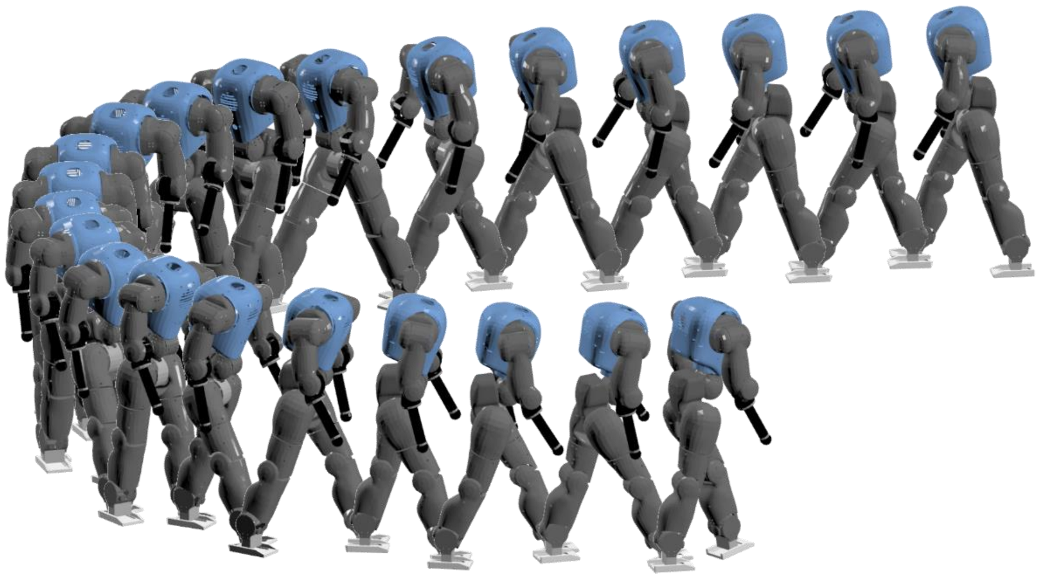
Rich and Robust Bio-Inspired Locomotion Control for Humanoid Robots



Ph.D. thesis – Public defense

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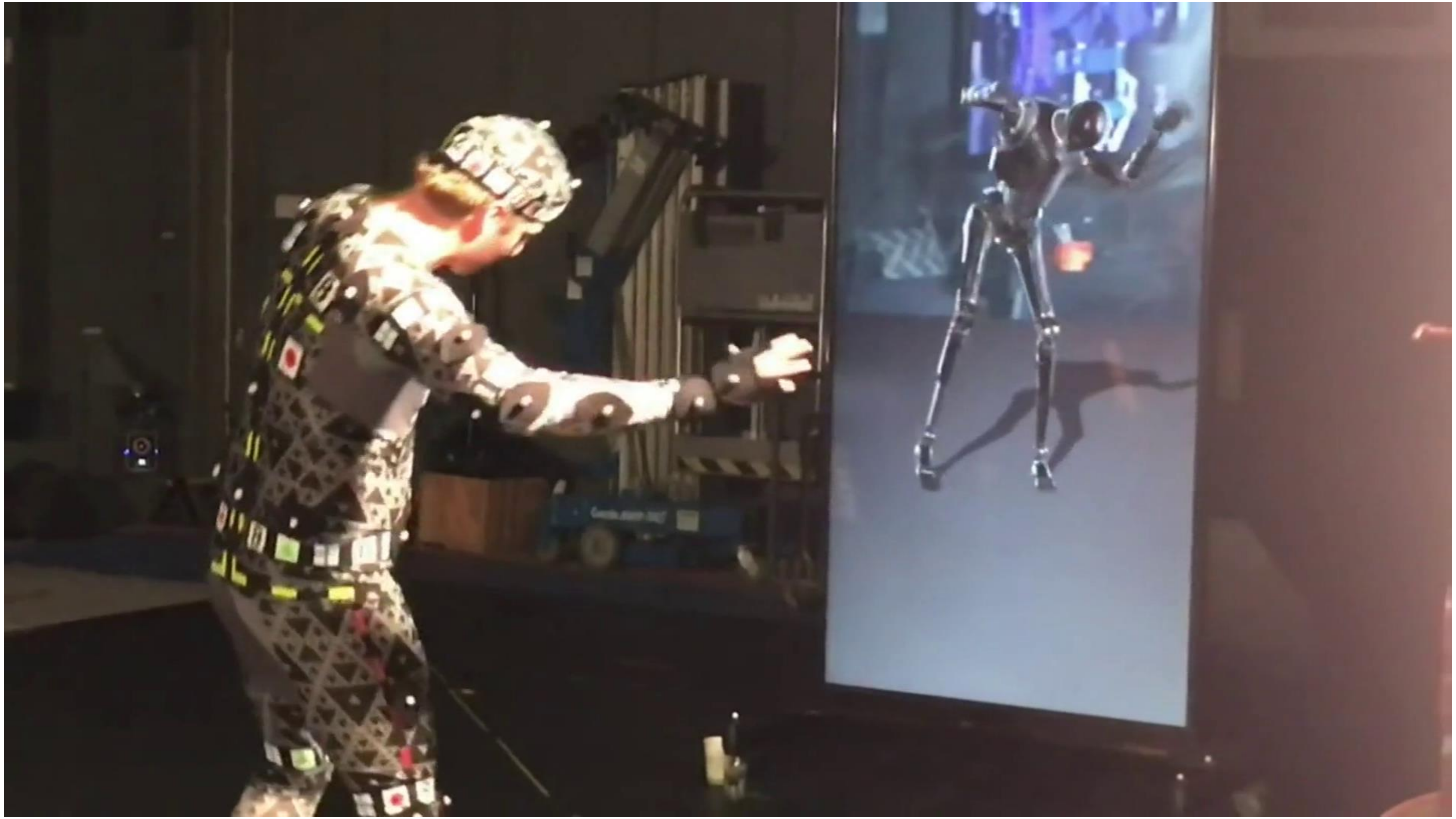
WALK-MAN

Robots capable to adapt to our environment

© Star Wars : Episode VII – The Force Awakens

Humanoid robots in movies



© Rogue One – A Star Wars Story

DARPA Robotics Challenge

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Overview

Introduction & Methods

Reflex-based controller

Forward gait modulation in 2D scenarios

Steering control in 3D scenarios

Conclusion

Outline

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Reflex-based controller

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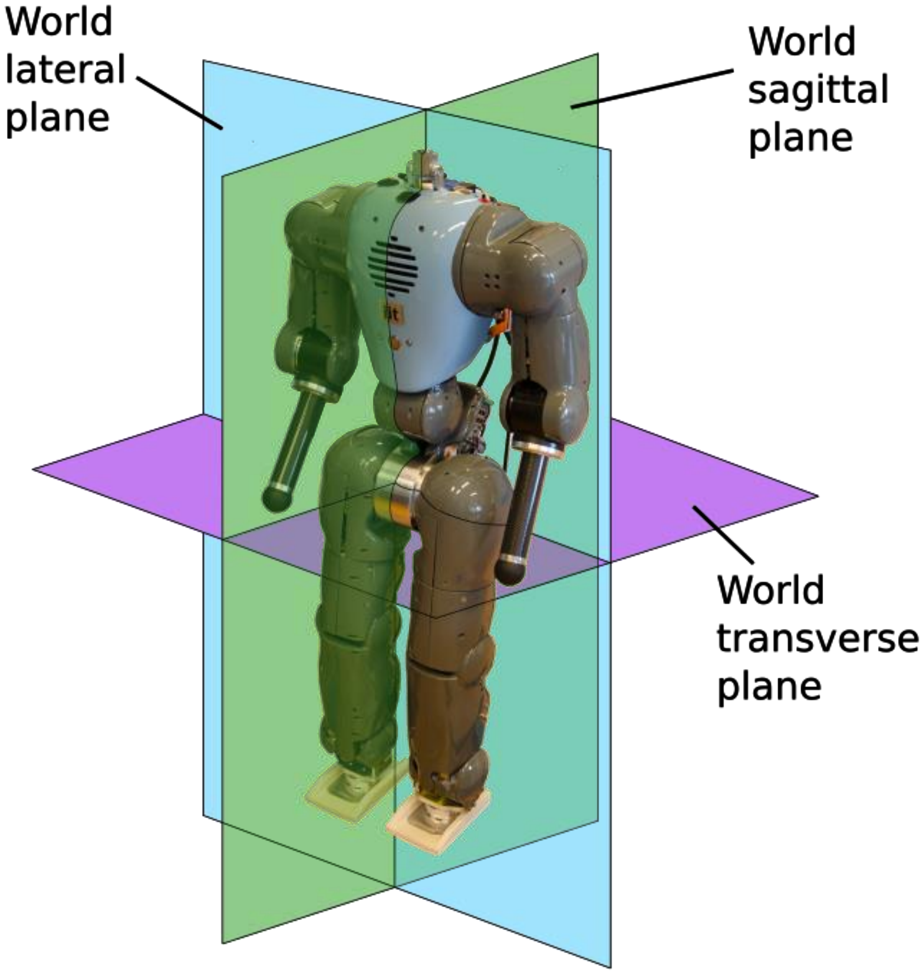
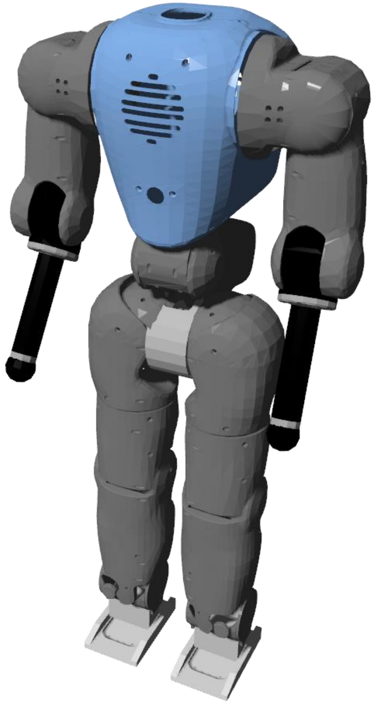
Biped embodiment: the COMAN robot



real COMAN

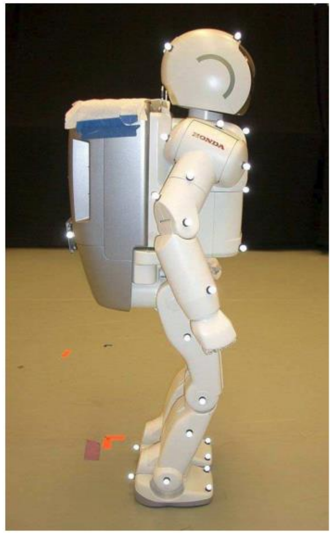


simulated COMAN

2D gait
waist motion only in
the world sagittal plane

3D gait
no motion constraint

Human walking skills for robots



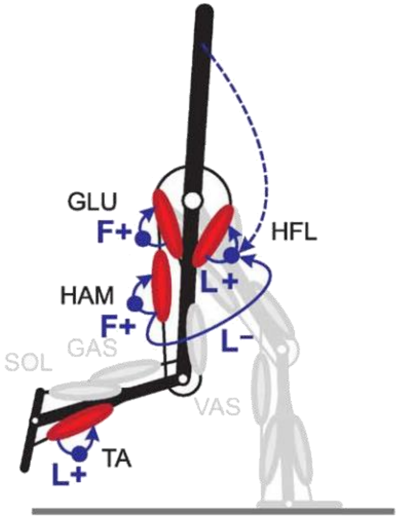
© Chestnutt, 2005

Traditional approaches

- versatile and well known
- energy inefficiency
- non human-like features

Bio-inspired limit cycle walkers

- energy efficiency
- human-like features
- many parameters to optimize
- mainly in simulation

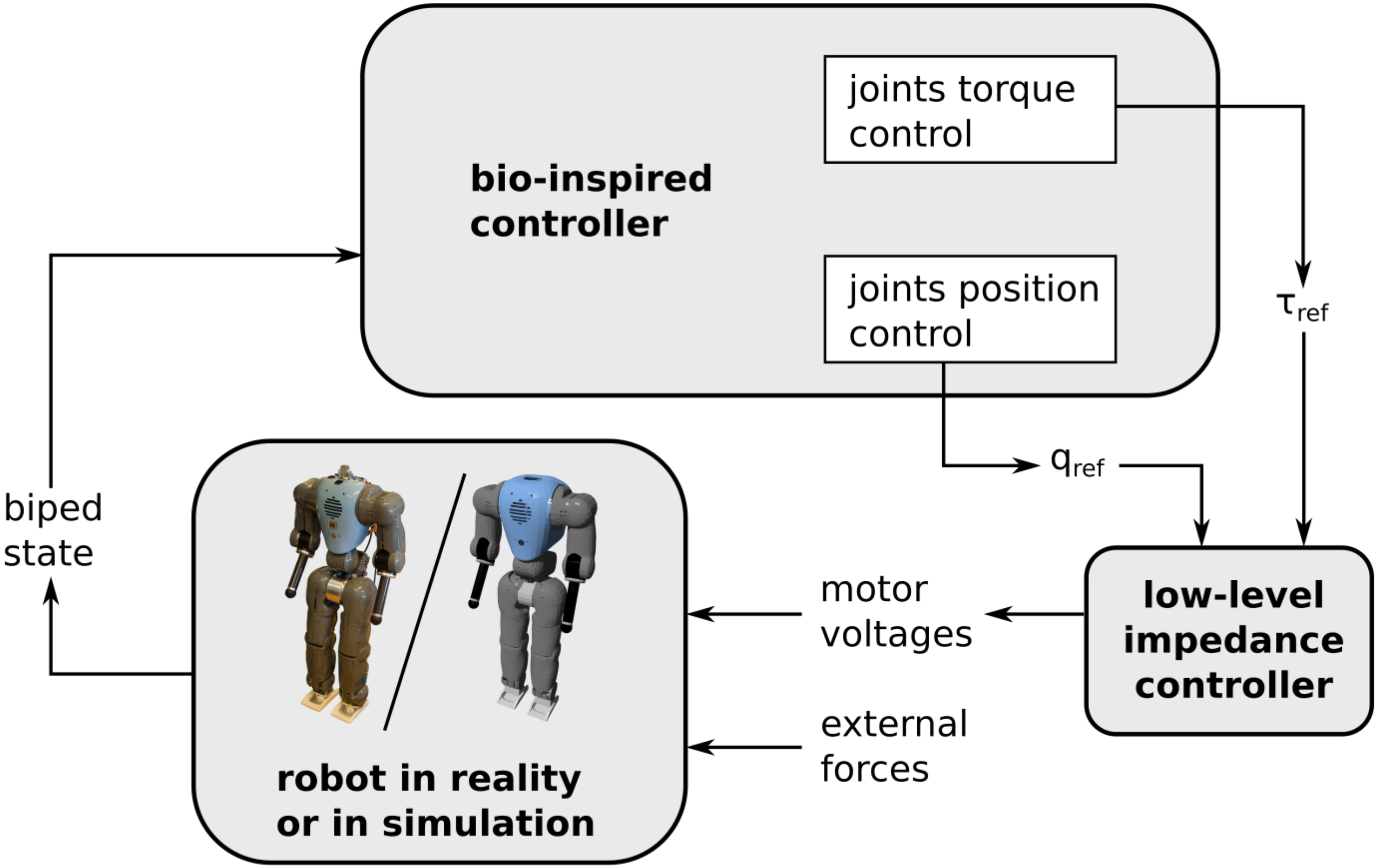


© Geyer, 2010

"***A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities***", H. Geyer and H. Herr, 2010

➡ Port bio-inspired controllers with **steering capabilities** to **humanoid robots**

General control framework



Outline

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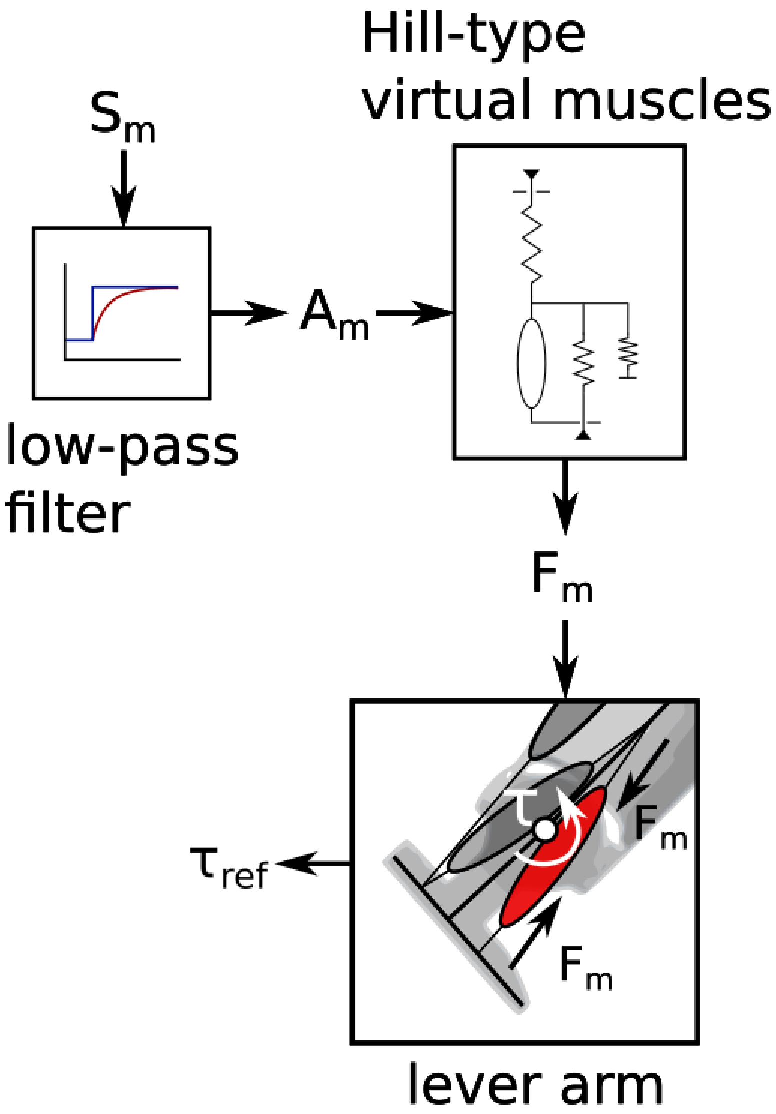
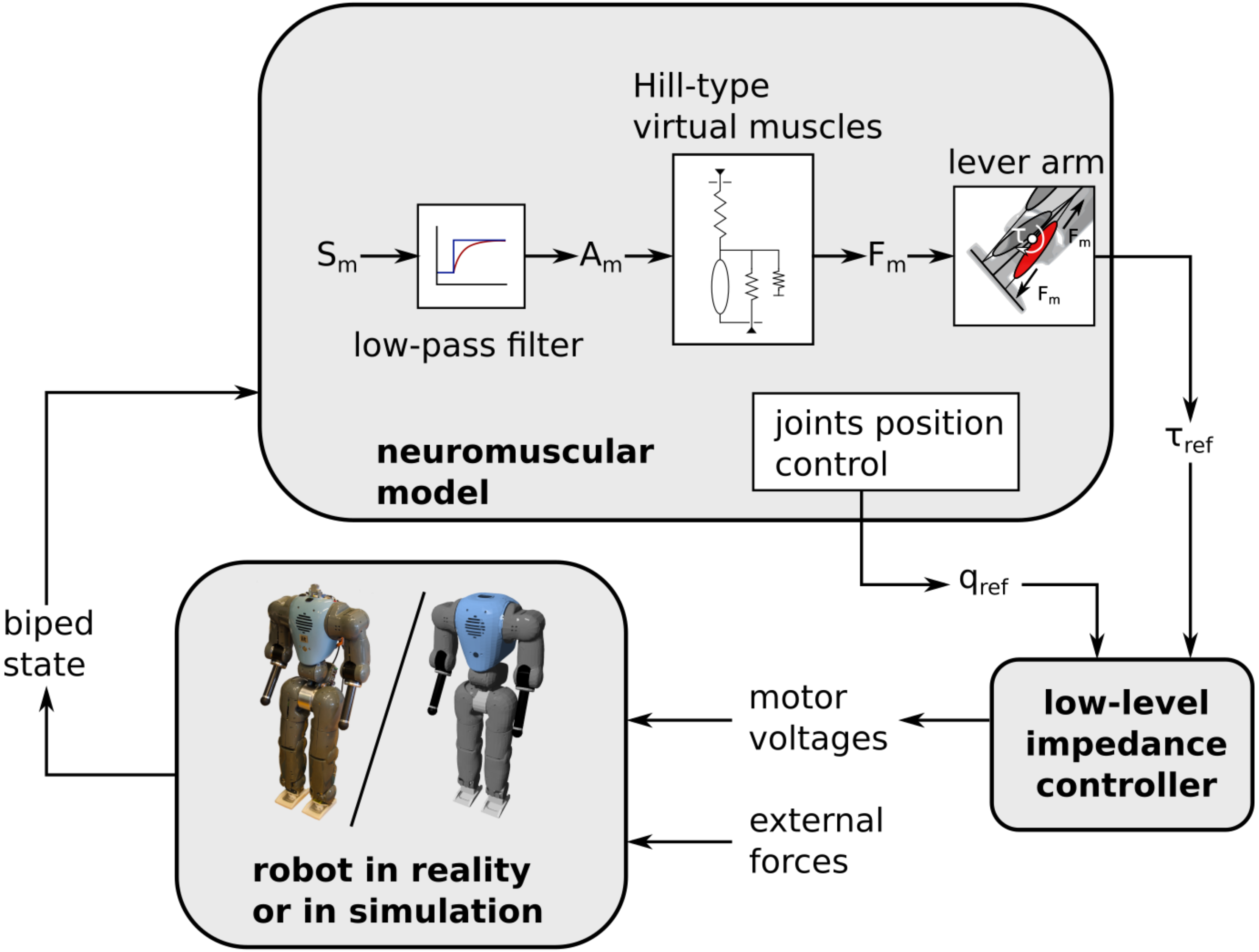
Muscle-based control



General control framework



Hill-type virtual muscles

lever arm

$S_m \rightarrow$ low-pass filter $\rightarrow A_m \rightarrow$ Hill-type virtual muscles $\rightarrow F_m \rightarrow$ lever arm

neuromuscular model

joints position control

τ_{ref}

q_{ref}

low-level impedance controller

motor voltages

external forces

robot in reality or in simulation

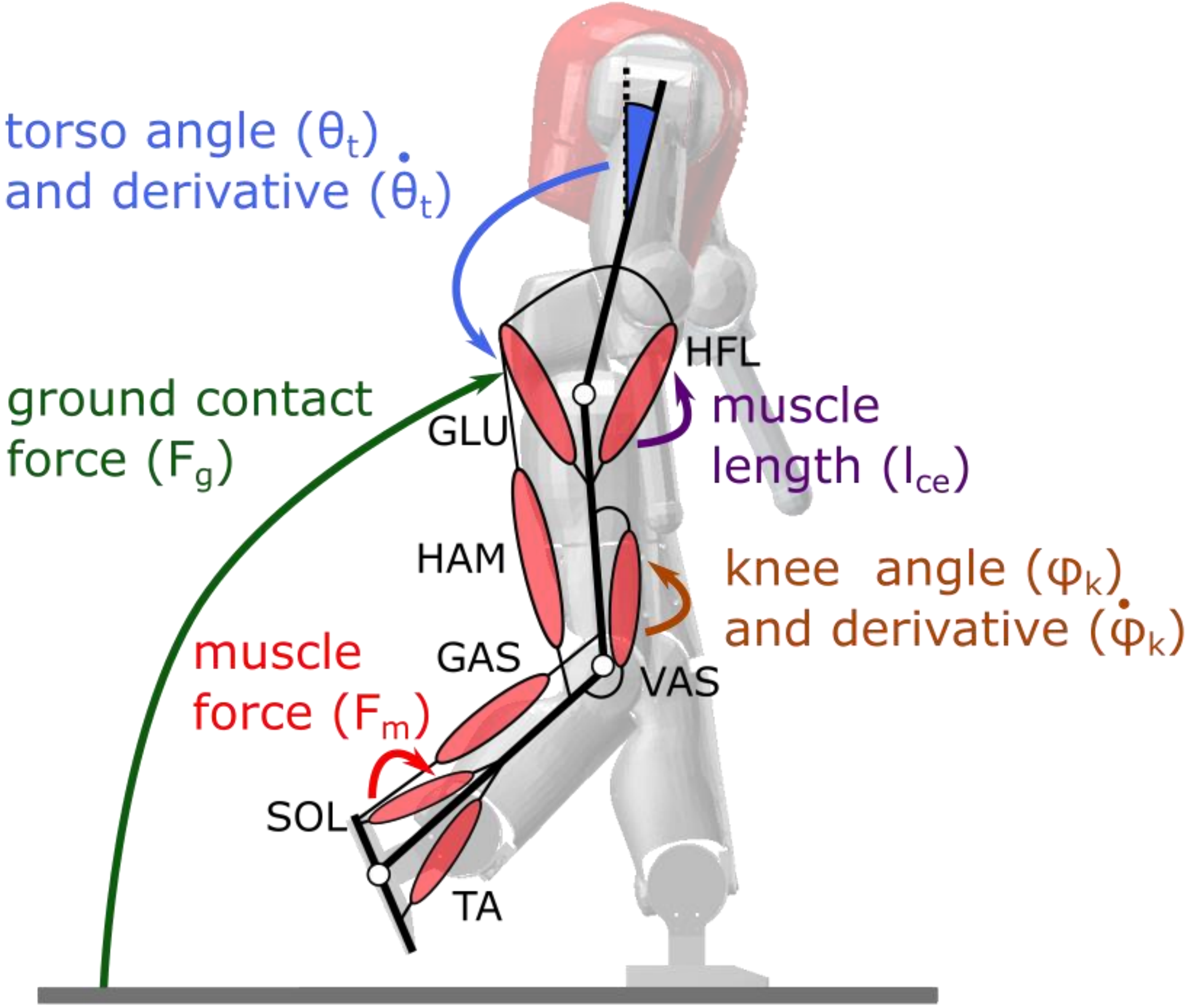
biped state

Reflex-based control

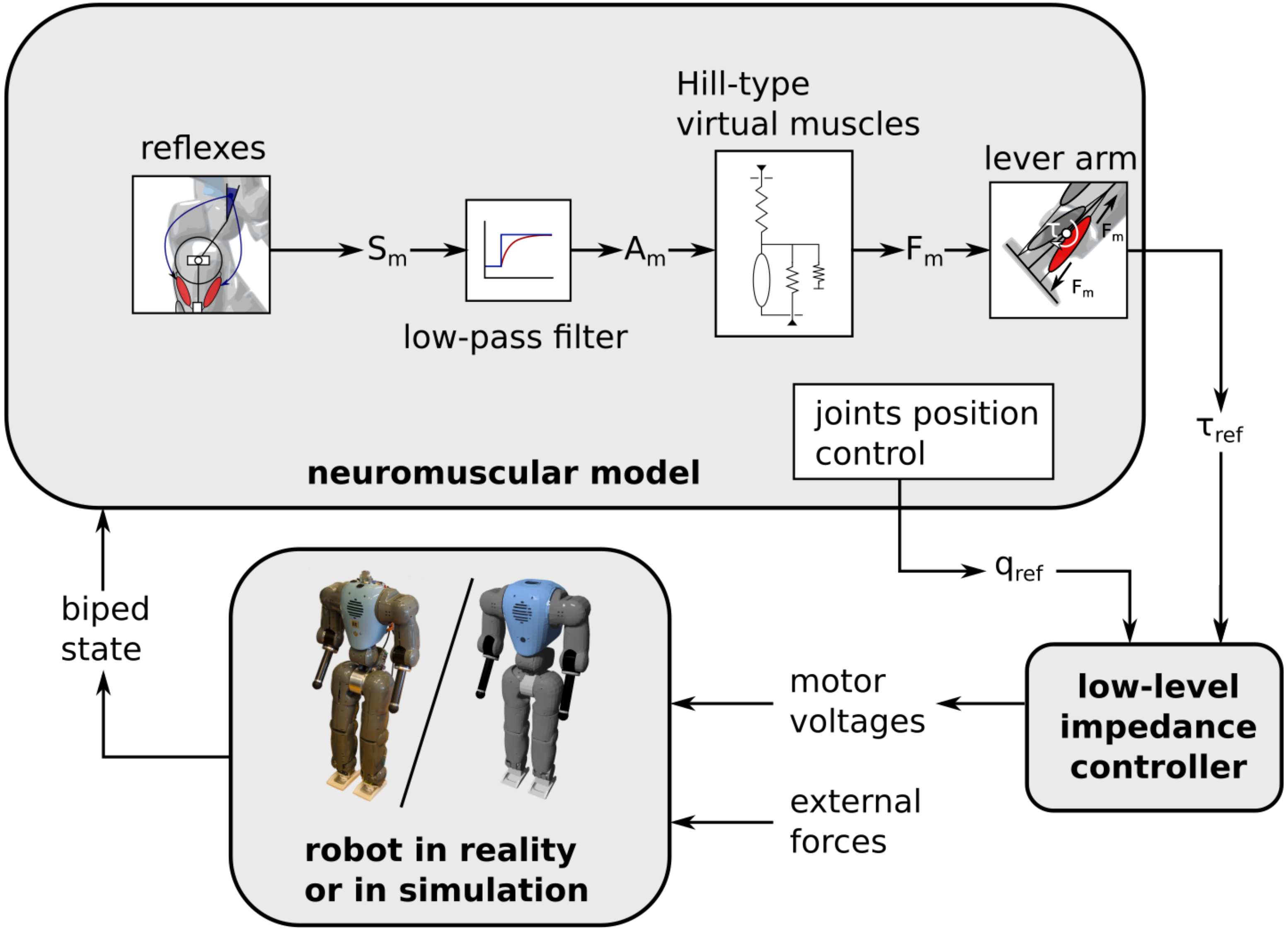
The biped is equipped with virtual **Hill-type muscles** in each leg.

Stimulation signals are computed based on **reflex rules**.

These rules are adapted from [Geyer and Herr, 2010].



General control framework

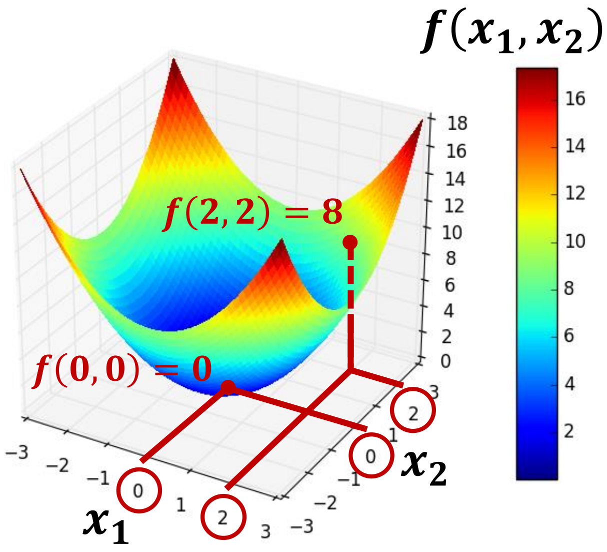


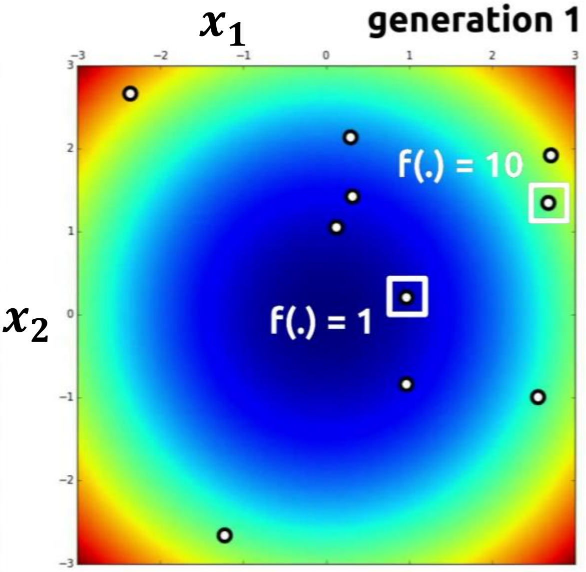
Particle Swarm Optimization (PSO)

$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ minimizing $f(x_1, x_2)$

$$f(x_1, x_2) = x_1^2 + x_2^2$$

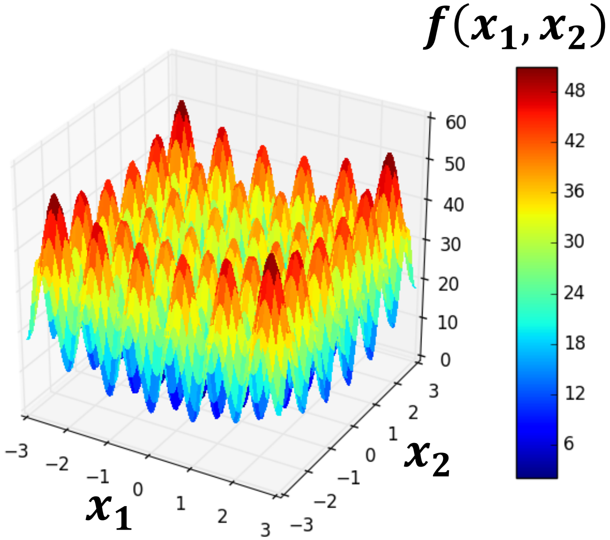
(Sphere function)

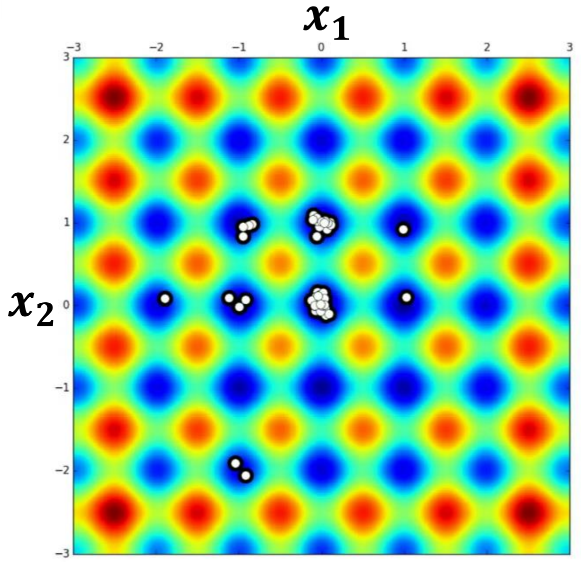




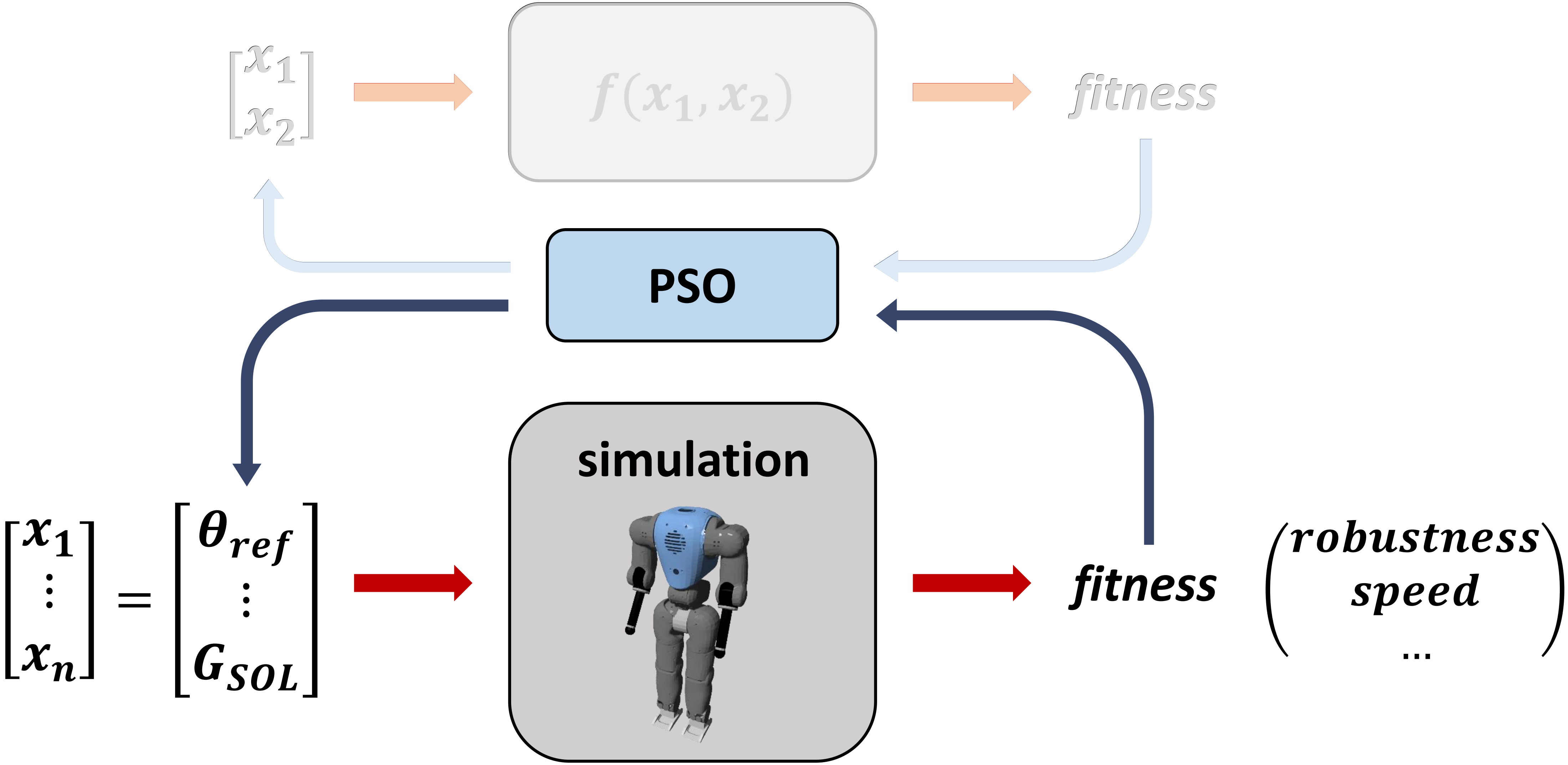
$$f(x_1, x_2) = 20 + \sum_{i=1}^{2} [x_i^2 - 10 \cos(2 \pi x_i)]$$

(Rastrigin function)





Particle Swarm Optimization (PSO)



$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ → $f(x_1, x_2)$ → *fitness*

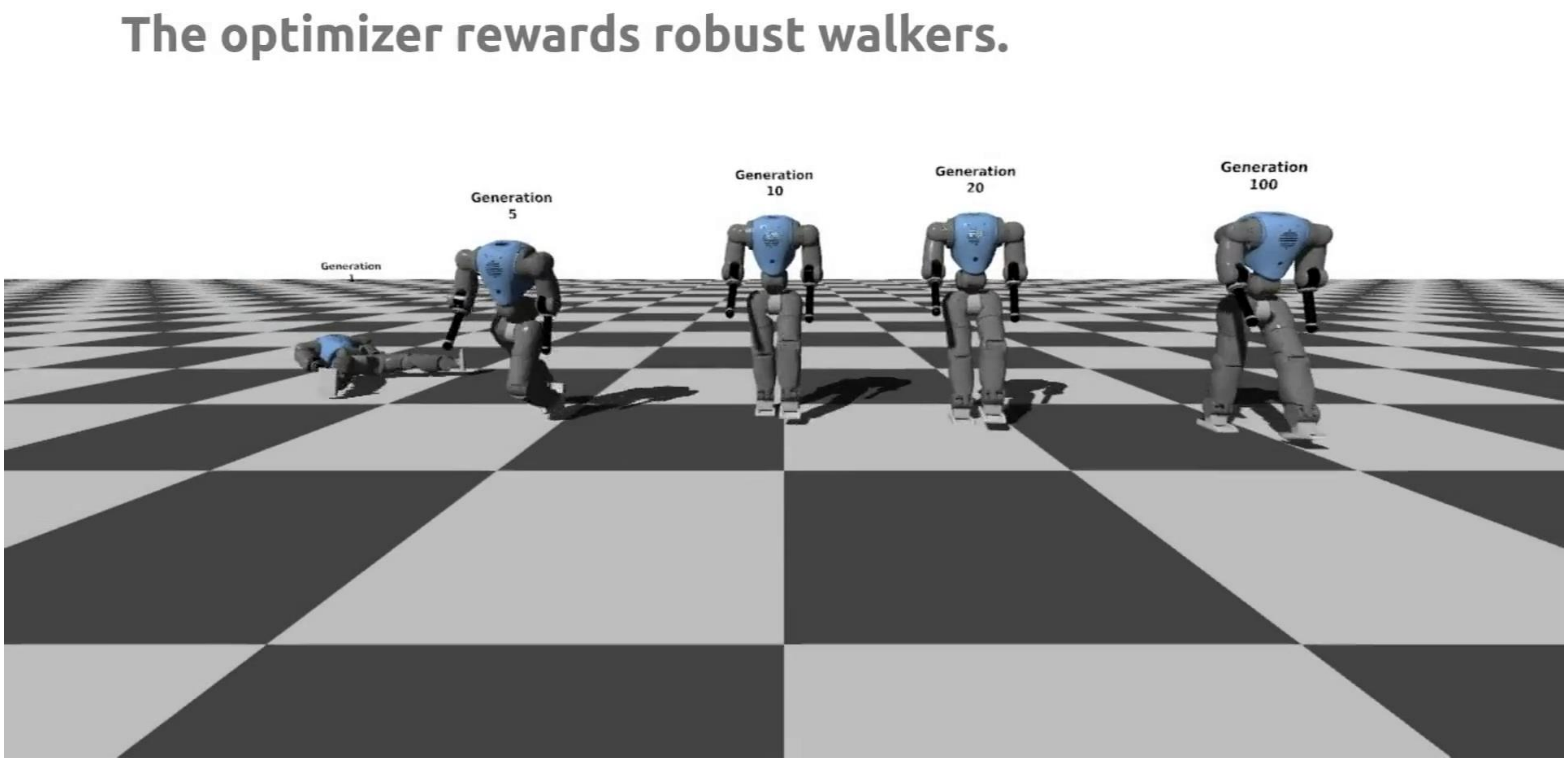
PSO

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} \theta_{ref} \\ \vdots \\ G_{SOL} \end{bmatrix}$$

→ **simulation** →

fitness $\begin{pmatrix} robustness \\ speed \\ \ldots \end{pmatrix}$

Learning through optimization


The optimizer rewards robust walkers.

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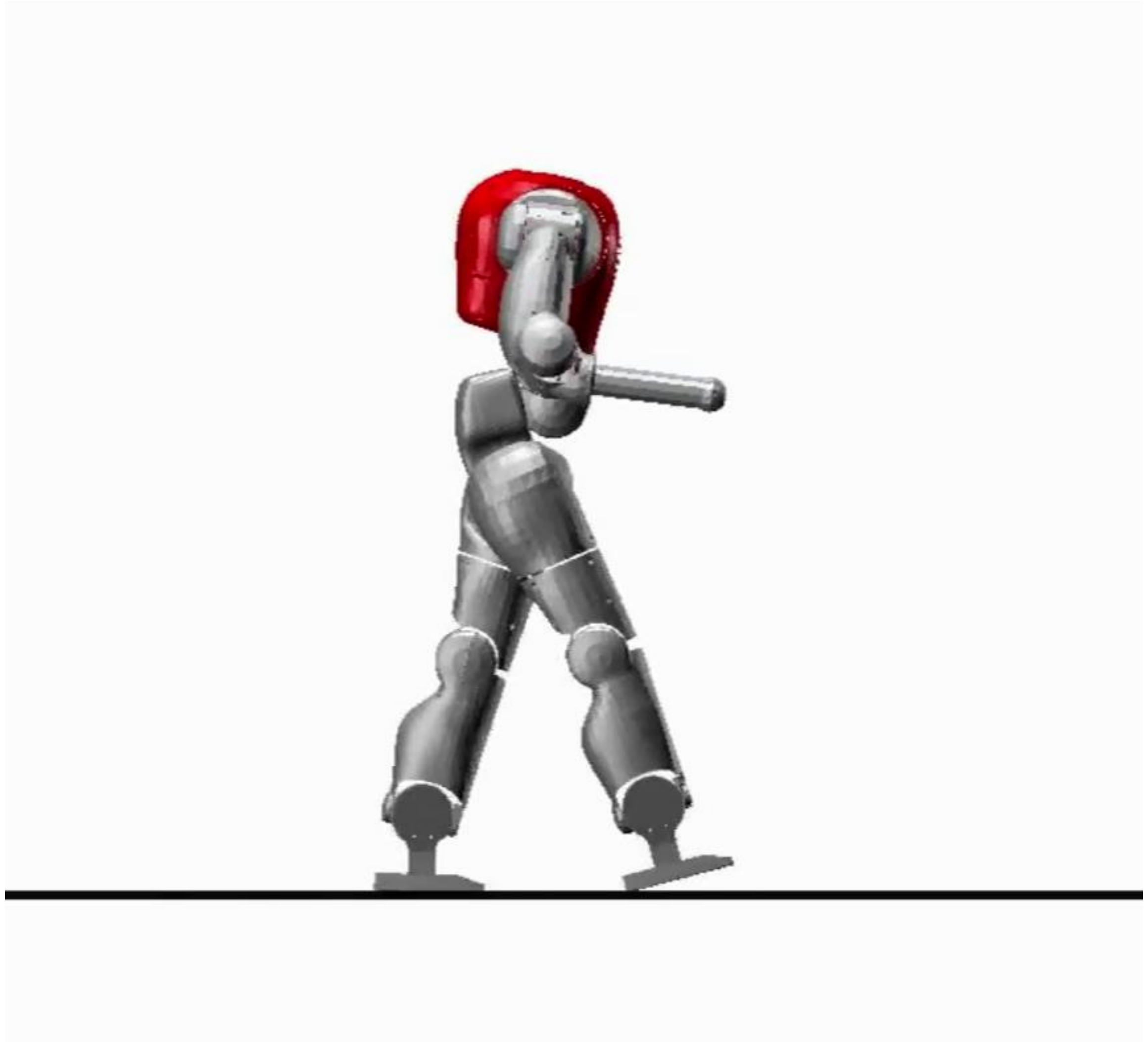
Optimized simulation gait for 2D scenarios



The reflex-based controller of [Geyer and Herr, 2010] is optimized in a **2D simulation environment**.

