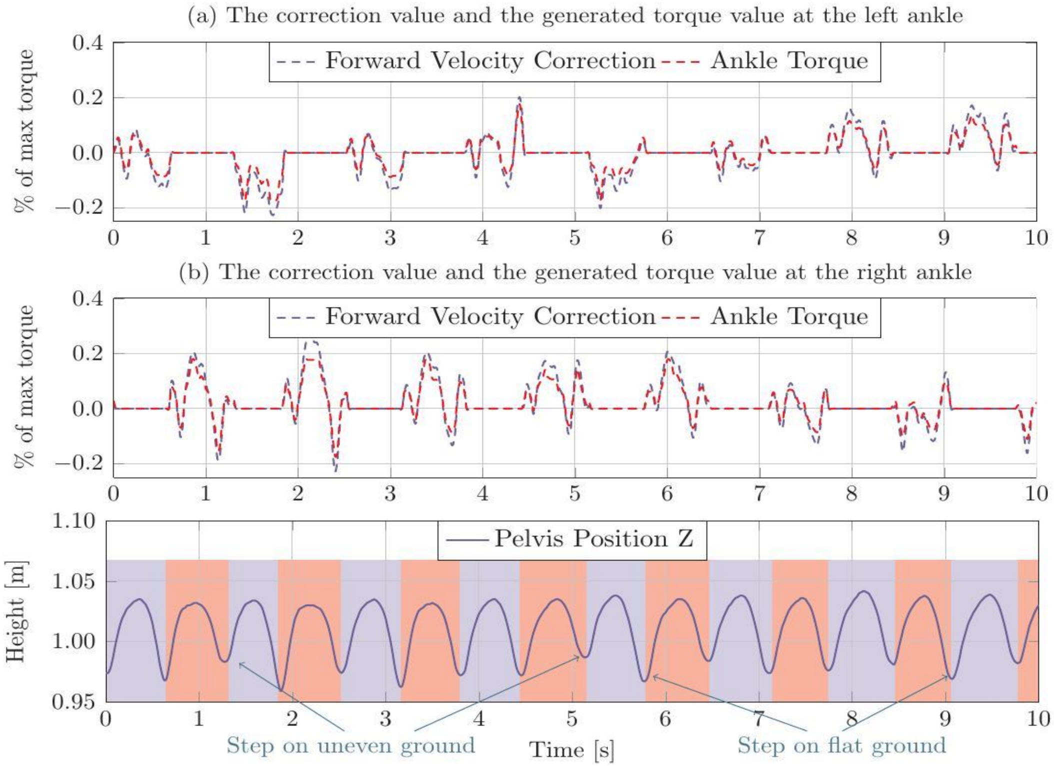
- Reflexes (R:Control Forward Velocity) produce compensating torques at ankle joints to reject disturbances



Example: Locomotion on Uneven Ground



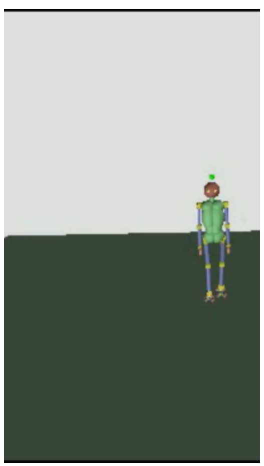
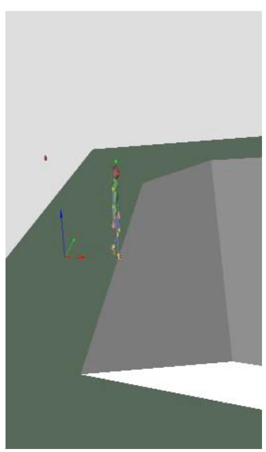
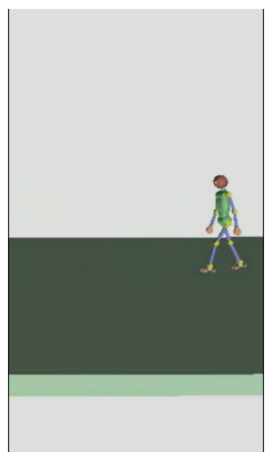
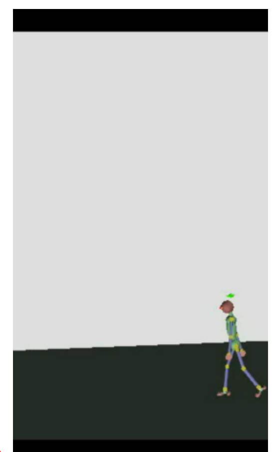
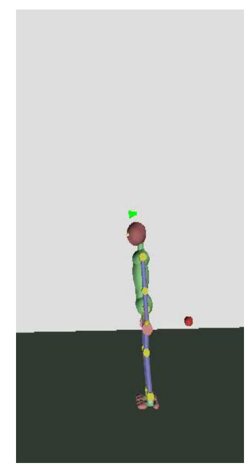
Example: Optimization on Uneven Ground



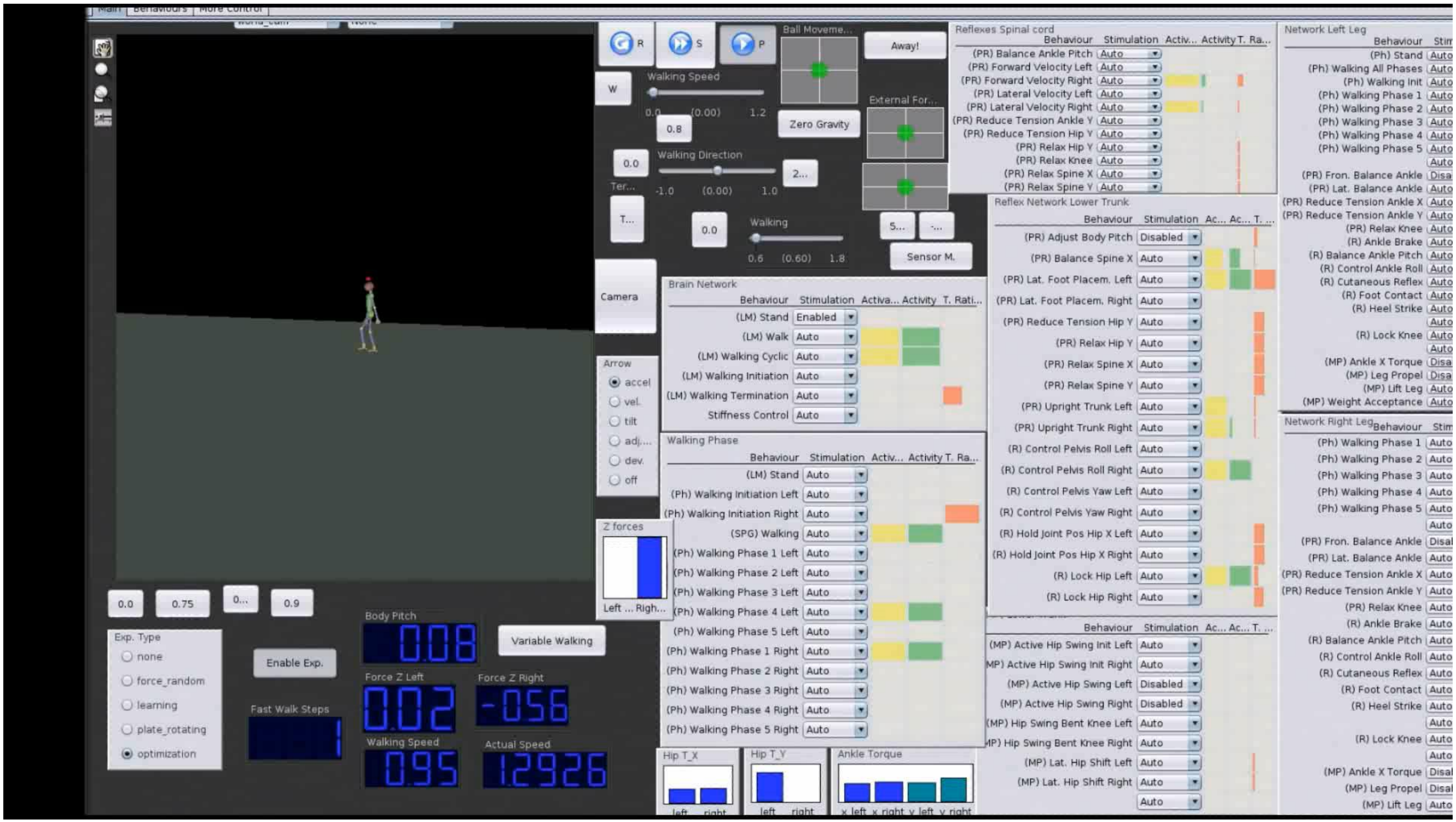
	Accumulated $\Delta Xcom$ during one cycle (m)	Accumulated compensation torque (Nm)
Before	3.586	940.3
after	3.198	855.4
improvement	0.388	9.02%

B4LC based Advanced Walking Skills

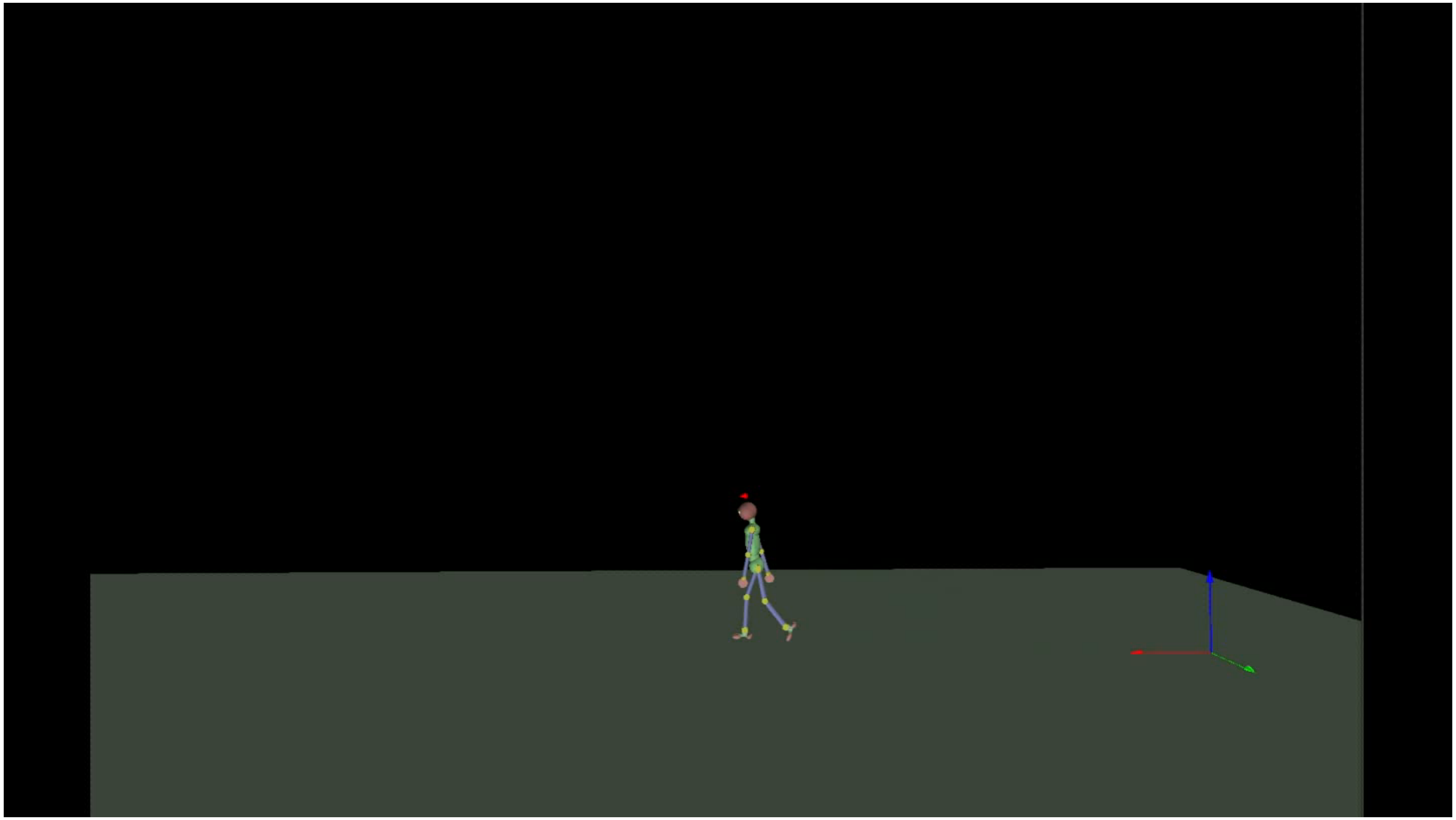
B4LC system

Curve walking	Upslope walking	Speed control	Push recovery	Push recovery standing	Walking Termination
					