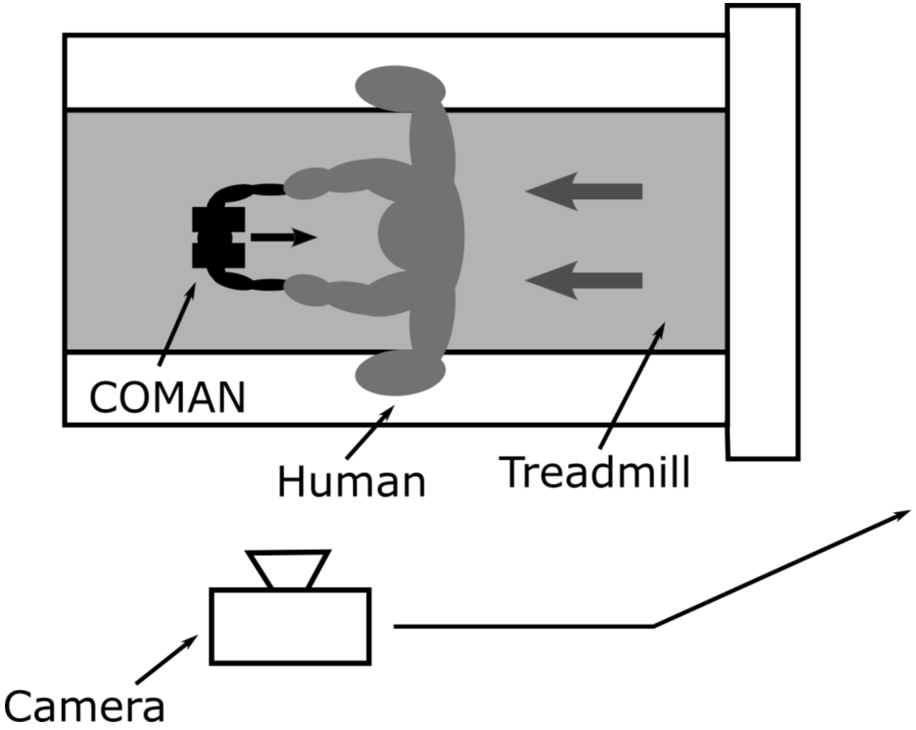
➡ The **exact same controller** is ported to the real robot.

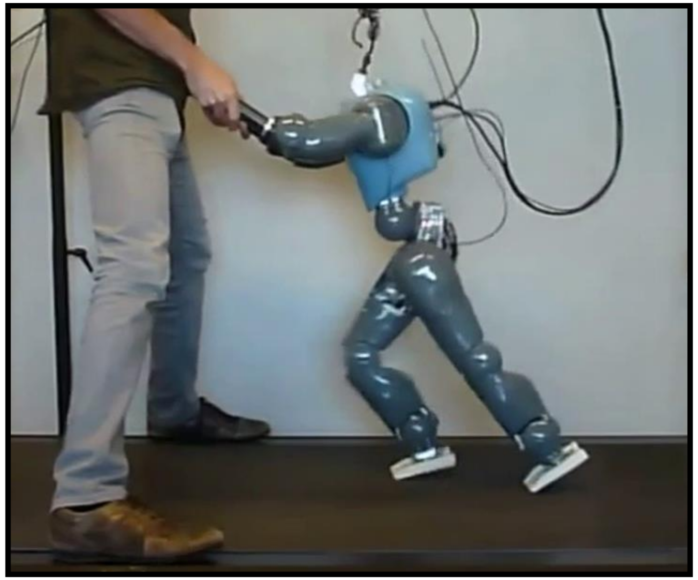
Lateral balance – experimental setup

Lateral balance

- constraints in simulation
- upper-body control on the real robot

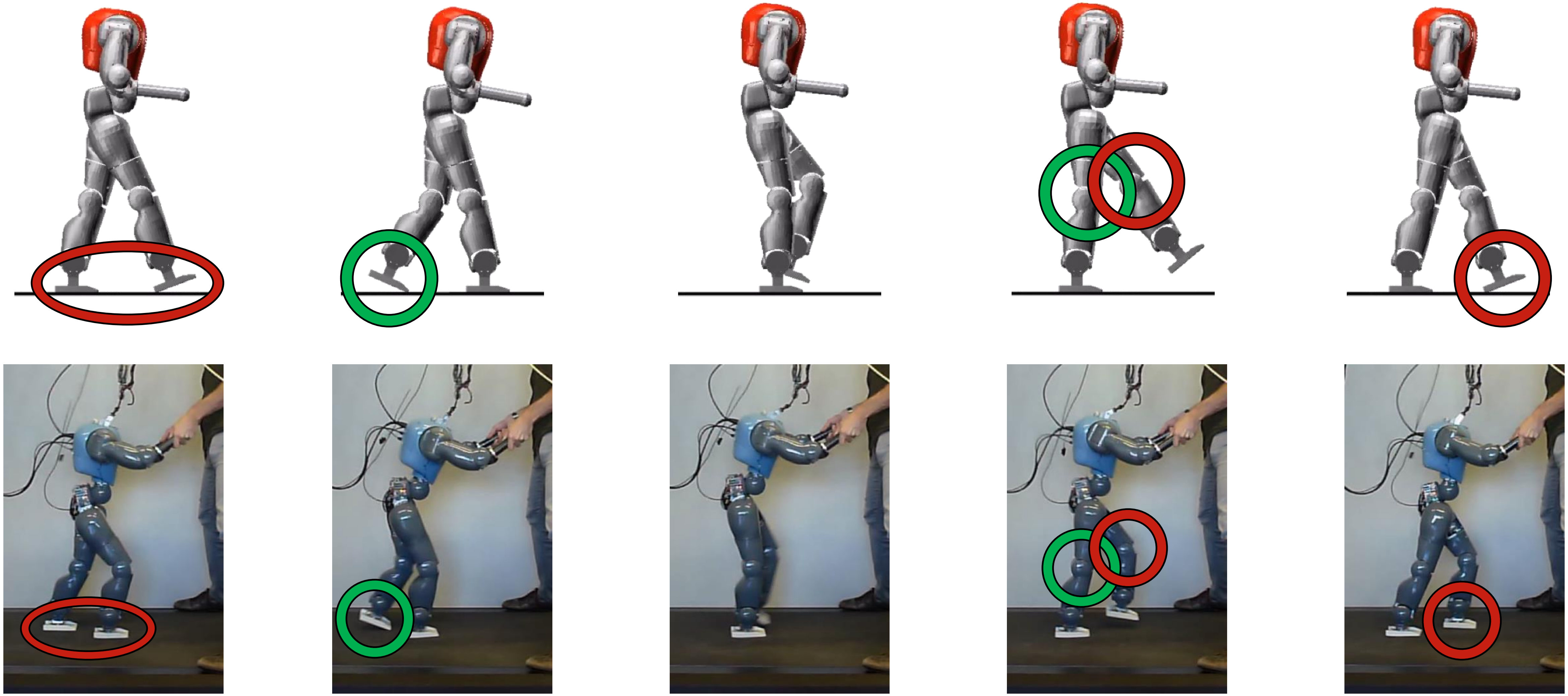
➡ **Help from a human operator**





Experimental validation on a treadmill

Simulation and experimental gaits



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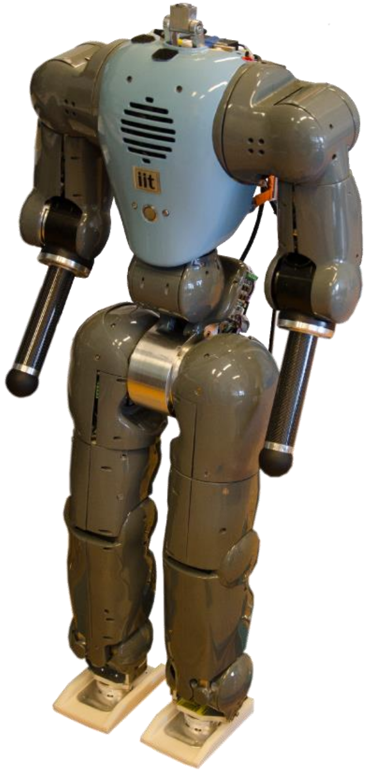
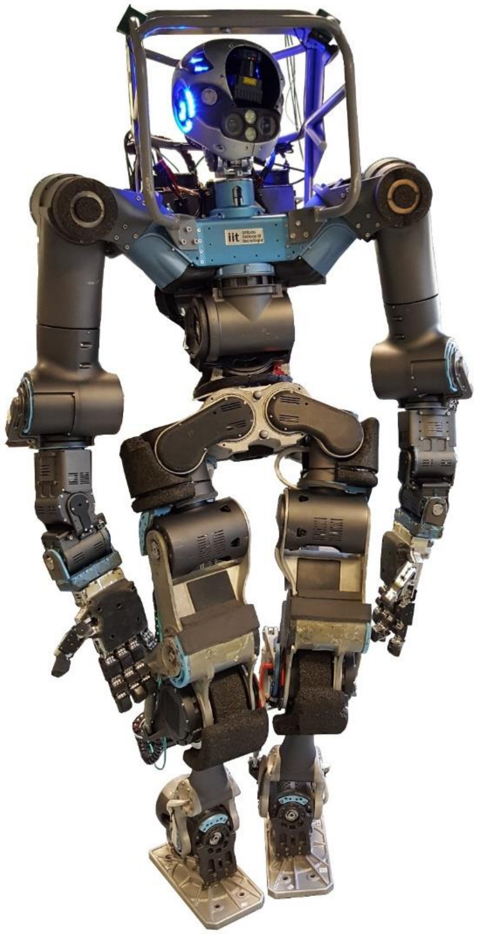
Adaptation to different robots

NAO



COMAN

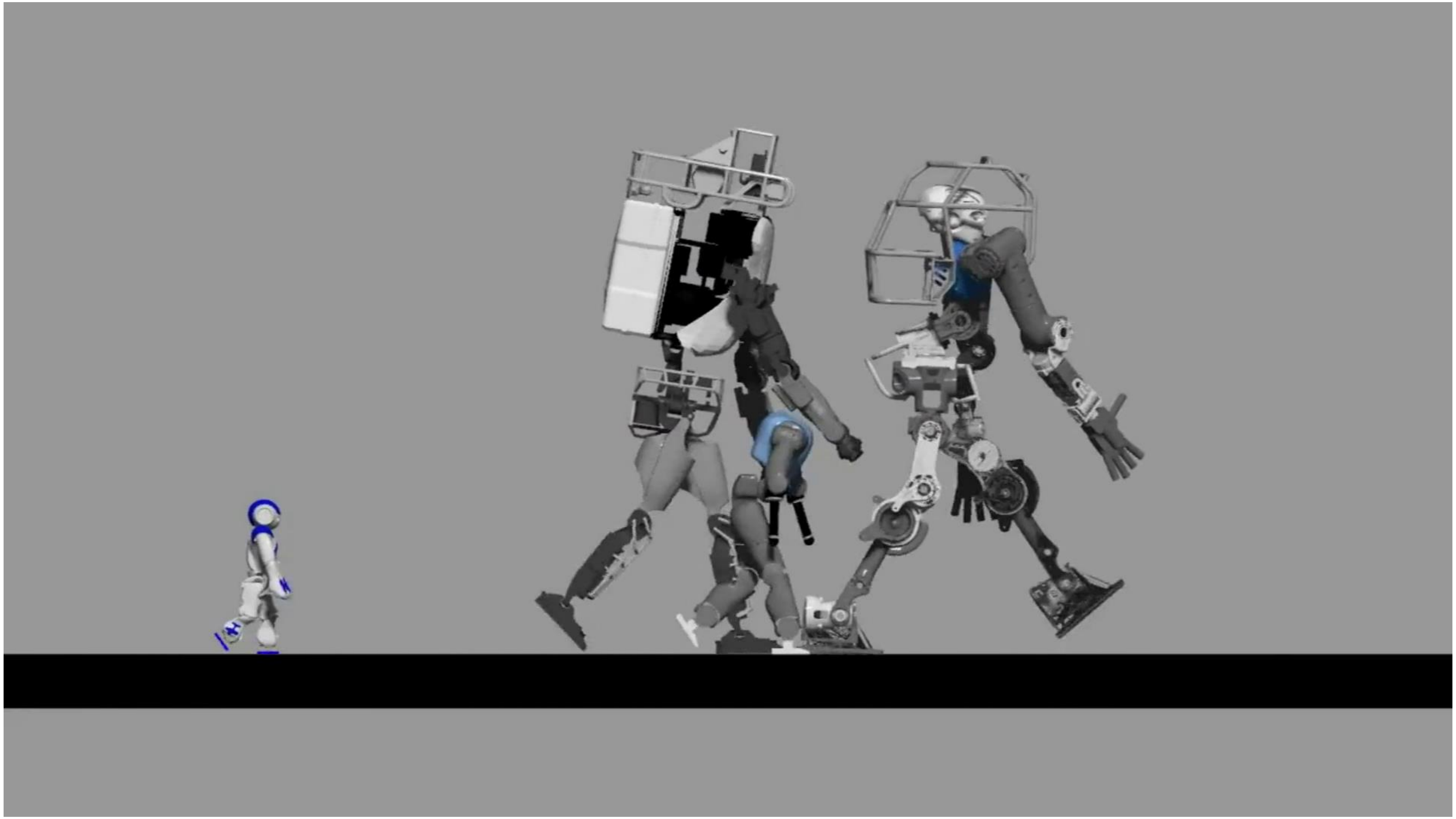


WALK-MAN

ATLAS

Adrien De Coninck

2D walking with different robots



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- Walking gaits
- Running gaits

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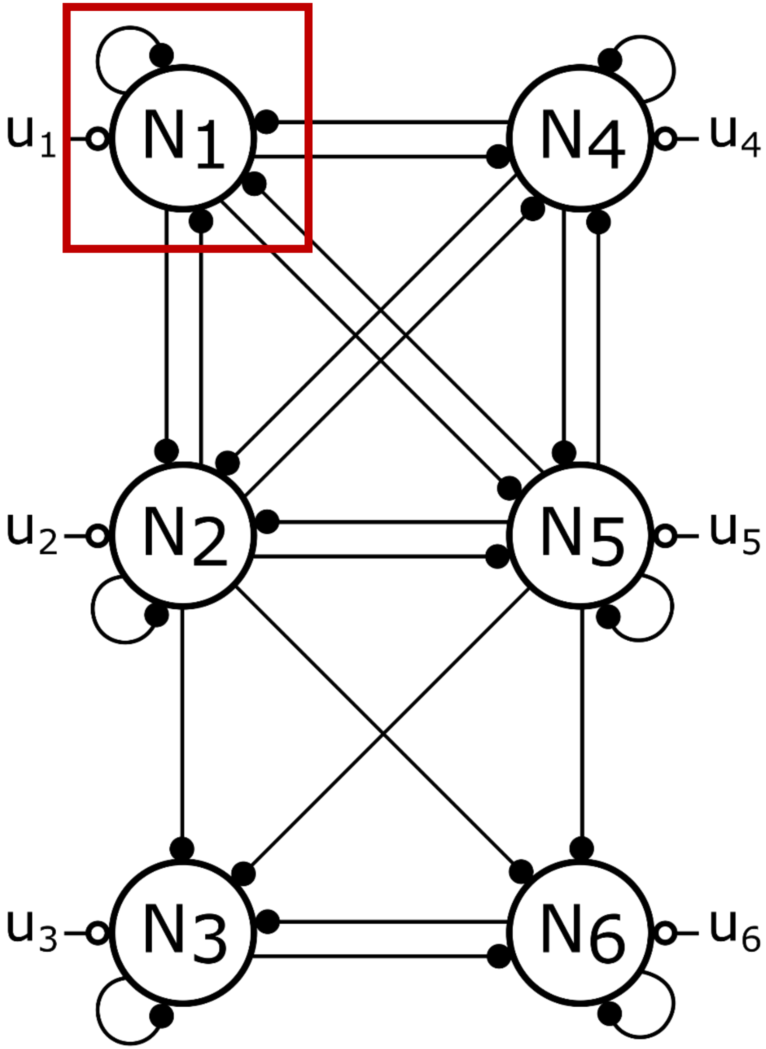
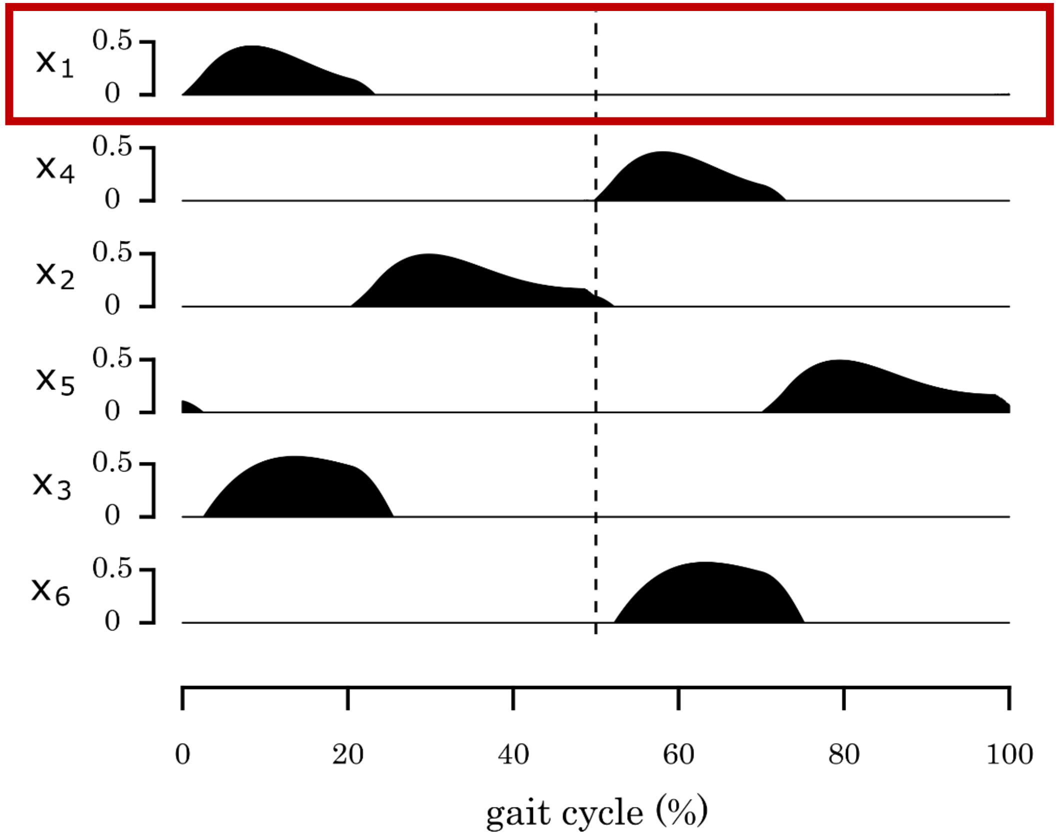
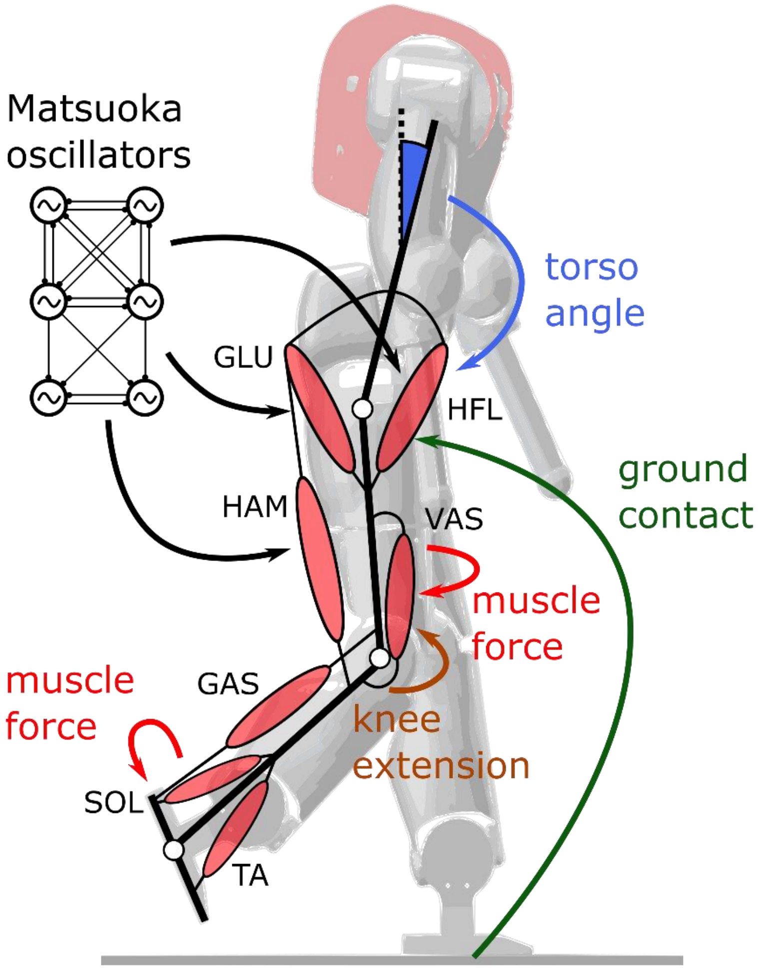
Central pattern generator (CPG)





2D walking gaits



Combining reflexes with a CPG

- Proximal muscles mainly driven by CPG
- Distal muscles mainly driven by reflexes

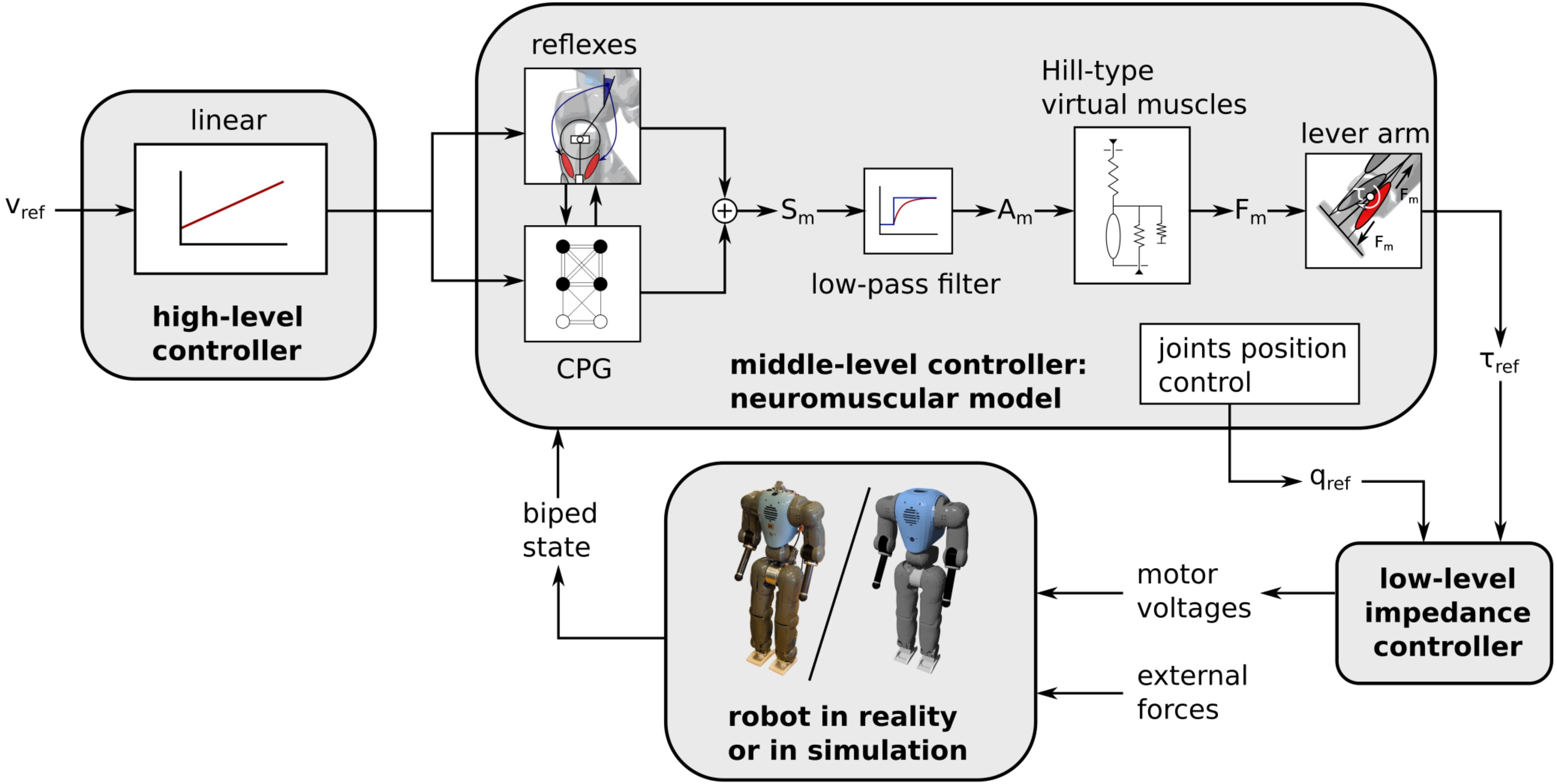
High-level parameters adapted as linear functions of the target speed

- 4 CPG parameters
- 1 reflex parameter

Getting different gaits

- Speeds ranging from 0.4 m/s to 0.9 m/s
- All parameters co-optimized in one single optimization

General control framework



v_{ref}

linear

high-level controller

reflexes

CPG

S_m

low-pass filter

A_m

Hill-type virtual muscles

F_m

lever arm

F_m

F_m

middle-level controller: neuromuscular model

joints position control

τ_{ref}

q_{ref}

biped state

robot in reality or in simulation

motor voltages

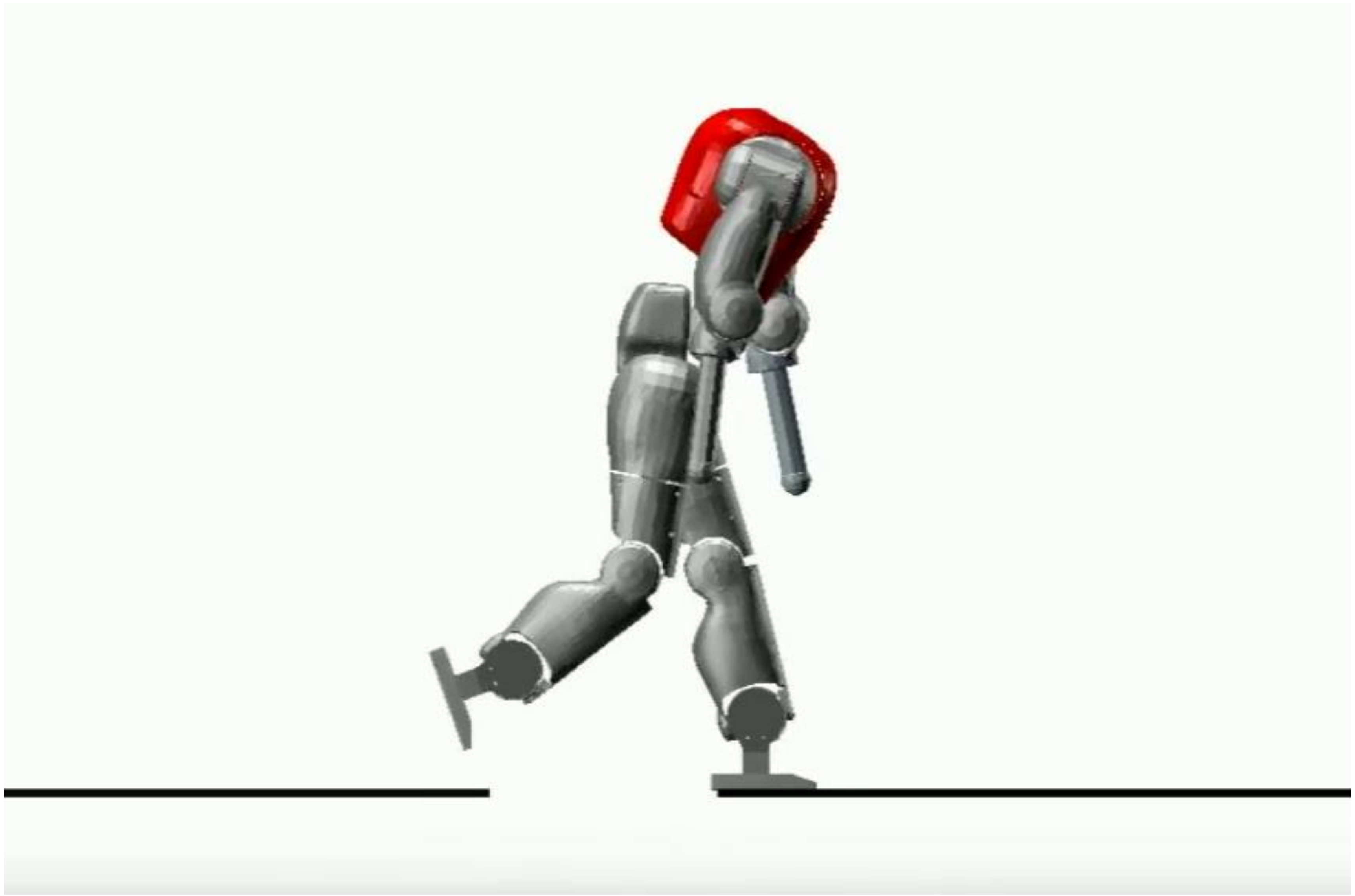
external forces

low-level impedance controller

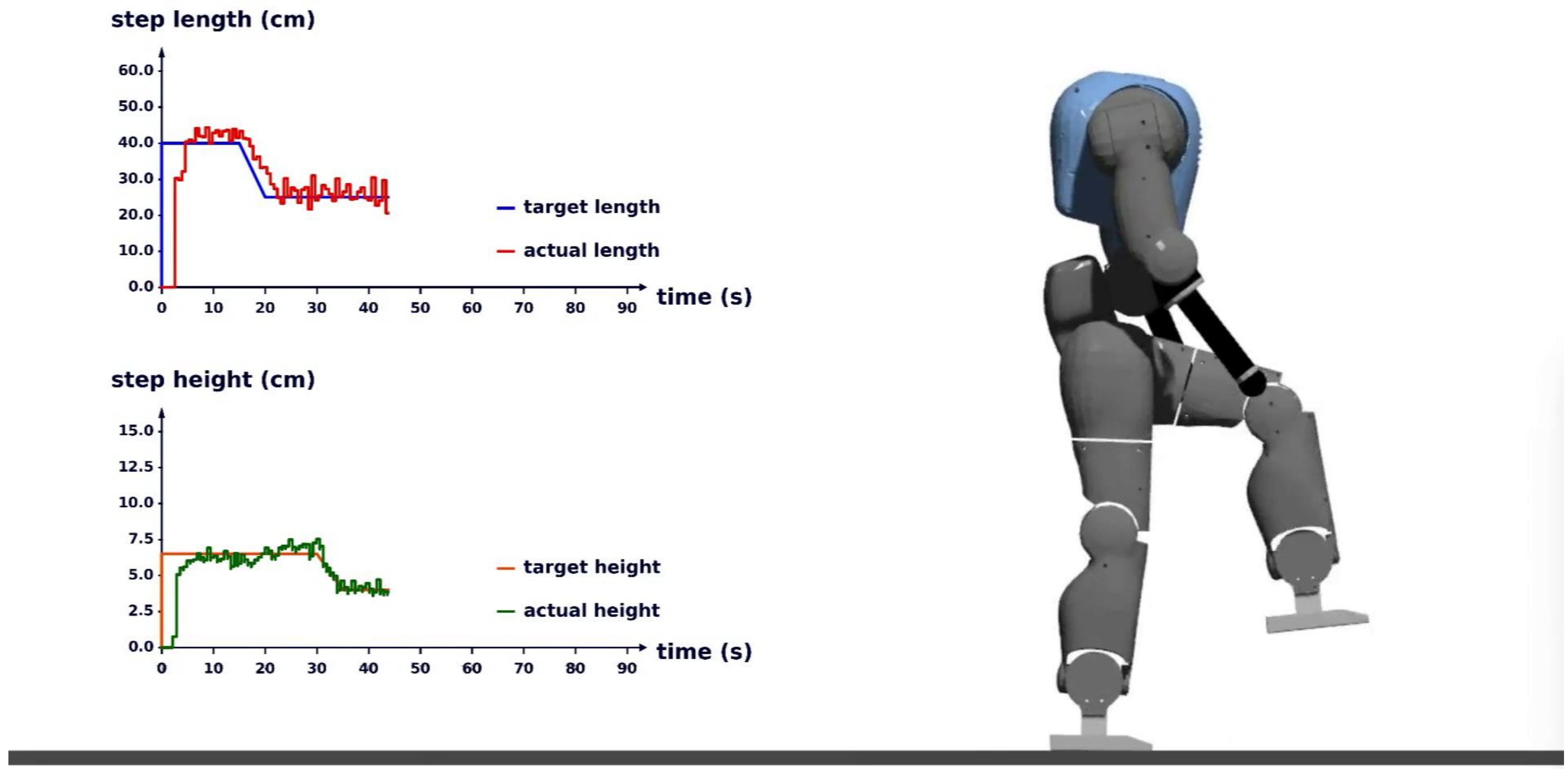
Forward speed modulation during 2D walking

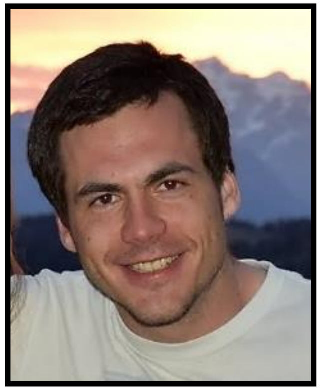
stride length and
stride frequency
continuously adapted

Crossing a hole with step length modulation



Steph height and length adaptations





Philippe Greiner

Outline

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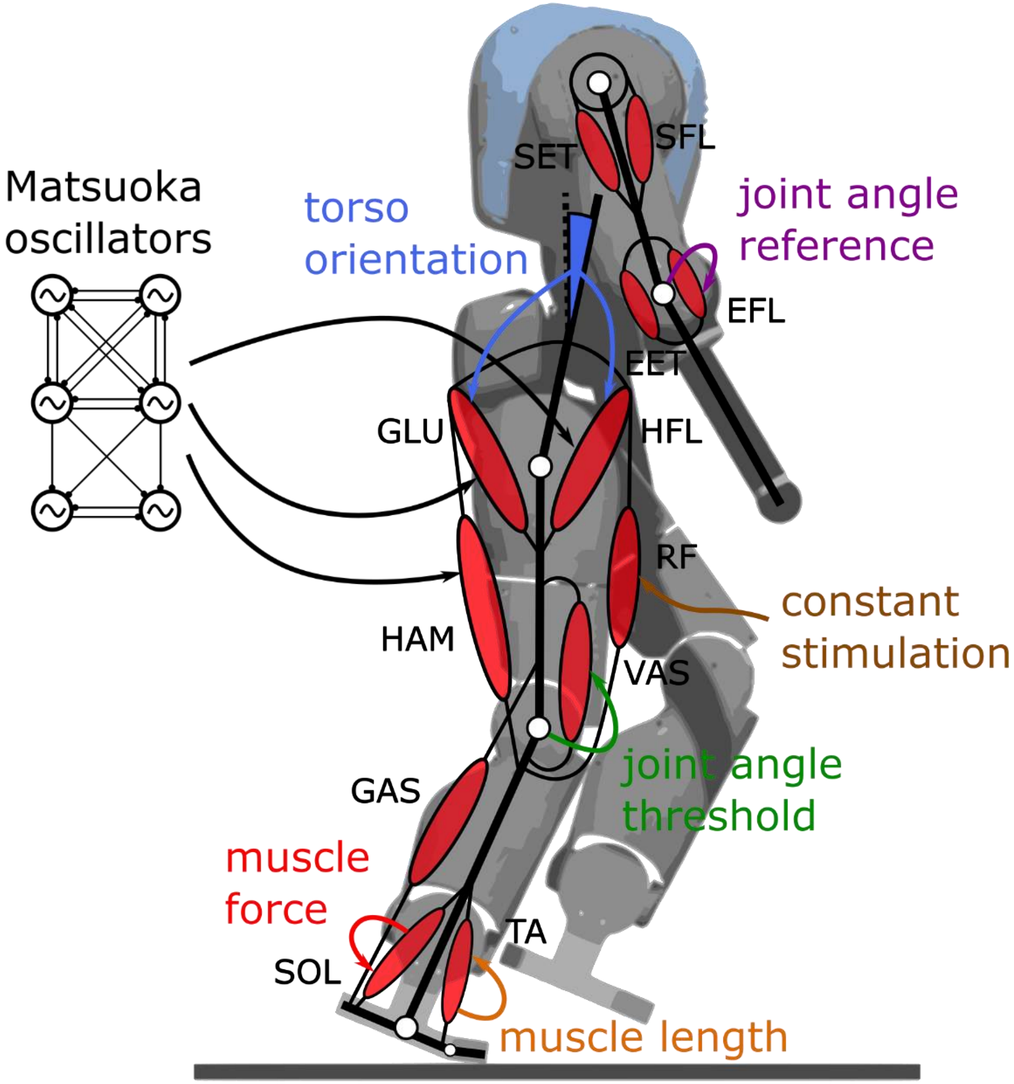
- Walking gaits
- Running gaits

Steering control in 3D scenarios

Conclusion

2D running gaits



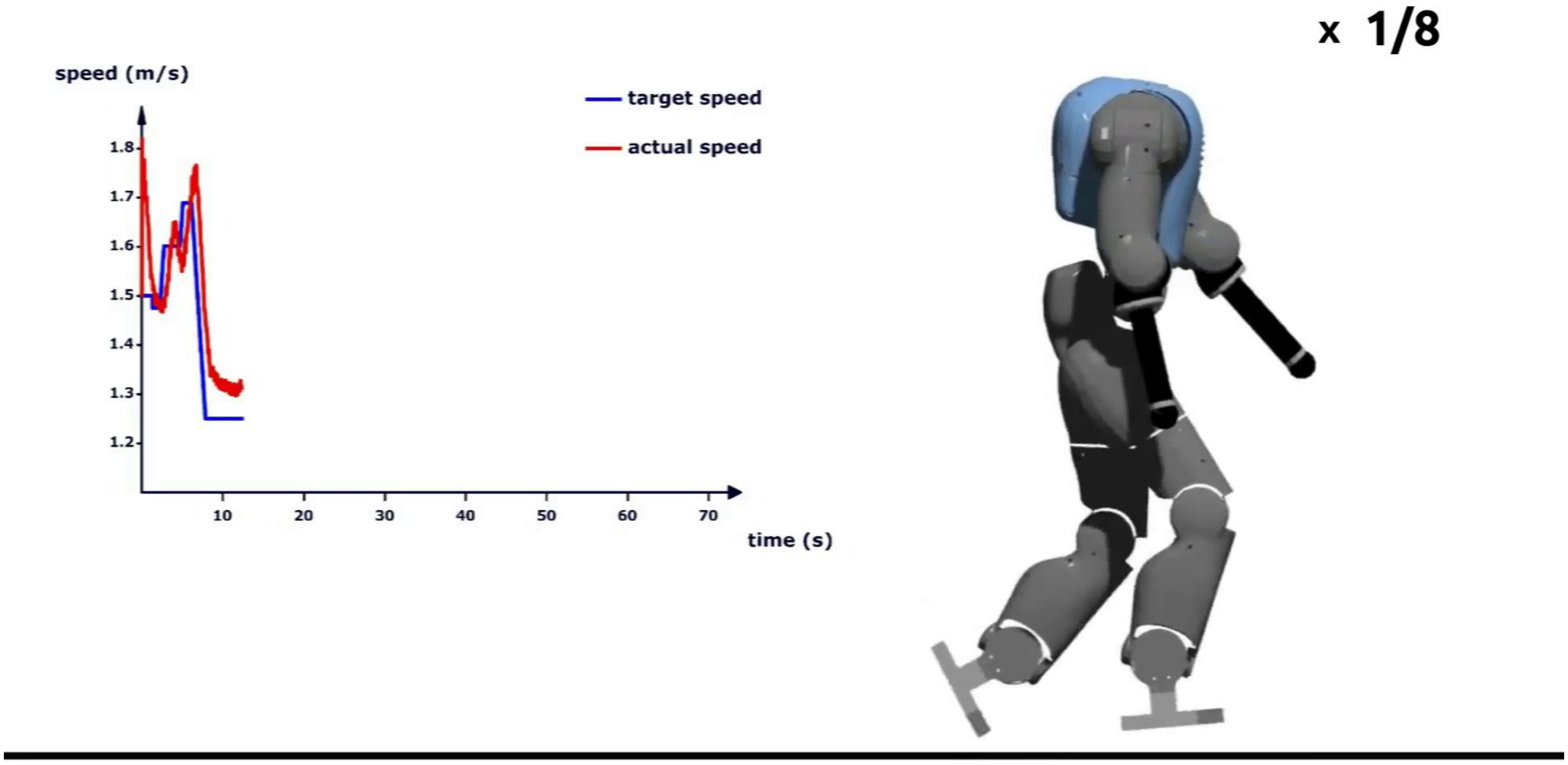
Extension to running gaits

- High-level parameters modulated as functions of the target speed
- All parameters co-optimized in one single optimization
- Speeds ranging from 1.3 m/s to 1.7 m/s


Bruno Somers


Matthew Harding

Forward speed modulation during 2D running



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- Bio-inspired balance controller
- Straight walking
- Heading control

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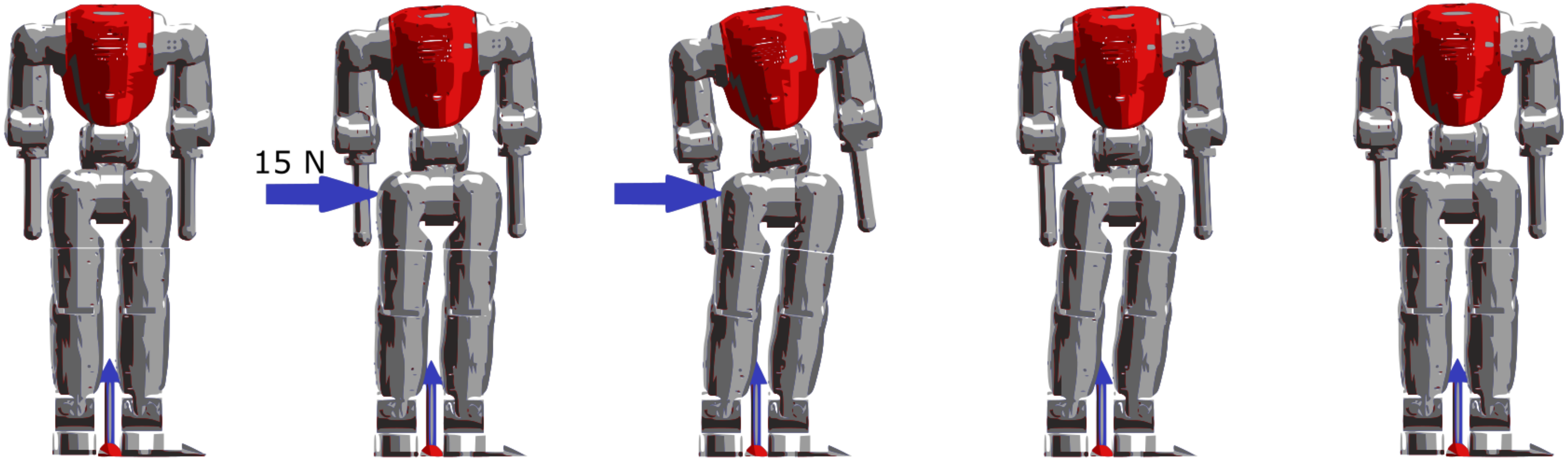
Bio-inspired balance controller