Various Speed Locomotion

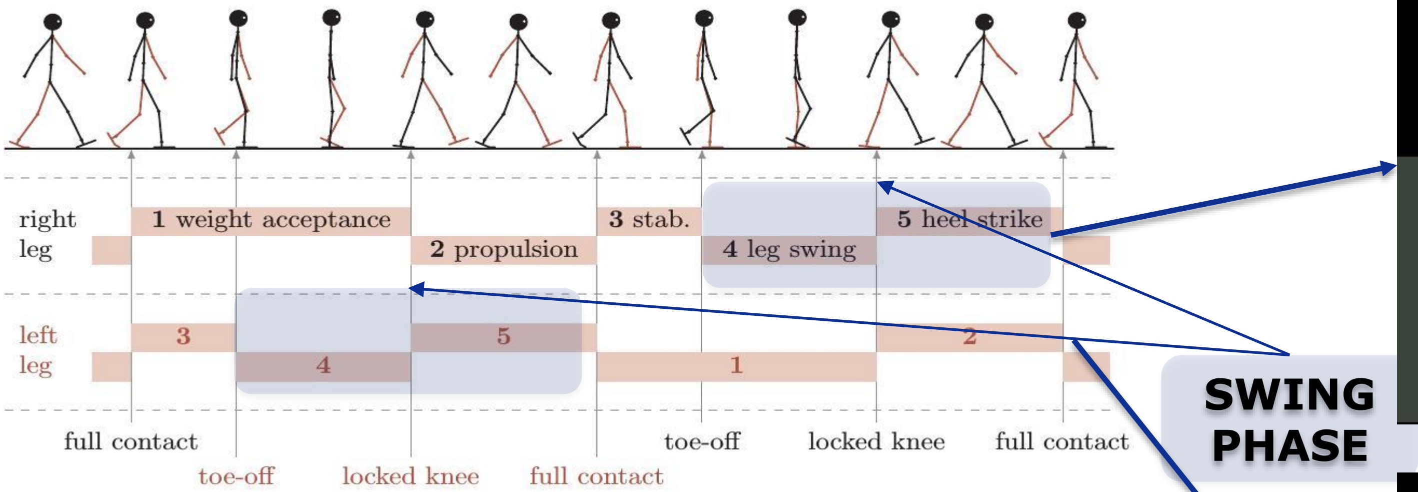


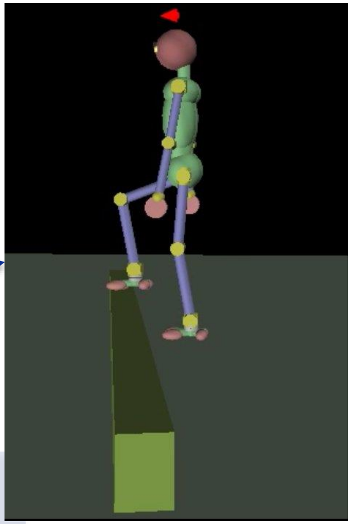
Push Recovery Locomotion

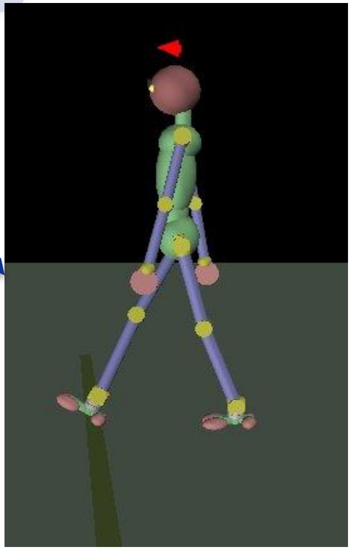


Locomotion without push recovery and with push recovery
F = 300 N

Stepping over Obstacle Locomotion



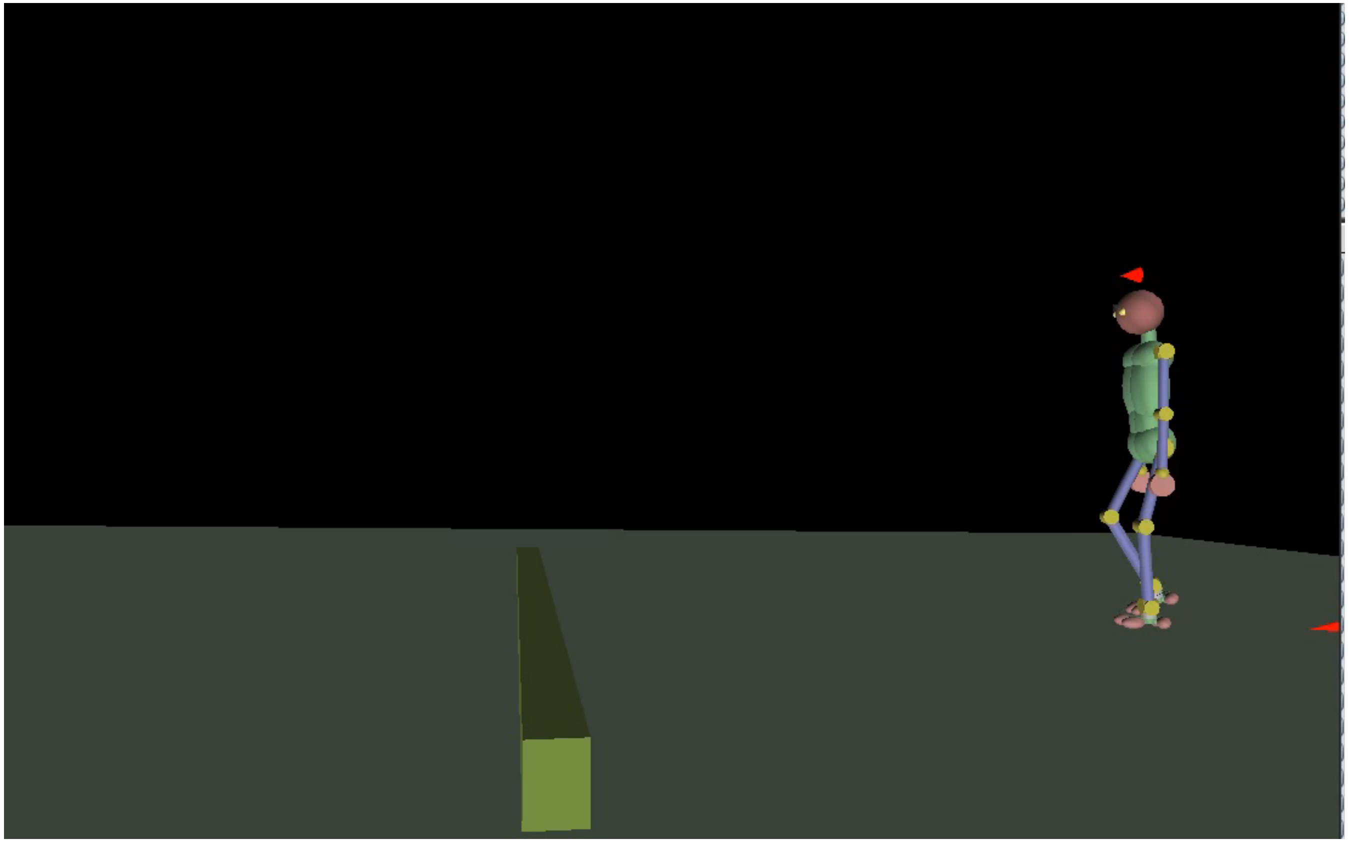




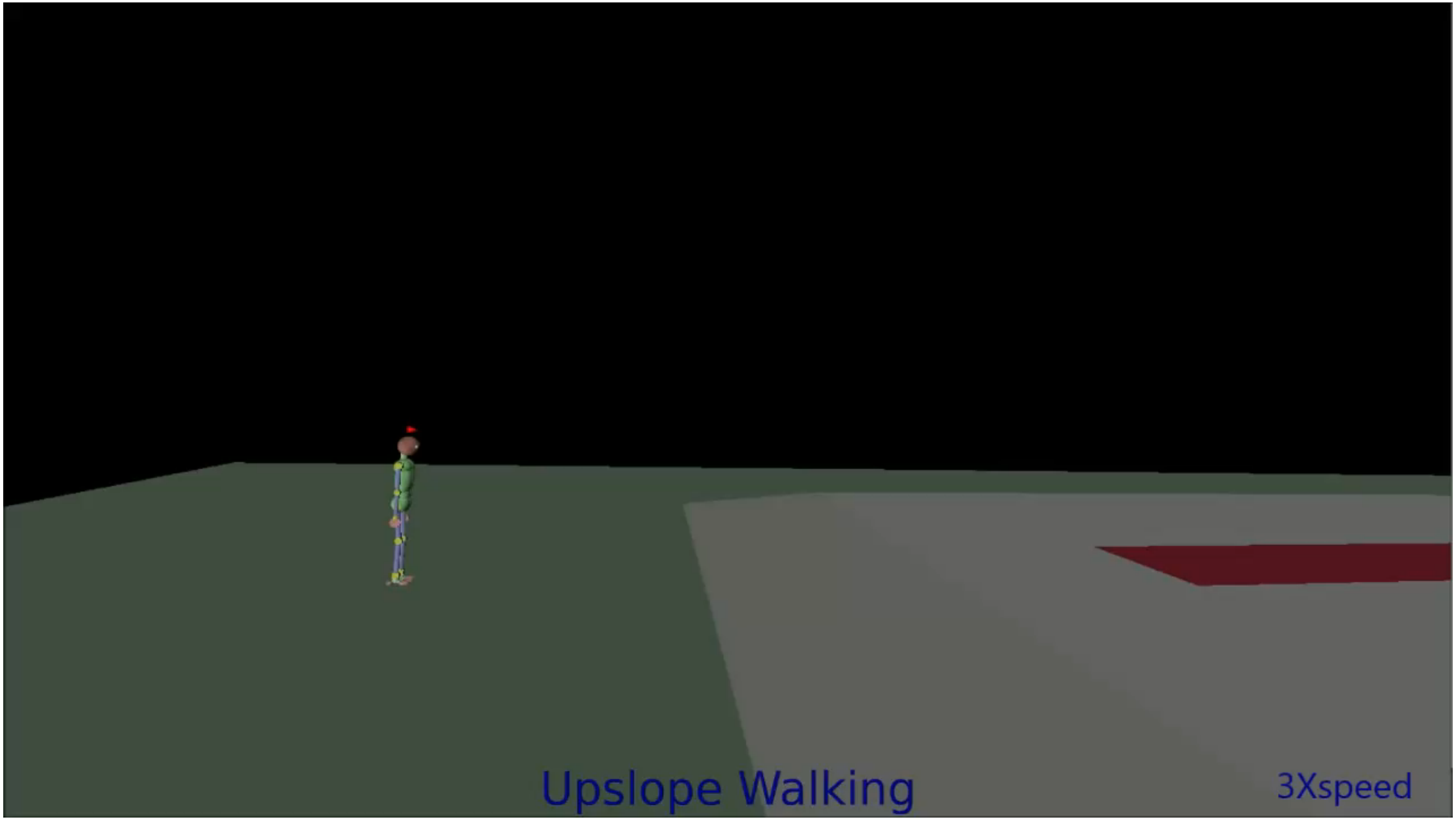
- The control units at the hip and knee joints are refined
  - Hip joint movement, e.g. motor pattern Active leg swing, reflexes Lock hip
  - Knee joint movement, e.g. reflexes Knee flexion

Stepping over Obstacle Locomotion

- Using PSO to search the parameters of 8 parameters
- 20cm height and 15cm width