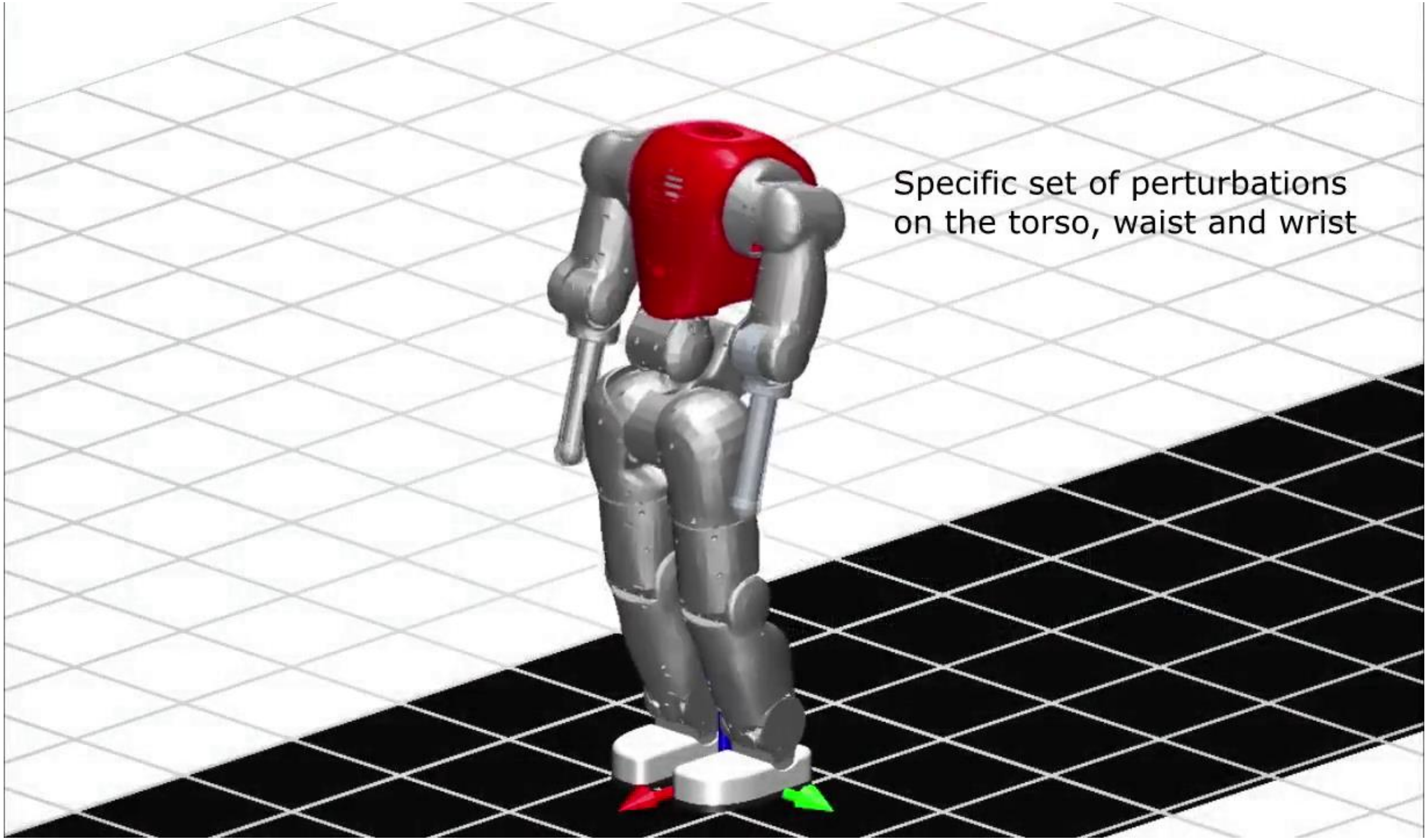


Balance controller

- Resist to external perturbations
- Automatically learn stimulation patterns
- Control the center of mass (COM) position

François Heremans

Resisting to external perturbations



Specific set of perturbations on the torso, waist and wrist

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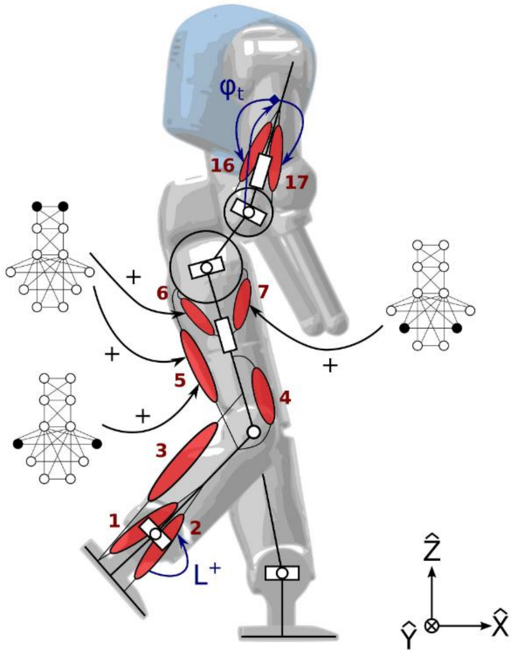
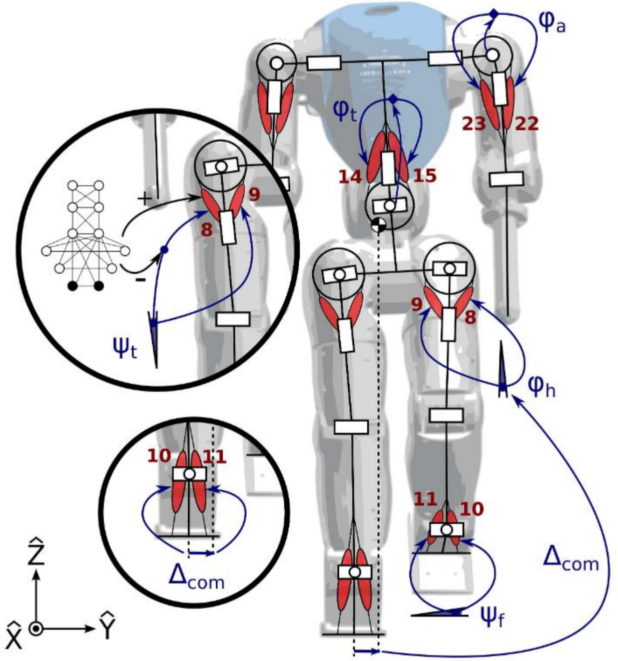
Extension to 3D control

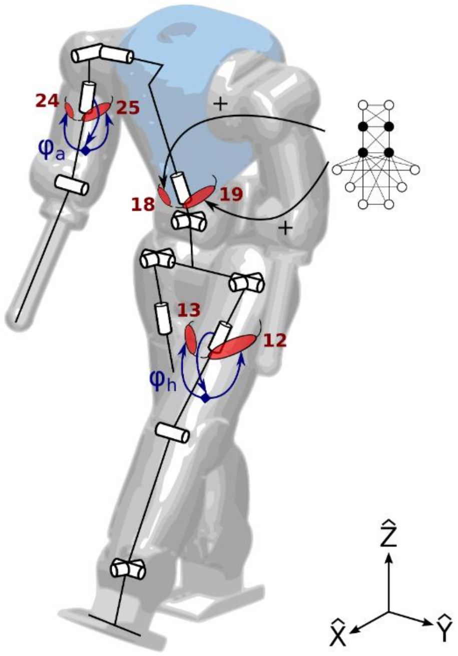
- New virtual **muscles** (in all the planes)
- New **reflex** signals
- **CPG** structure incremented



Sagittal plane

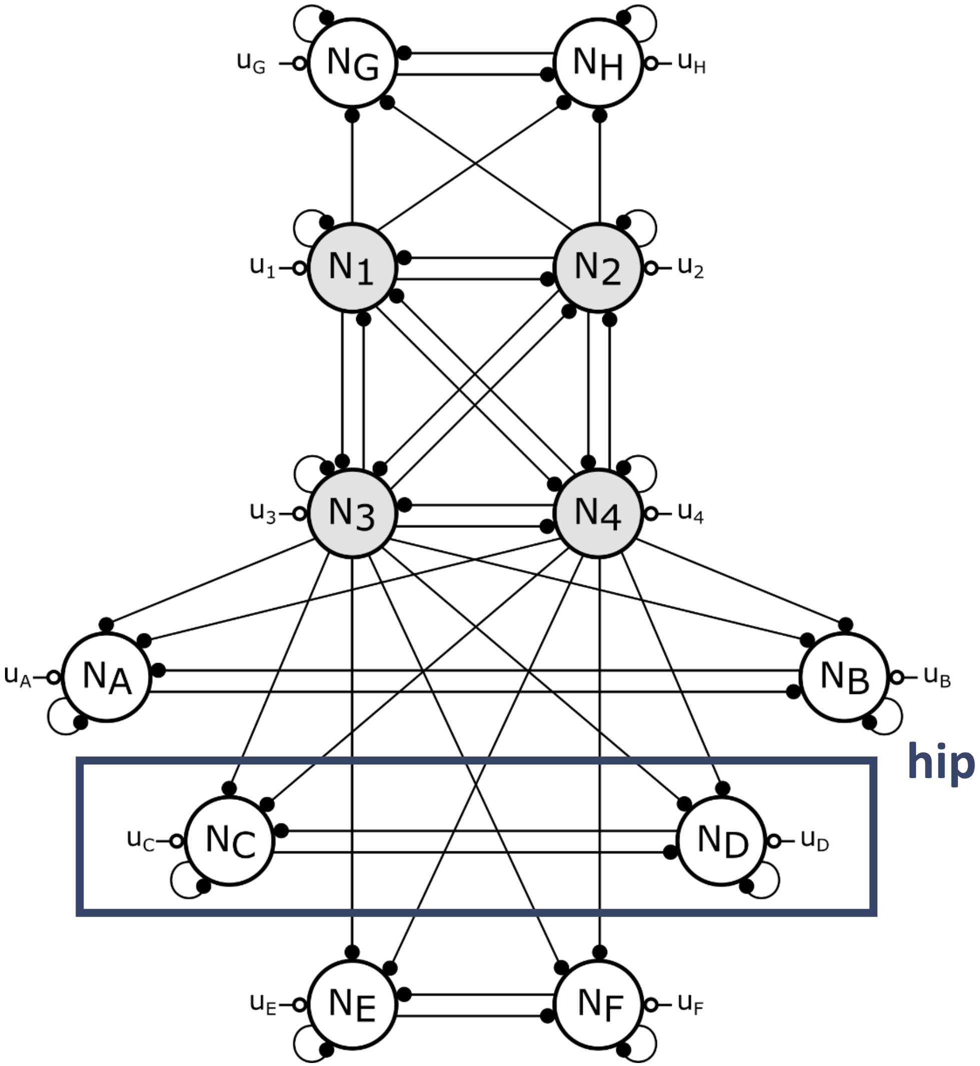


Lateral plane

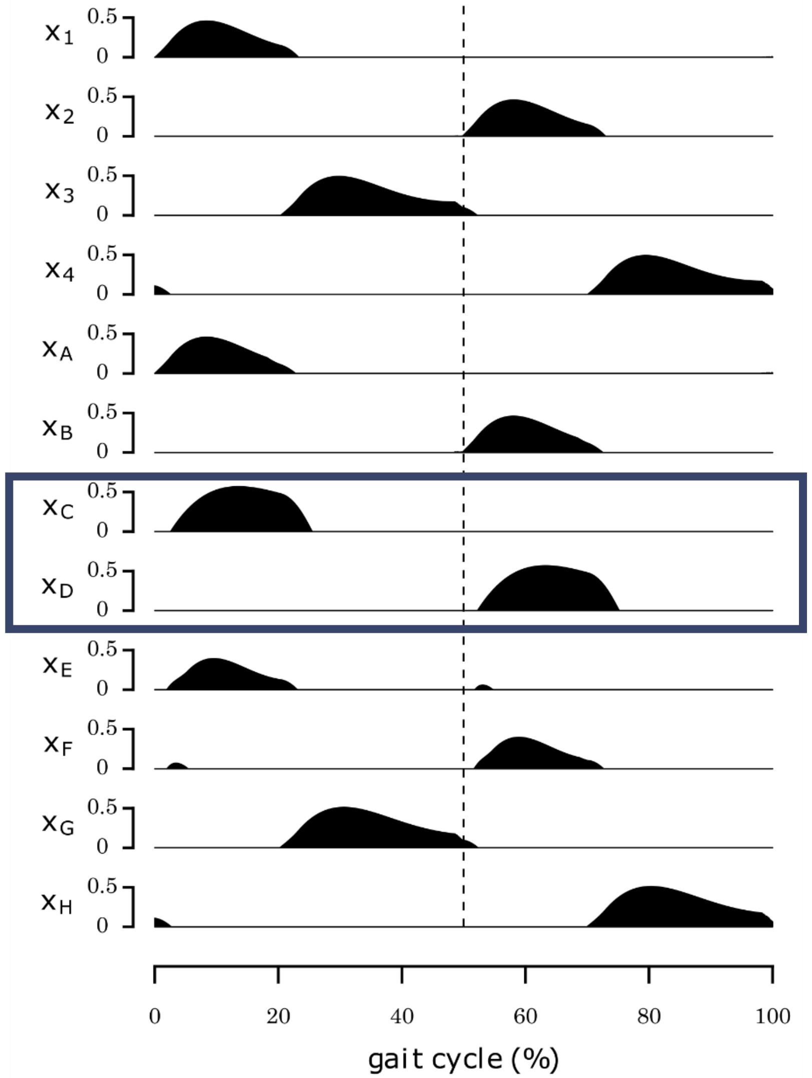


Transverse plane

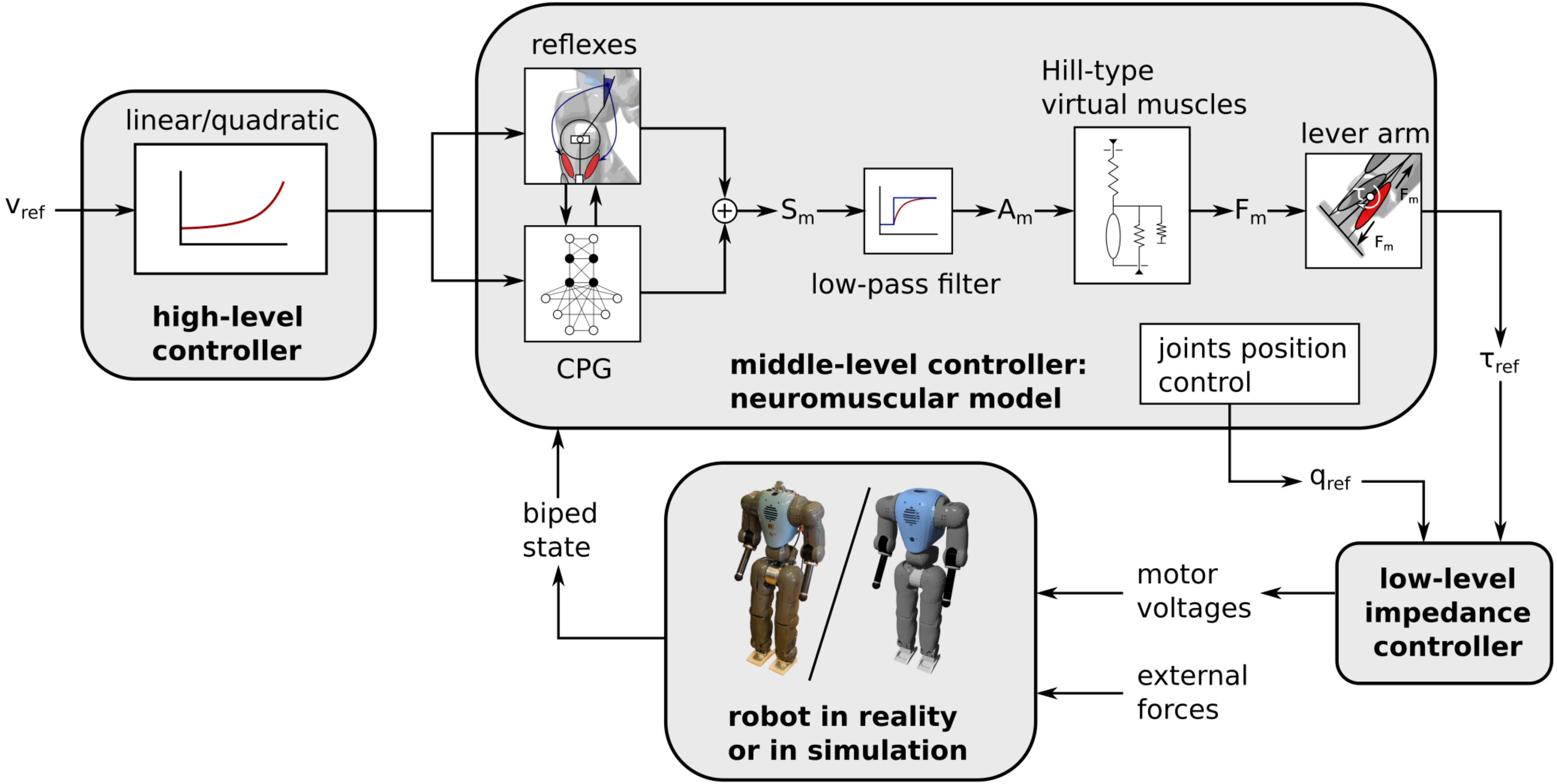
CPG structure for straight walking



hip flexion



General control framework



v_{ref}

linear/quadratic

high-level controller

reflexes

CPG

S_m

low-pass filter

A_m

Hill-type virtual muscles

F_m

lever arm

middle-level controller: neuromuscular model

joints position control

τ_{ref}

q_{ref}

low-level impedance controller

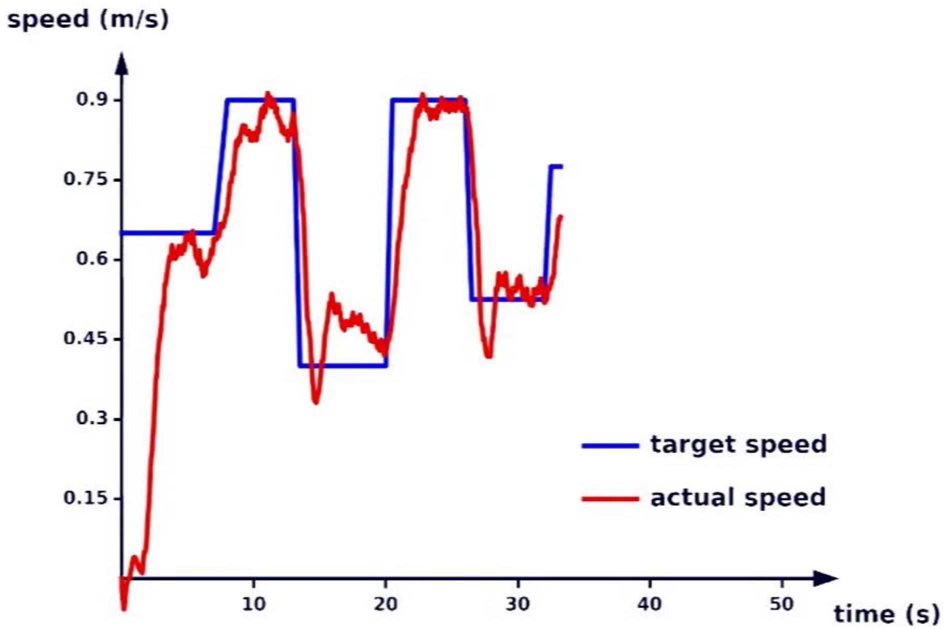
motor voltages

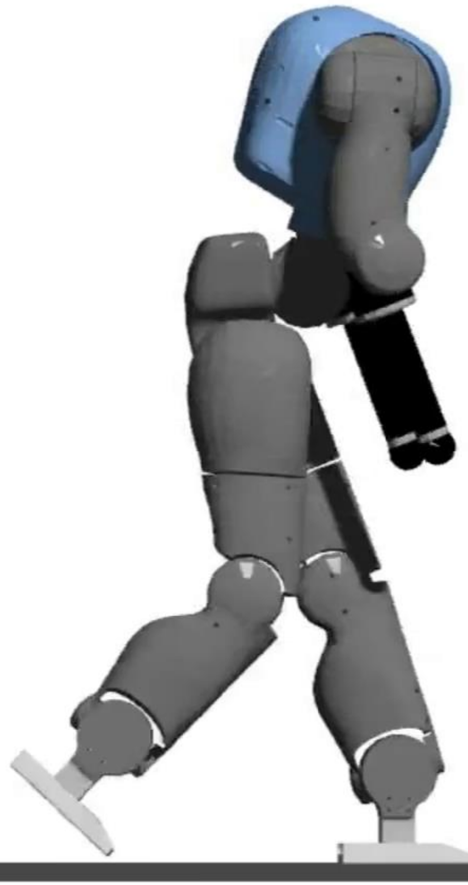
external forces

robot in reality or in simulation

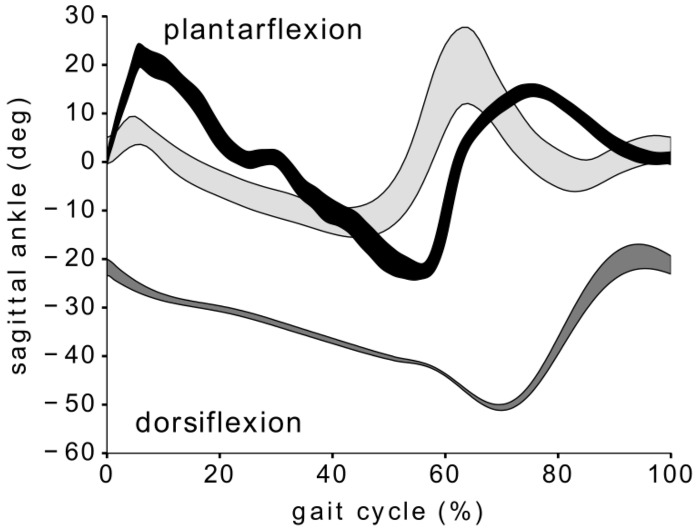
biped state

Forward speed tracking

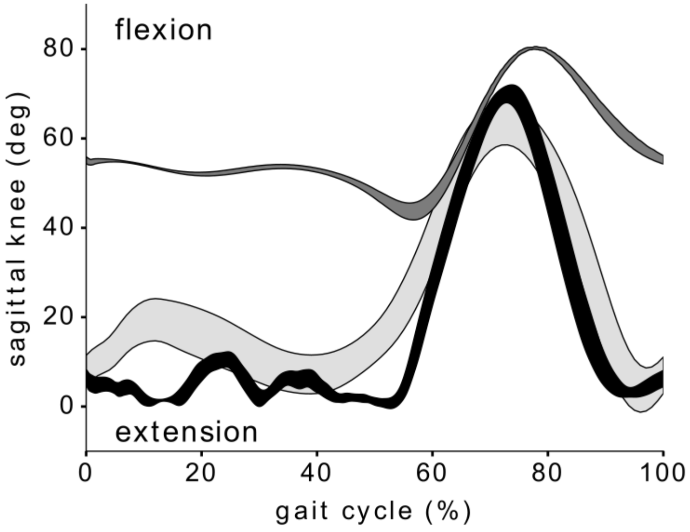




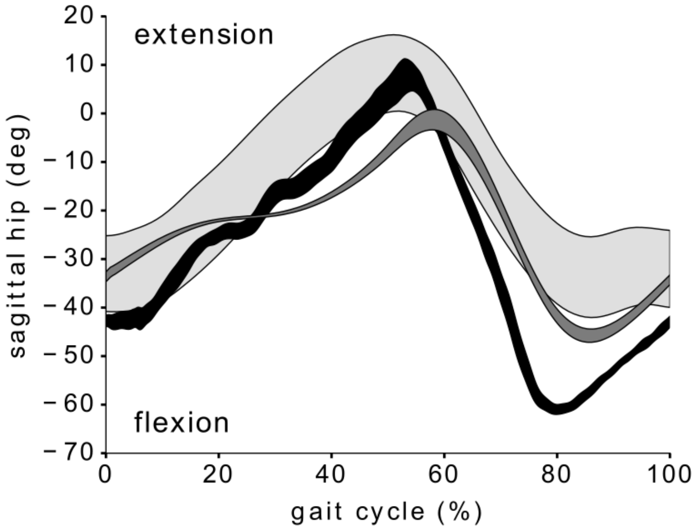
Comparisons to human and tradional data



sagittal ankle angle



sagittal knee angle



sagittal hip angle

■ neuromuscular

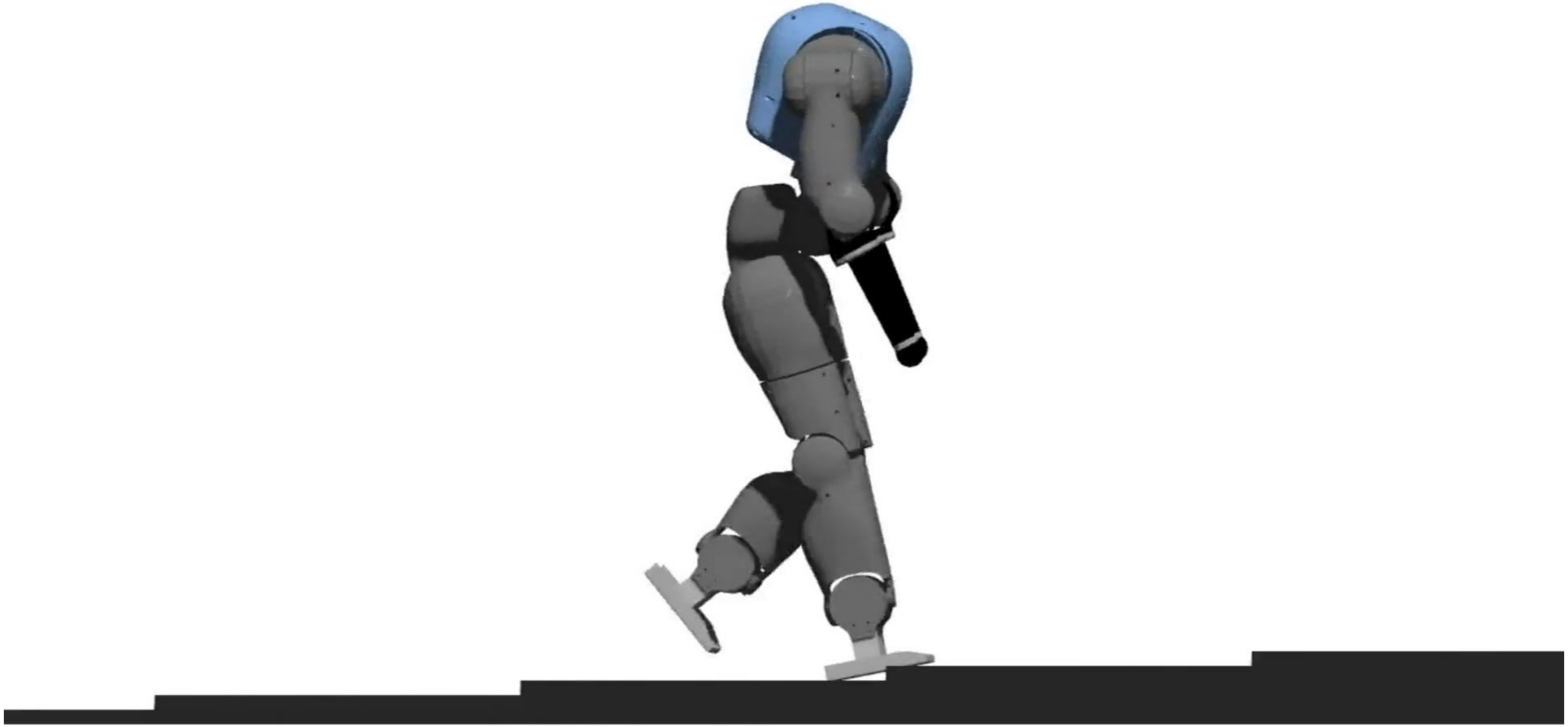
□ human-data

▨ traditional control

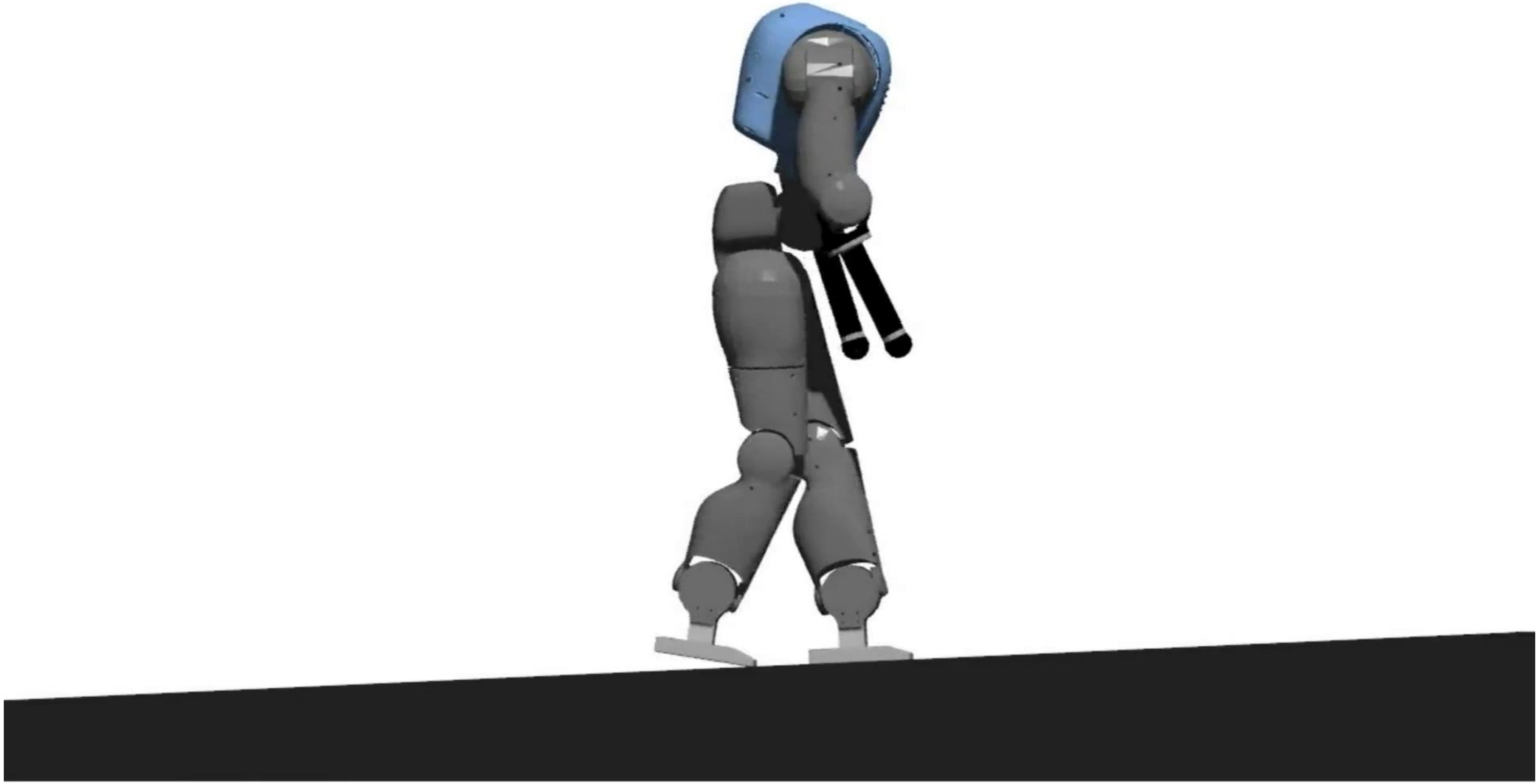
→ **Neuromuscular controller**

- more human-like
- more energetically efficient
- faster speeds

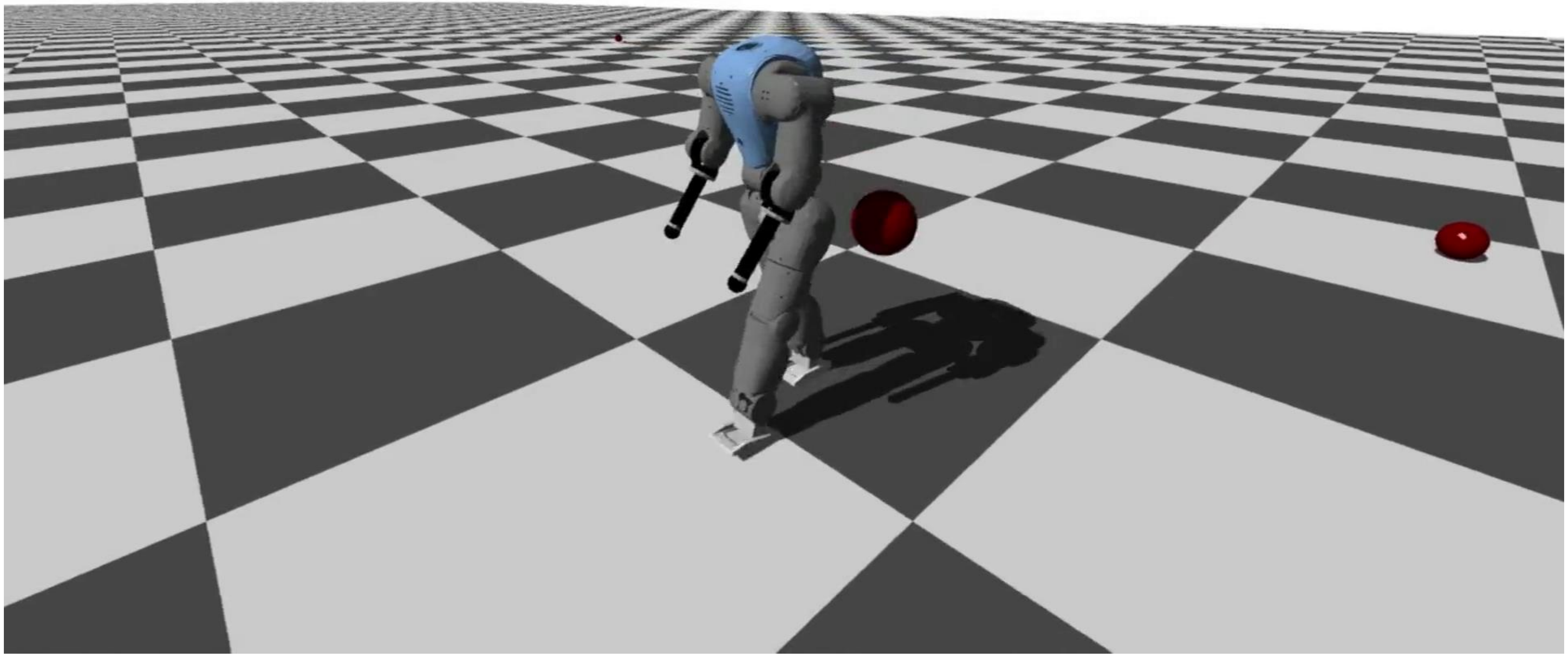
Blind walking: stairs



Blind walking: slope



Blind walking impacted by flying balls



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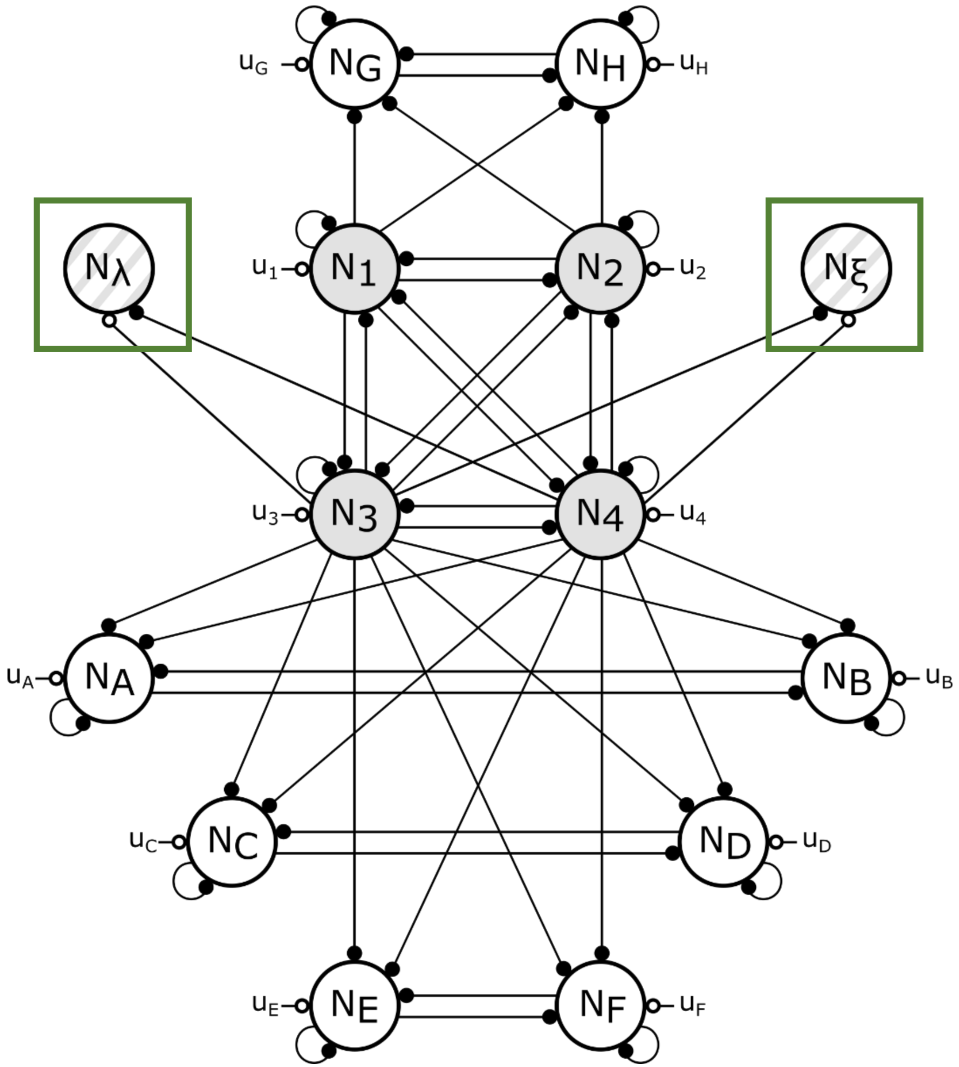
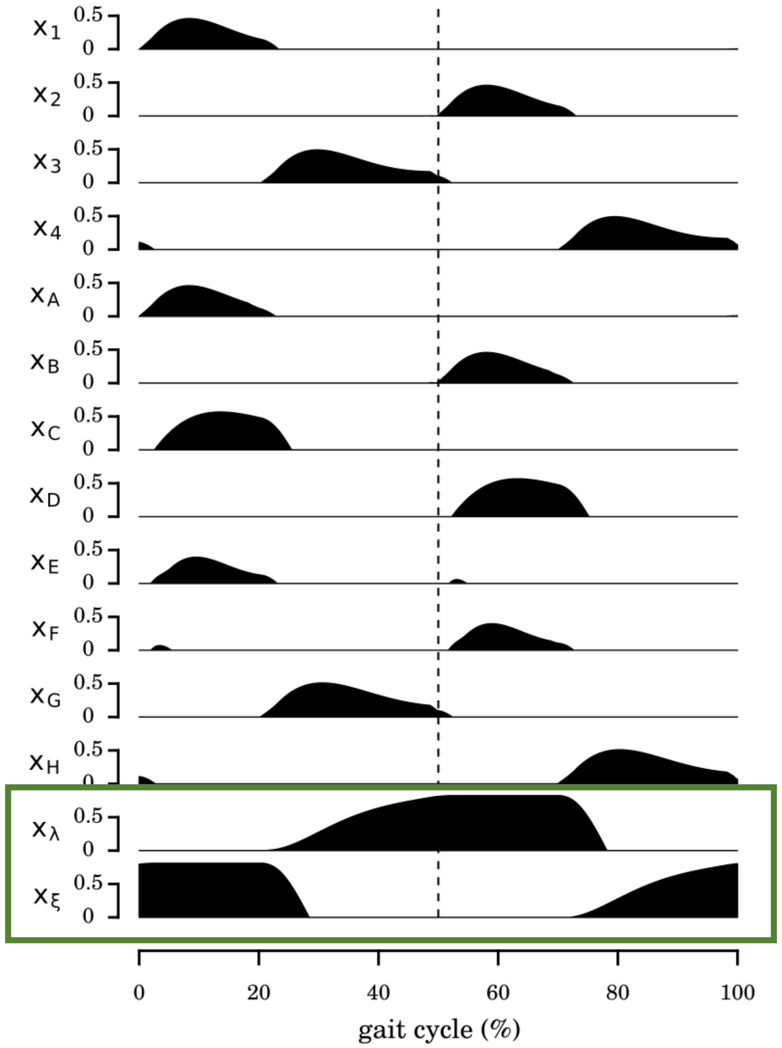
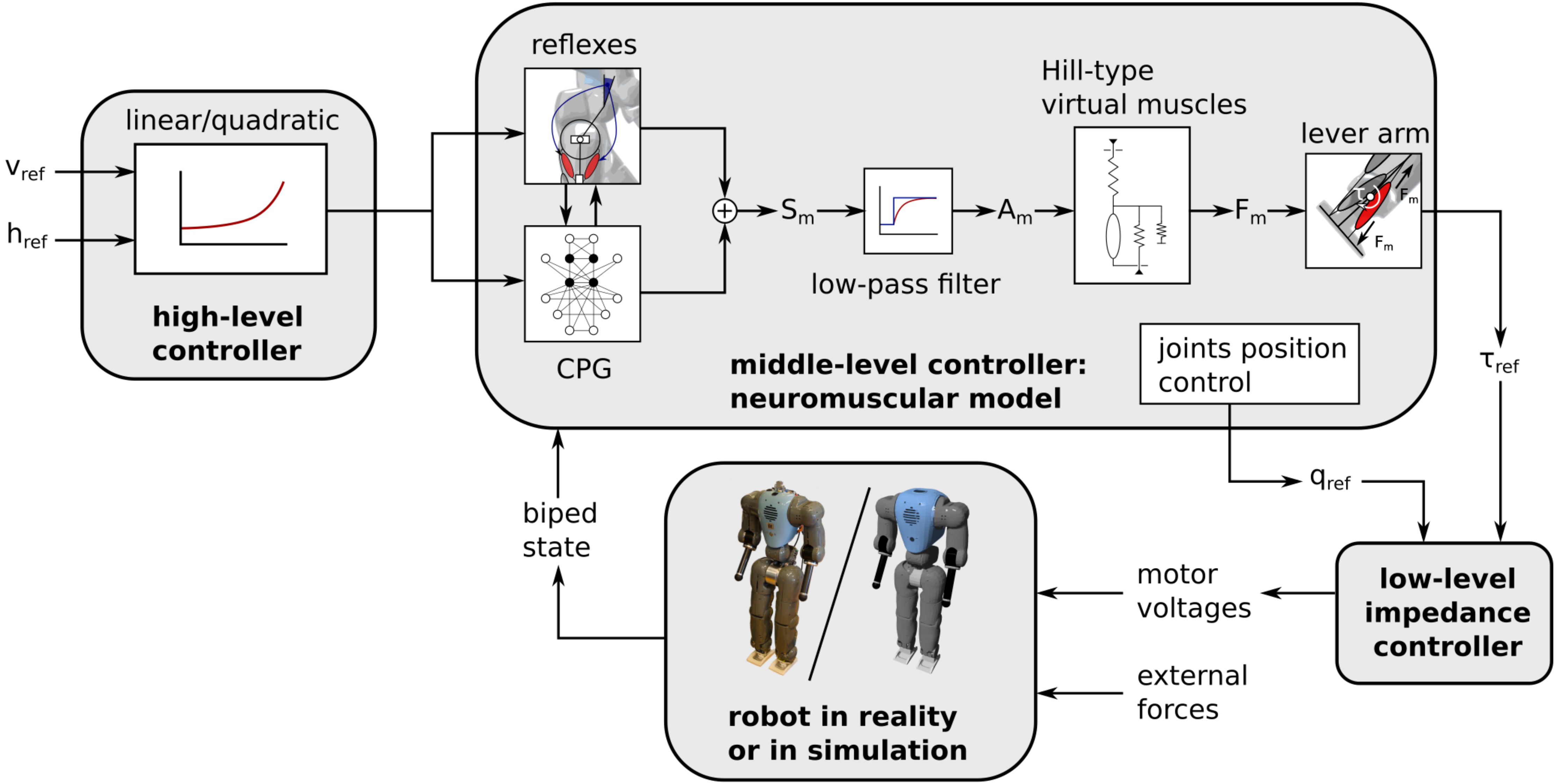
CPG structure for heading control