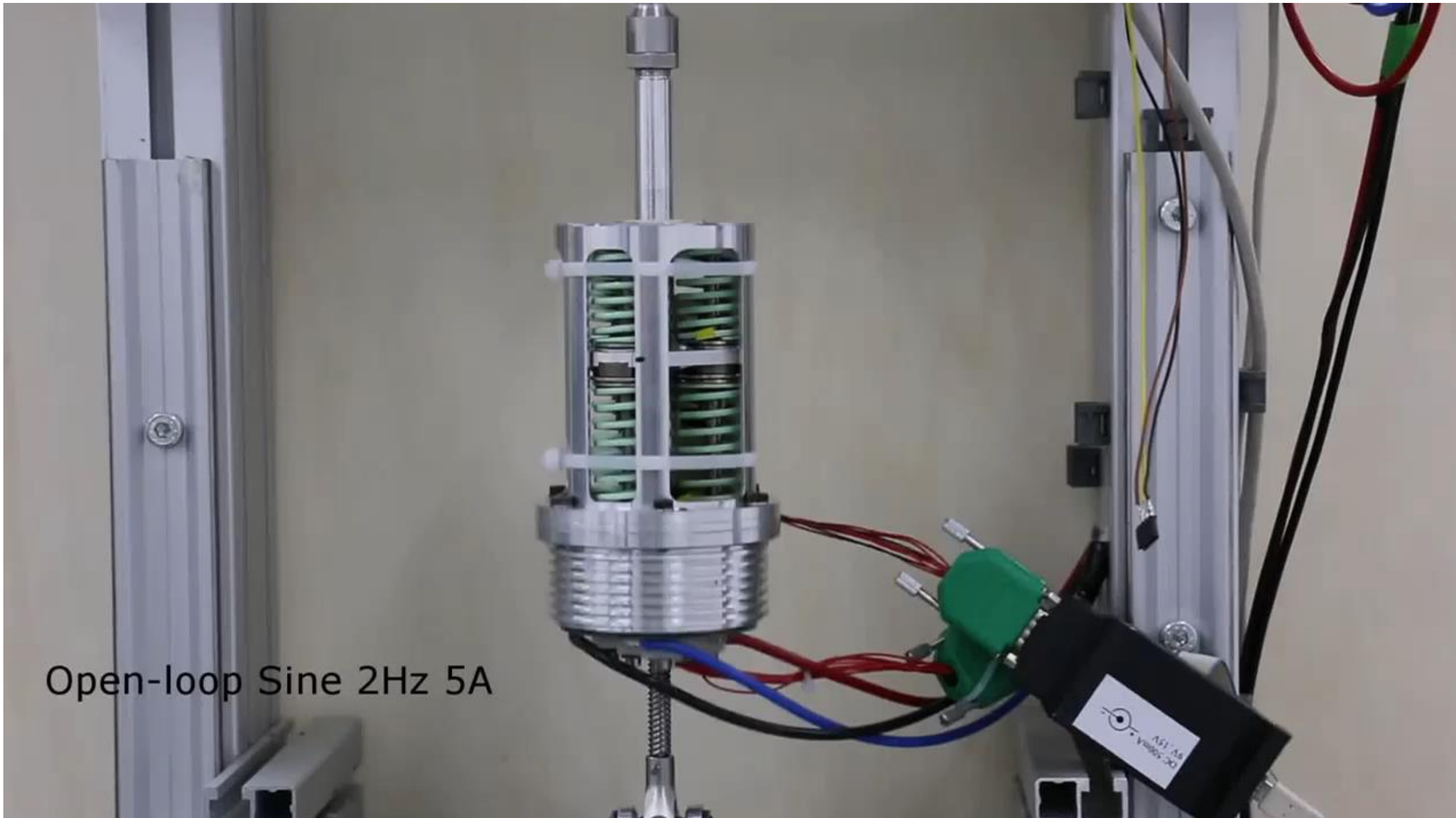
Experimental Validation



SEA – Theoretical Characteristcs

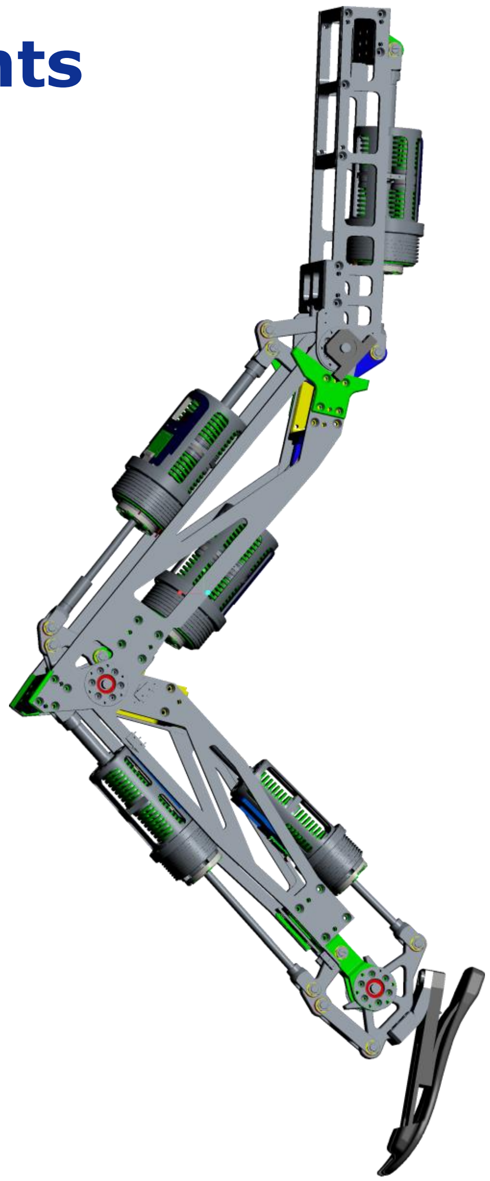
- Force
  - Continuous: 800 N
  - Maximal: 2800 N
- Max speed: 400 mm/s
- Max travel: 145 mm
- Weight: ca 1,3 kg
- Dimensions
  - Length: 225 mm
  - Diameter: 84.5 mm

Open-loop actuation

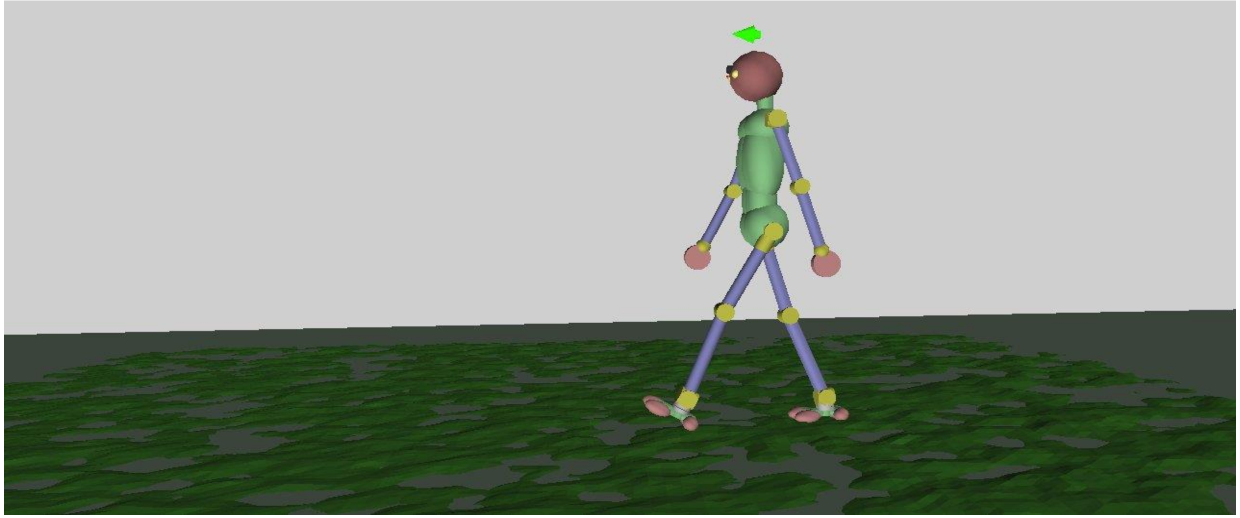


Robotic Leg with biarticular elements

- Leg with mono- and biarticular actuation
  - 3 mono-articular SEAs at each joint
  - 2 bi-articular SEAs spanning
    - Hip and knee
    - Knee and ankle
- Prosthetic foot
  - Simulates human foot arch
  - Introduces additional compliance



Thank you for your attention!



Reflex Controllers for Cyclic Walking I

Phase	Reflexes	Sensor Event	Action
1 & 2	*Lateral Balance Ankle*	Always on during these phases	Generating torques to ankle x
1	*Control Forward Velocity Ankle*	Always on during this phase	Correcting torques to ankle y and knee
1 & 2	*Stabilize Pelvis*	Always on during these phases	Correcting angle to hip x
2	*Keep Knee Angle*	Always on during this phase	Keeping the knee neutral
4	*Cutaneous reflex*	Only on during the beginning of the swing phase(when small ground contact still existing)	Generating torques to ankle y and knee
4 & 5	*Lateral Foot Placement*	Always on during these phases	Correcting the desired angle of hip x

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Reflex Controllers for Cyclic Walking II

Phase	Reflexes	Sensor Event	Action
4 & 5	*Lock Hip*	Only on when hip x in activation zone	Keeping hip x stiff
4	*Lock Knee*	Only on when angle of knee in activation zone	Keeping knee stiff
4 & 5	*Keep Ankle Y Angle*	Always on during these phases	Correcting angle of ankle y
5	*Heel Strike*	On after heel contact measured	Generating torques to ankle y
1 → 5	*Upright Trunk*	Always on in all phases	Generating torques to ankle y and knee
4 & 5	*Lateral Foot Placement*	Always on during these phases	Generating torques to hip x

Motor Patterns for Cyclic Walking

Phase	Motor Patterns	Sensor Event	Action
2 & 3	*Leg Propel*	Triggered since phase 2	Generating torques to ankle y and knee
3	*Hip Swing*	Stimulated from phase 3 onwards	Generating torques for hip x,y,z
3 & 4	*Arm Swing*	Always on during these phases	Generating torques for ipsilateral and contralateral arms
5	*Heel Strike*	On after heel contact measured	Generating torques to ankle y
5 & 1	*Weight Acceptance*	Activated during these phases	Generating torques to ankle y and knee

Control Units for Advanced Locomotion I

Phase	Motor Pattern / Reflex	Locomotion Skills	Actions	New unit
2 & 3	*Leg Propel*	Various speed walking	Adapt ankle torques	No
3	*Hip Swing*	Various speed walking	Adapt hip torques for different step length	No
3 & 4	*Arm Swing*	Various speed walking	Adapt arm swing frequency for various speed	No
4 & 5	*Lock Hip*	Various speed walking	Adapt step length for various speed	No
4	*Lock Knee*	Various speed walking	Enable ground clearance	No
1 & 2	*Lateral Balance Ankle*	Various speed walking	Adapt lateral ankle torques	No

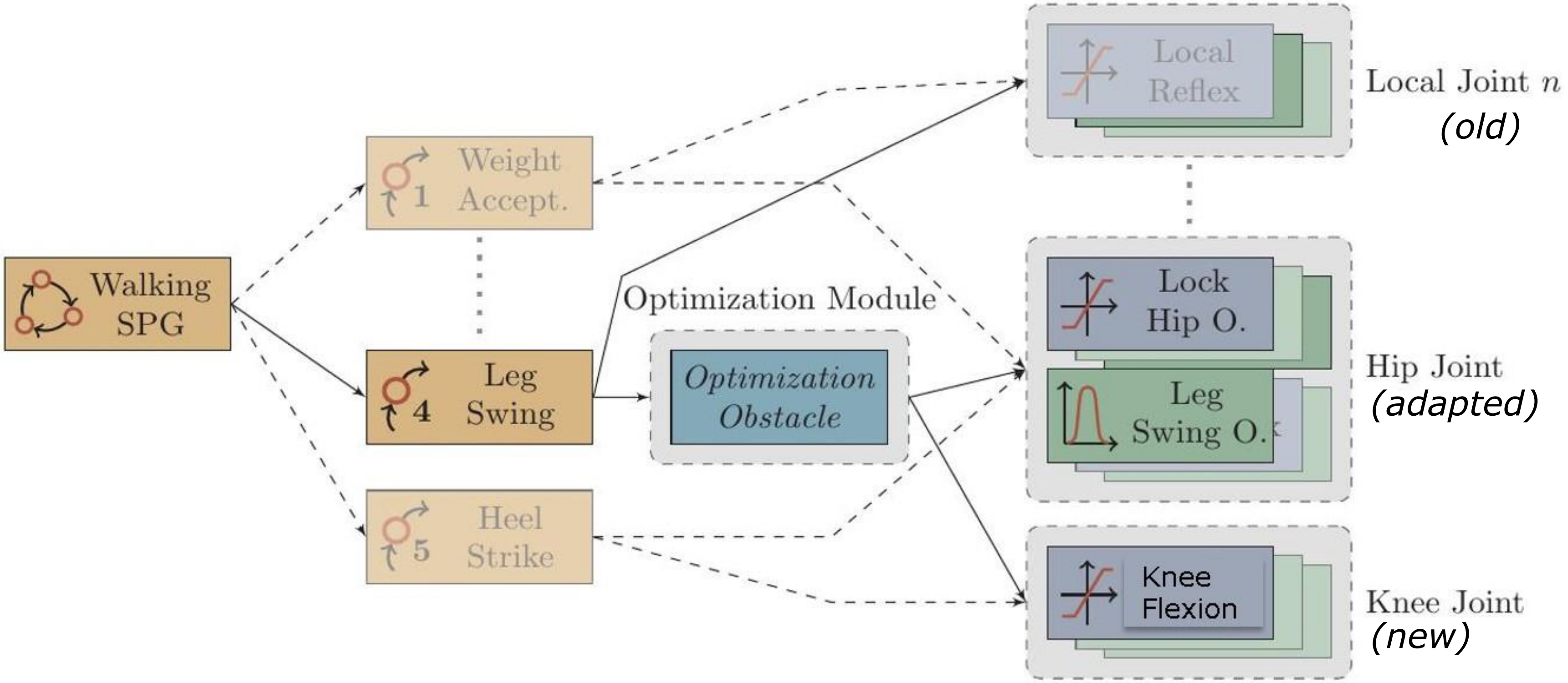
Control Units for Advanced Locomotion II