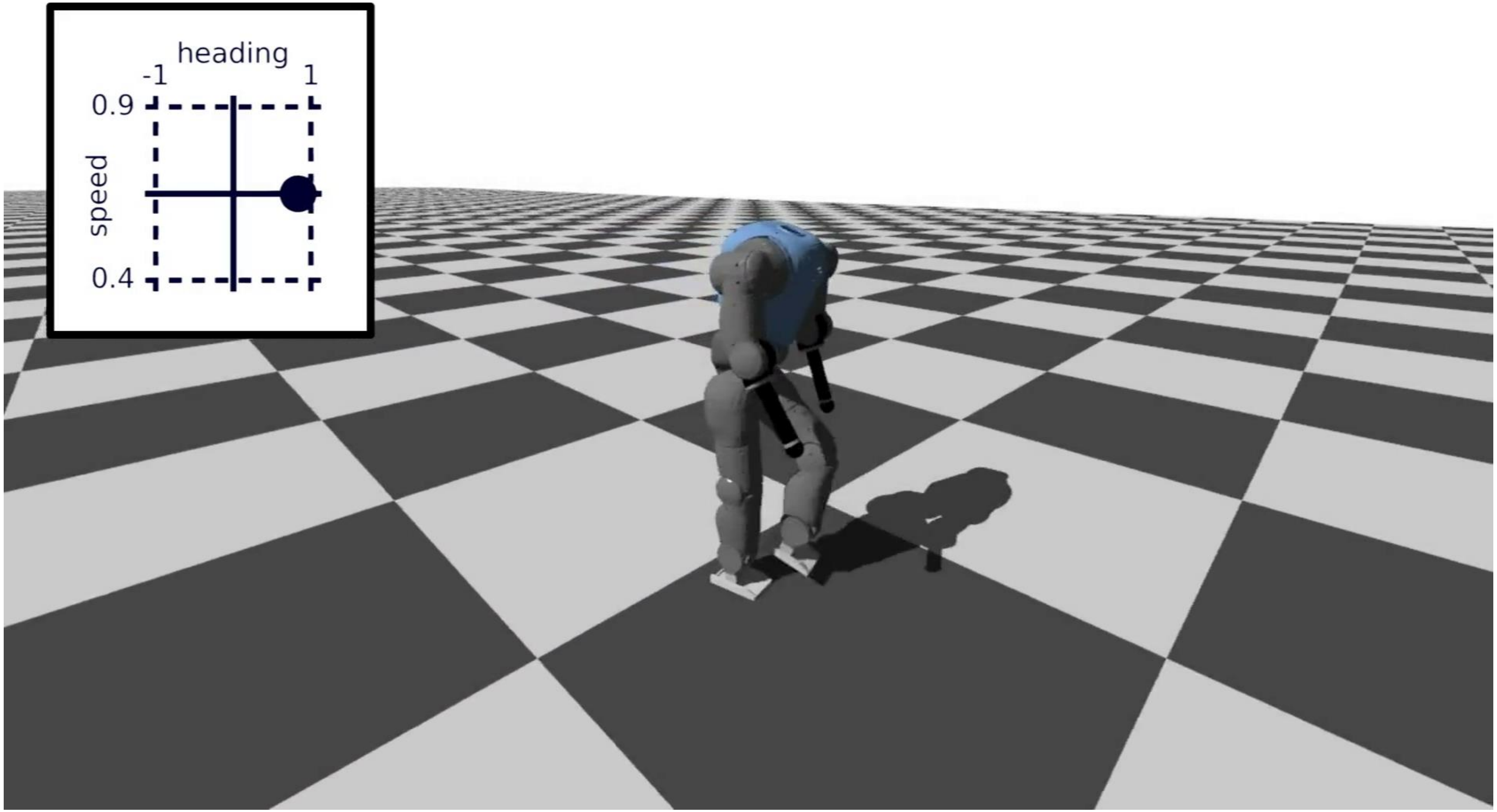




General control framework

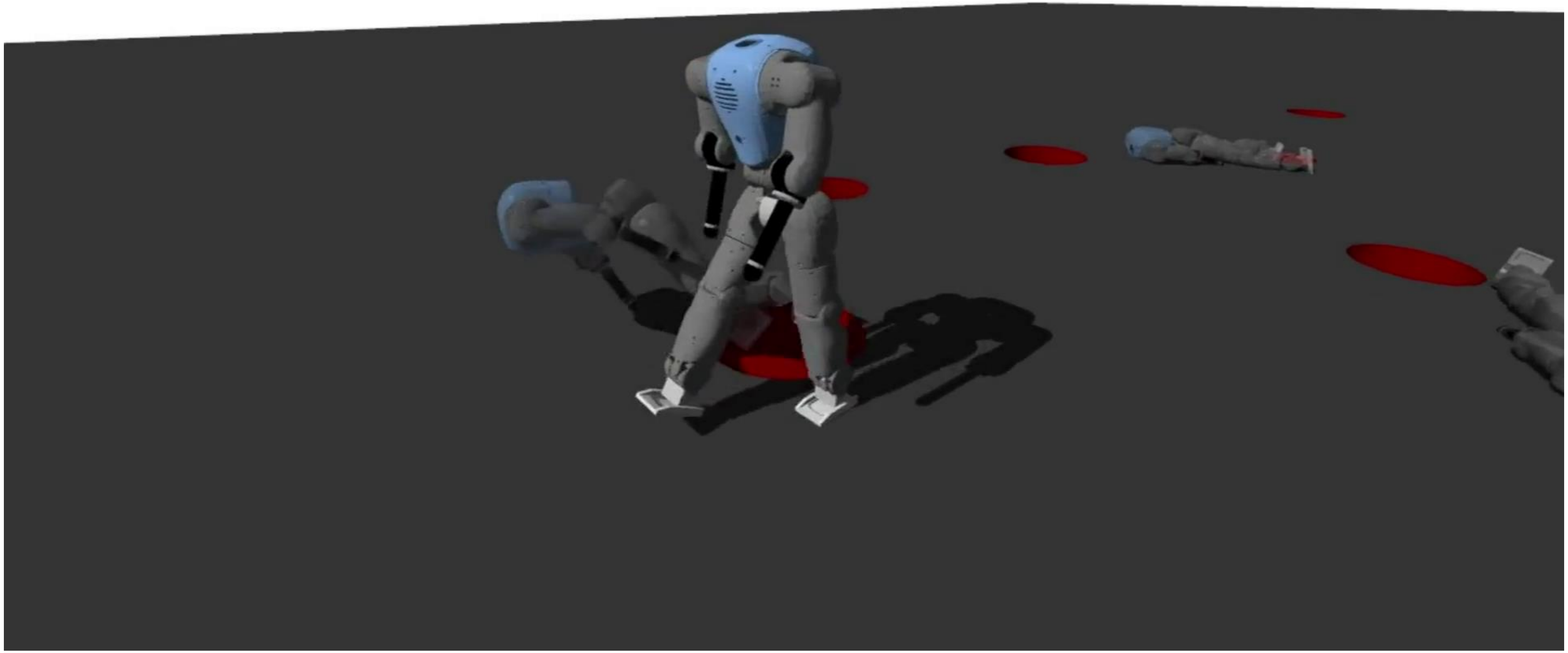


Forward speed and steering control



3D walking: avoiding holes

Depending on the commands received,
the walker either falls in a hole or escapes it.



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Original contributions

Reflex-based controller

- **Experimental** validation of a neuromuscular controller
- Porting the controllers to **different robots**
- Hill **muscle model** numerical integration
- Feet with human-like **compliance**

Gait modulation in 2D scenarios

- Gait modulation during **walking** gaits
- Speed modulation during **running** gaits

Steering control in 3D scenarios

- Bio-inspired **balance** controller
- Forward speed modulation during **straight** walking
- **Heading** modulation (steering control)

Future directions

- Extend the **panel of motions**
  - stairs climbing
  - side stepping
  - …
- Study **gait finalization**
- Obtain **slow walking** gaits
  - speeds below 0.3 m/s
- Investigate **real human** locomotion
- Test the 3D walking controller on a **real robot**
- …

Acknowledgements

Advisors

Prof. Renaud Ronsse

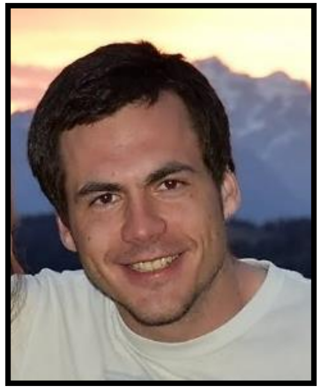
Prof. Auke Ijspeert

Master theses & semester project students

François Heremans

Adrien De Coninck

Bruno Somers



Philippe Greiner

Matthew Harding

Acknowledgements

CEREM

BioRob

Acknowledgements

List of publications

Journal papers

- **Van der Noot N**, Ijspeert AJ and Ronsse R (conditionally accepted) **Bio-inspired controller achieving forward speed modulation with a 3D bipedal walker**. *International Journal of Robotics Research*.
- Zobova AA, Habra T, **Van der Noot N**, Dallali H, Tsagarakis NG, Fisette P and Ronsse R (2017) **Multi-physics modelling of a compliant humanoid robot**. *Multibody System Dynamics* 39 (1-2), pp. 95-114.

Conference papers

- Heremans F, **Van der Noot N**, Ijspeert AJ and Ronsse R (2016) **Bio-inspired balance controller for a humanoid robot**. In: *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, Singapore, 26-29 June 2016, pp. 441-448.
- Colasanto L, **Van der Noot N** and Ijspeert AJ (2015) **Bio-inspired walking for humanoid robots using feet with human-like compliance and neuromuscular control**. In: *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*, Seoul, 3-5 Nov. 2015, pp. 26-32.

List of publications

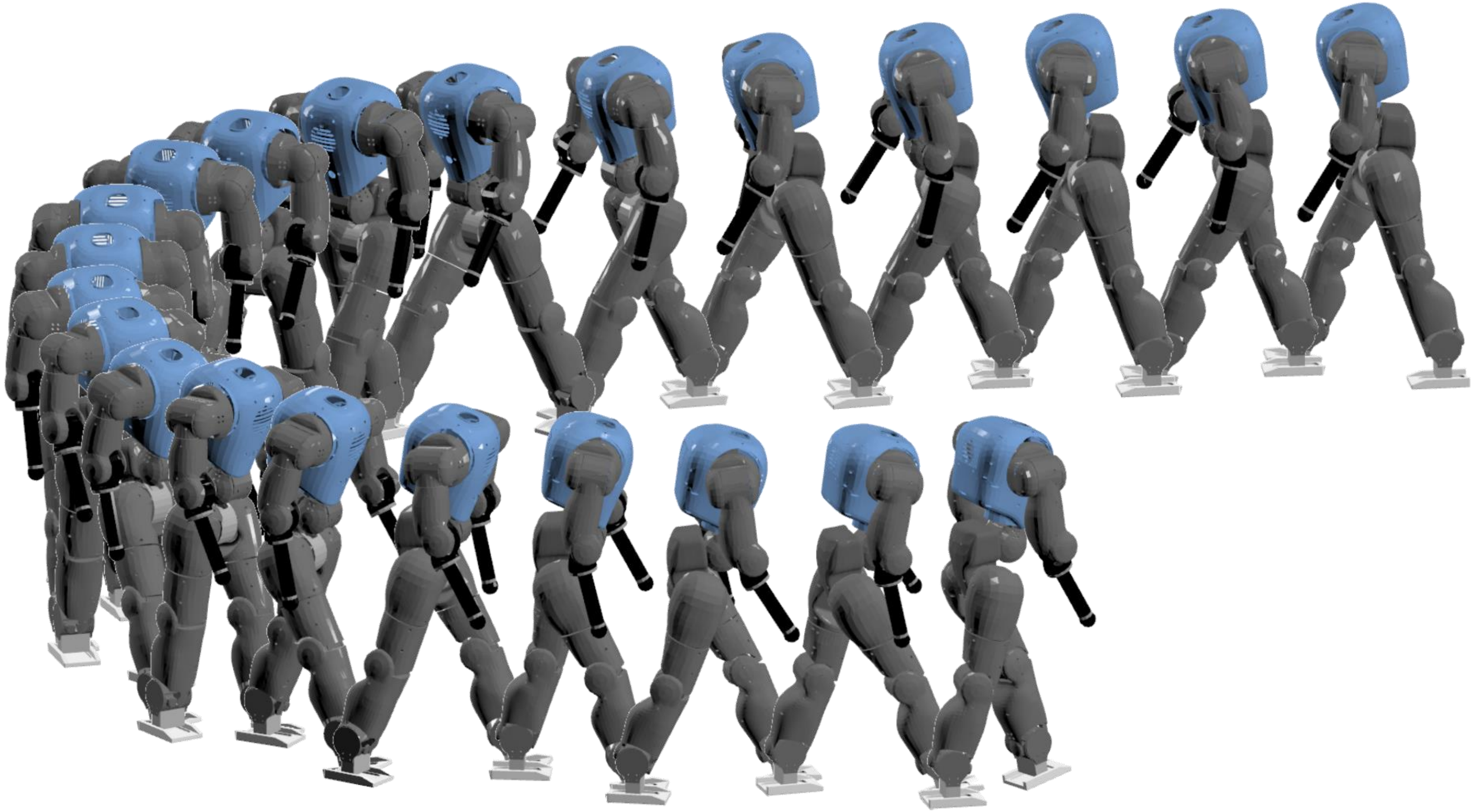
- **Van der Noot N**, Colasanto L, Barrea A, van den Kieboom J, Ronsse R and Ijspeert AJ (2015) **Experimental validation of a bio-inspired controller for dynamic walking with a humanoid robot**. In: *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Hamburg, Sept. 28 2015-Oct. 2 2015, pp. 393-400.
- Zobova AA, Habra T, **Van der Noot N**, Dallali H, Tsagarakis NG, Fisette P and Ronsse R (2015) **Multi-physics modelling of a compliant humanoid robot**. In: *ECCOMAS Thematic Conference Multibody Dynamics 2015*, Barcelona, 29 June-02 July 2015.
- **Van der Noot N**, Ijspeert AJ and Ronsse R (2015) **Biped gait controller for large speed variations, combining reflexes and a central pattern generator in a neuromuscular model**. In: *2015 IEEE International Conference on Robotics and Automation (ICRA)*, Seattle, WA, 26-30 May 2015, pp. 6267-6274.
- **Van der Noot N** and Barrea A (2014) **Zero-Moment Point on a bipedal robot under bio-inspired walking control**. In: *MELECON 2014 - 17th IEEE Mediterranean Electrotechnical Conference*, Beirut, 13-16 April 2014, pp. 85-90. DOI: 10.1109/MELCON.2014.6820512.

List of publications

Poster presentations

- **Van der Noot N**, Ijspeert AJ and Ronsse R (2016) **Neuro-Muscular Controller Based on Reflexes and a Central Pattern Generator to Achieve Gait Modulation**. In: *KoroiBot Final Workshop*, Heidelberg, 13-14 September 2016.
- **Van der Noot N**, Ijspeert AJ and Ronsse R (2016) **Humanoid Robot Control Recruiting Muscles, Reflexes and a Central Pattern Generator**. In: *IEEE-EMB Benelux Chapter and the 14th National Day on Biomedical Engineering*, Brussels, 4 March 2016.
- **Van der Noot N**, Colasanto L, Ronsse R and Ijspeert AJ (2015) **Porting Reflex-Based Muscles Control to Real Humanoid Robots**. In: *2015 IEEE International Conference on Robotics and Automation (ICRA) - Workshop on Dynamic Locomotion and Balancing*, Seattle, WA, 26 May 2015.
- **Van der Noot N**, Dzeladini F, Ijspeert AJ and Ronsse R (2014) **Simplification of the Hill Muscle Model Computation for Real-Time Walking Controllers with Large Time Steps**. In: *Dynamic Walking*, Zurich, 10-13 June 2014.

Respice finem



Outline

Introduction & Methods

Reflex-based controller

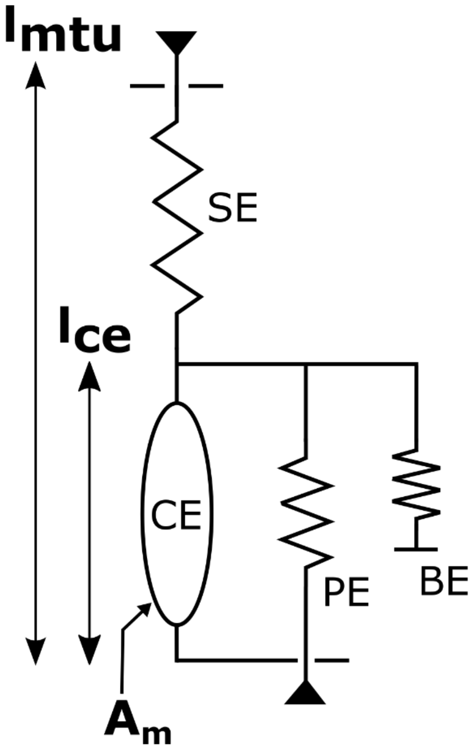
Forward speed modulation in 2D scenarios

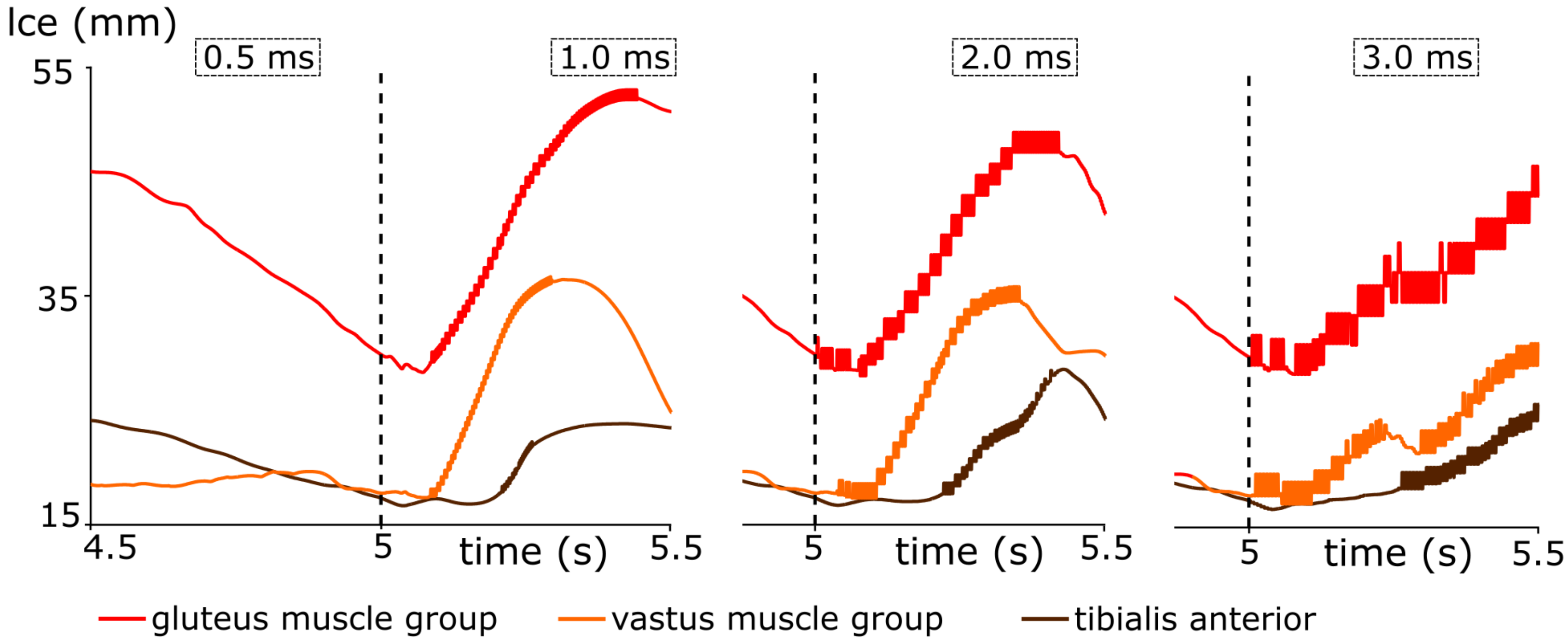
Steering control in 3D scenarios

Conclusion

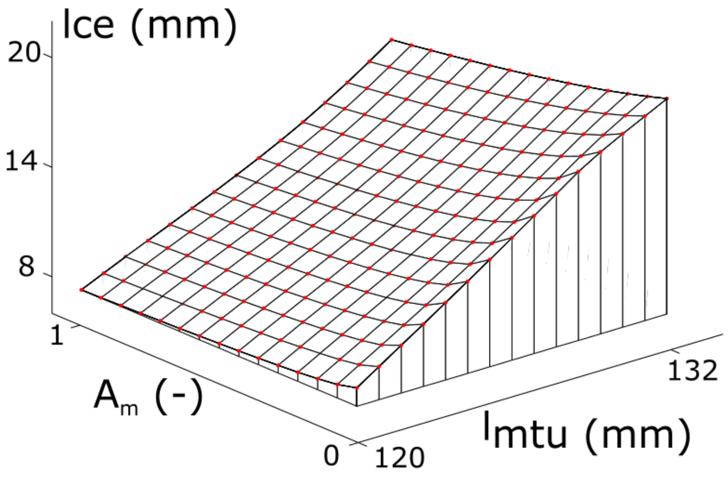
Supplementary material

Hill muscle model integration problem

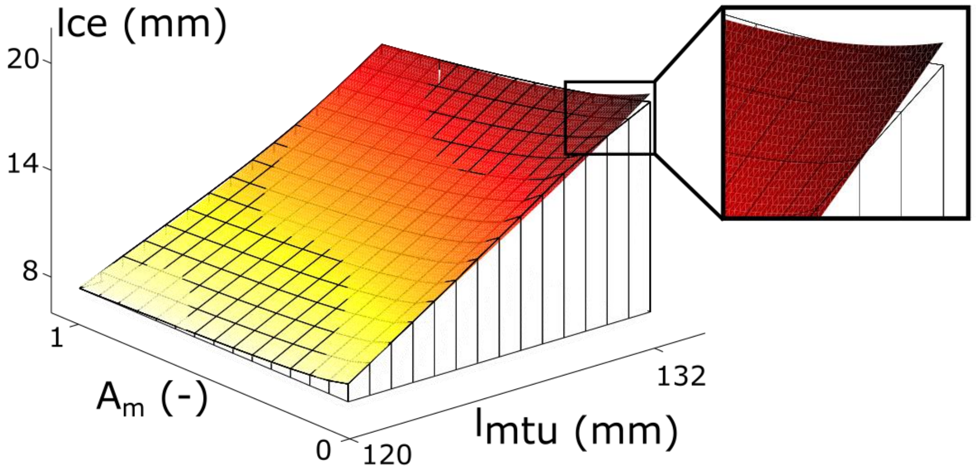




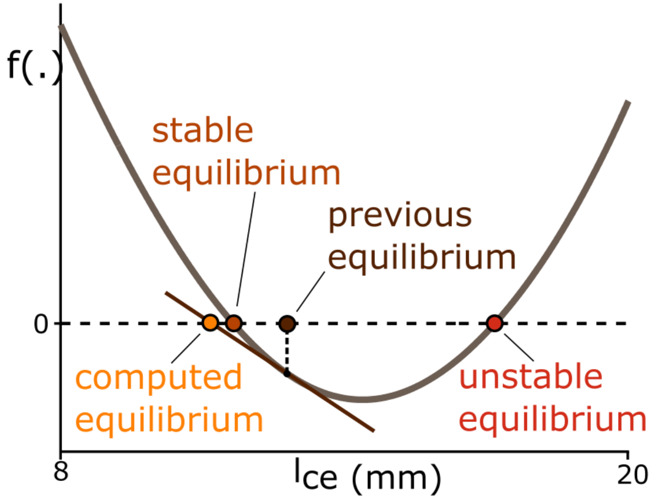
Hill muscles: computing the steady-state values



Look Up Table (LUT)

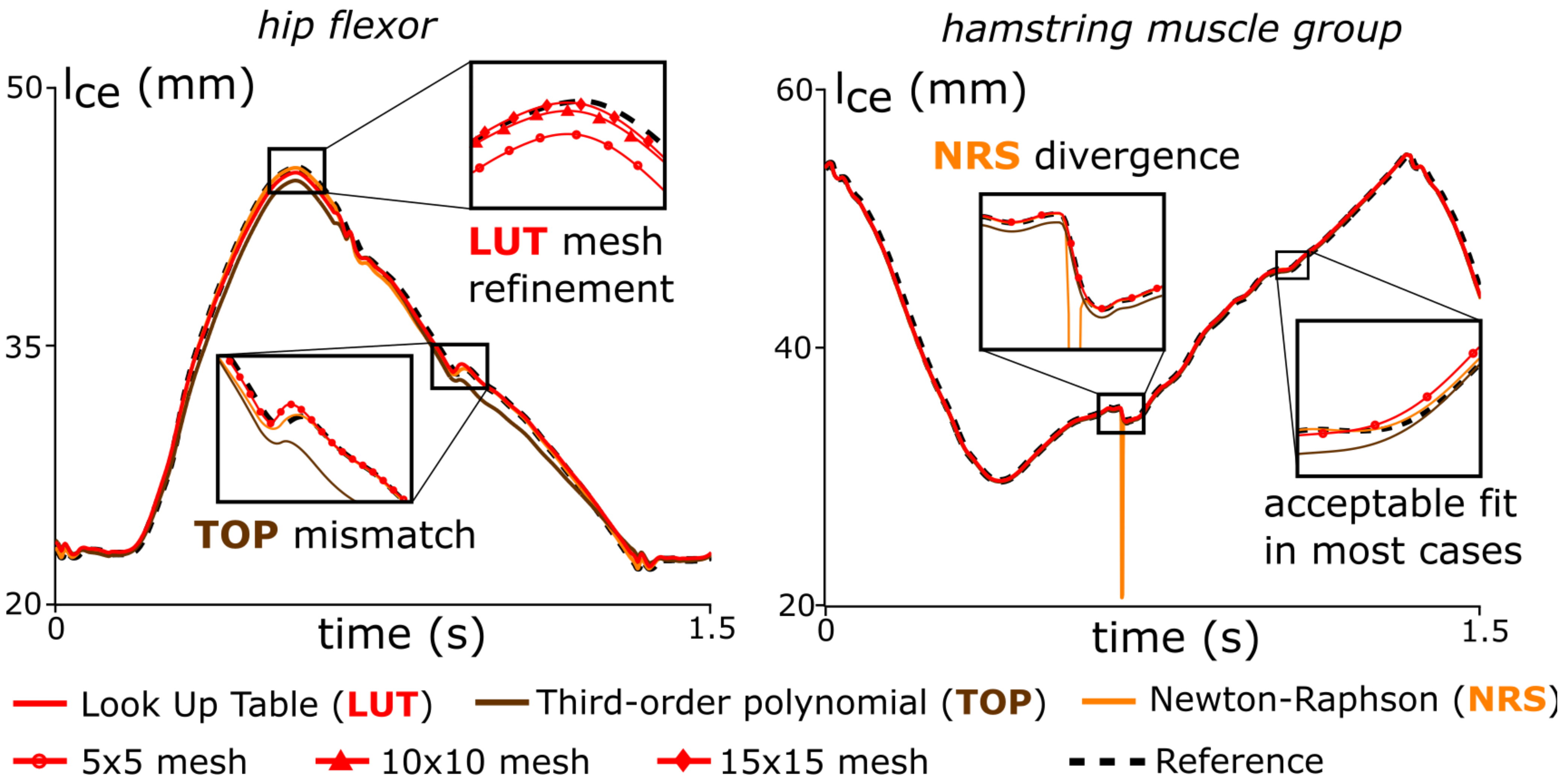


Third-order polynomial (TOP)

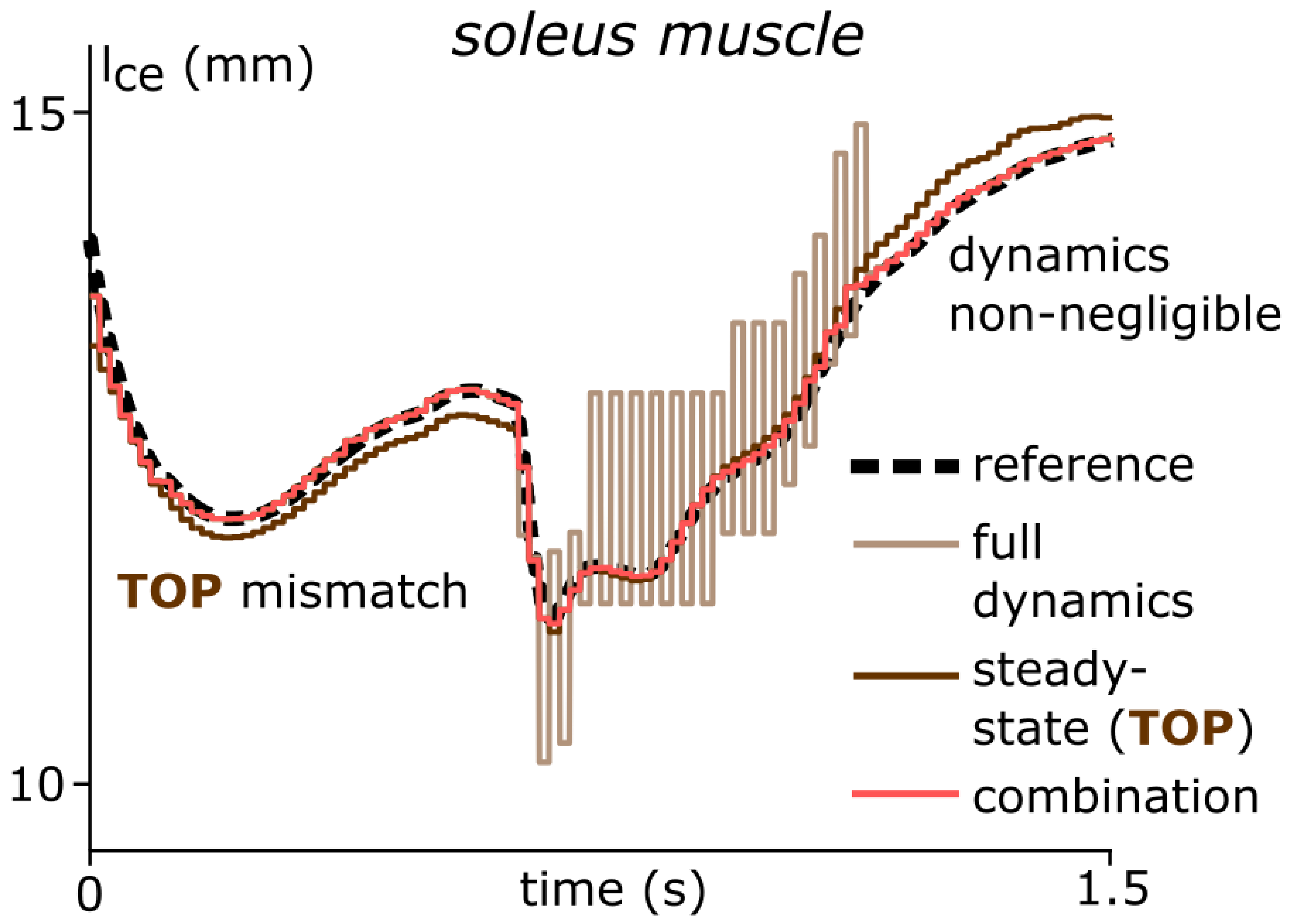


Newton-Raphson scheme (NRS)

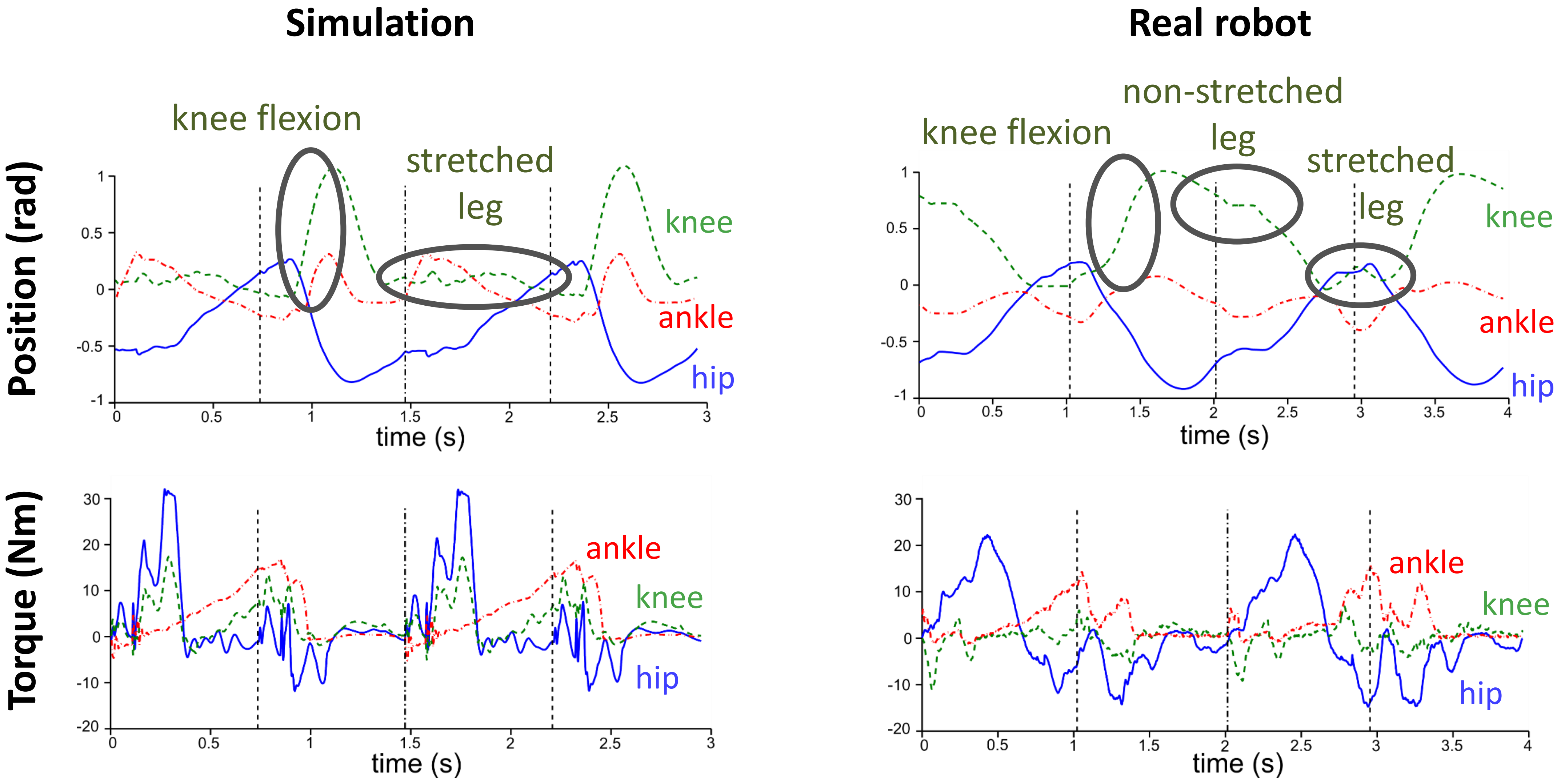
Hill muscles: steady-state approximation results



Combining approximations and full dynamics



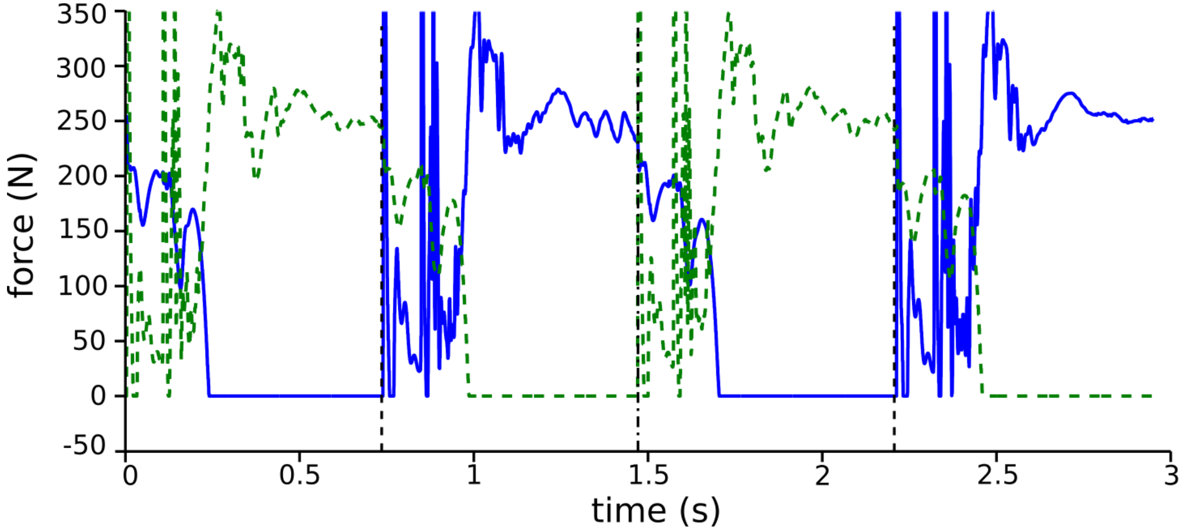
Real experiment: simulation and experimental gaits


Simulation

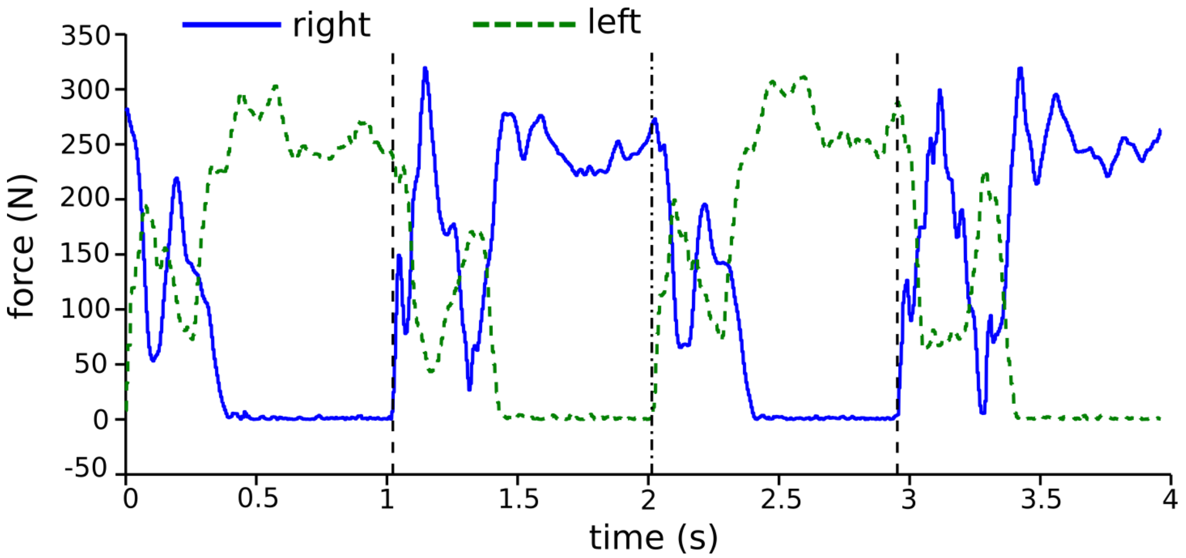
Real robot

Real experiment: vertical feet forces

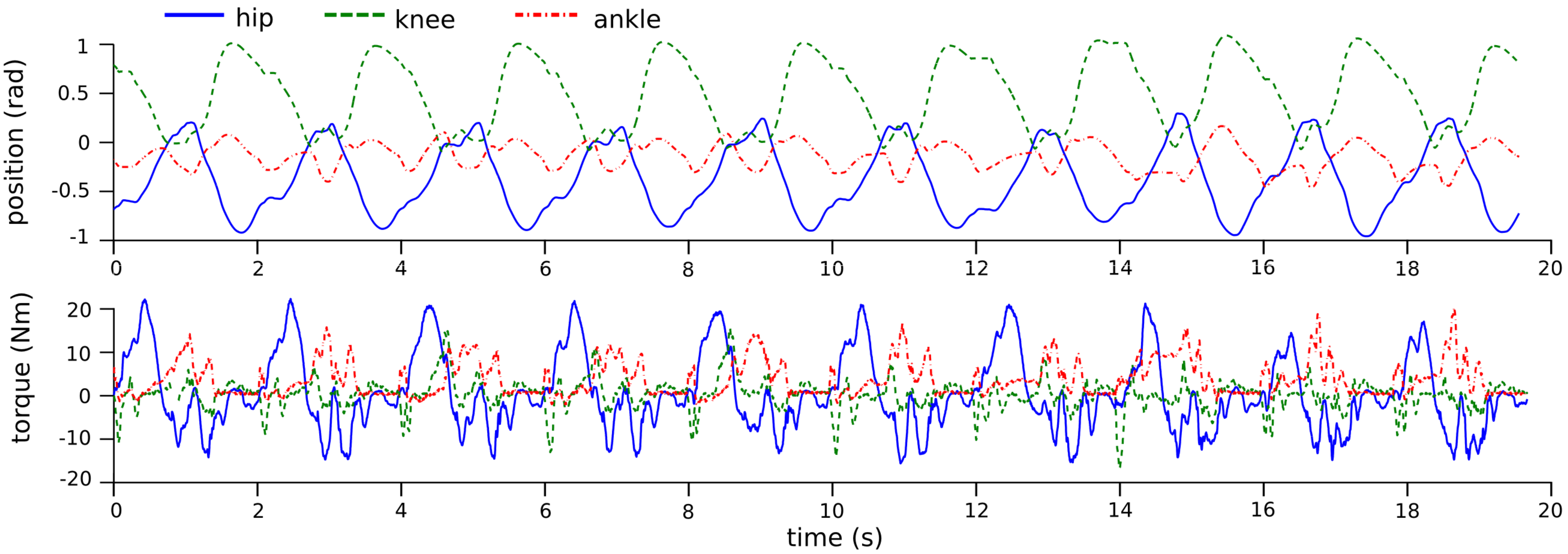
Simulation forces



Real experiment forces

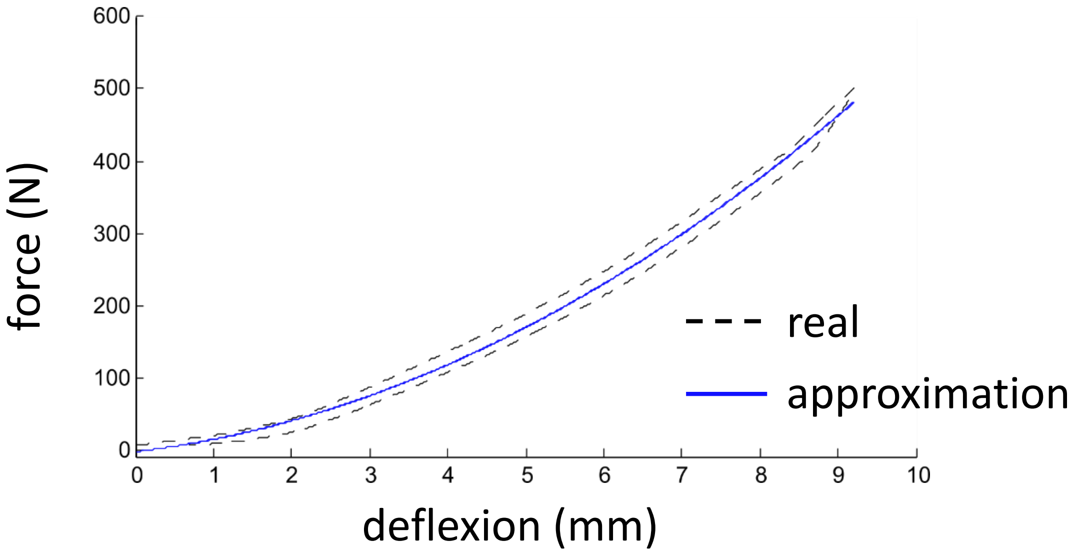


Real experiment: long walk



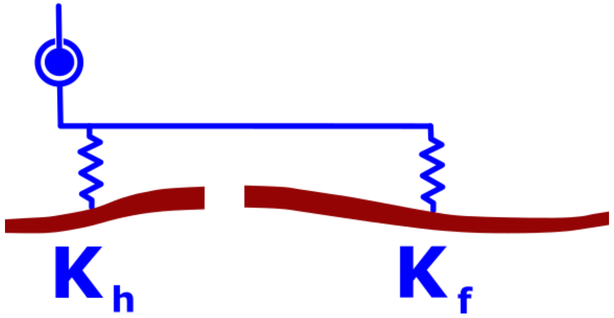
Feet with human-like compliance

Flex-Foot Junior prosthesis



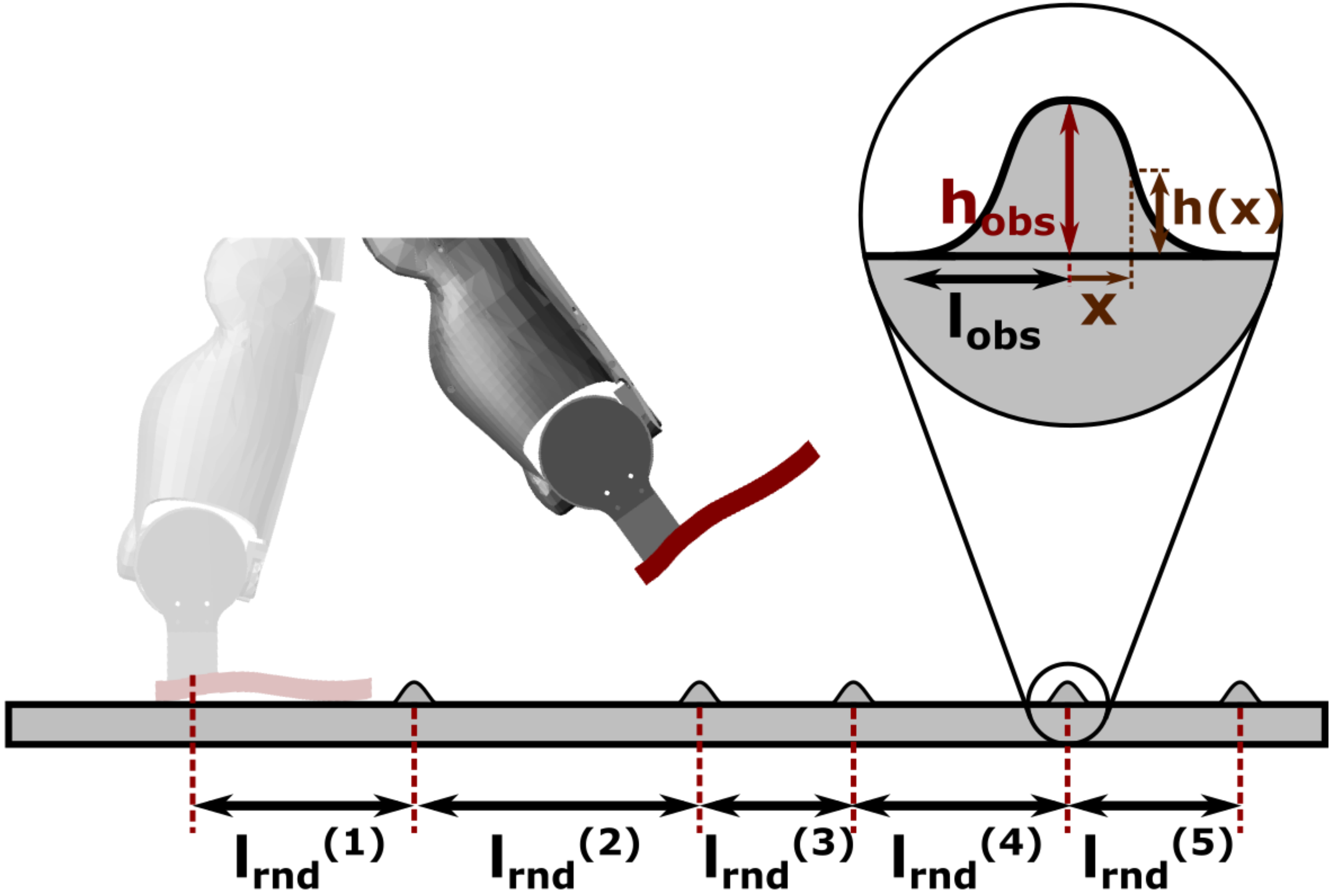
Force-displacement characteristic

Luca Colasanto

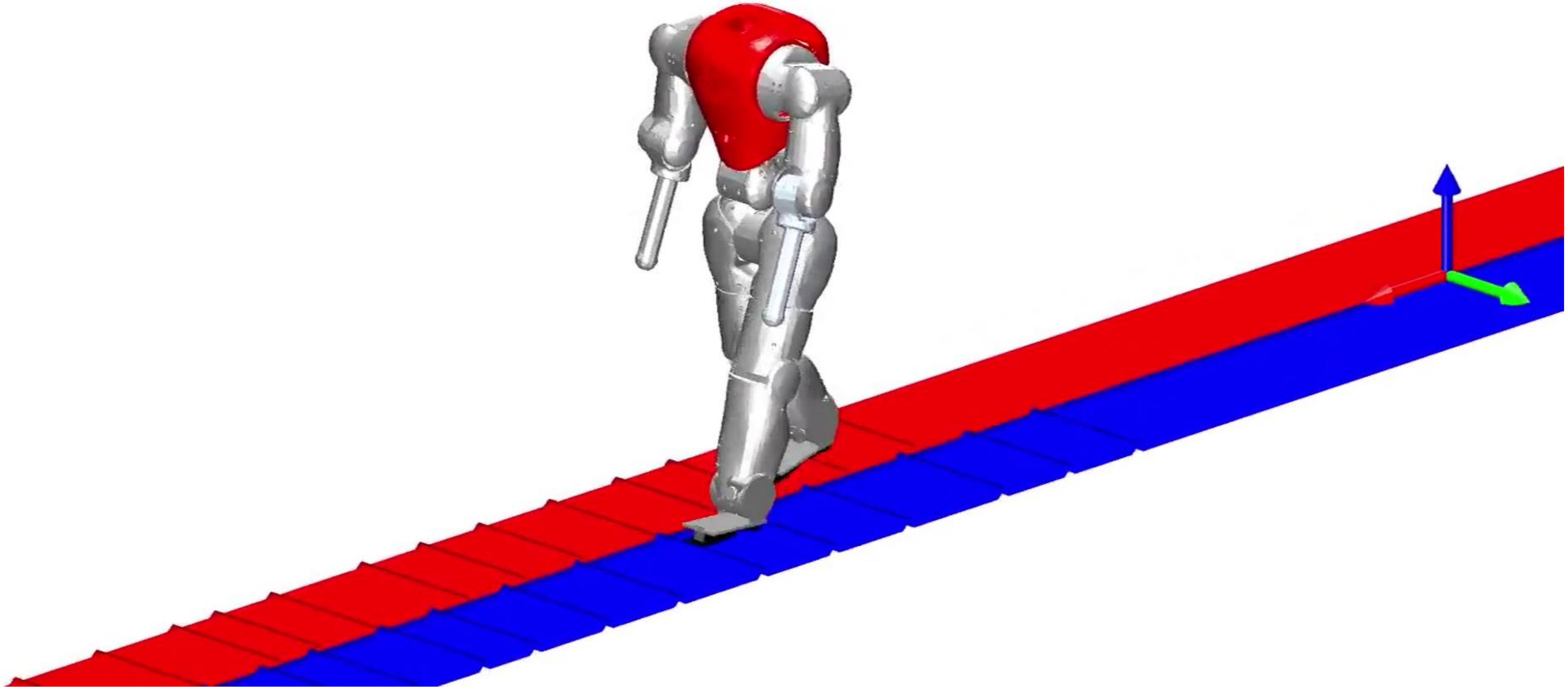


Compliant foot design

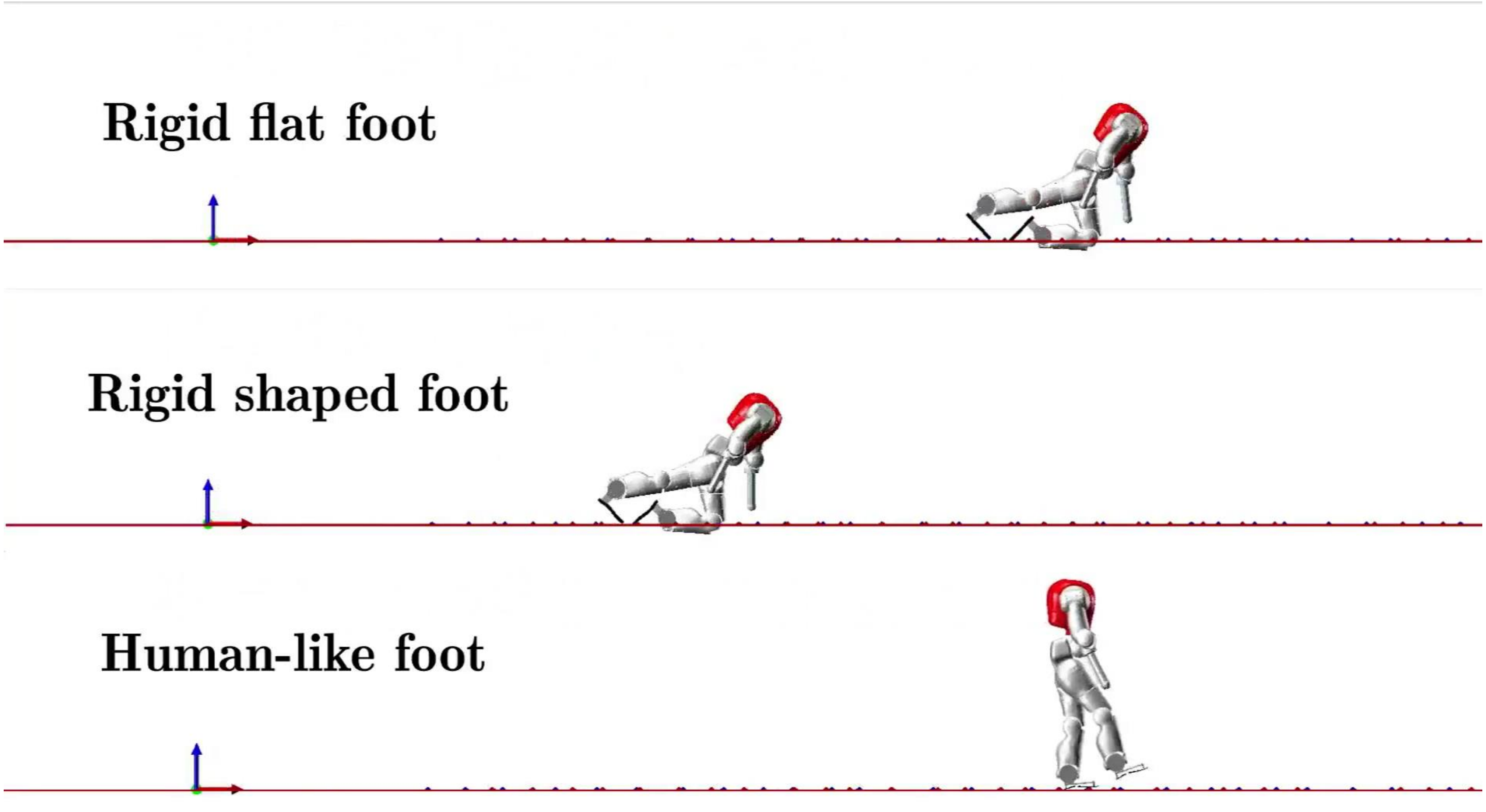
Feet comparisons: ground bumps description



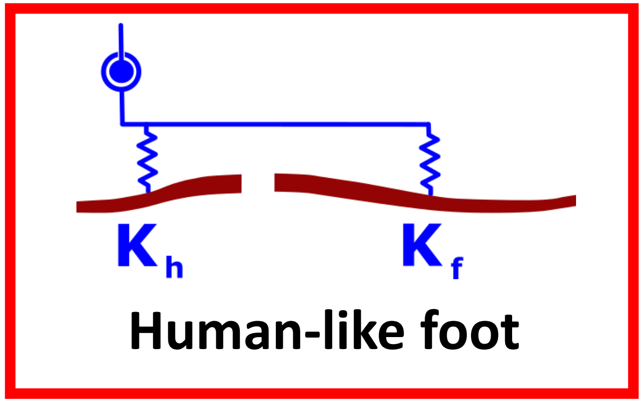
Compliant feet on uneven terrains



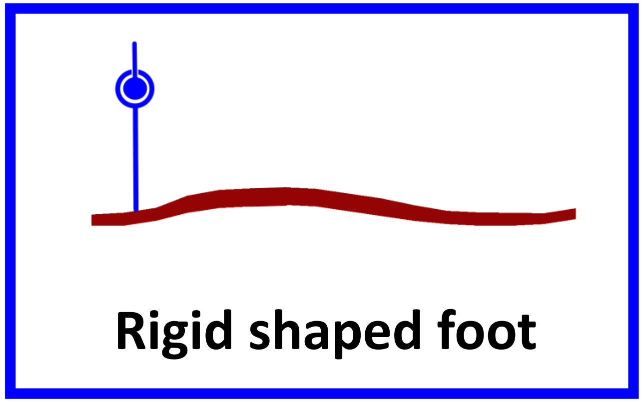
Feet comparisons on uneven terrains



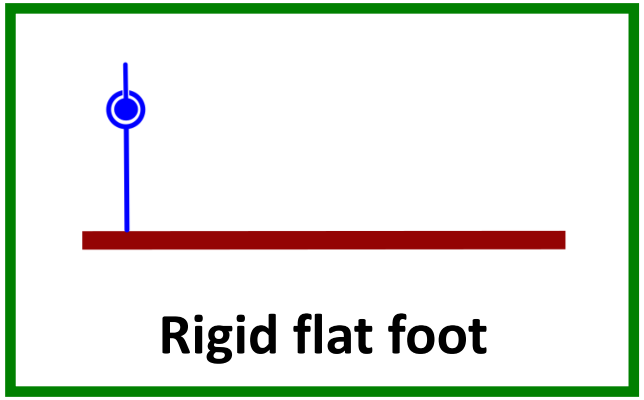
Feet comparisons: energy and robustness



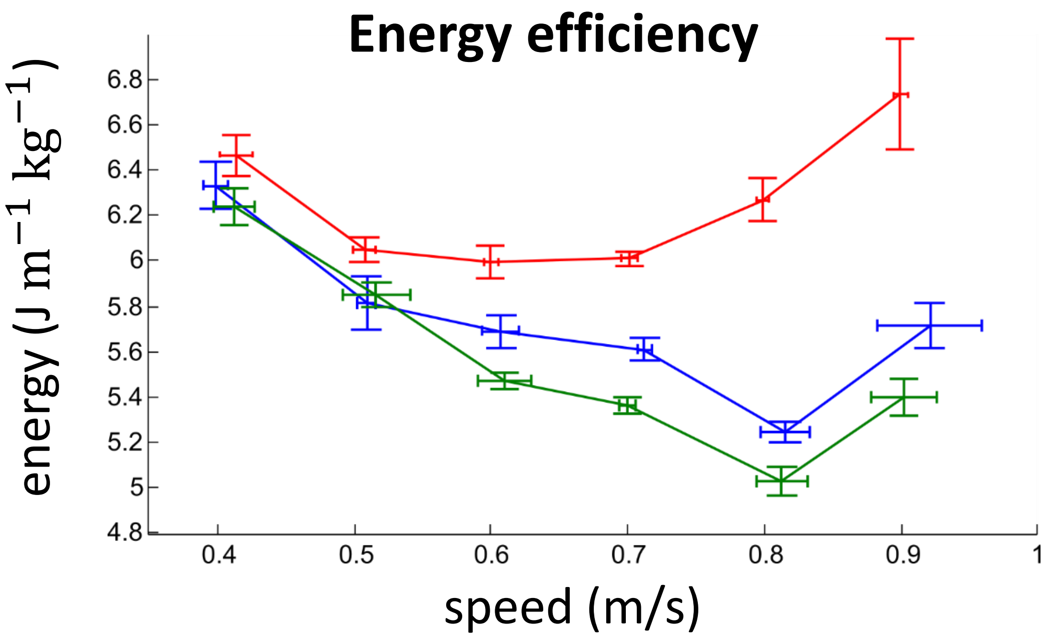
Human-like foot



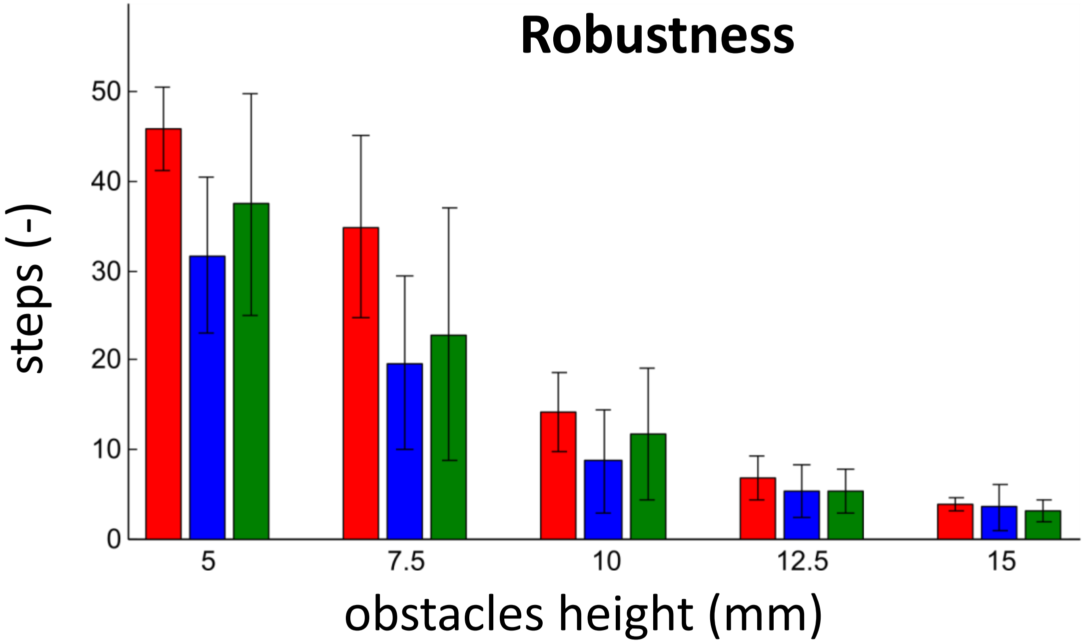
Rigid shaped foot



Rigid flat foot

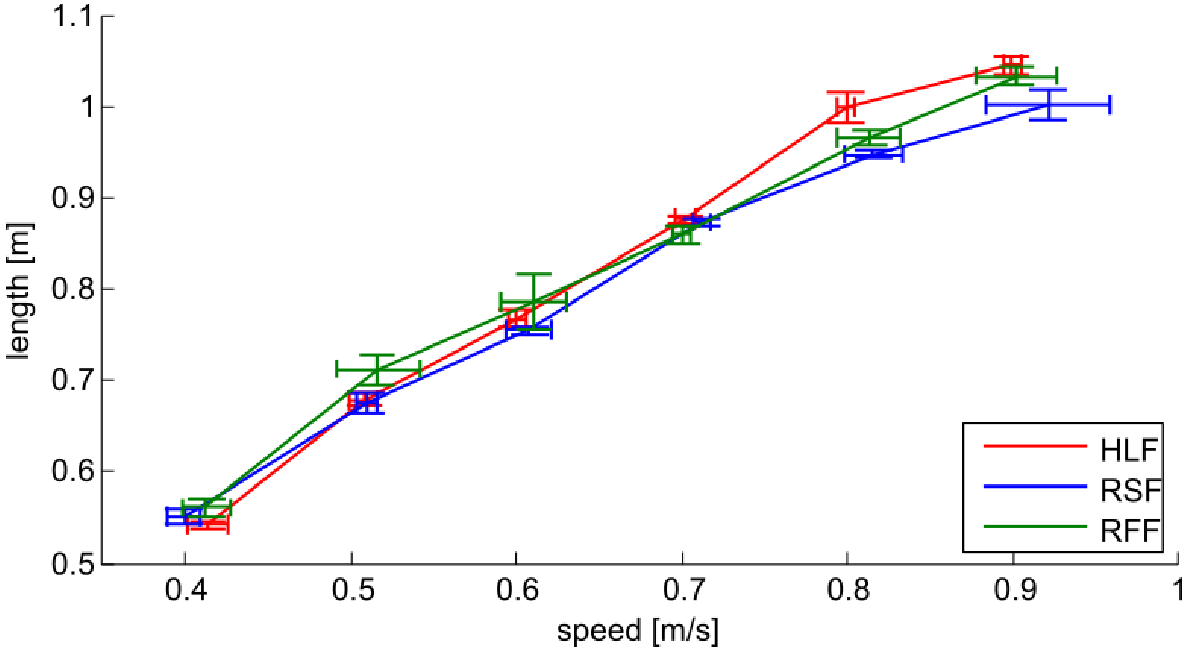


Energy efficiency

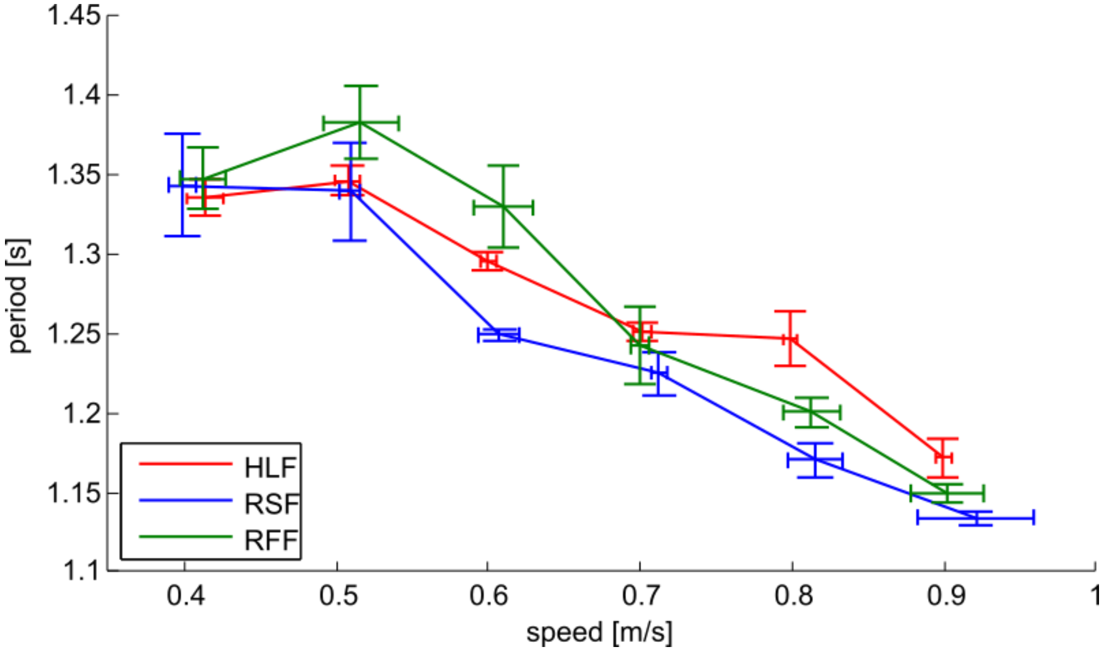


Robustness

Feet comparisons: stride length and period

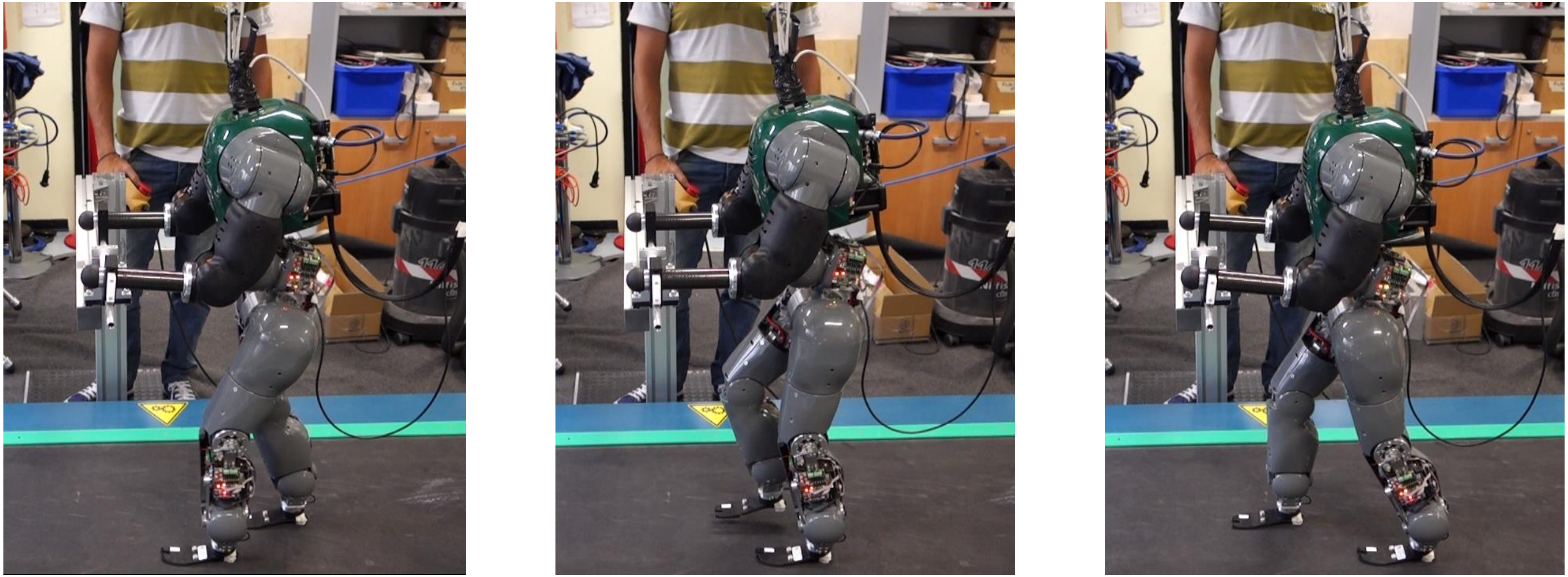


Stride length

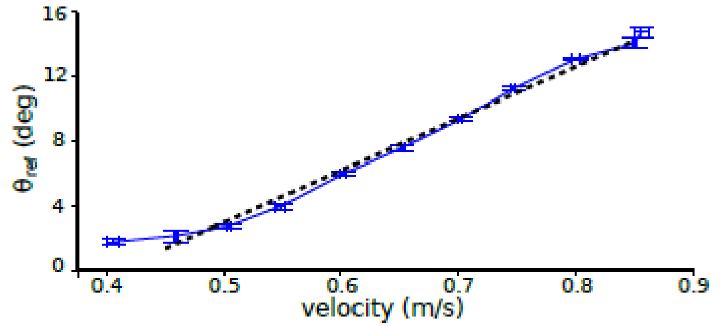


Stride period

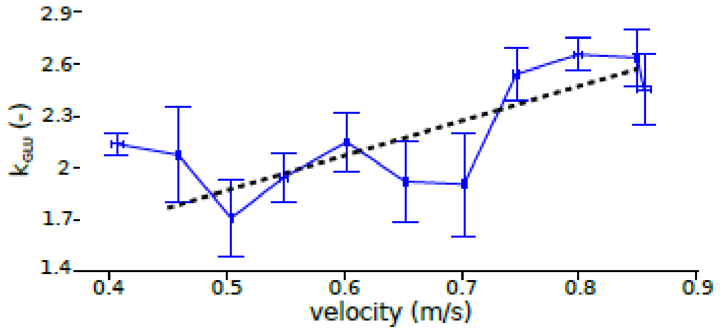
Real experiment: flexible feet



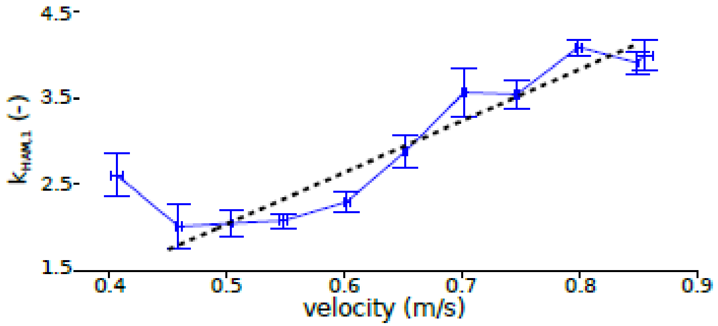
2D walking: speed parameters



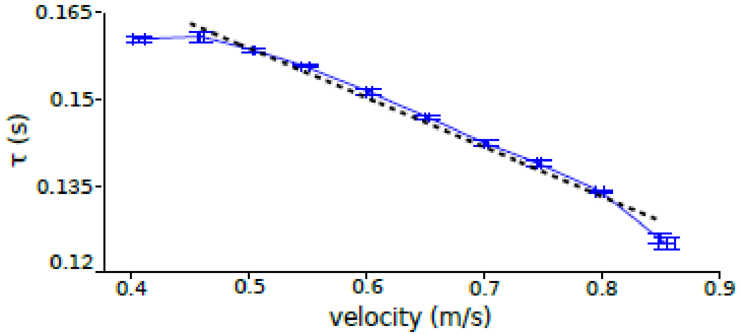
(a) Trunk reference angle θ_{ref}



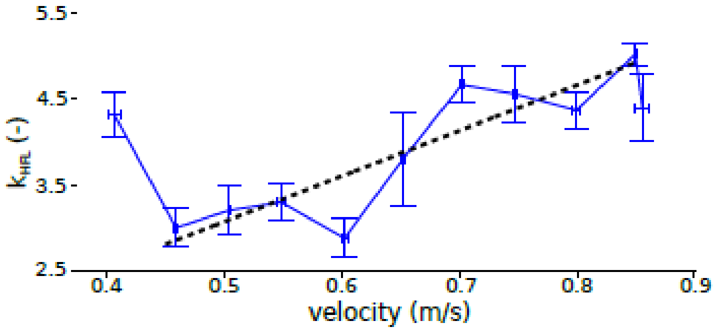
(b) Stimulation gain k_{GLU}



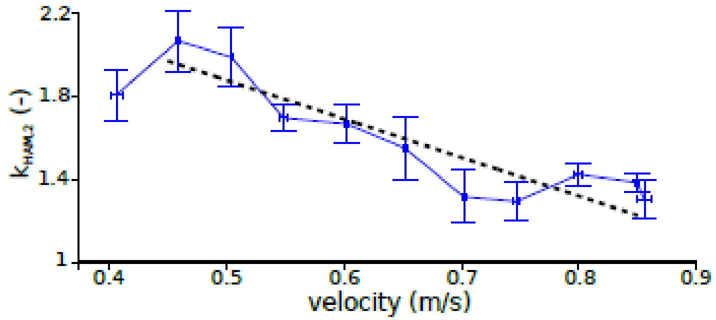
(c) Stimulation gain $k_{HAM,1}$



(d) Oscillator time constant τ



(e) Stimulation gain k_{HFL}

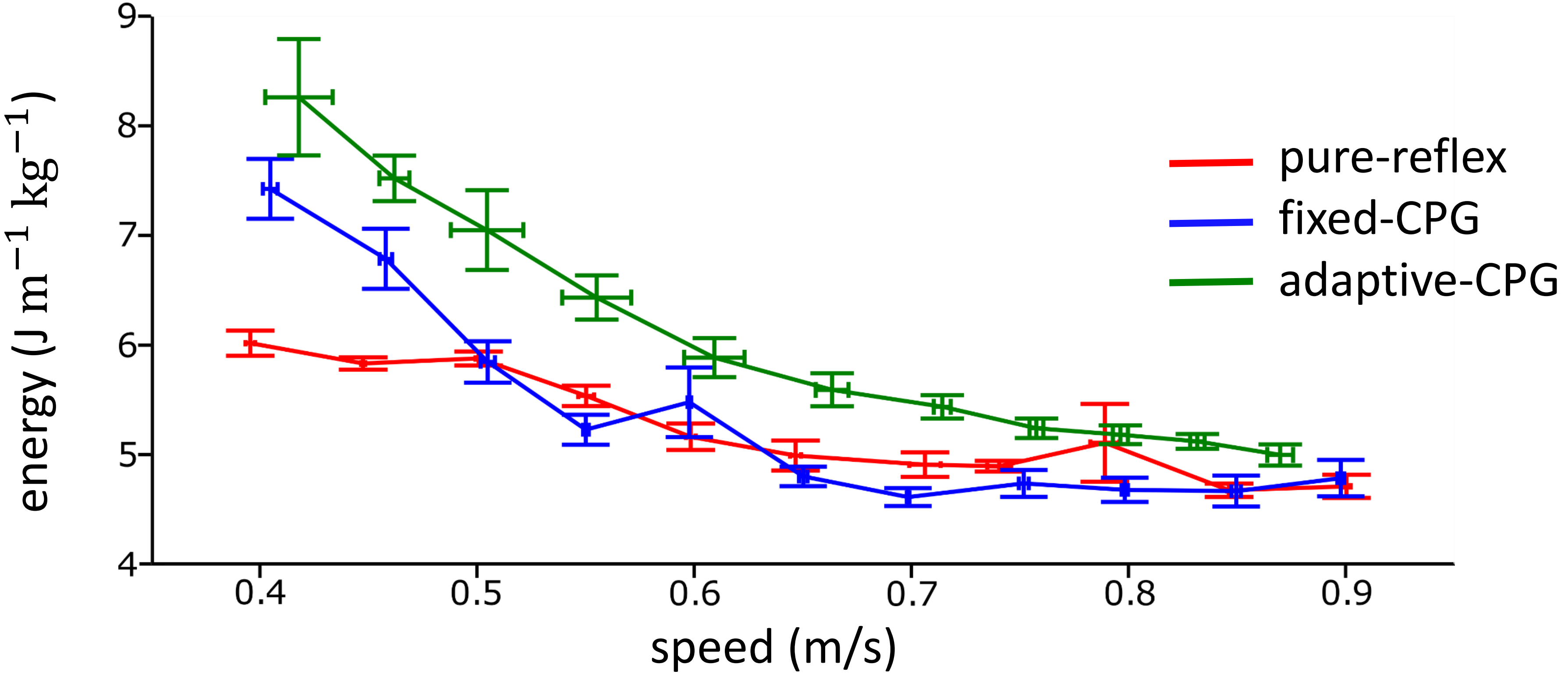


(f) Stimulation gain $k_{HAM,2}$

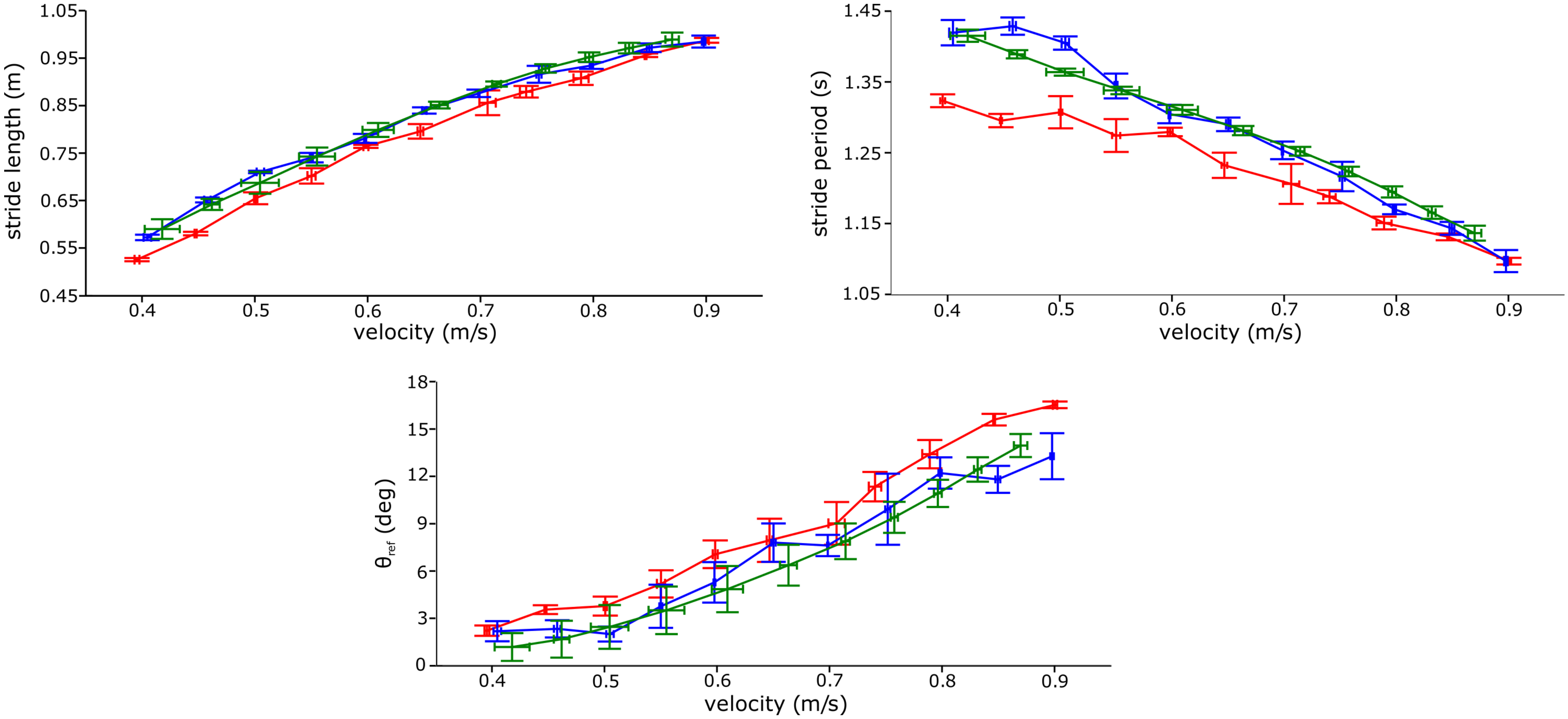
2D walking: metabolic energy consumption

Small increase in **energy consumption** for the adaptive-CPG controller.

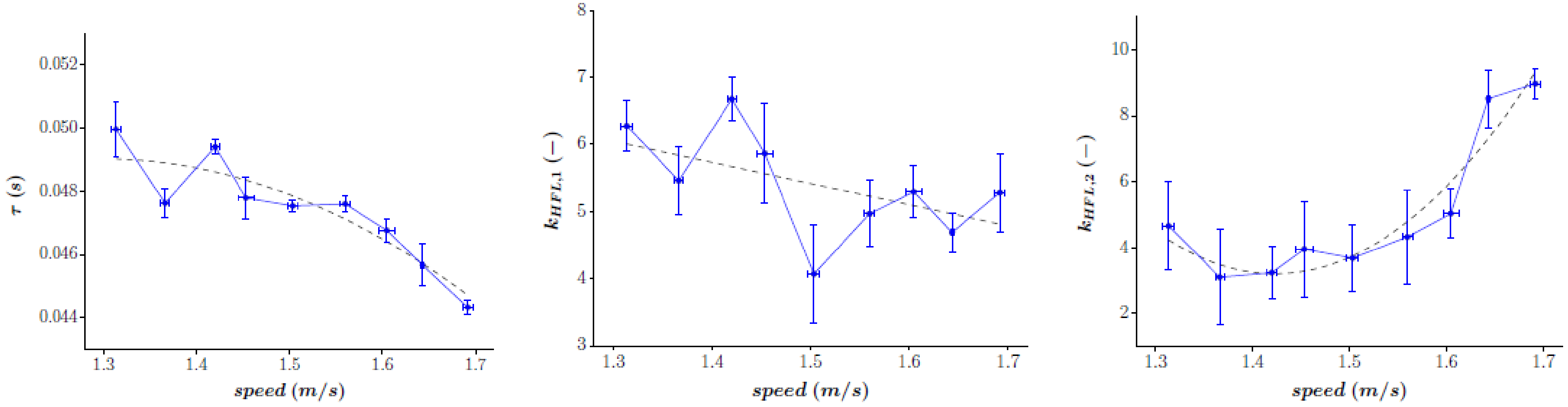
Reasonable price to pay for the resulting **versatility**.