Phase	Motor Pattern / Reflex	Locomotion Skills	Actions	New unit
2 & 3	*Leg Propel*	Push recovery	Adapt ankle torques for instability	No
3	*Hip Swing*	Push recovery	Adapt hip torques for larger step length	No
4 & 5	*Lock Hip*	Push recovery	Adapt hip angle for smooth heel strike	No
1	*Hip extension*	Push recovery	Enable hip extension for stance leg when push in early swing phase	Yes
1	*Knee Flexion*	Push recovery	Enable knee flexion for stance leg when push in early swing phase	Yes
1 & 2	*Hold Knee*	Push recovery	Increase knee stiffness in recovery phase	Yes

Control Units for Advanced Locomotion III

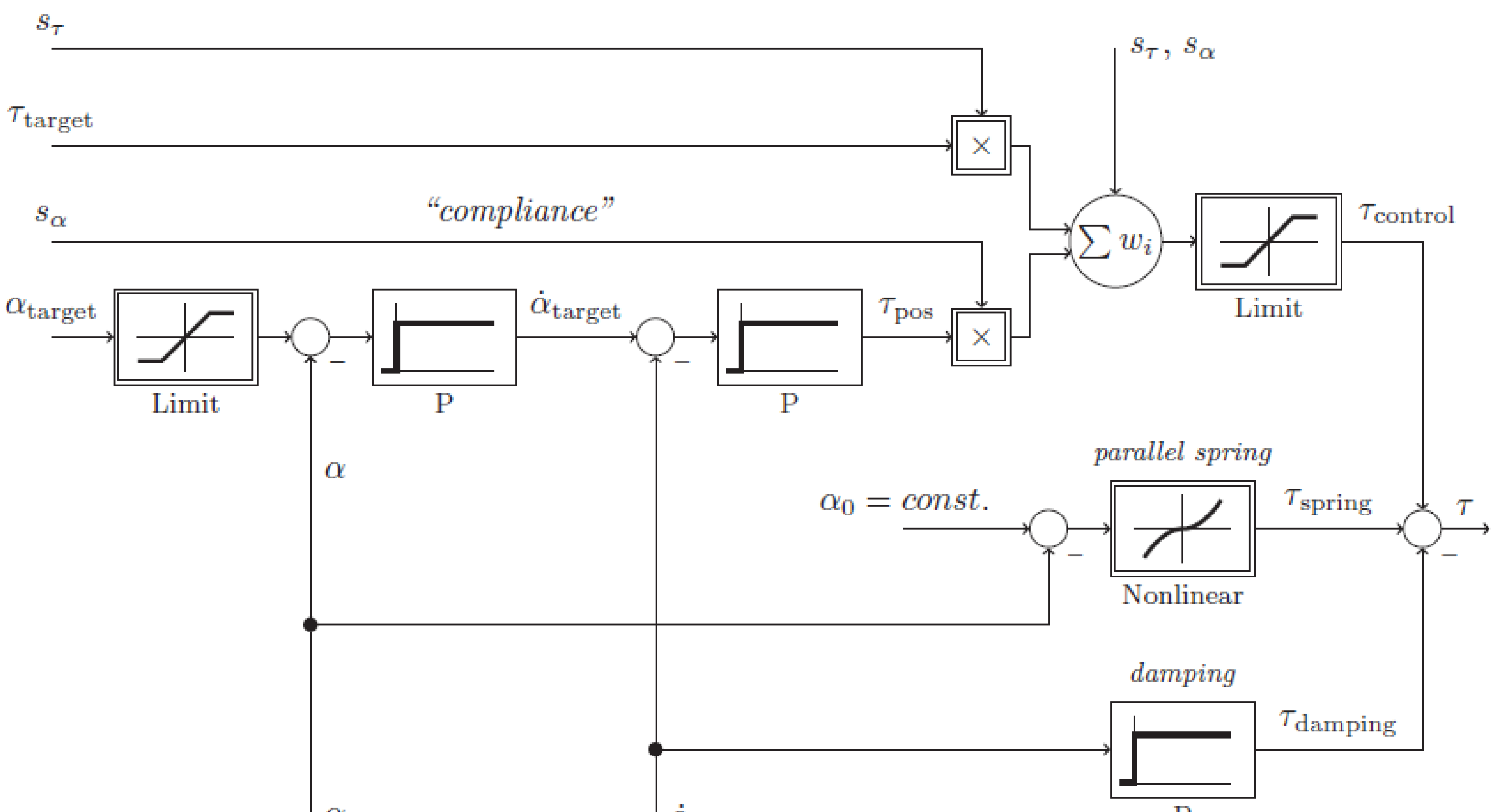
Phase	Motor Pattern / Reflex	Locomotion Skills	Actions	New unit
3	*Hip Swing*	Stepping over obstacle	Adapt hip torques for larger swing angle	No
4 & 5	*Lock Hip*	Stepping over obstacle	Adapt hip angle for larger swing angle	No
1	*Knee Flexion*	Stepping over obstacle	Actively control knee joint until knee is stretched	Yes

Example: Network during Obstacle Walking Phases 4/1



- The control units at the hip and knee joints are refined
  - Hip joint: Leg swing & Lock hip
  - Knee joint: Knee flexion

Joint Control



$$\tau_{control} = \frac{s_\tau(\tau_{target} s_\tau) + s_\alpha(\tau_{pos} s_\alpha)}{s_\tau + s_\alpha}$$

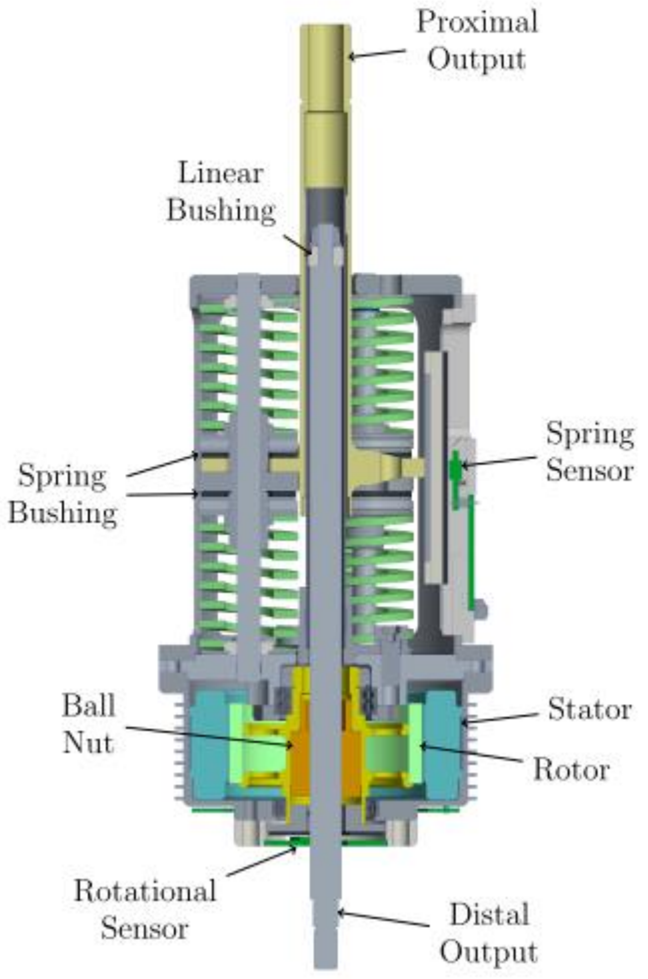
$$\tau_{spring} = \mathrm{sgn}(\alpha_0 - \alpha) \cdot K_{spring} \cdot (\alpha_0 - \alpha)^2.$$

Key Design Factors

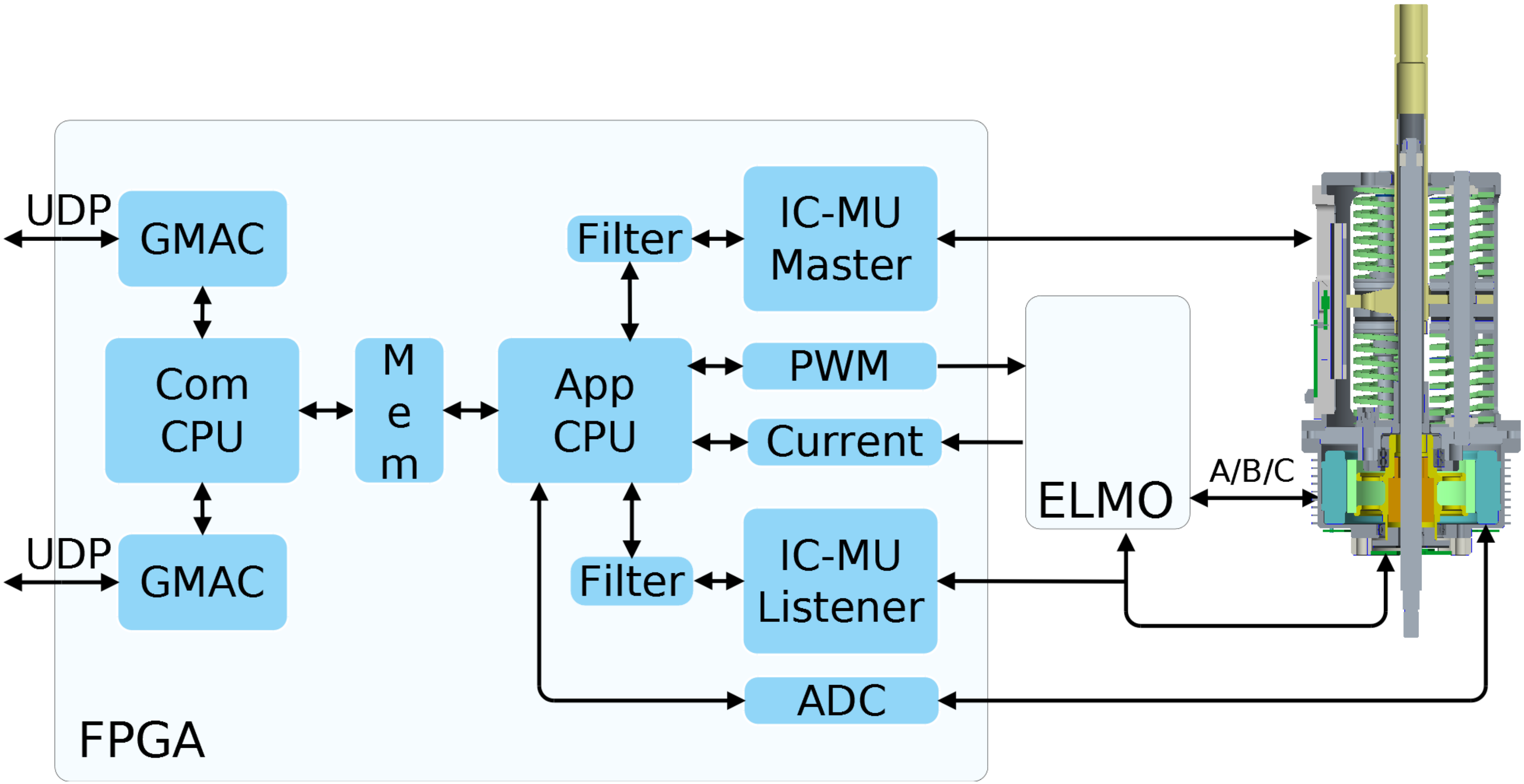
- Compliance
  - Impact tolerance
    - Deal with uncertainties
  - Energy storage
    - Reduced metabolic cost
    - Increased mechanical output
  - Modulation of stiffness/damping
- Passivity and torque/force control
    - Ballistic movements
- Hierarchical feedback mechanisms
    - Physically distributed

RRLAB SEA Implementation

- Drivetrain
  - Robodrive 70x18
  - Ball screw pitch of 8mm
    - Torque to force efficiency of 97%
    - Force to torque efficiency of 97%
  - → Increased energy recuperation
  - Ball nut integrated in rotor shaft
- Spring system
  - Proximal placement [1]
  - Standard die springs
  - Linear guides
  - Rotational spring bushings



Embedded Electronics

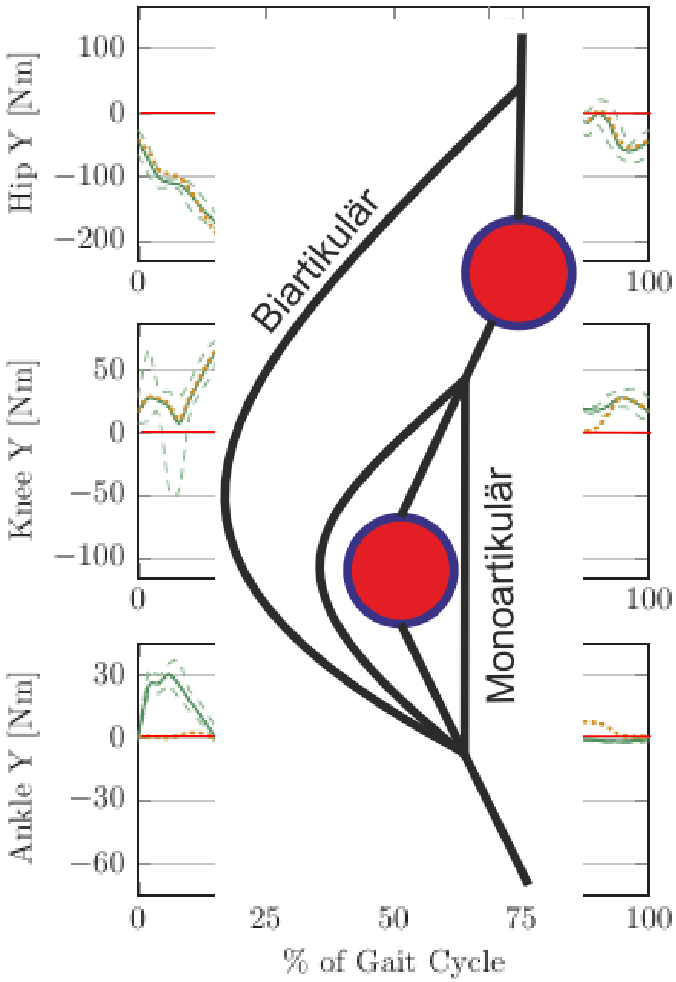


www.finroc.org

S. Schuetz, M. Reichardt, M. Arndt, and K. Berns, "Seamless extension of a robot control framework to bare metal embedded nodes,"in Informatik 2014, ser. Lecture Notes in Informatics (LNI), Stuttgart, Germany, 2014, pp. 1307–1318.

Bi-articular muscles

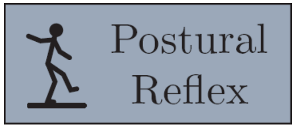
- Muscles acting across two joints
- Redirect muscle action
  - e.g. vertical jumping
- Energy transfer between proximal and distal joints
  - Implication can be found in torque profiles obtained from Luksch[10]



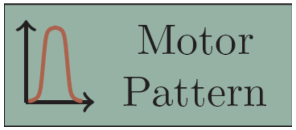
[Luksch 10] T. Luksch, "Human-like Control of Dynamically Walking Bipedal Robots", Ph.D. dissertation, TU Kaiserslautern, 2010.

Reflexes and Motor Patterns

Reflex action provides the basic feedback mechanism in human motion control. Local reflexes show a tight coupling between sensor information and motor action. Reflexes show a **feedback controller-like behavior** with a linear or nonlinear relation between sensor data and control output. The other type of reflexes works **event-based:** as soon as a certain sensor event occurs, the output state is changed.



The reflex action at one place of the robot can be the result of a sensor event at the opposite end of the machine, possibly supported by a simplified dynamical model. The state variables most frequently used or calculated by postural reflexes are estimations of **the upper body orientation, the rough position or velocity of the center of mass, or load distribution in the feet**. In collaboration with the local reflexes, the postural reflexes **enhance the global stability** of the biped.



The stimulation of certain regions in the spinal cord result in muscle action producing coordinated joint or limb motions. These components or motion primitives seem also to be recruited in phases of locomotion. The corresponding control unit of this concept is called motor pattern. They produce **uniform patterns of torques for one or more joints in a feed-forward manner.** They always work locally.