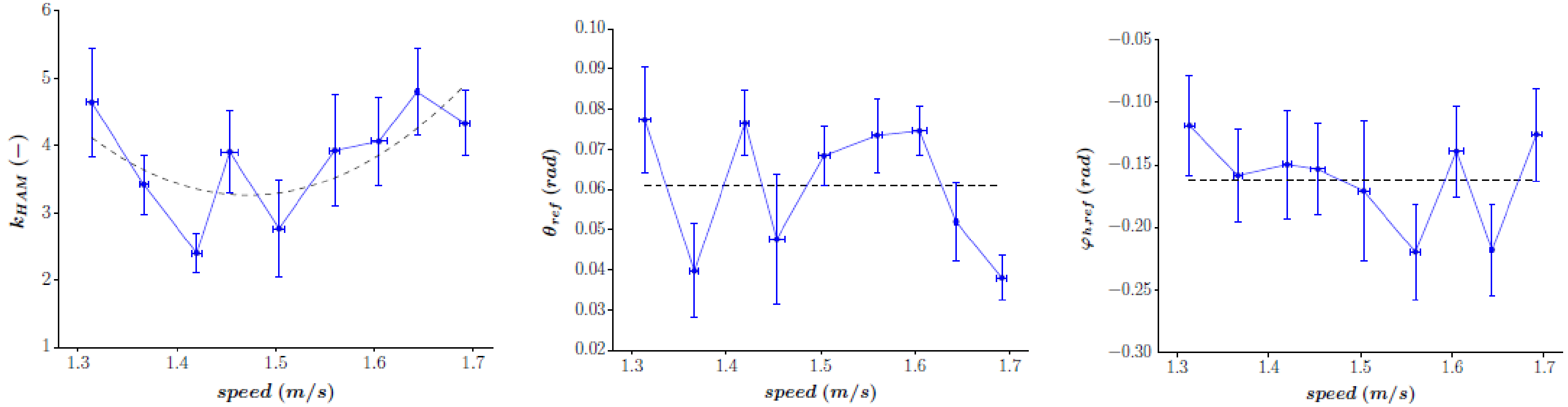
2D walking: characteristics



2D running: speed parameters (I)

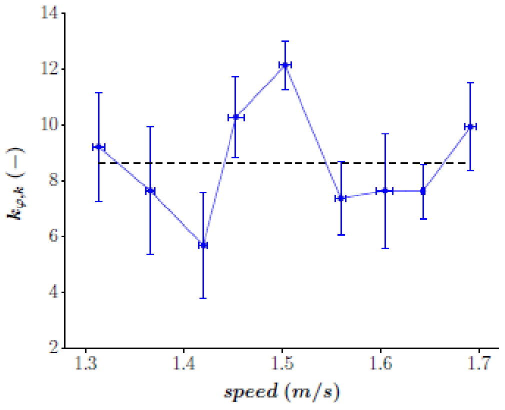


(a) CPG time constant τ (b) CPG gain $k_{HFL,1}$ (c) CPG gain $k_{HFL,2}$

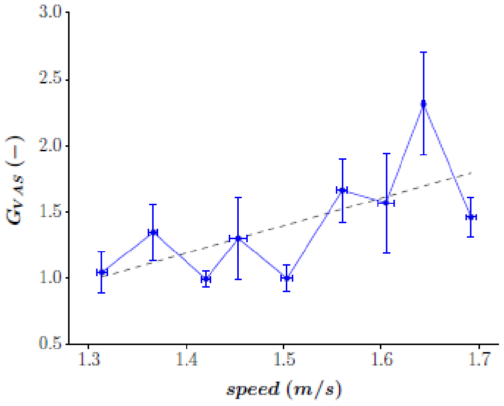


(d) CPG gain k_{HAM} (e) Torso orientation reference θ_{ref} (f) Hip angle reference $\varphi_{h,ref}$

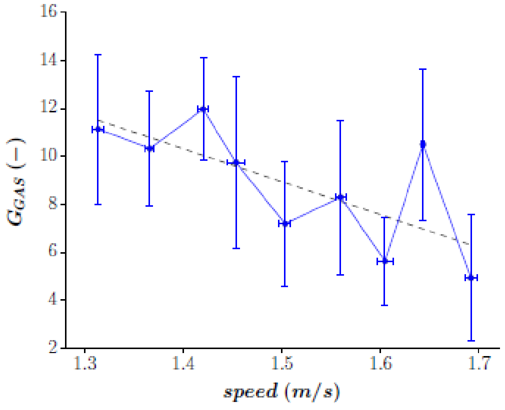
2D running: speed parameters (II)



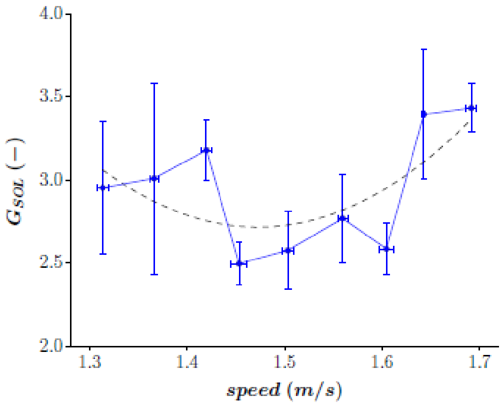
(g) Knee angle gain $k_{\varphi,k}$



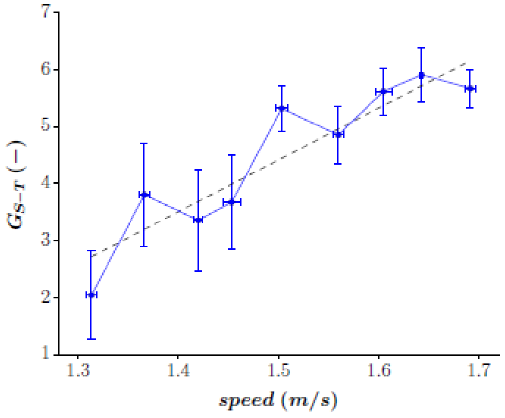
(h) reflex gain G_{VAS}



(i) reflex gain G_{GAS}

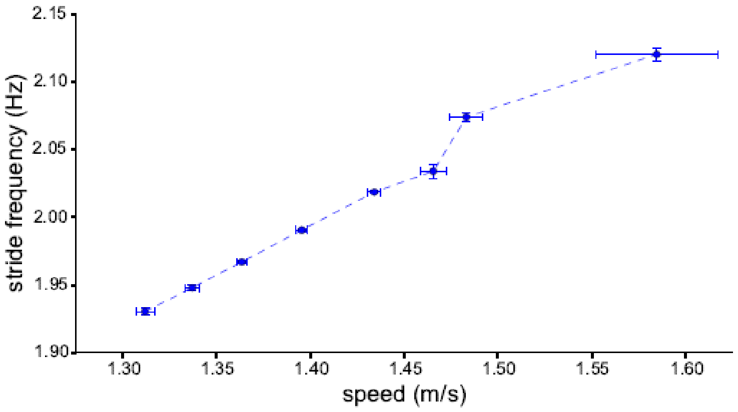


(j) reflex gain G_{SOL}

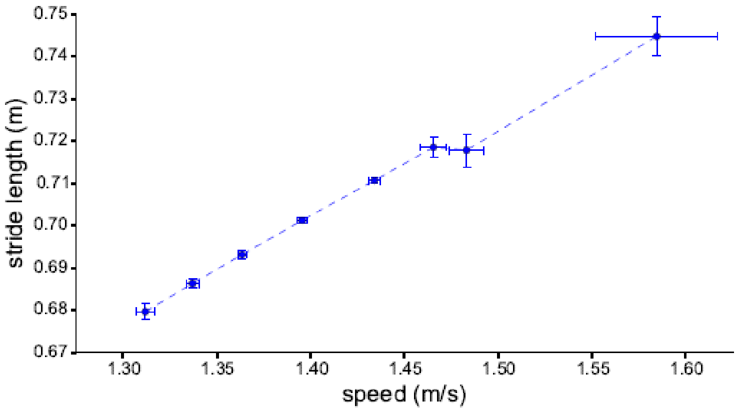


(k) reflex gain G_{S-T}

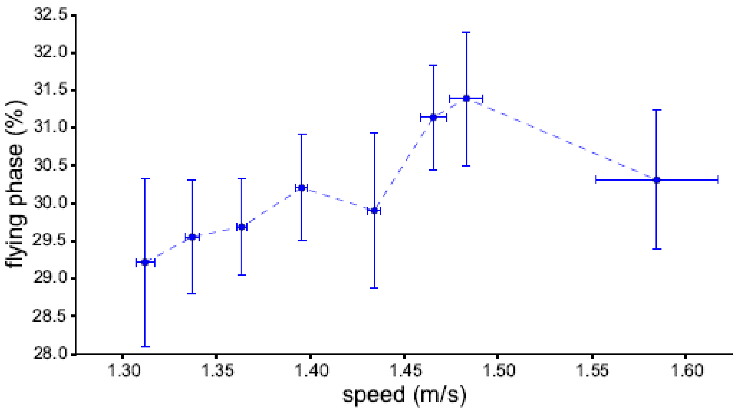
2D running: characteristics



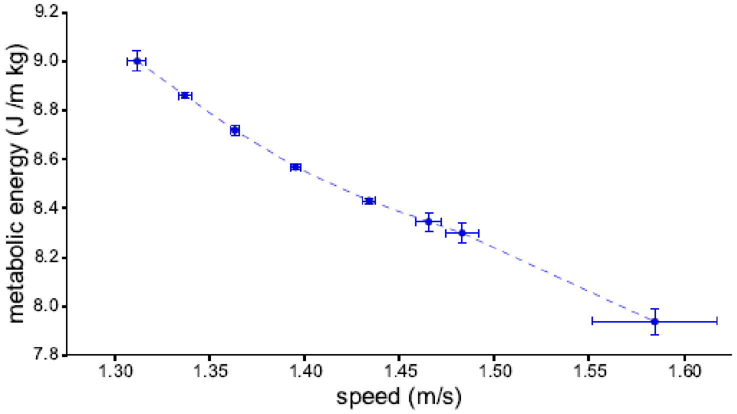
(a) stride frequency



(b) stride length

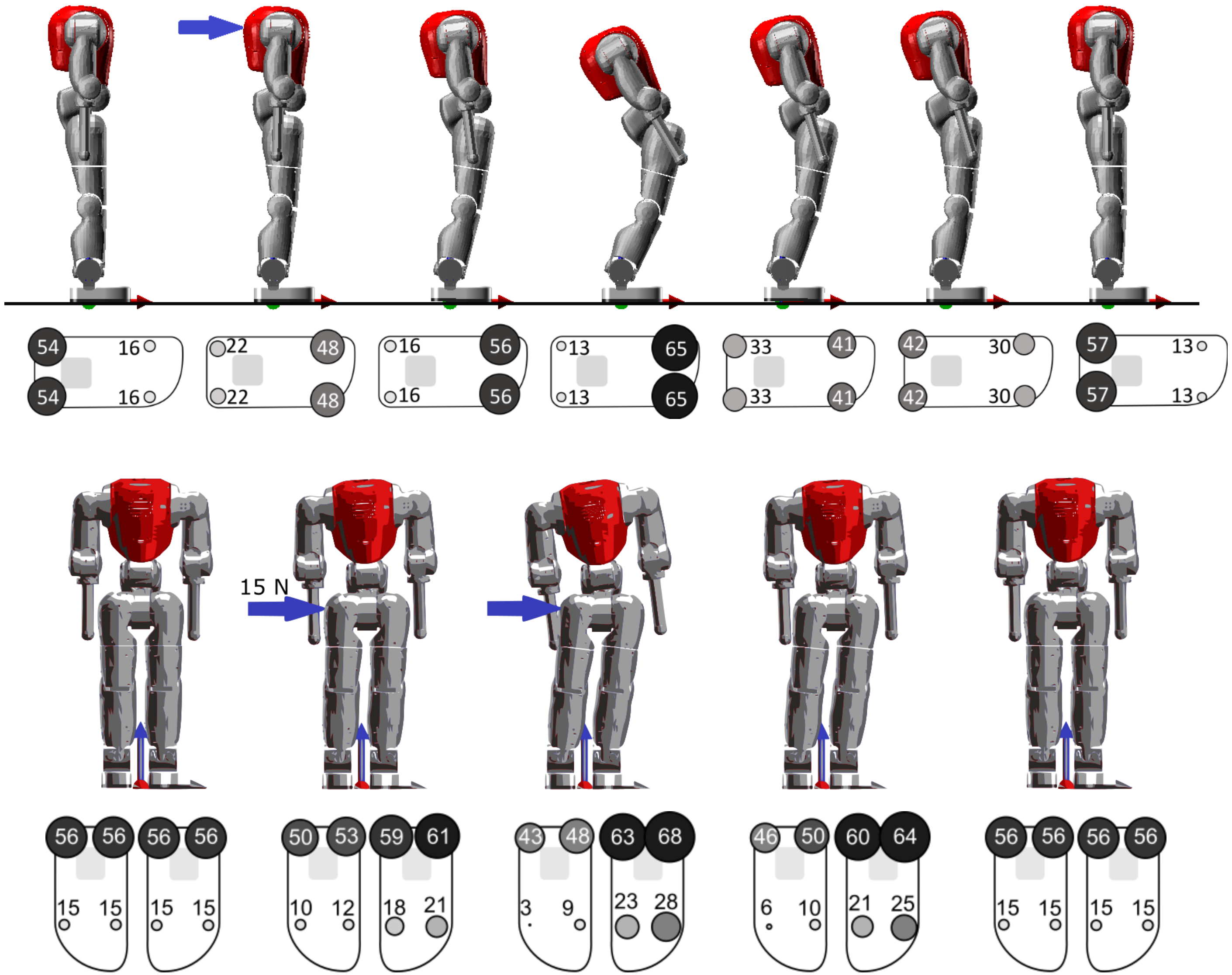


(c) flying phase ratio

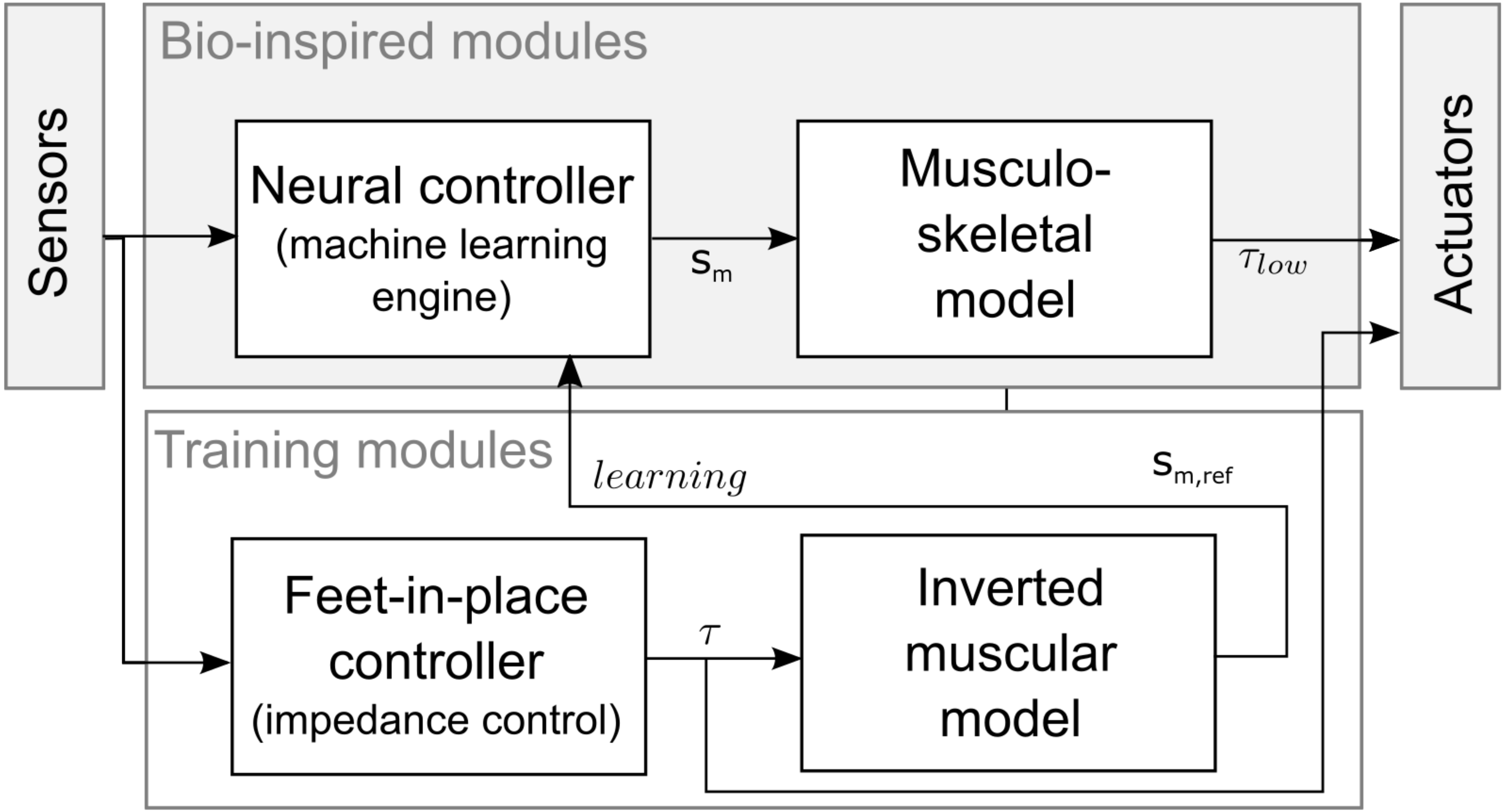


(d) metabolic energy consumption

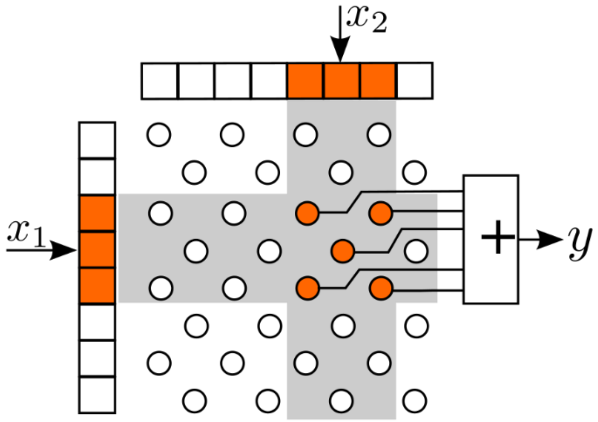
Pushes: feet contact forces



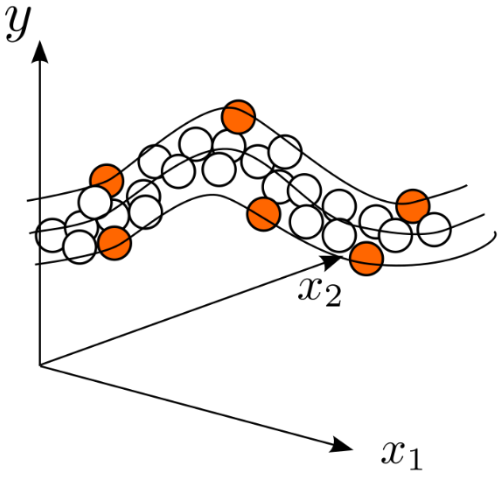
Learning process



Neural controller: a regression engine



CMAC



SVR

Sensors

Regression

Learning

Prediction

-

Training reference

Cerebellum Model for Articulation Control (CMAC)

Based on the cerebellum organization

Neural network

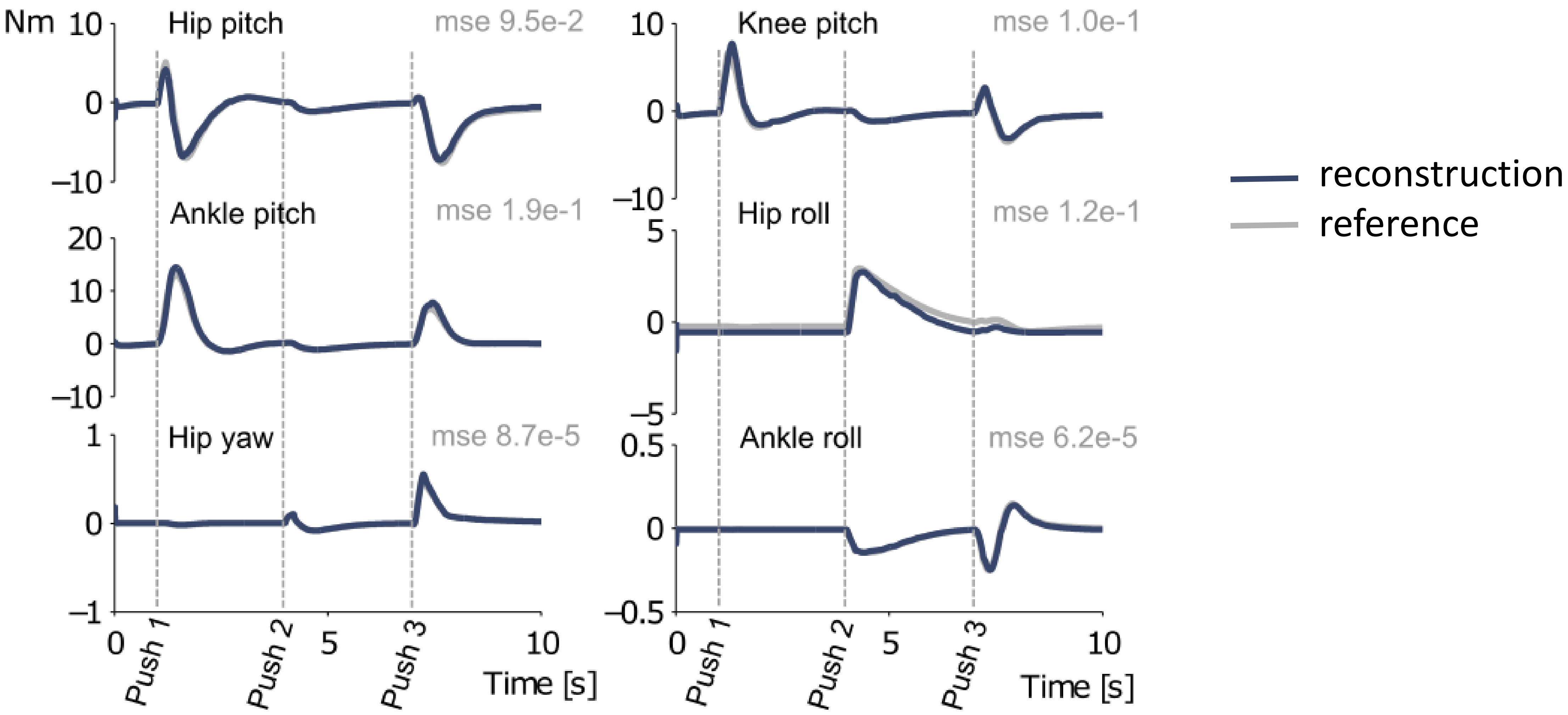
[Smith 1998]

Support Vector Regression (SVR)

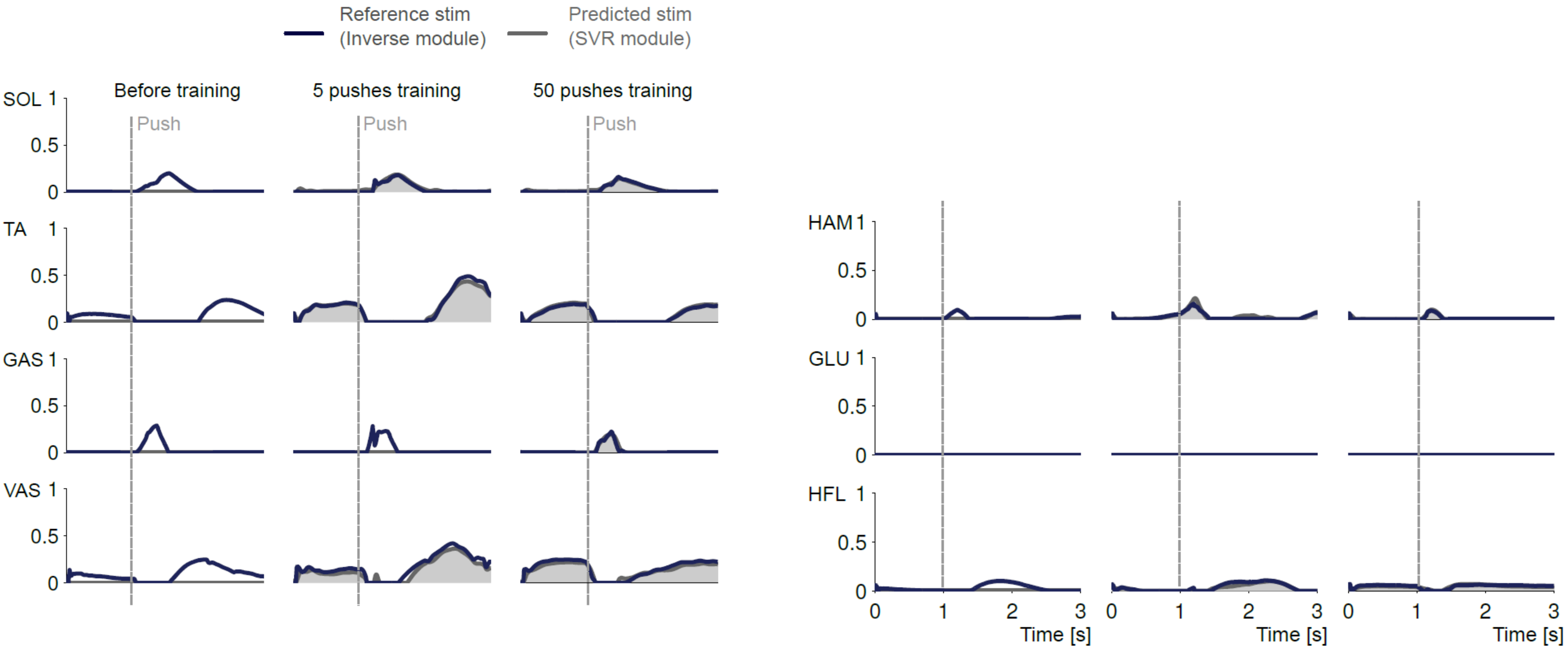
Mathematical model

Data points selected as support vectors

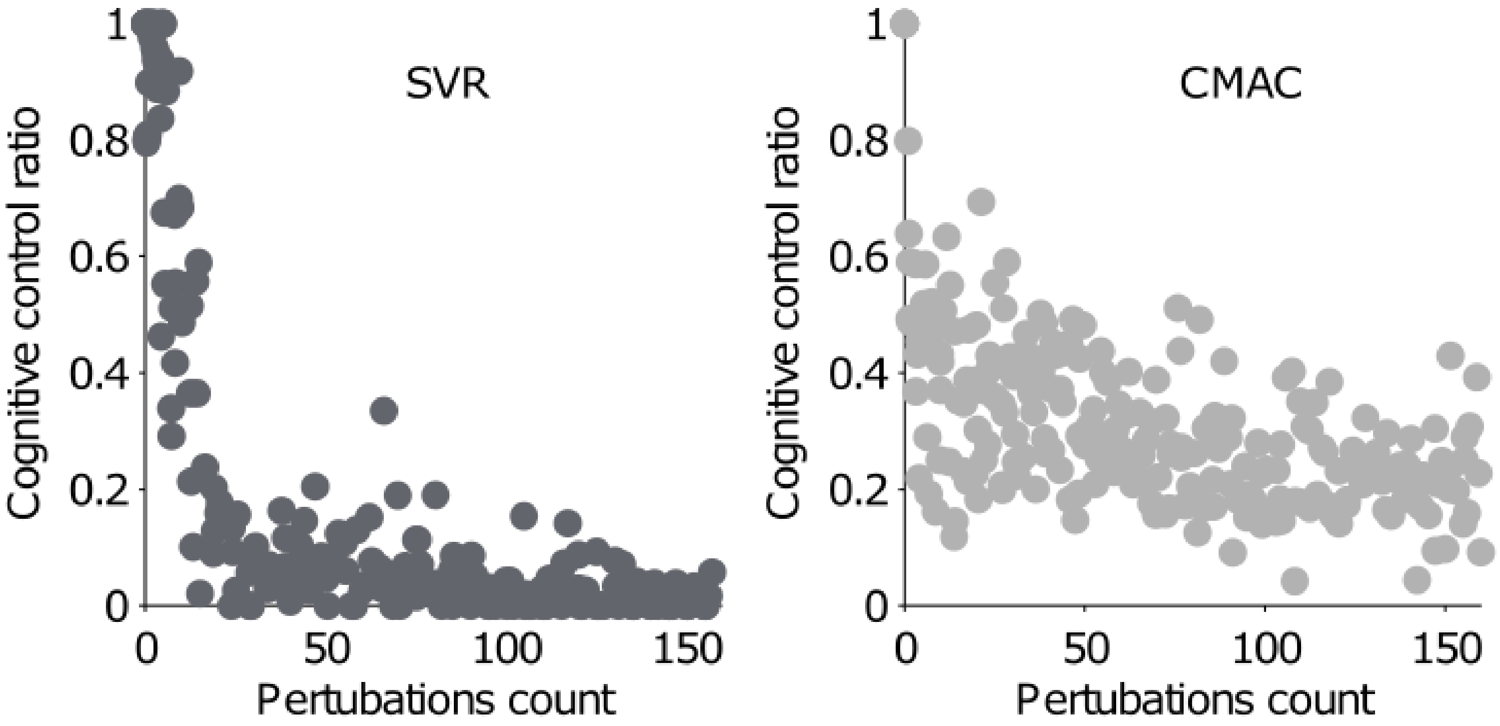
Torques reconstruction



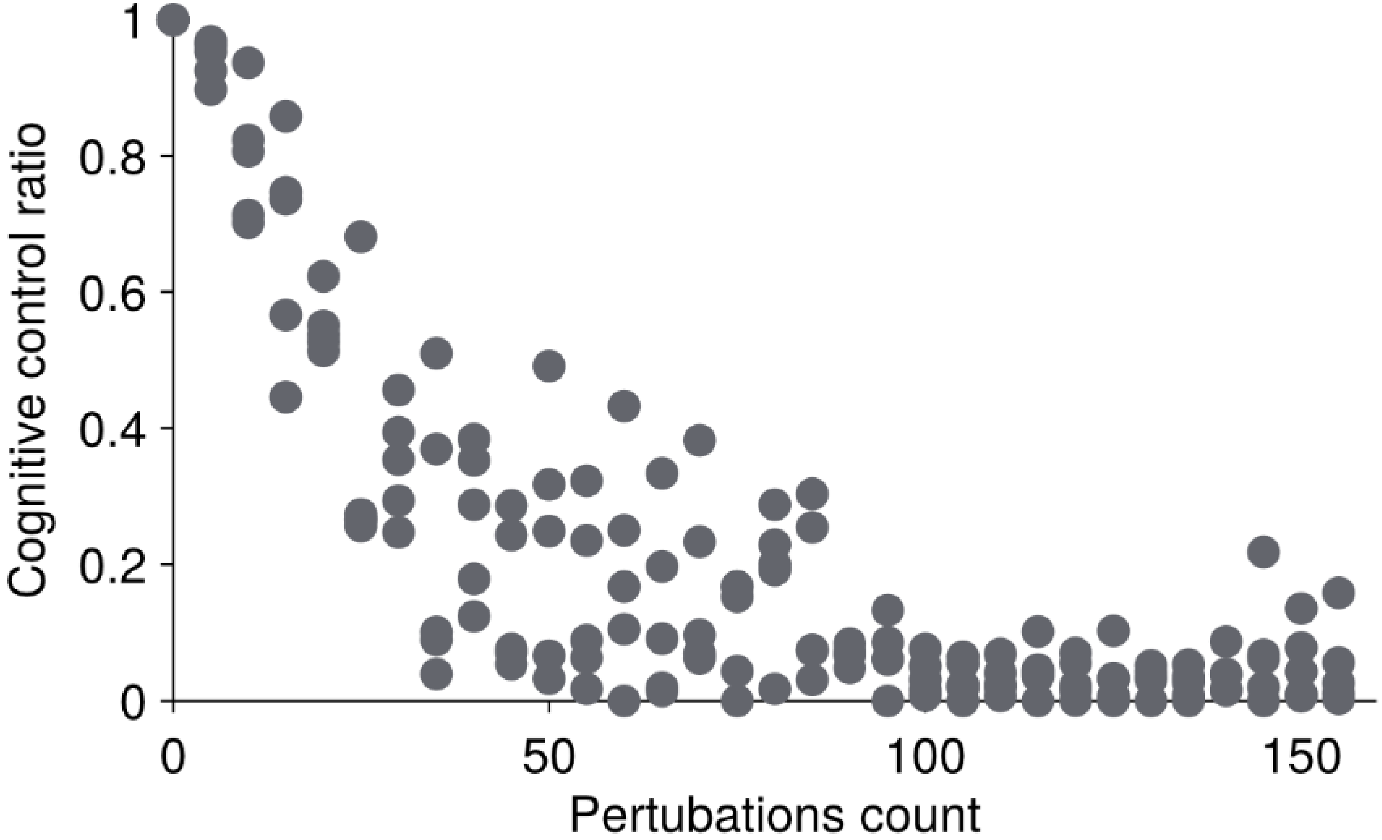
Stimulations reconstruction



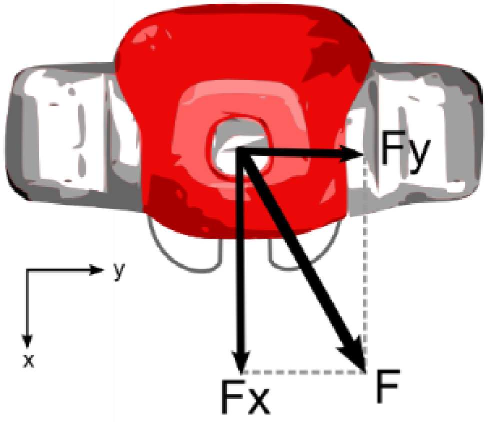
COG ration: sagittal plane



COG ration: transverse plane



Horizontal perturbation



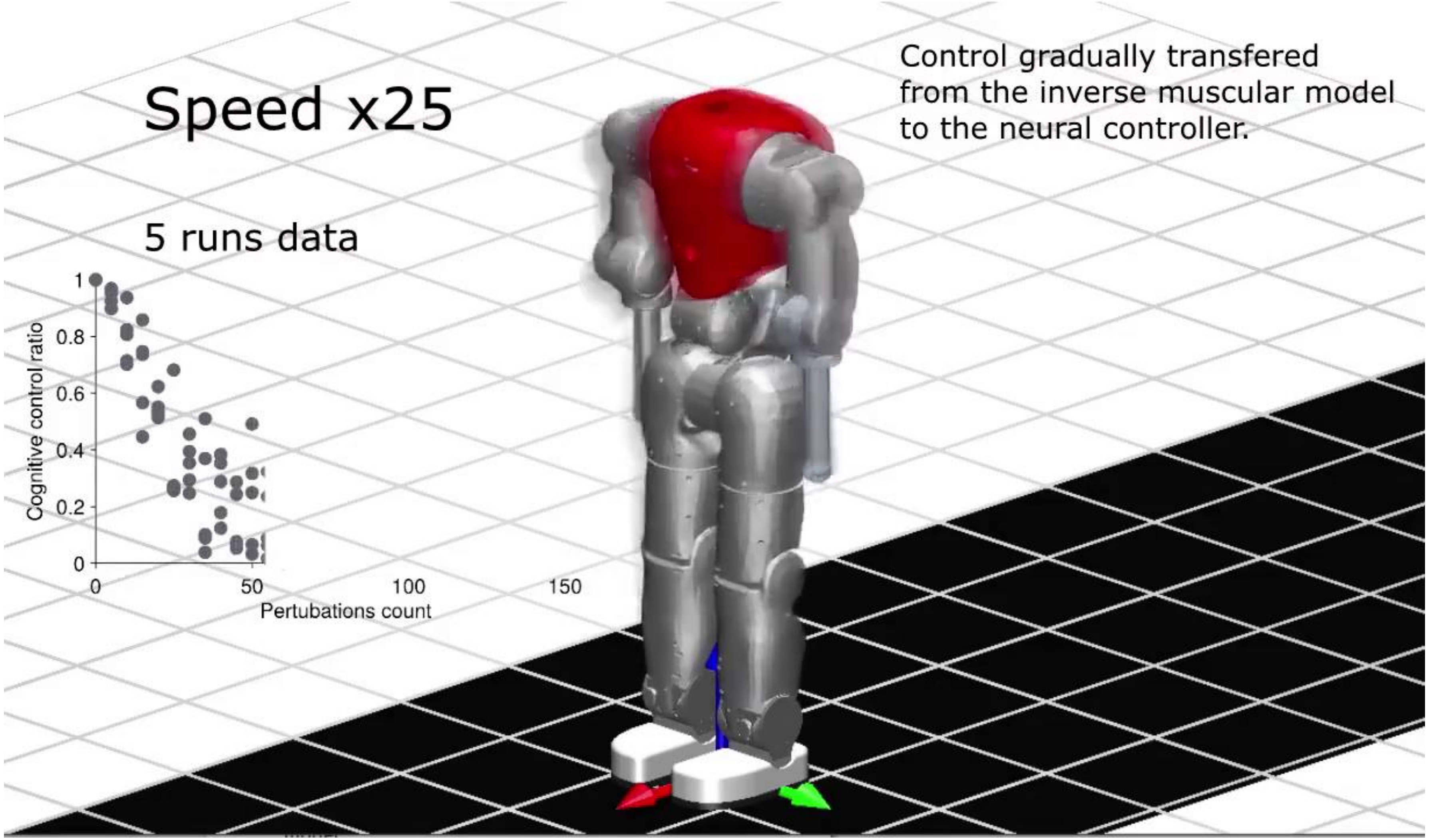
Magnitude

Uniform distribution

Fx in [-5 , 15]N

Fy in [-10, 10]N

Learning performances



Speed x25

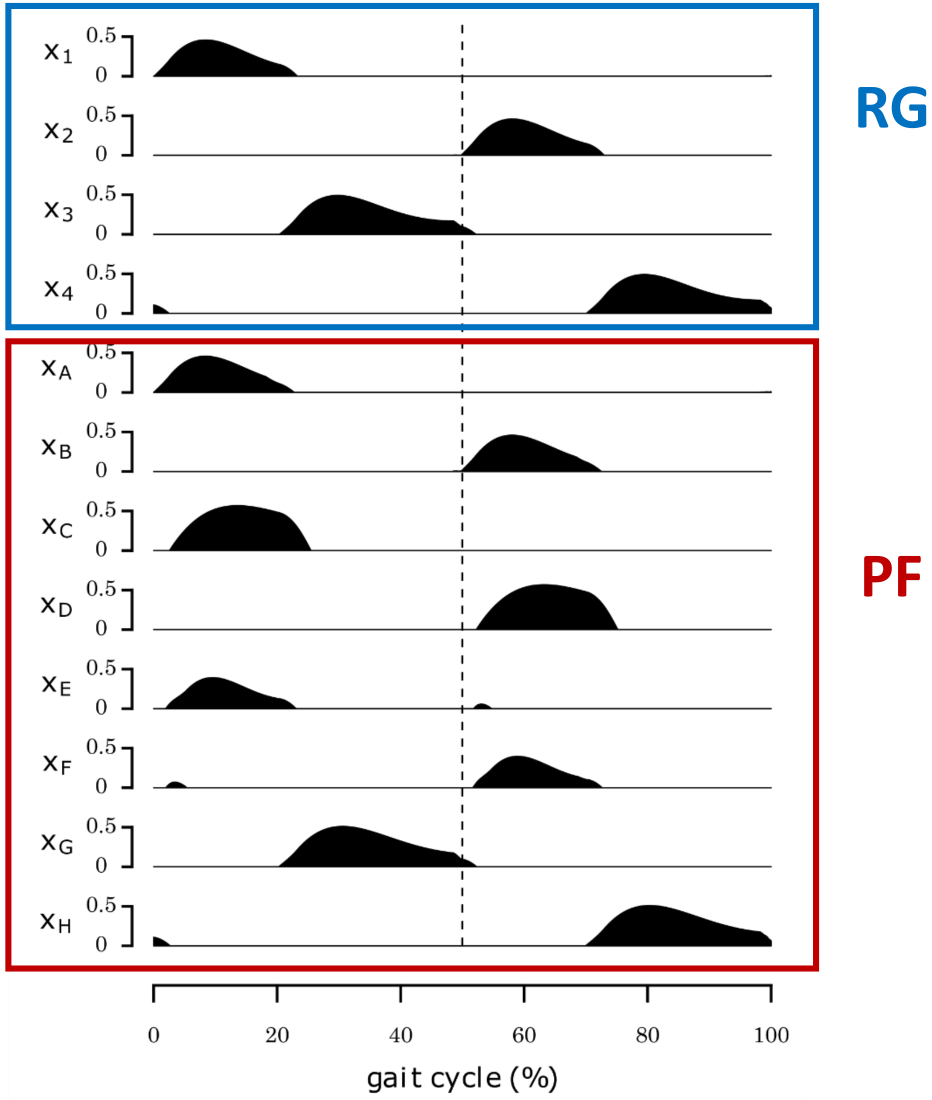
5 runs data

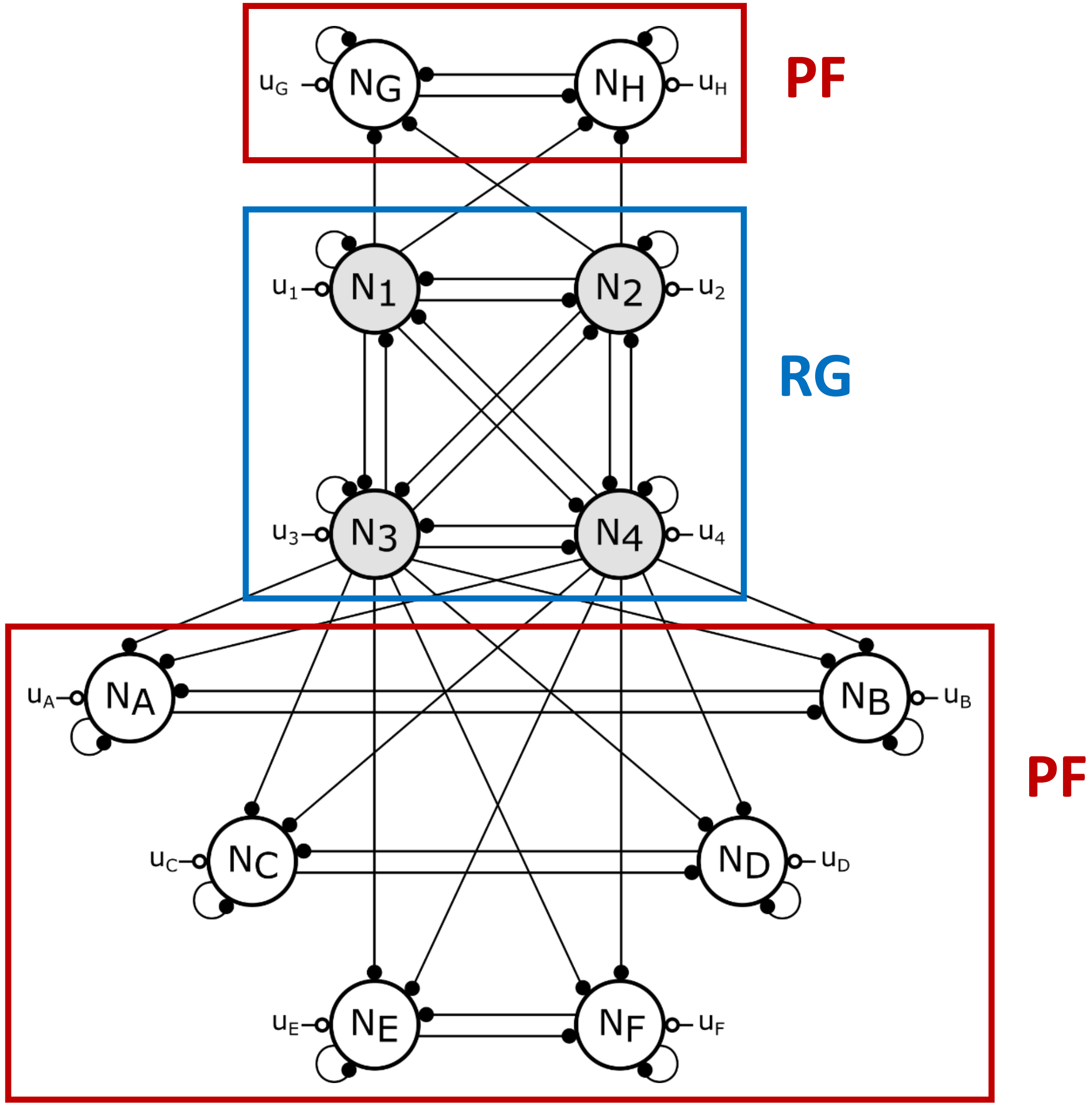
Control gradually transfered from the inverse muscular model to the neural controller.

Cognitive control ratio

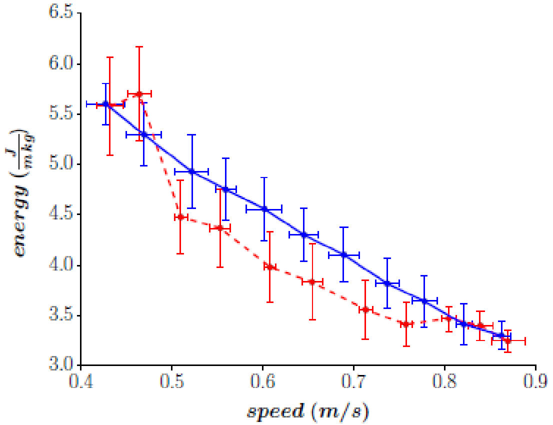
$$\frac{\text{training time}}{\text{elapsed simulation time}}$$

CPG structure for straight walking

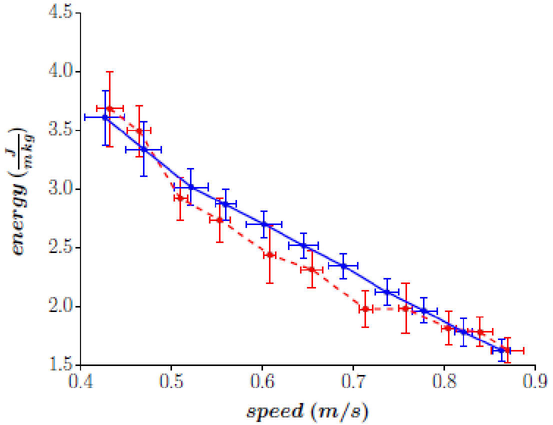




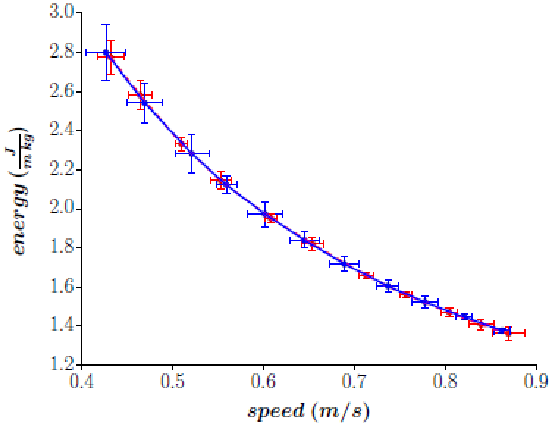
3D straight walking: characteristics



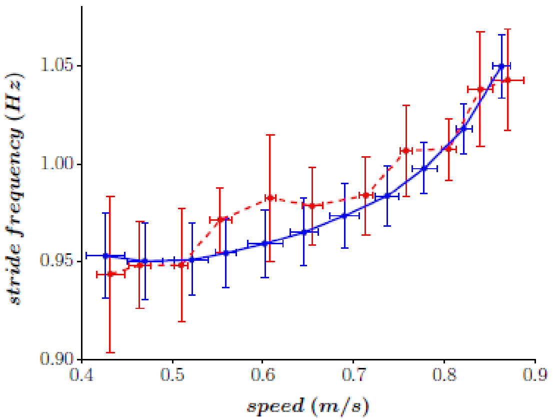
(a) energy sagittal muscles



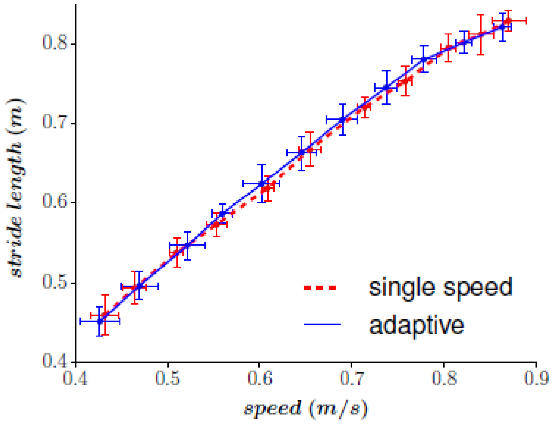
(b) energy lateral muscles



(c) energy transverse muscles

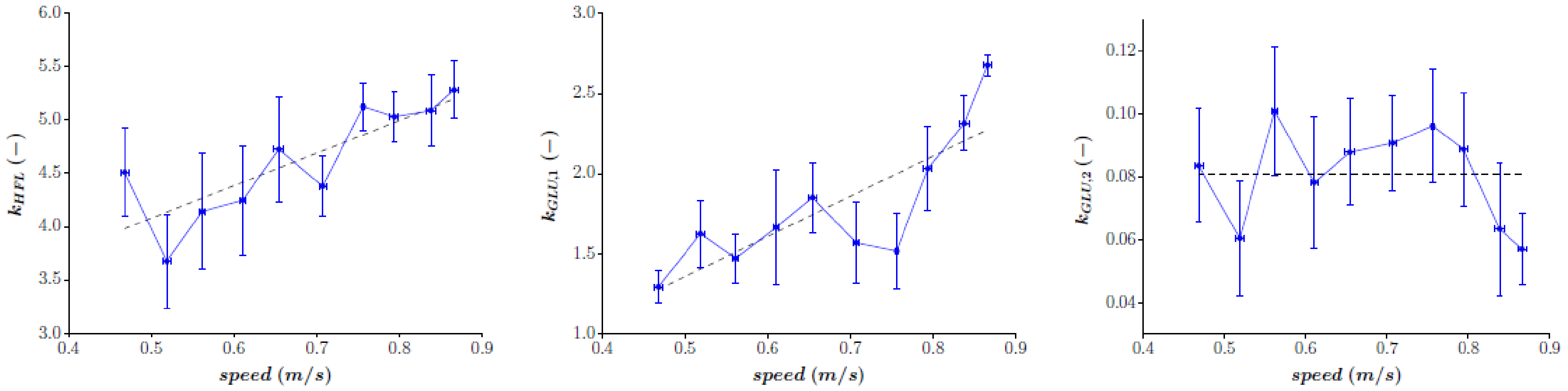


(d) stride frequency



(e) stride length

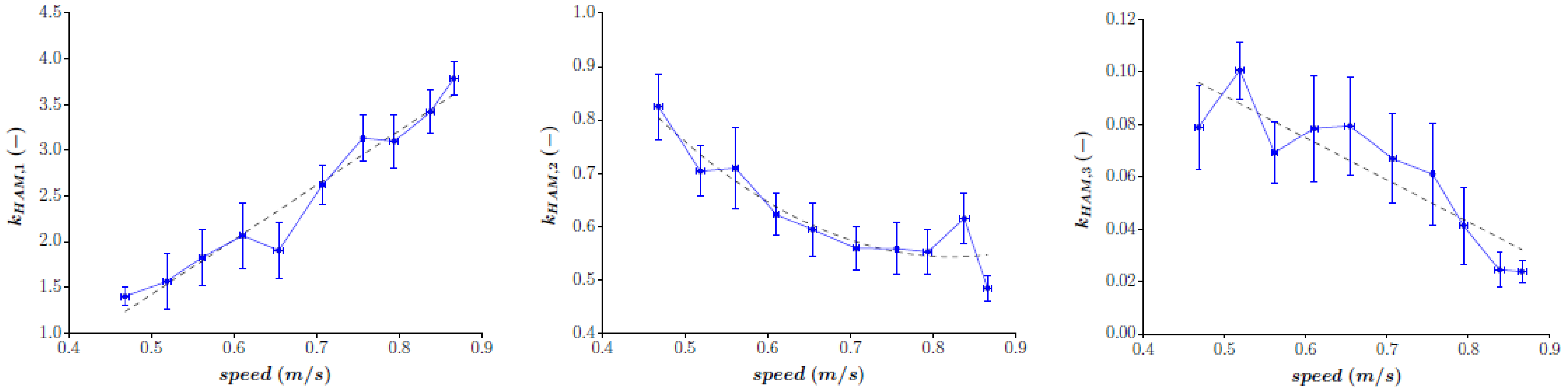
3D walking: speed parameters (I)



(a) Stimulation gain k_{HFL}

(b) Stimulation gain $k_{GLU,1}$

(c) Stimulation gain $k_{GLU,2}$

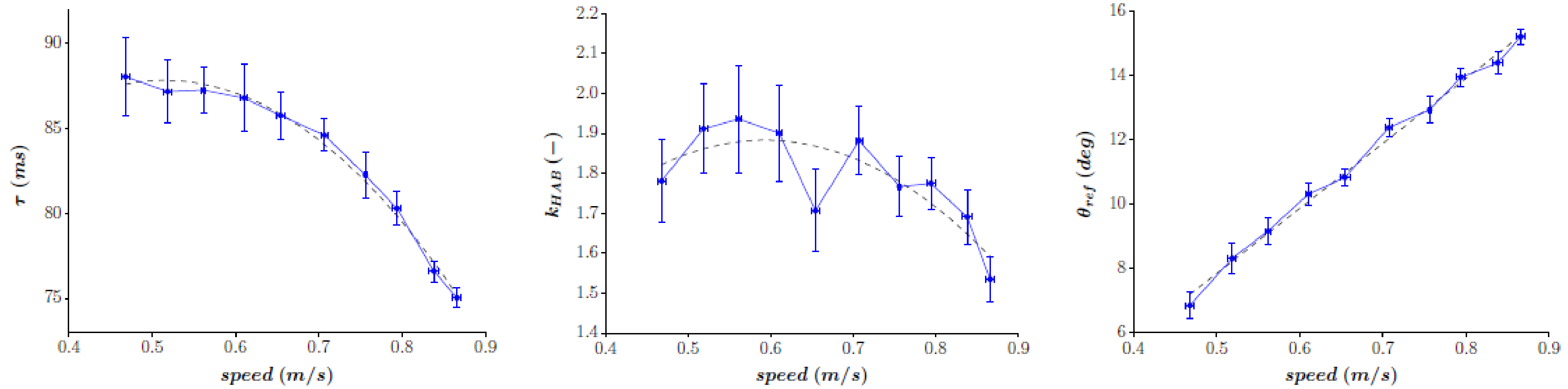


(d) Stimulation gain $k_{HAM,1}$

(e) Stimulation gain $k_{HAM,2}$

(f) Stimulation gain $k_{HAM,3}$

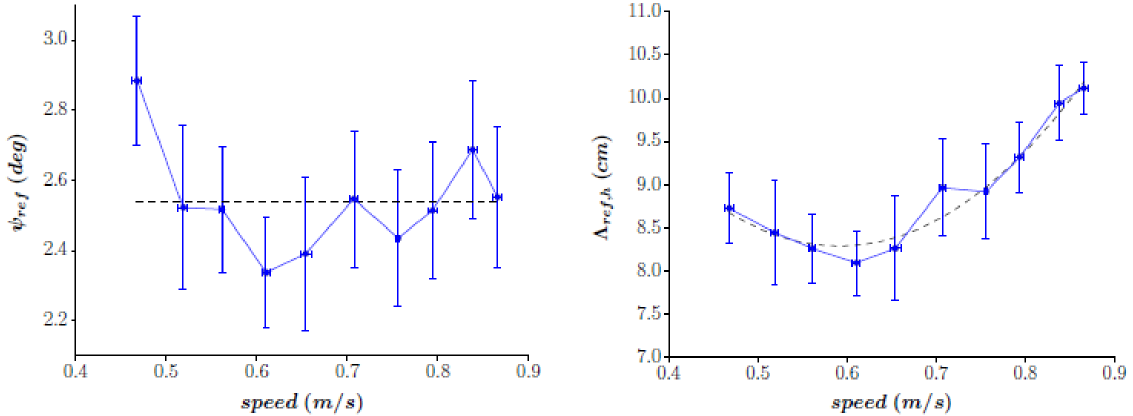
3D walking: speed parameters (II)



(g) CPG time constant τ

(h) Stimulation gain k_{HAB}

(i) Sagittal torso reference θ_{ref}



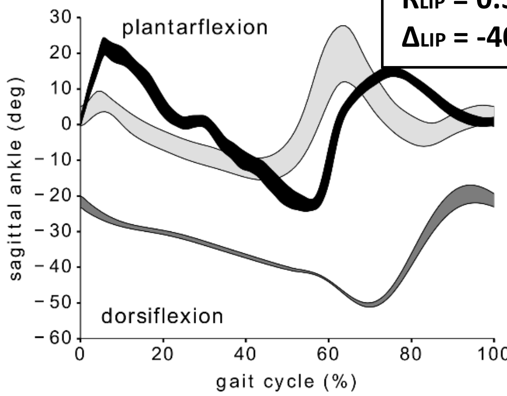
(j) Lateral torso reference Ψ_{ref}

(k) COM reference $\Lambda_{ref,h}$

Comparisons to human and LIP-based data

$R_{neur} = 0.8$
$\Delta_{neur} = -9\ \%$

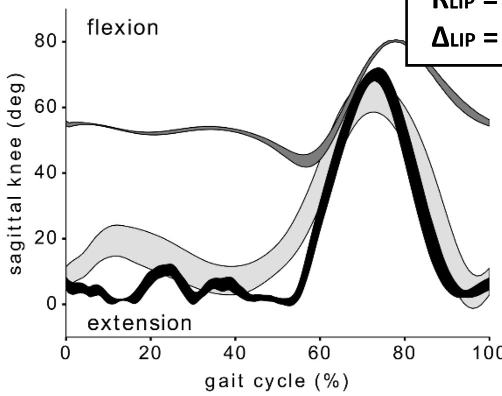
$R_{LIP} = 0.32$
$\Delta_{LIP} = -40\ \%$



sagittal ankle angle

$R_{neur} = 0.95$
$\Delta_{neur} = 0\ \%$

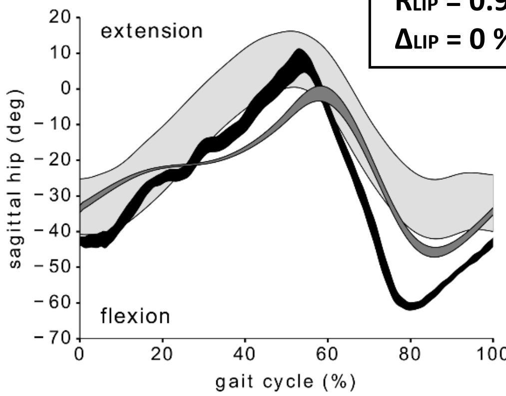
$R_{LIP} = 0.87$
$\Delta_{LIP} = -6\ \%$



sagittal knee angle

$R_{neur} = 0.97$
$\Delta_{neur} = 0\ \%$

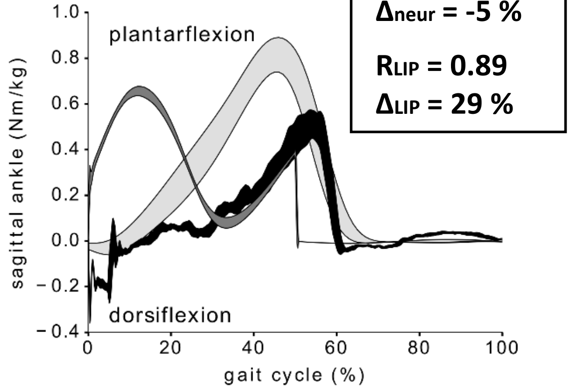
$R_{LIP} = 0.93$
$\Delta_{LIP} = 0\ \%$



sagittal hip angle

$R_{neur} = 0.92$
$\Delta_{neur} = -5\ \%$

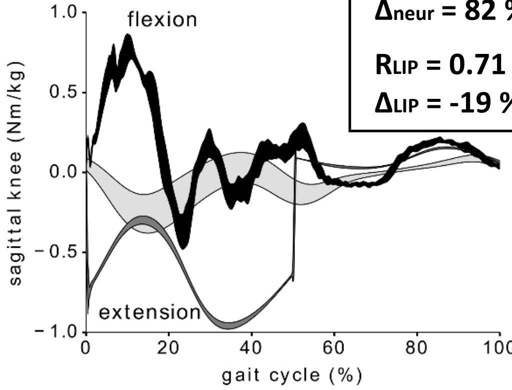
$R_{LIP} = 0.89$
$\Delta_{LIP} = 29\ \%$



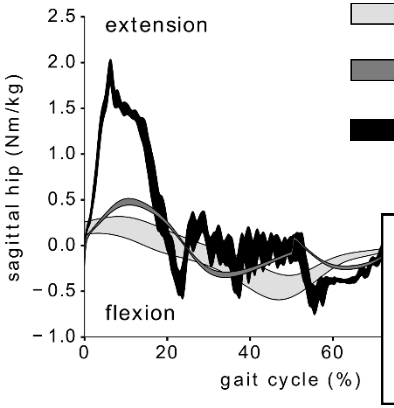
sagittal ankle torque

$R_{neur} = 0.24$
$\Delta_{neur} = 82\ \%$

$R_{LIP} = 0.71$
$\Delta_{LIP} = -19\ \%$



sagittal knee torque



▭ human-data
▨ LIP-based
■ neuromuscular

$R_{neur} = 0.53$
$\Delta_{neur} = -3\ \%$

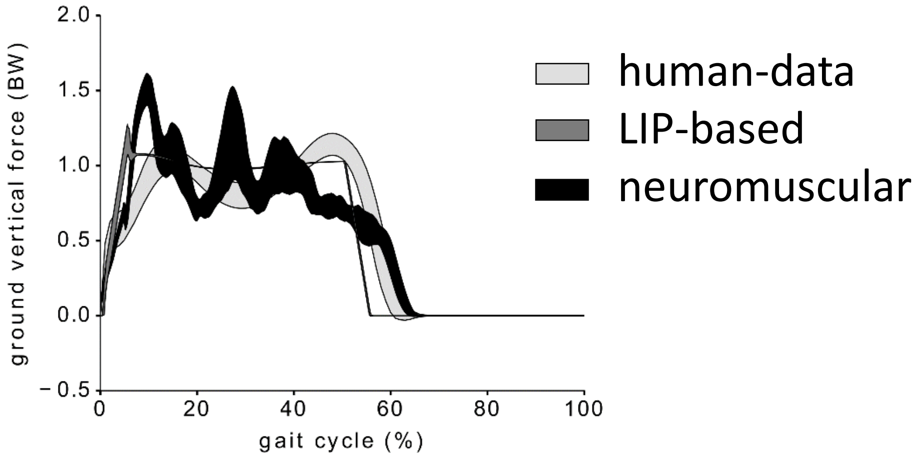
$R_{LIP} = 0.66$
$\Delta_{LIP} = -1\ \%$

sagittal hip torque

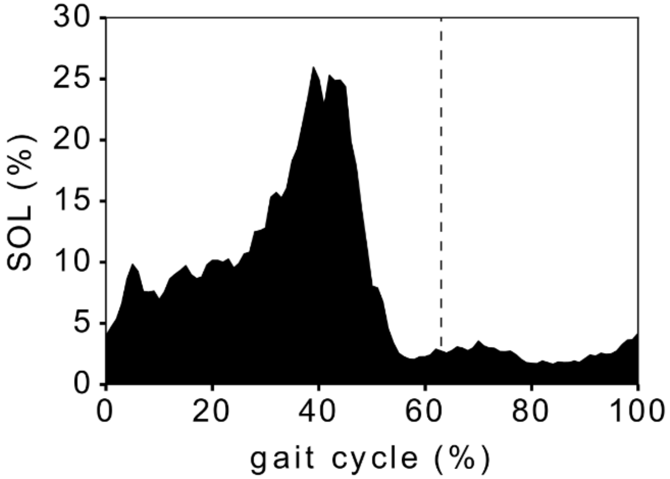
Comparisons to human and LIP-based data

R_{neur} = 0.96
Δ_{neur} = 1 %

R_{LIP} = 0.98
Δ_{LIP} = 3 %



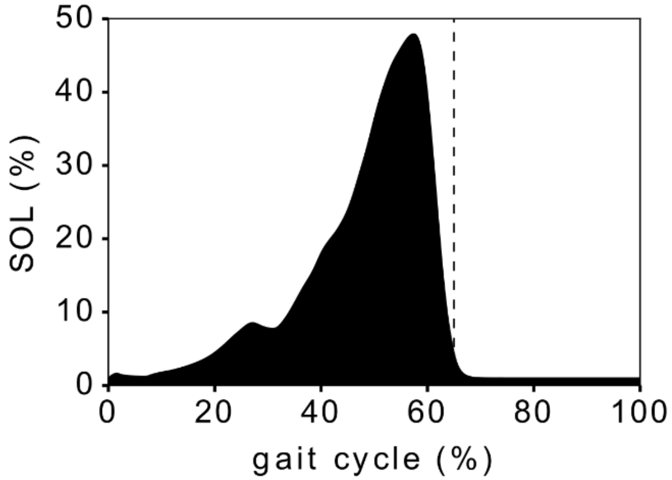
vertical ground reaction forces



human soleus EMG

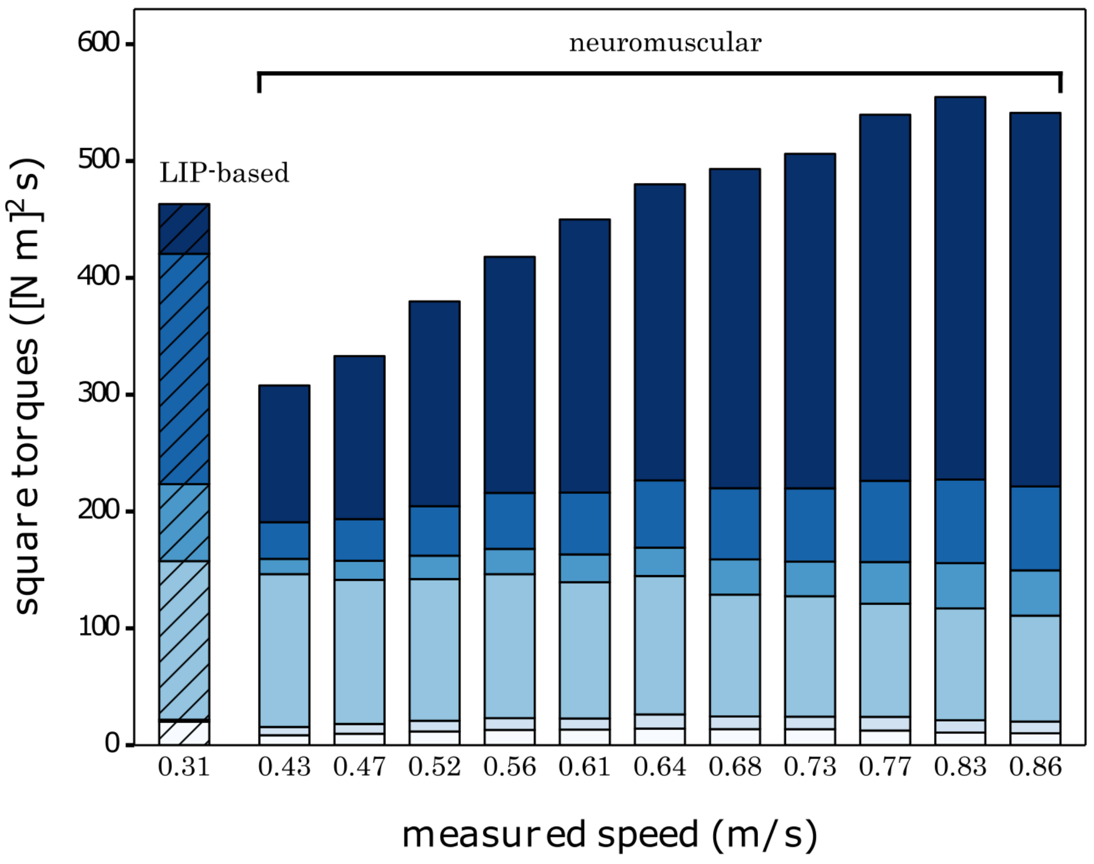
R_{neur} = 0.96

Δ_{neur} = -14 %

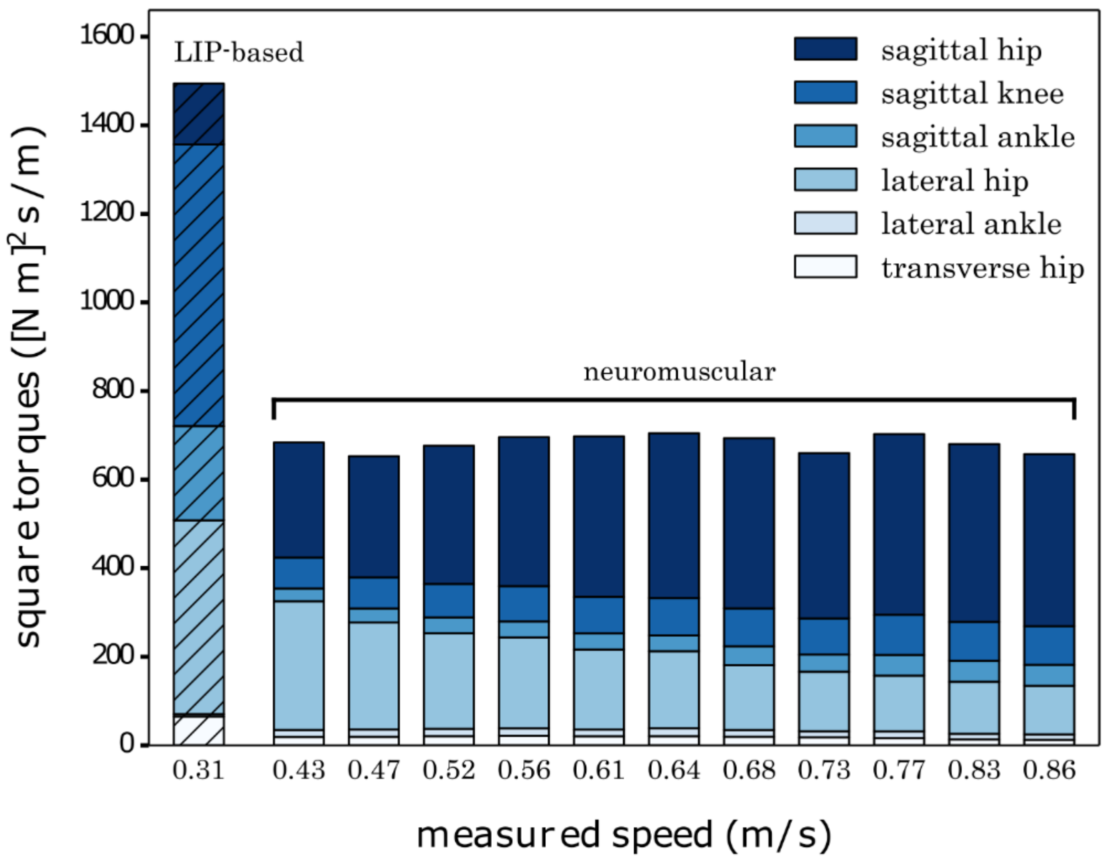


COMAN soleus activation

Energetic consumption: square torques integration

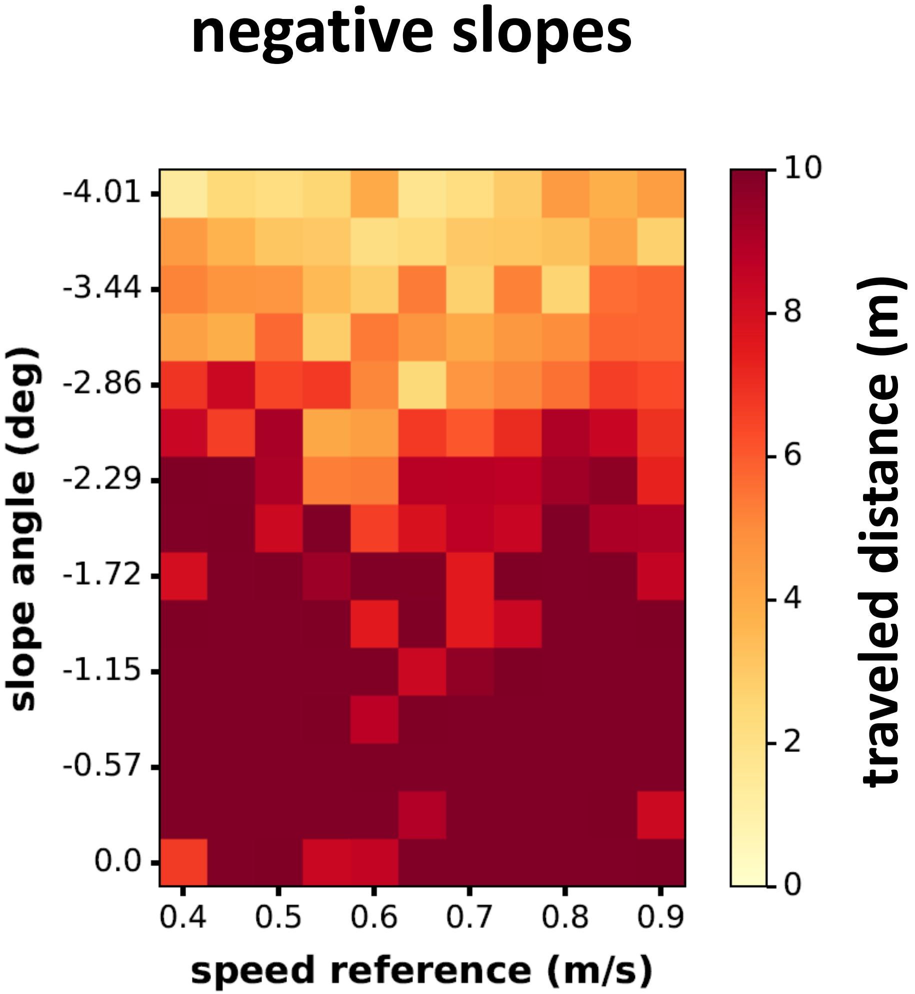


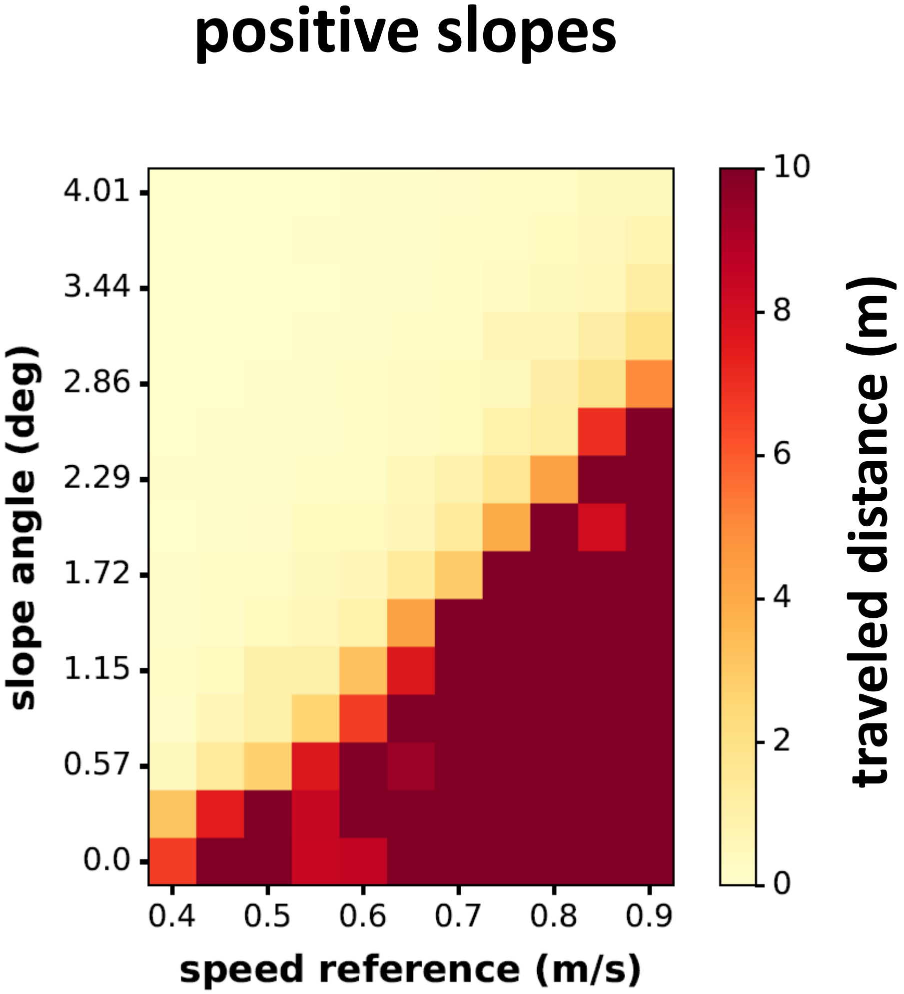
square torques per gait cycle



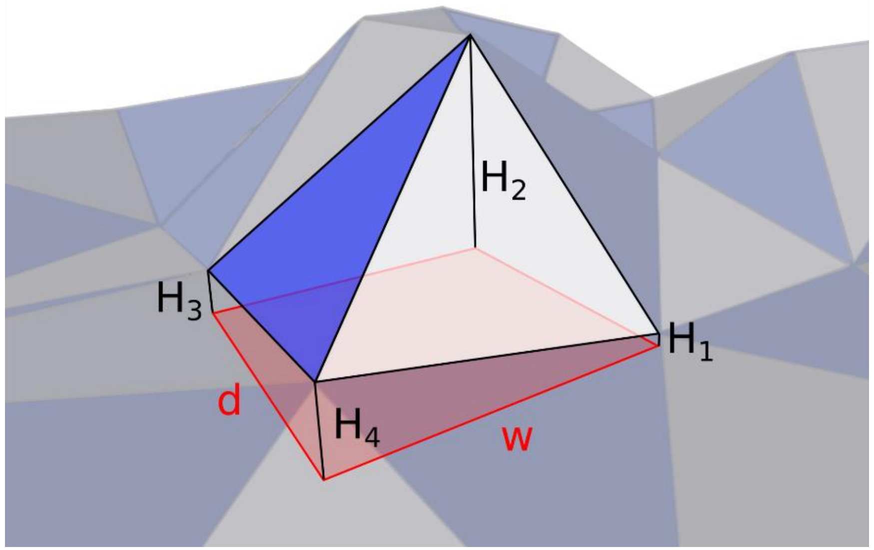
square torques per gait cycle, divided by traveled distance

Robustness: facing unknown slopes

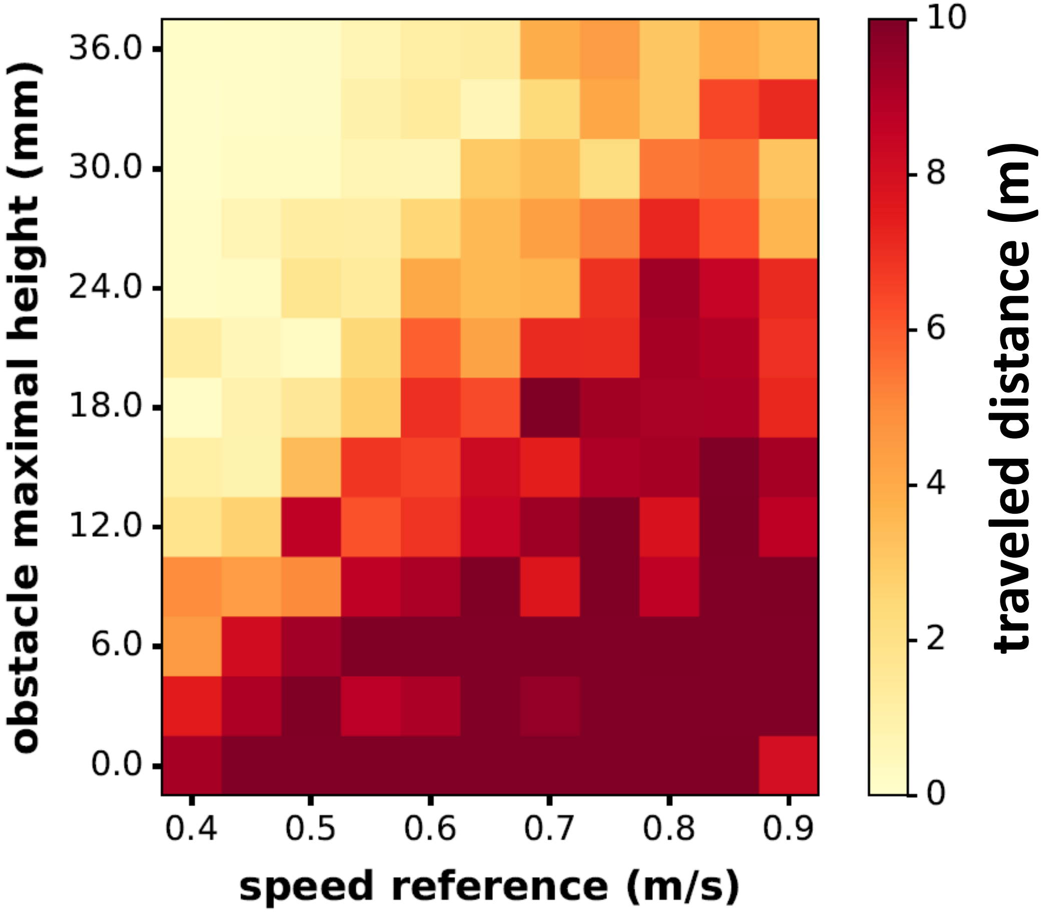




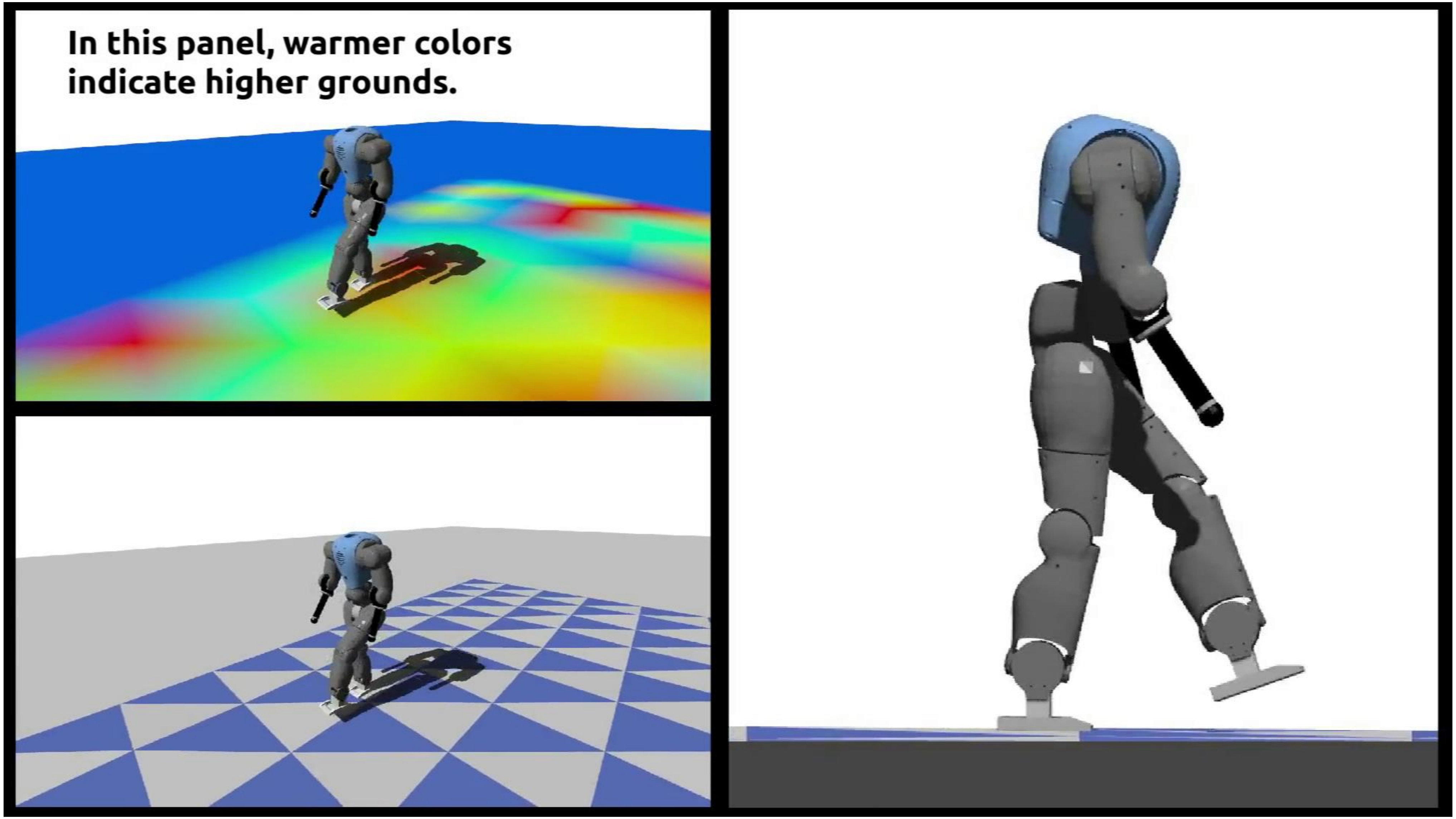
Robustness: blind walking on irregular ground



ground description

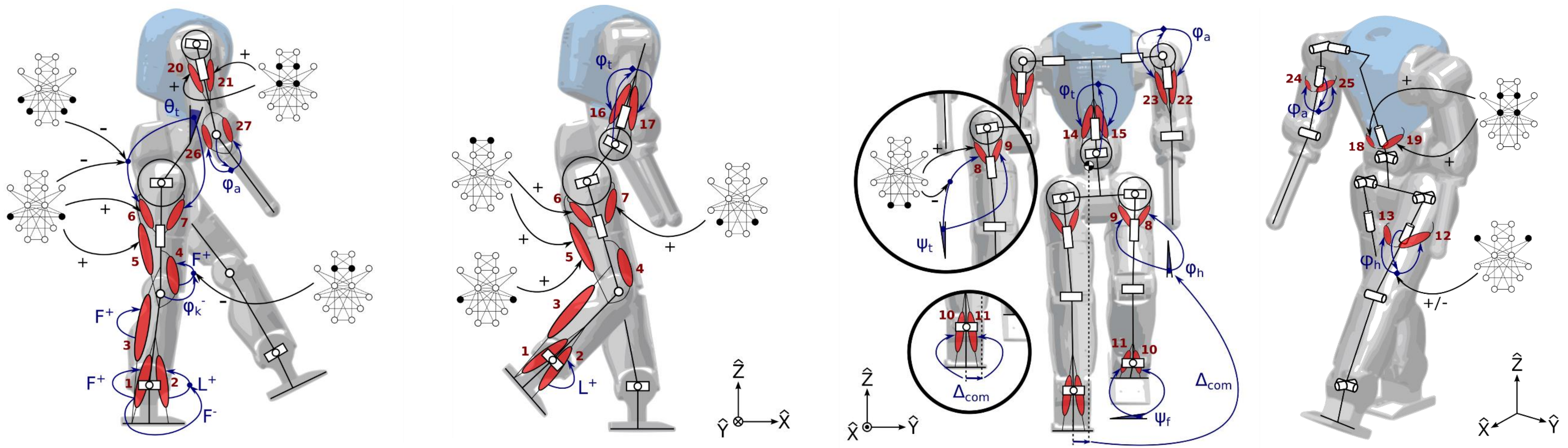


Blind walking on irregular ground



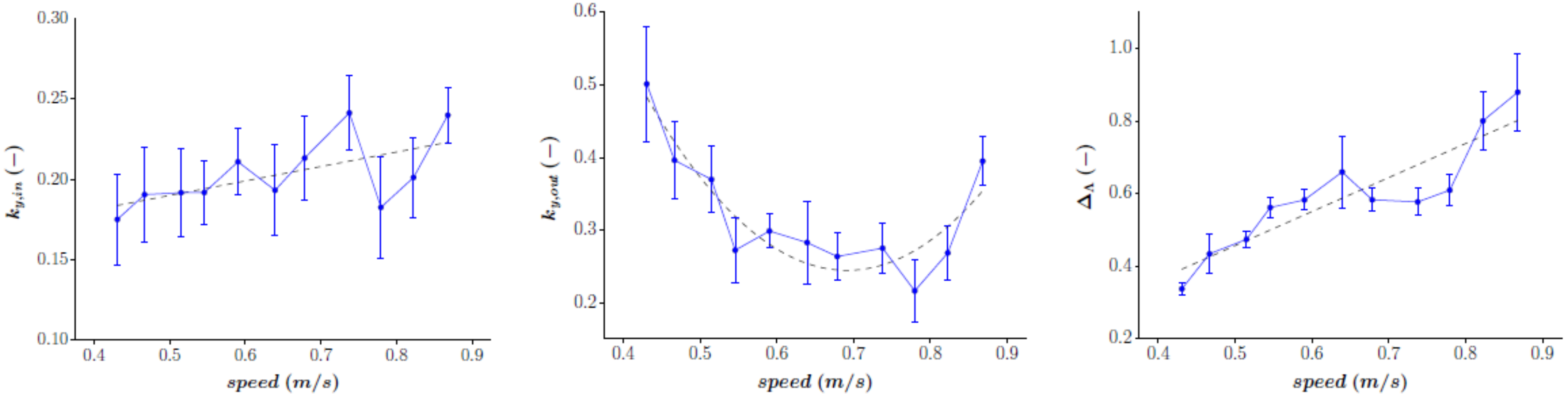
Full 3D control

- New virtual **muscles** (in all the planes)
- New **reflex** signals
- **CPG** structure incremented