Optimization Methodology

- It searches a space by adjusting the trajectories of individual vectors, called ‘particles’, as they are conceptualized as moving as points in multidimensional space
- The velocity and position of particle are updated as:

$$v_i^{k+1} = \omega \cdot v_i^k + c_1 \cdot Rand \cdot (Pbest_i^k - x_i^k)$$
$$+ c_2 \cdot Rand \cdot (Gbest^k - x_i^k)$$

ω: inertia weight

c_1 and c_2: acceleration constant

$rand$: random number between 0 and 1

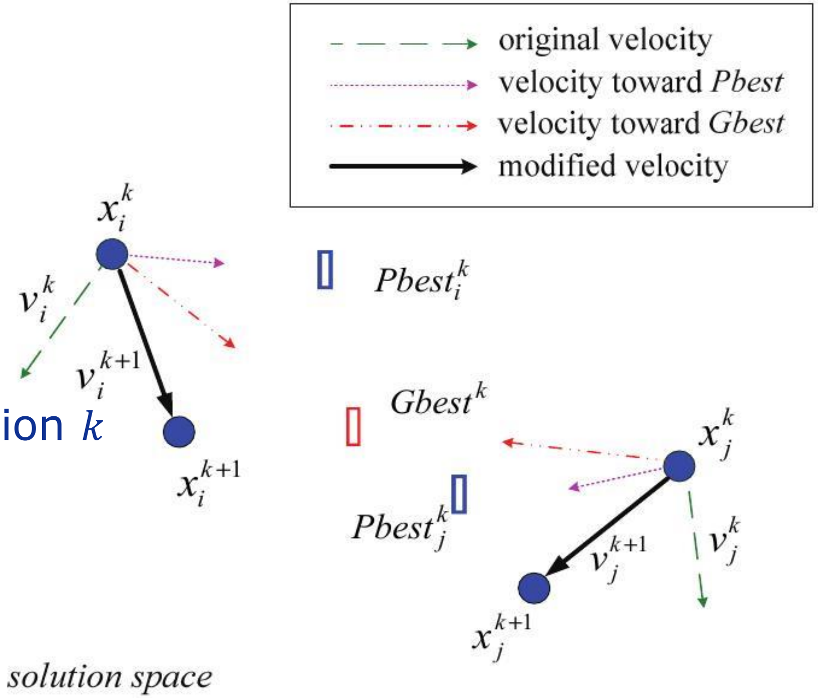
$Gbest$: best position of group in iteration k

$Pbest_i^k$: best position of the particle i in iteration k

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

x_i^k: position of particle i in iteration k

v_i^k: velocity of particle i in iteration k



Expectation-Maximization based Reinforcement Learning I

- Action a is calculated by combining the weight parameters $\boldsymbol{\theta}$ of the radial basis function network and the basis function $\boldsymbol{\Phi}(s)$

$$a = \boldsymbol{\theta}^T \boldsymbol{\Phi}(s)$$

where $\Phi_j(s) = \exp(-\frac{(s-\mu_j)^2}{2\sigma^2})$ for $j = 1,2, \dots \dots, N$

- Undiscounted accumulated reward in the iteration n

$$R(n) = \sum_0^T r(t)$$

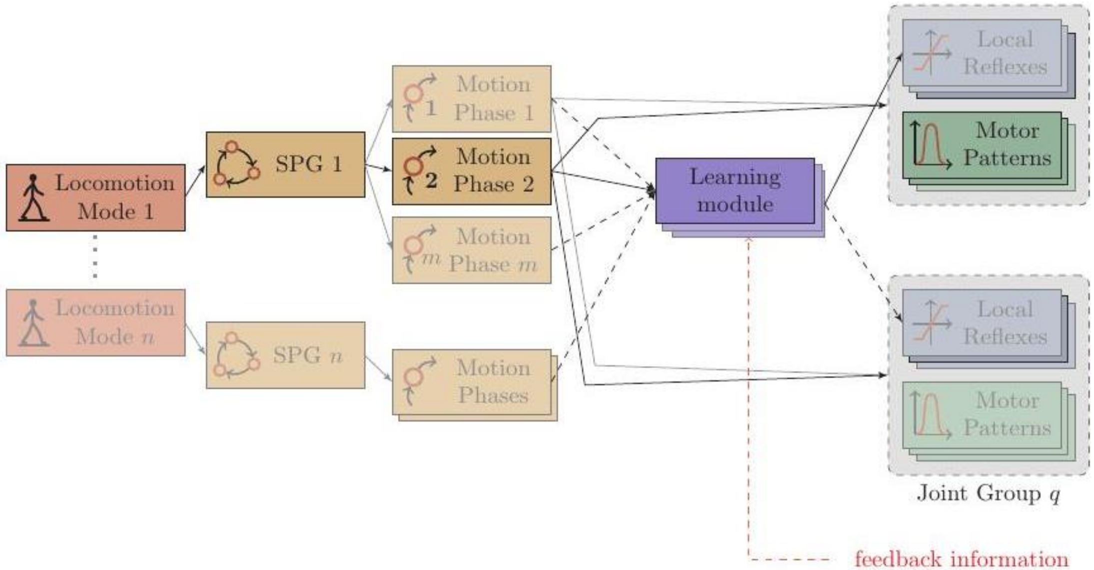
- The parameter $\boldsymbol{\theta}_n$ in the iteration n is updated to θ_{n+1} in the iteration $n+1$ with previous K best iterations

$$\boldsymbol{\theta}_{n+1} = \boldsymbol{\theta}_n + \frac{\sum_{k=1}^{K}(\boldsymbol{\theta}_k - \boldsymbol{\theta}_n)R(k)}{\sum_{k=1}^{K} R(k)}$$

- Stop learning until $\boldsymbol{\theta}_{n+1} = \boldsymbol{\theta}_n$

Expectation-Maximization based Reinforcement Learning II

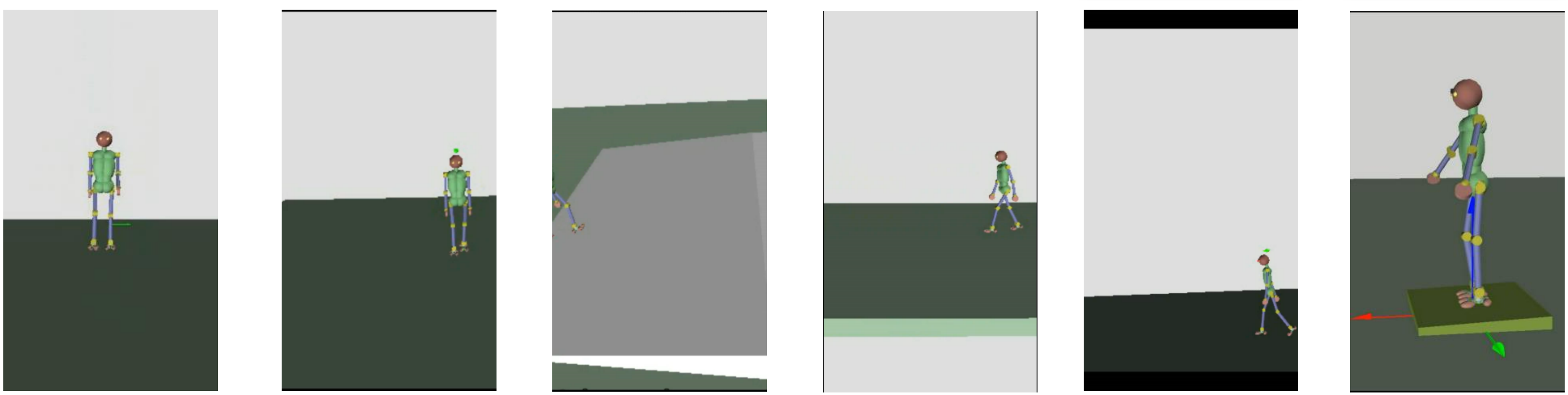
- Learning module is between Motion Phase and Reflexes.
- The sensory information is feedback as state inputs to RL module.
- RL module calculates action values based on radial basis function network.
- The action is exerted at the reflexes.
- Rewards to update network until expected returns obtained.



Behavior-Based Bio-inspired Bipedal Locomotion

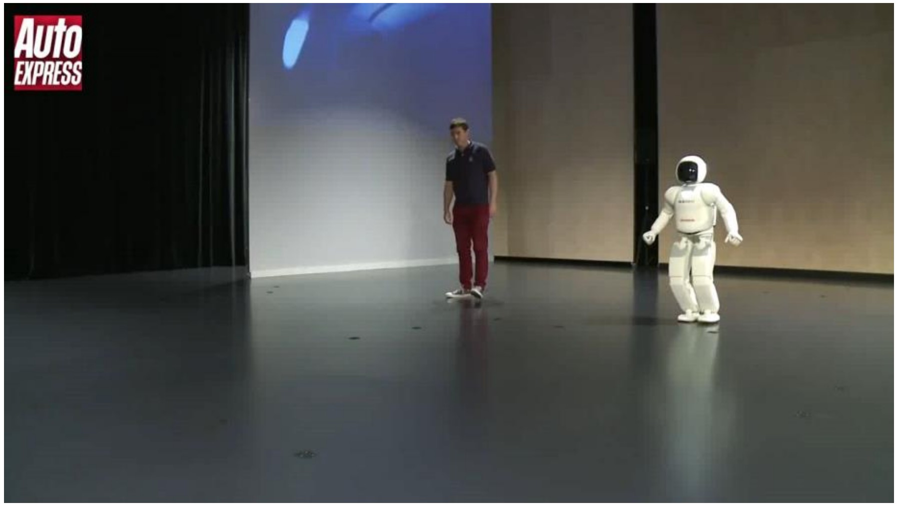
B4LC system

- Even ground locomotion
- Curve locomotion
- Upslope locomotion
- Speed control
- Push recovery
- Balancing standing



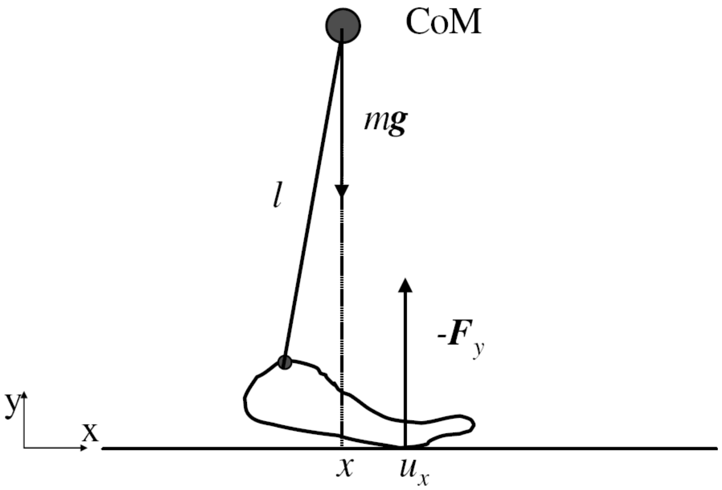
State-of-the-art in bipedal robots

- Lola (TUM), ASIMO (HONDA), HRP-4C (JAIST), Atlas (Google).



Postural Control

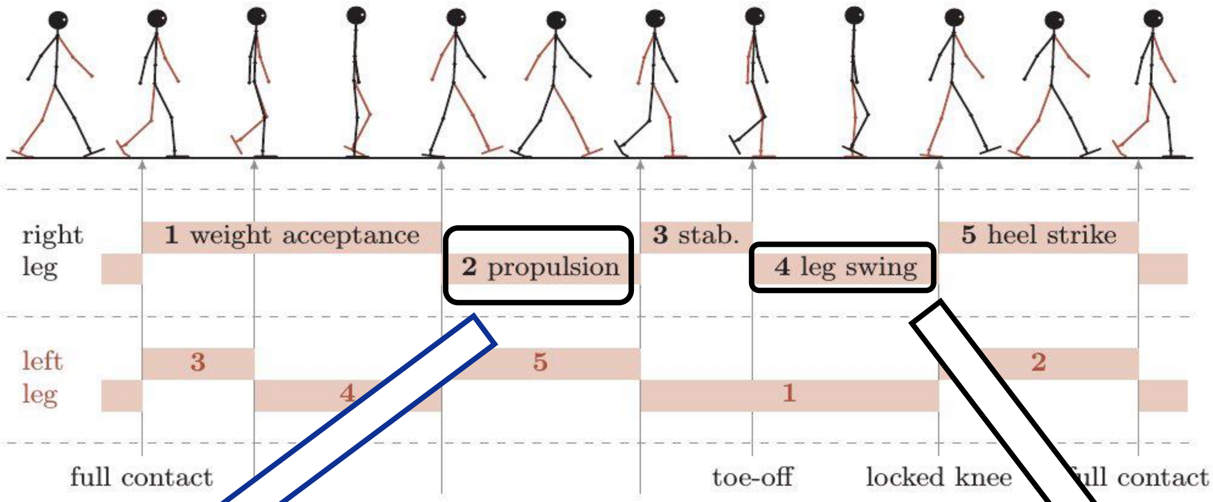
Schematic diagram of the inverted pendulum model [Hof08].



Implications for Robotics:

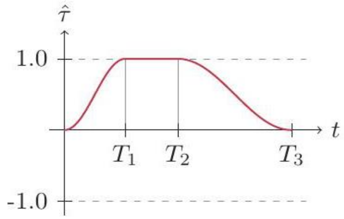
Postural control includes maintaining body stability in the sagittal and front plane and controlling forward velocity. This is a **high-level skill** requiring an estimation of the robot's pose using information on joint angles, acceleration, and velocity information from an inertial measurement unit, and optical flow from vision, if available. **Adjusting the foot placement** seems to have the major influence on whole body balancing. Anticipatory torque patterns seem to be necessary to compensate segment movements resulting from mass inertia during normal walking, especially in the hip and trunk joints.

Various Speed Locomotion



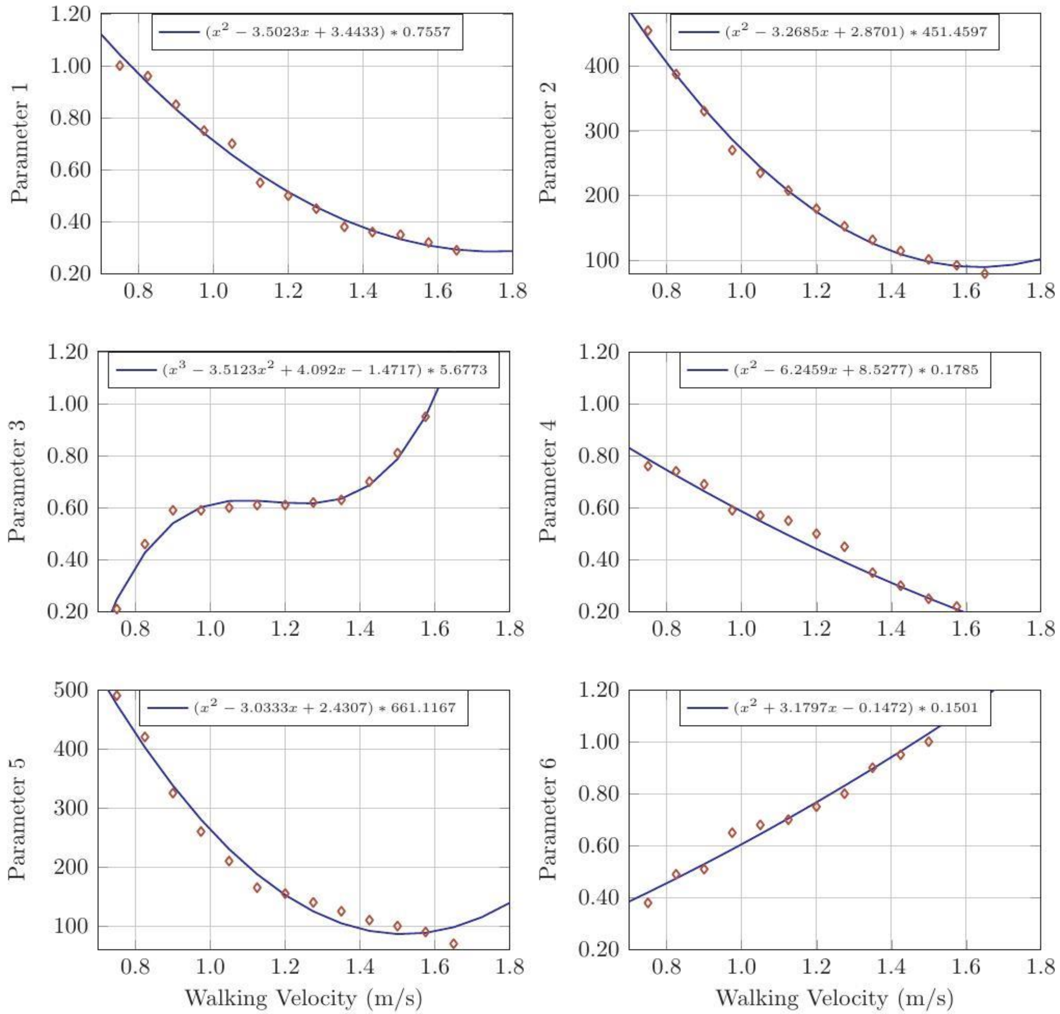
MP: Leg Propel

MP: Active Hip Swing



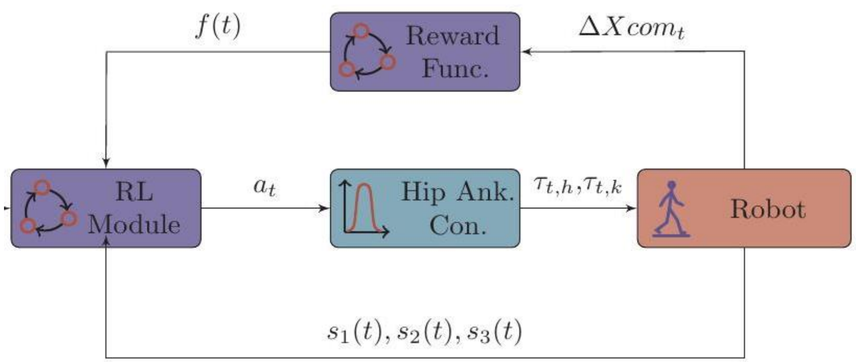
T_1 T_2 T_3 **are searched with respect to different velocities**

Various Speed Locomotion

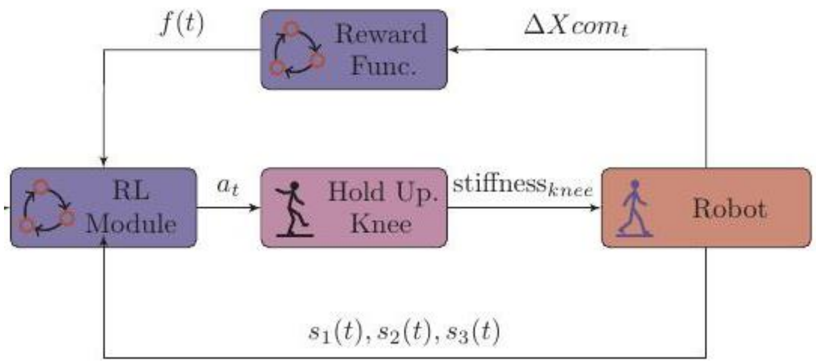


- Searching the 18 parameters using PSO
- Using linear least square to define the functions that parameters with respect to walking velocities
- Good performance from 0.625 m/s to 1.625 m/s

Push Recovery Locomotion



RL learns hip and ankle joints



RL learns knee joints

- Using RL module to control the hip, ankle and knee joints movement during pushes
- Reward functions considering stability in sagittal and frontal plane

Reward functions:

$$r(t) = e^{(-k_s|\Delta XcoM_{s,t}|-k_t|\Delta XcoM_{l,t}|)}$$

$$R_s(e) = k_{su}e^{-(step_{max}-step_{ach}(e))/step_{max}}$$

$$R(e) = \sum_{t=1}^{t_e} r(t) + R_s(e)$$