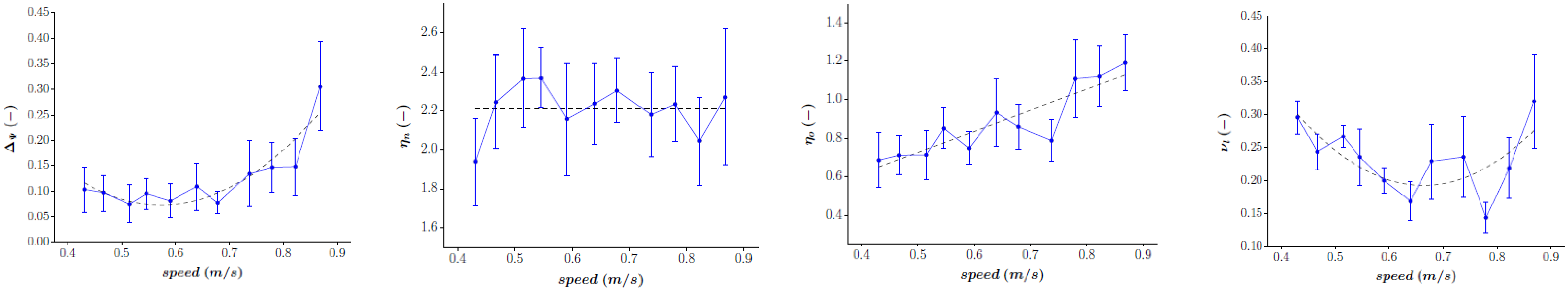


Sagittal plane **Lateral plane** **Transverse plane**

Heading control: speed parameters

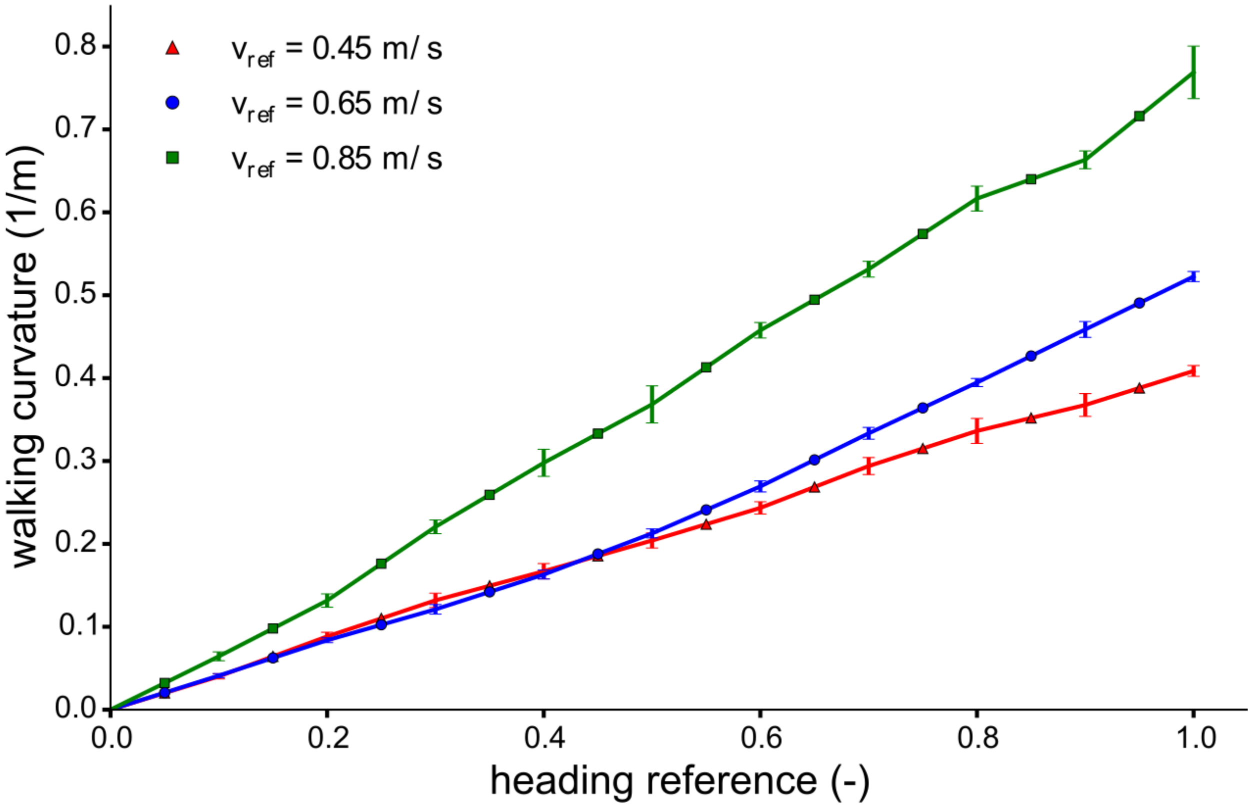


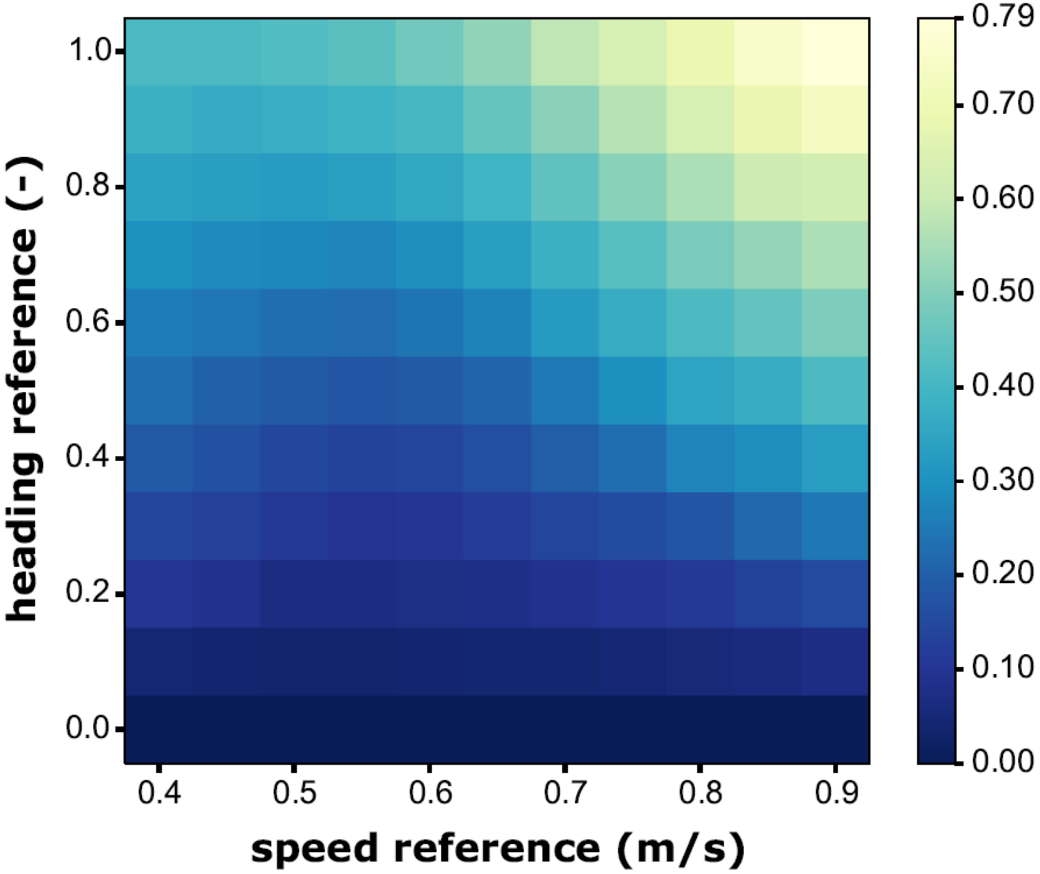
(a) Transverse gain $k_{y,in}$ (b) Transverse gain $k_{y,out}$ (c) COM modulation Δ_Λ



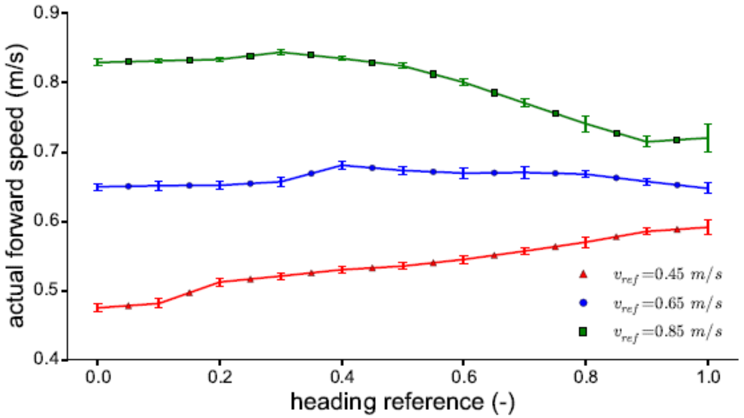
(d) Hip modulation Δ_Ψ (e) CPG connexion η_n (f) CPG connexion η_o (g) Lateral excitation ν_l

Walking curvature

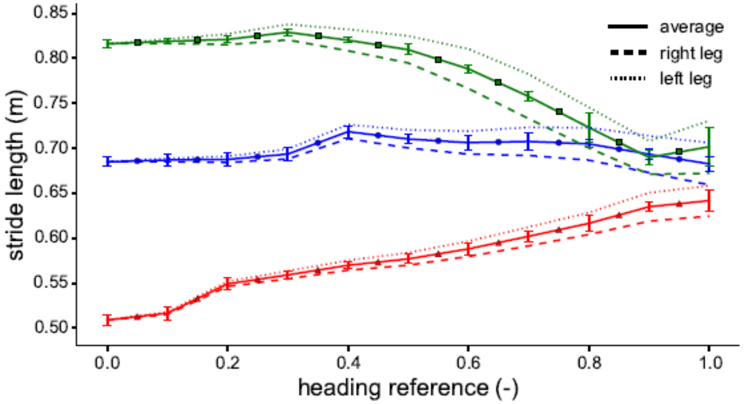




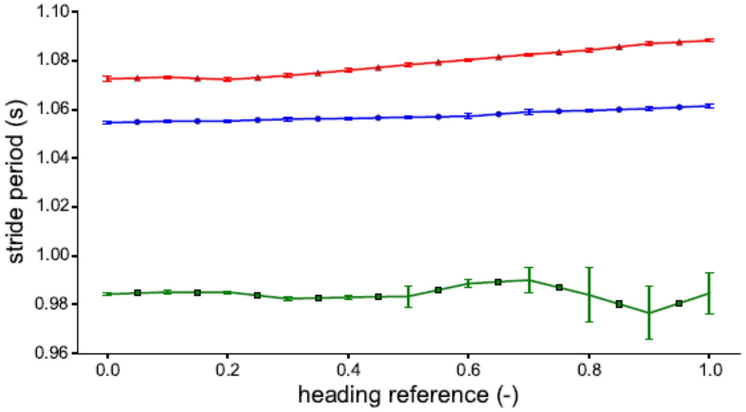
Steering characteristics



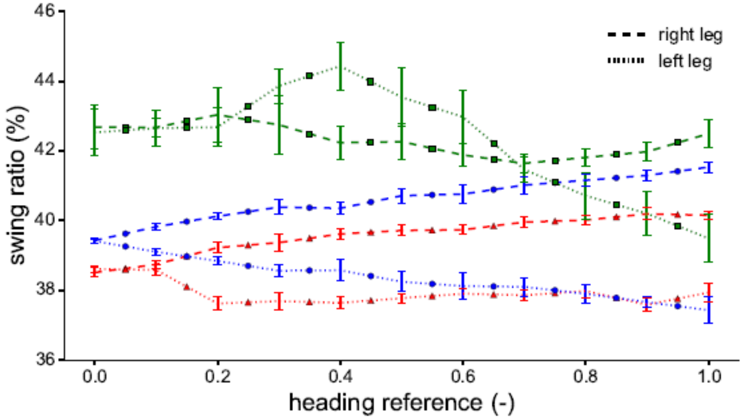
(a) real speed



(b) stride length

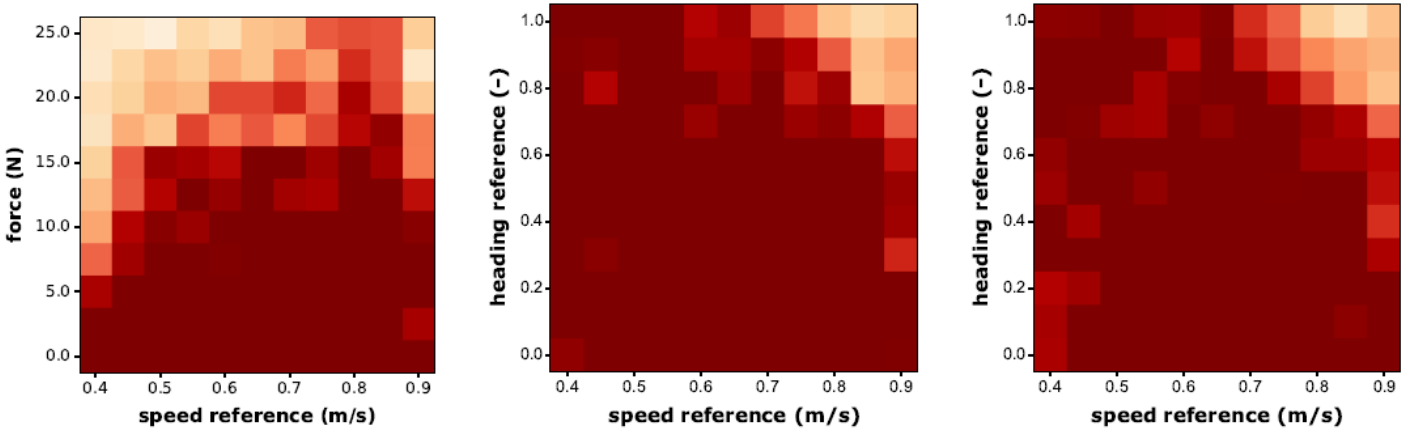


(c) stride period

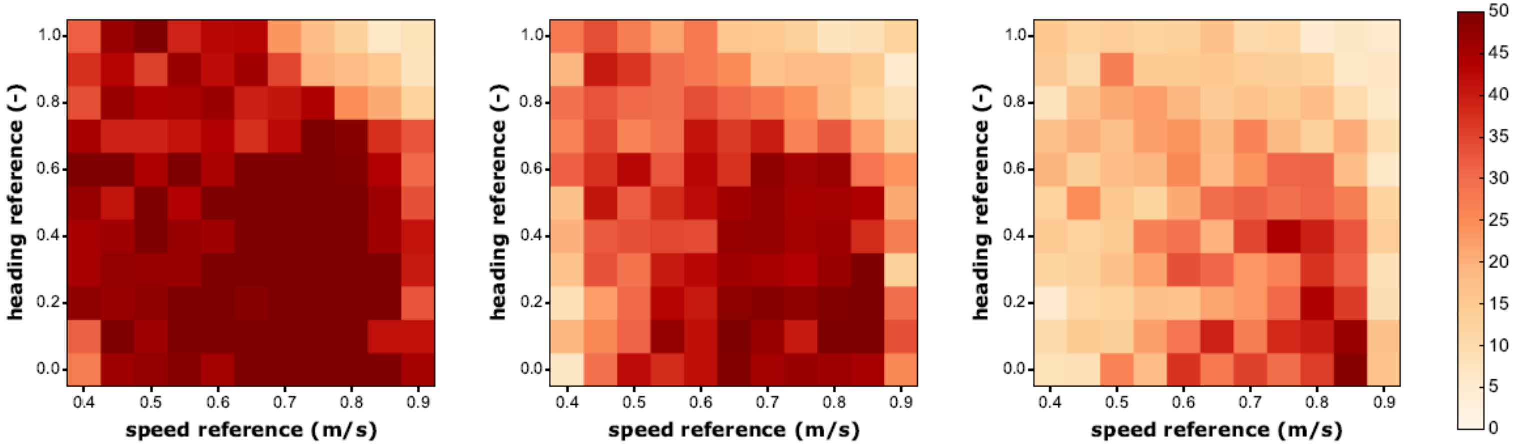


(d) swing ratio

Steering robustness

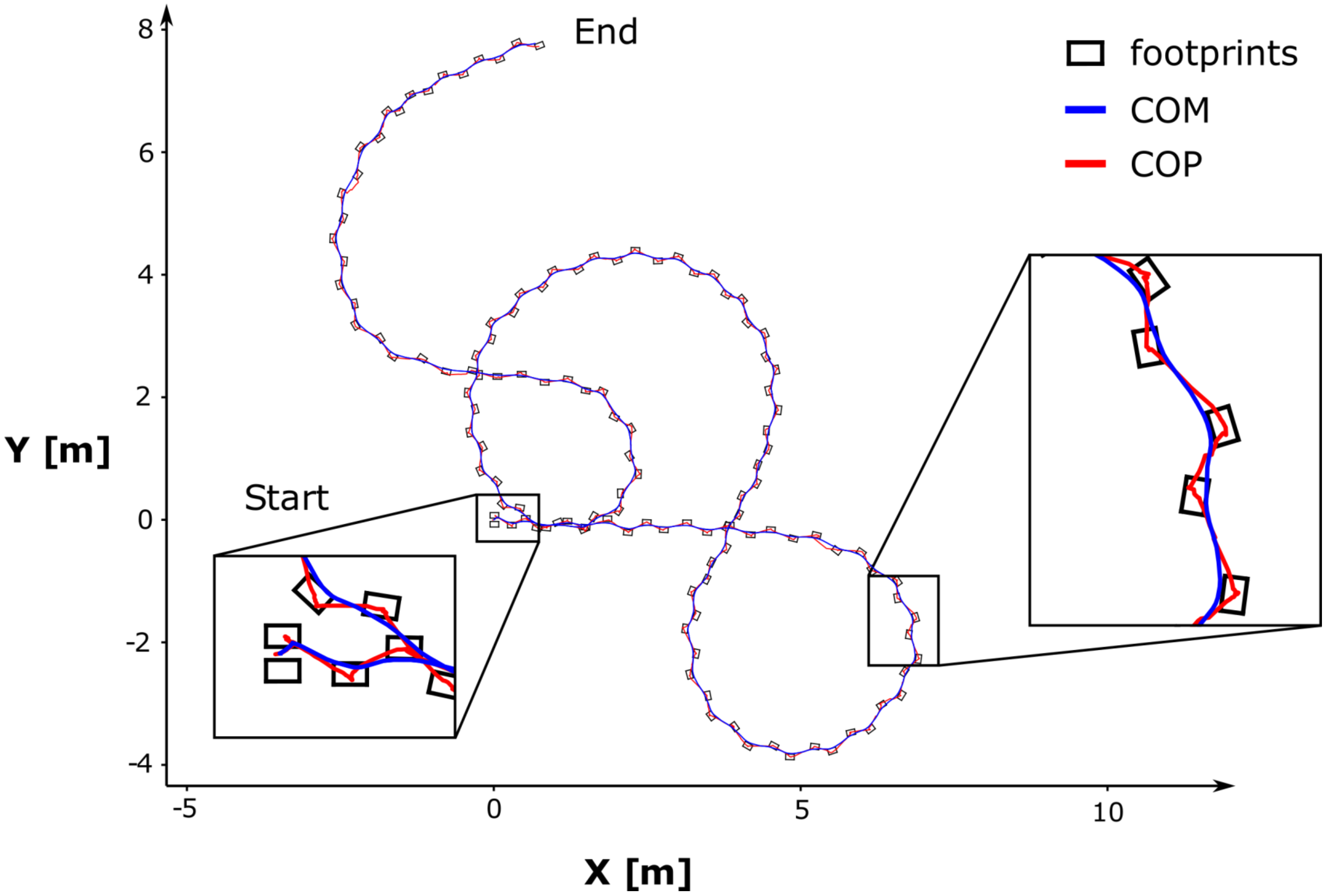


(a) straight walking, forces: $0 - 25\,N$ (b) right steering, force: $0\,N$ (c) right steering, force: $5\,N$

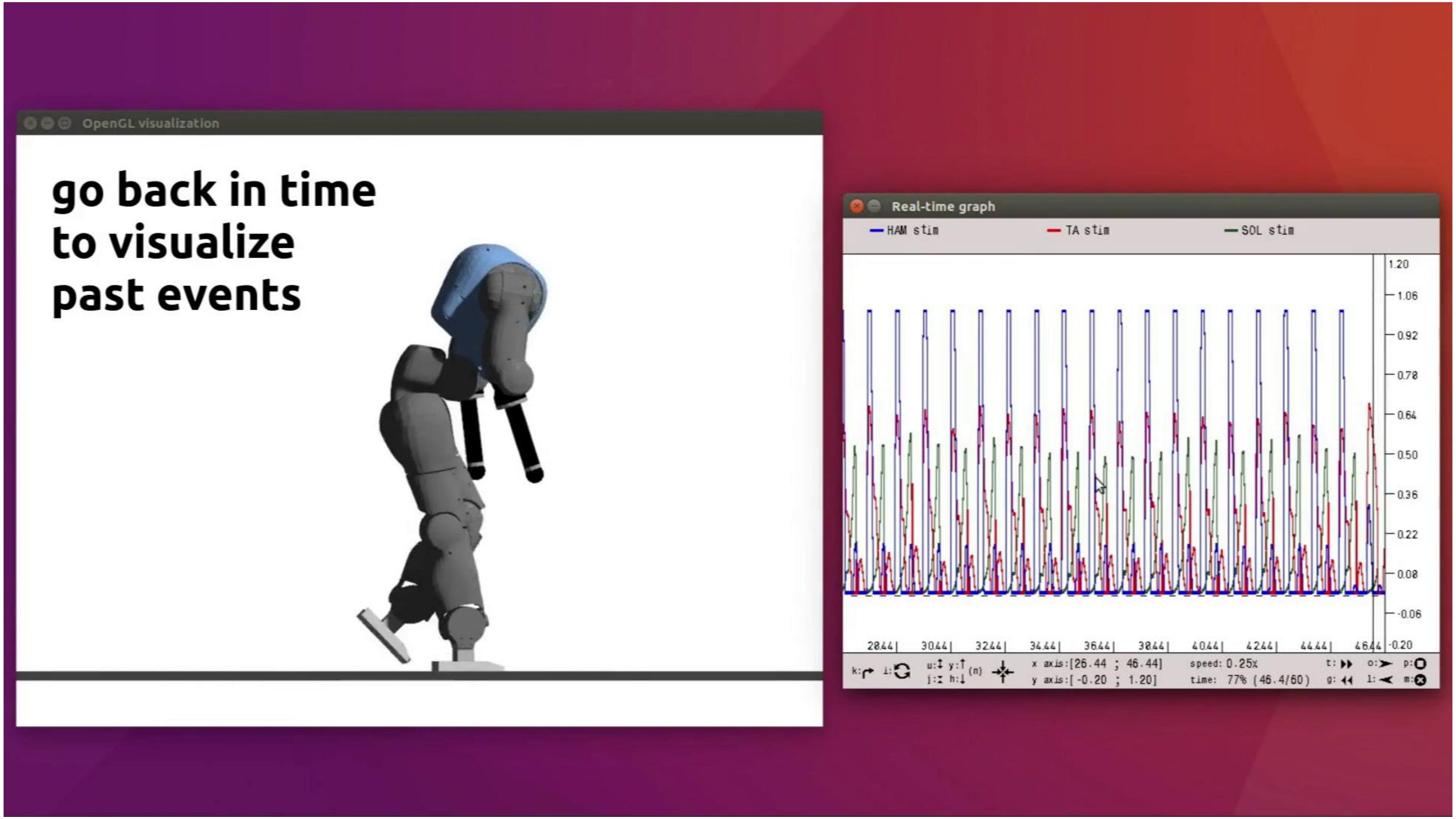


(d) right steering, force: $10\,N$ (e) right steering, force: $15\,N$ (f) right steering, force: $20\,N$

Footprints during steering



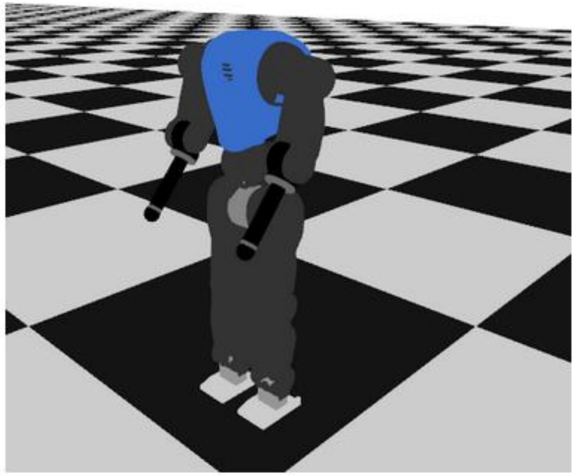
Robotran: real-time features



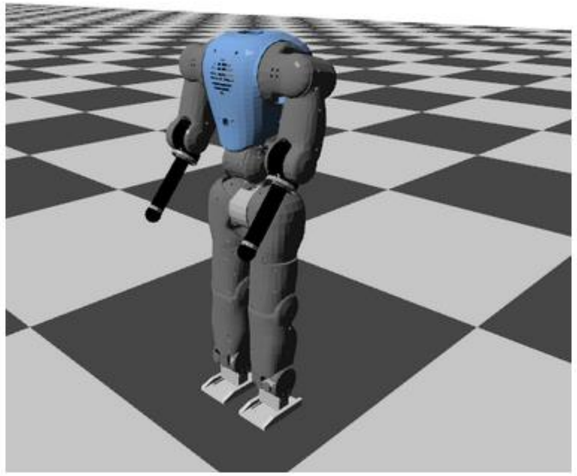
go back in time
to visualize
past events

x axis:[26.44 ; 46.44]
y axis:[-0.20 ; 1.20]
speed: 0.25x
time: 77% (46.4/60)

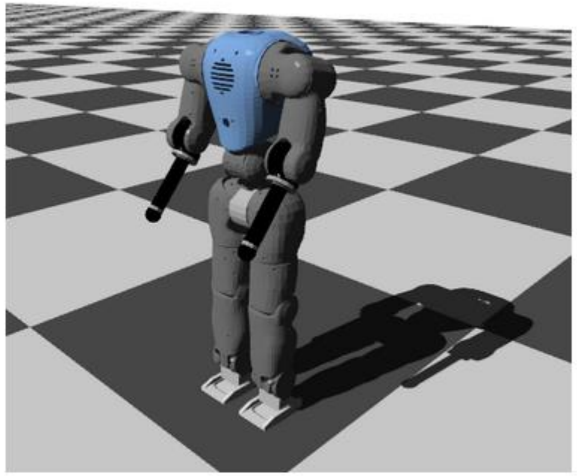
OpenGL features



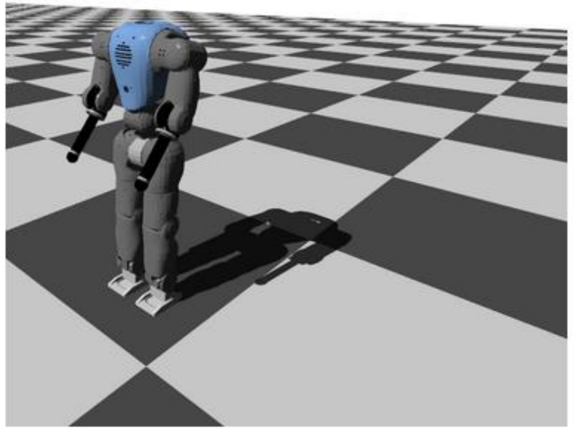
basic shader



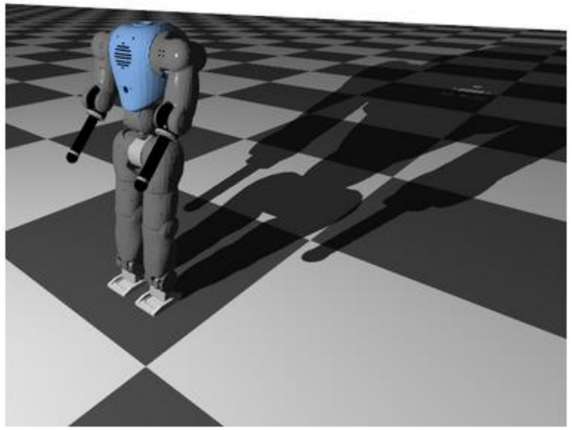
shader with lights



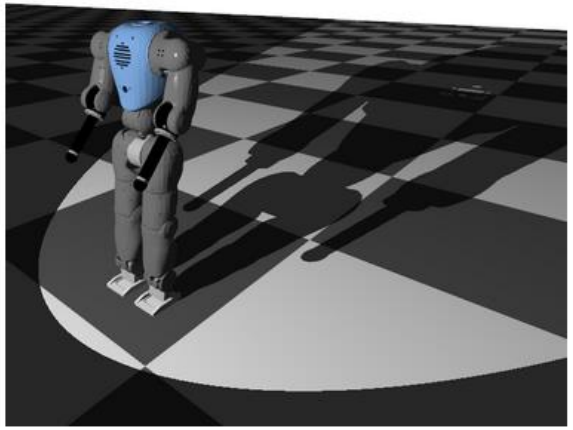
shader with lights and shadows



directional light

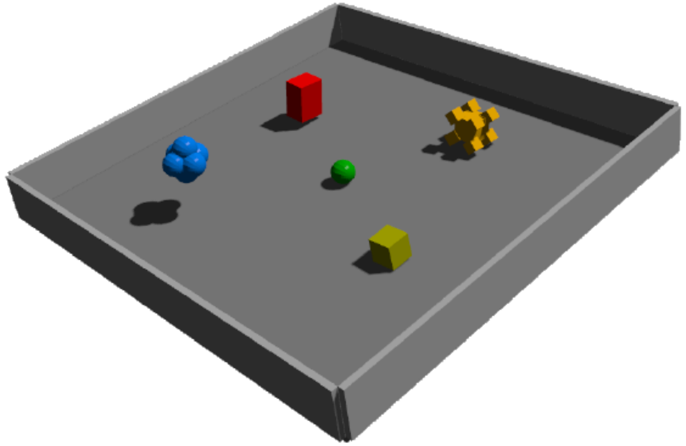


point light

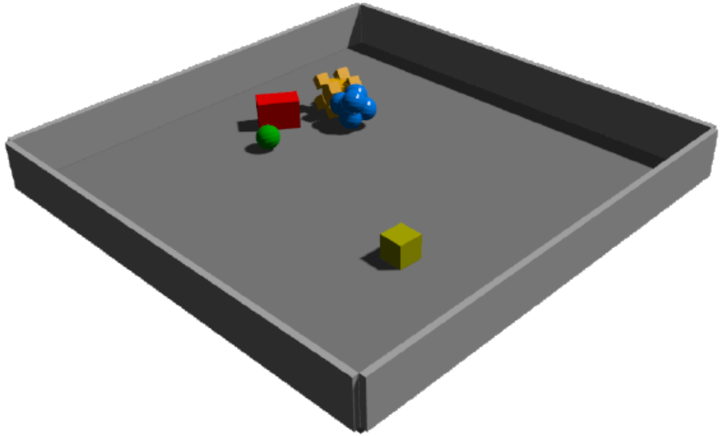


spot light

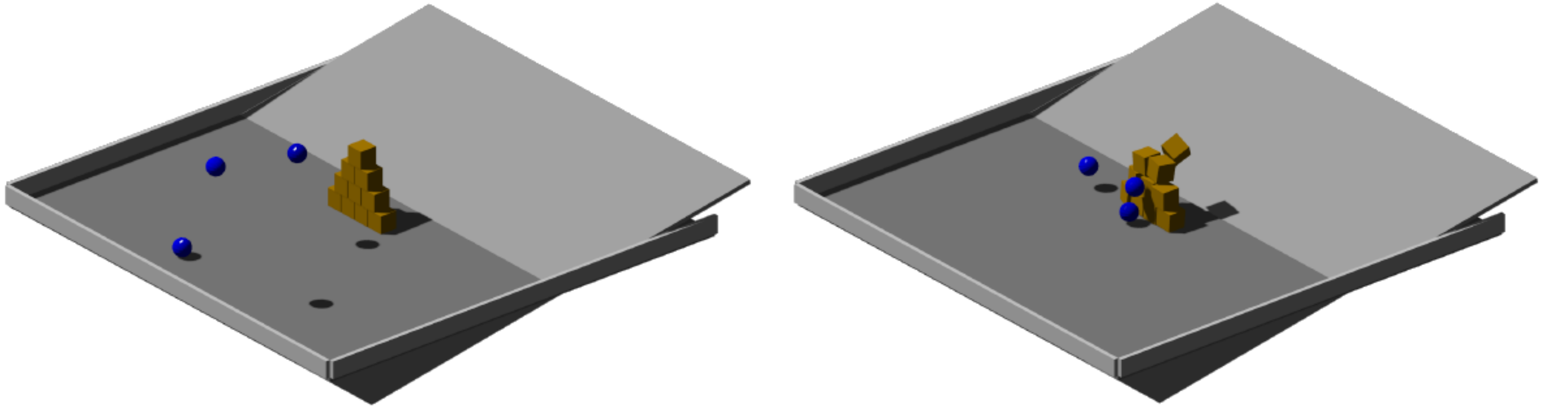
Primitive shapes contact model



(a) objects released on the moving plane

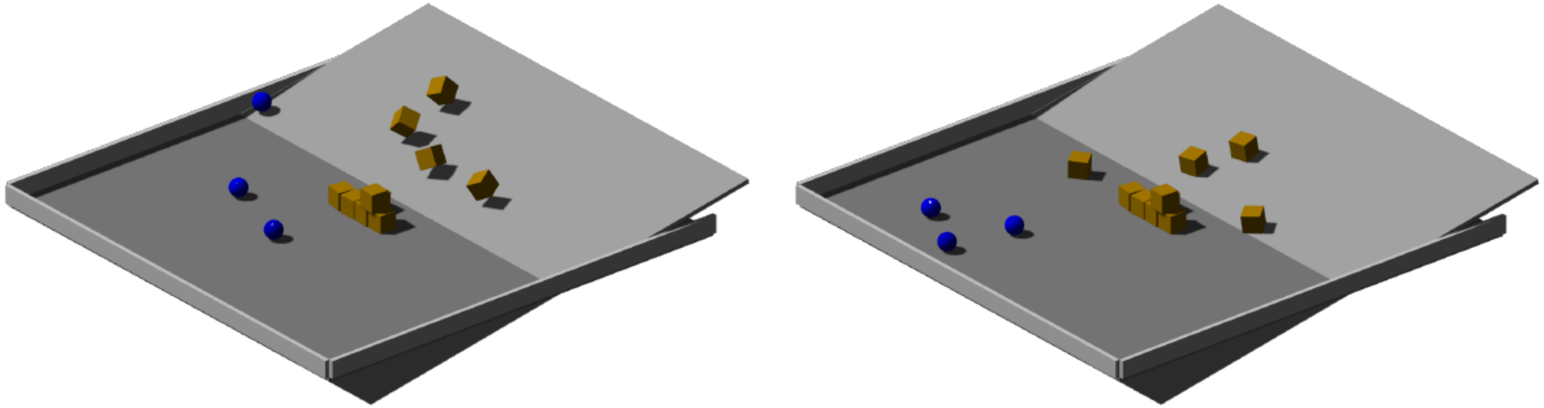


(b) positions of the objects after after a few seconds



(a) before impacts

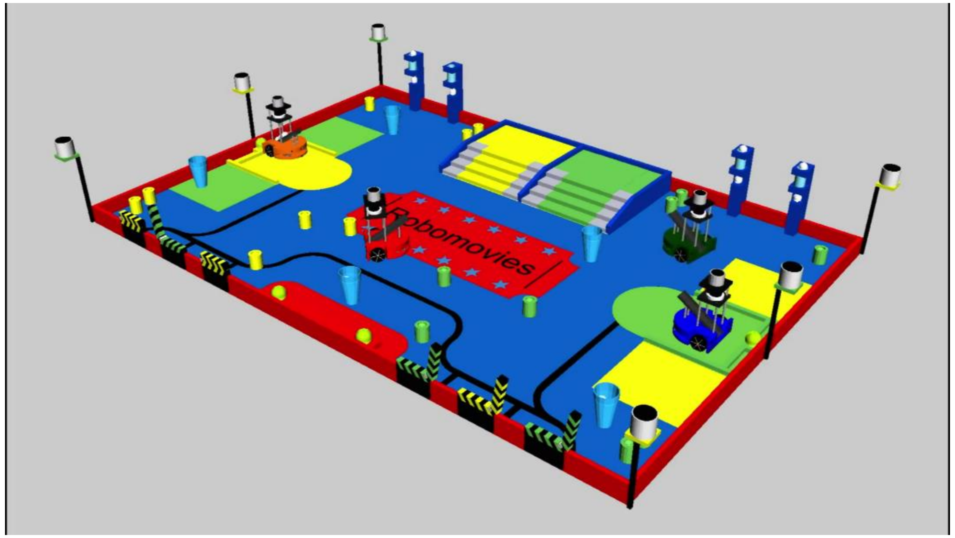
(b) during impacts

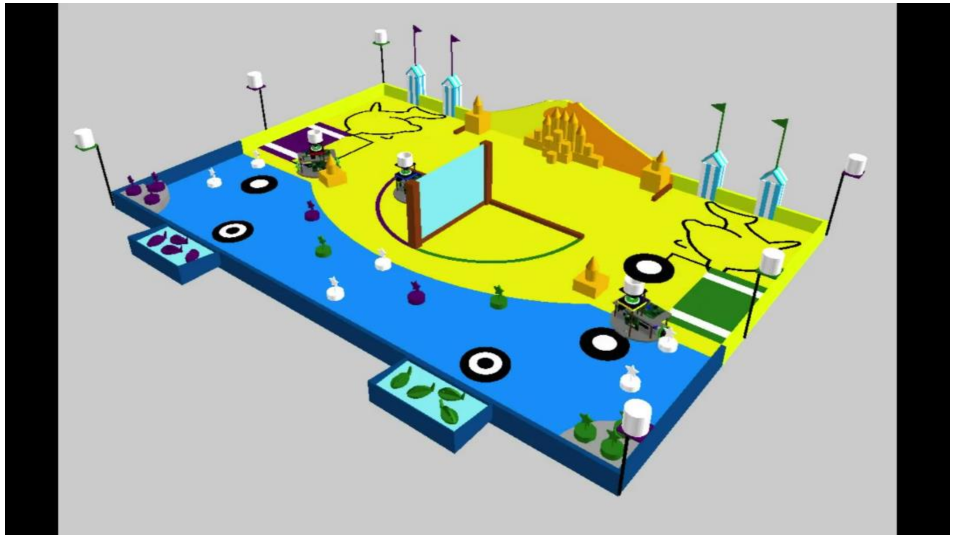


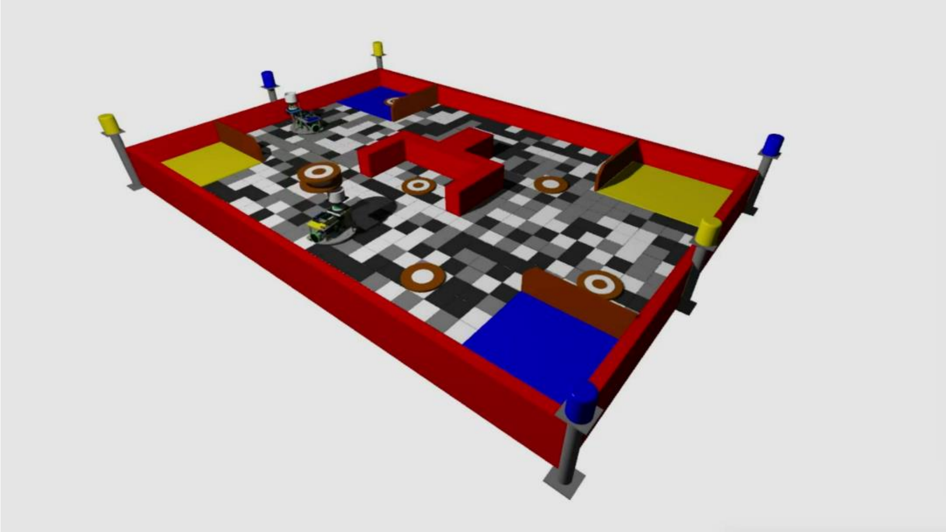
(c) after impacts

(d) boxes in standstill position

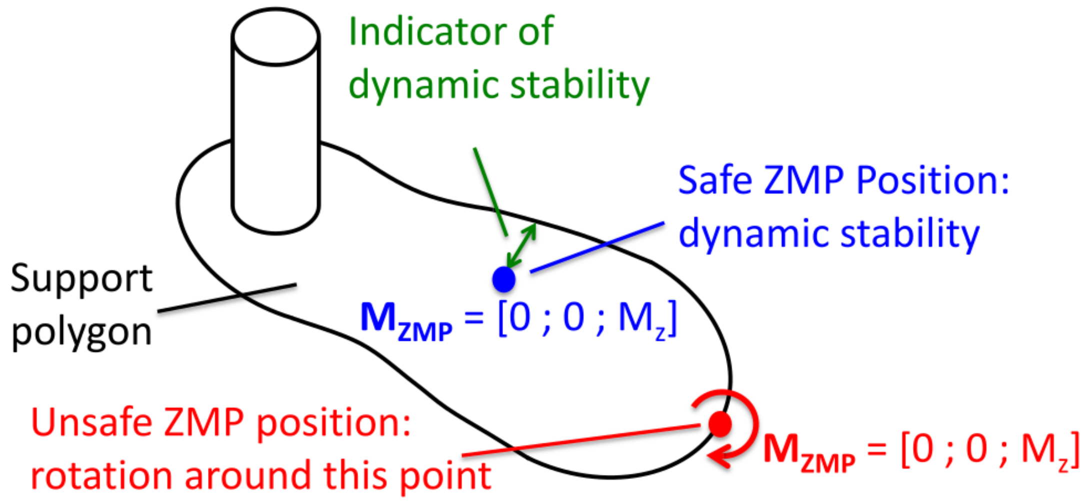
LMECA 2732 (UCL) & MICRO-452 (EPFL) courses







Zero-moment point



Indicator of dynamic stability

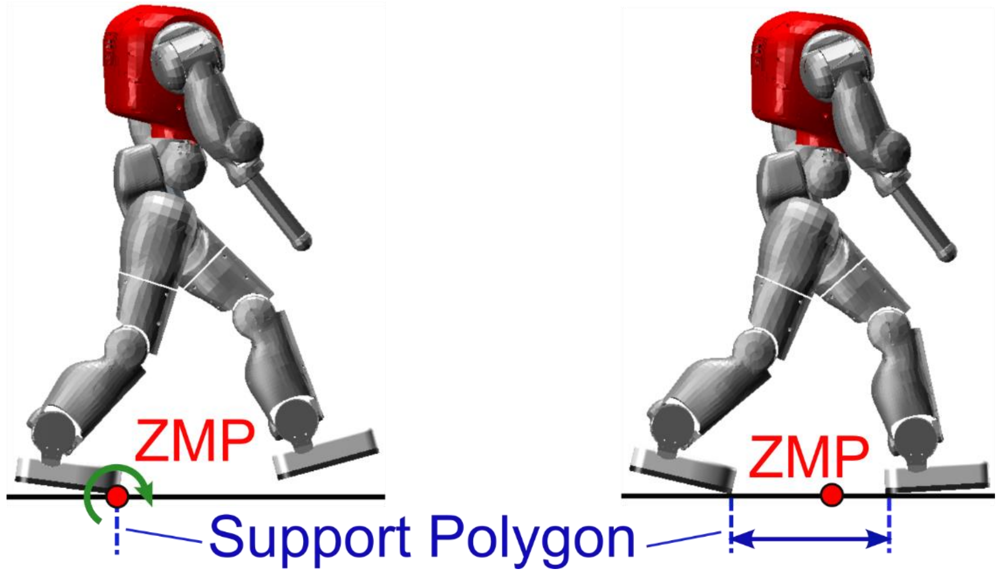
Safe ZMP Position: dynamic stability

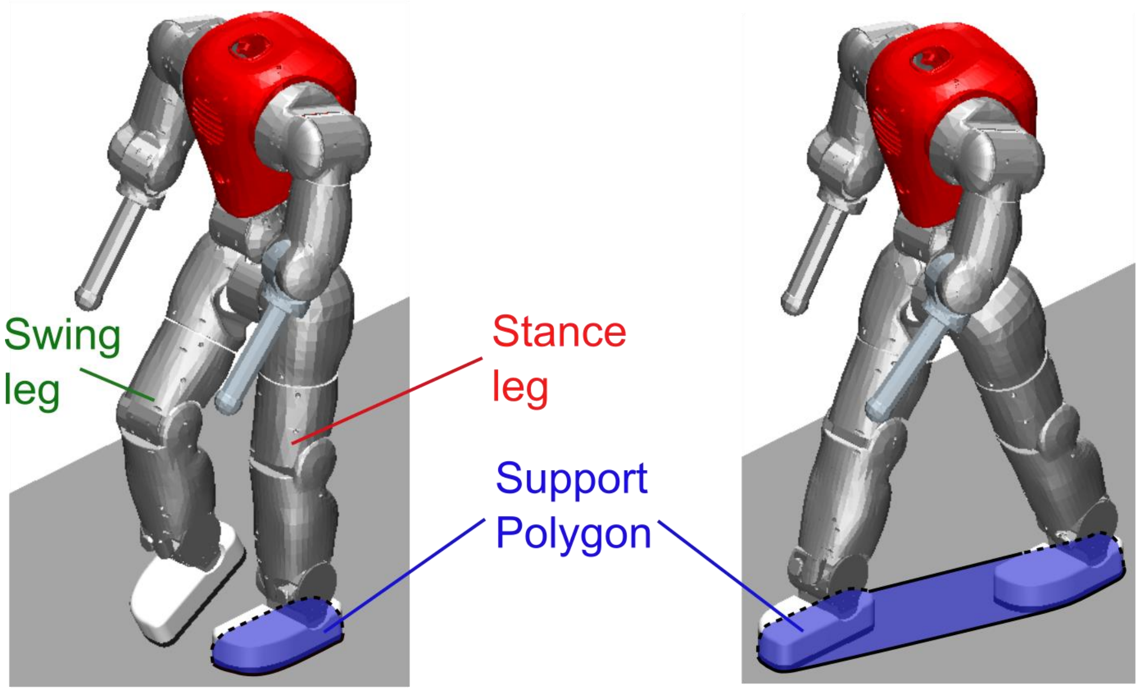
Support polygon

$\mathbf{M}_{\mathbf{ZMP}} = [0\ ;\ 0\ ;\ M_z]$

Unsafe ZMP position: rotation around this point

$\mathbf{M}_{\mathbf{ZMP}} = [0\ ;\ 0\ ;\ M_z]$

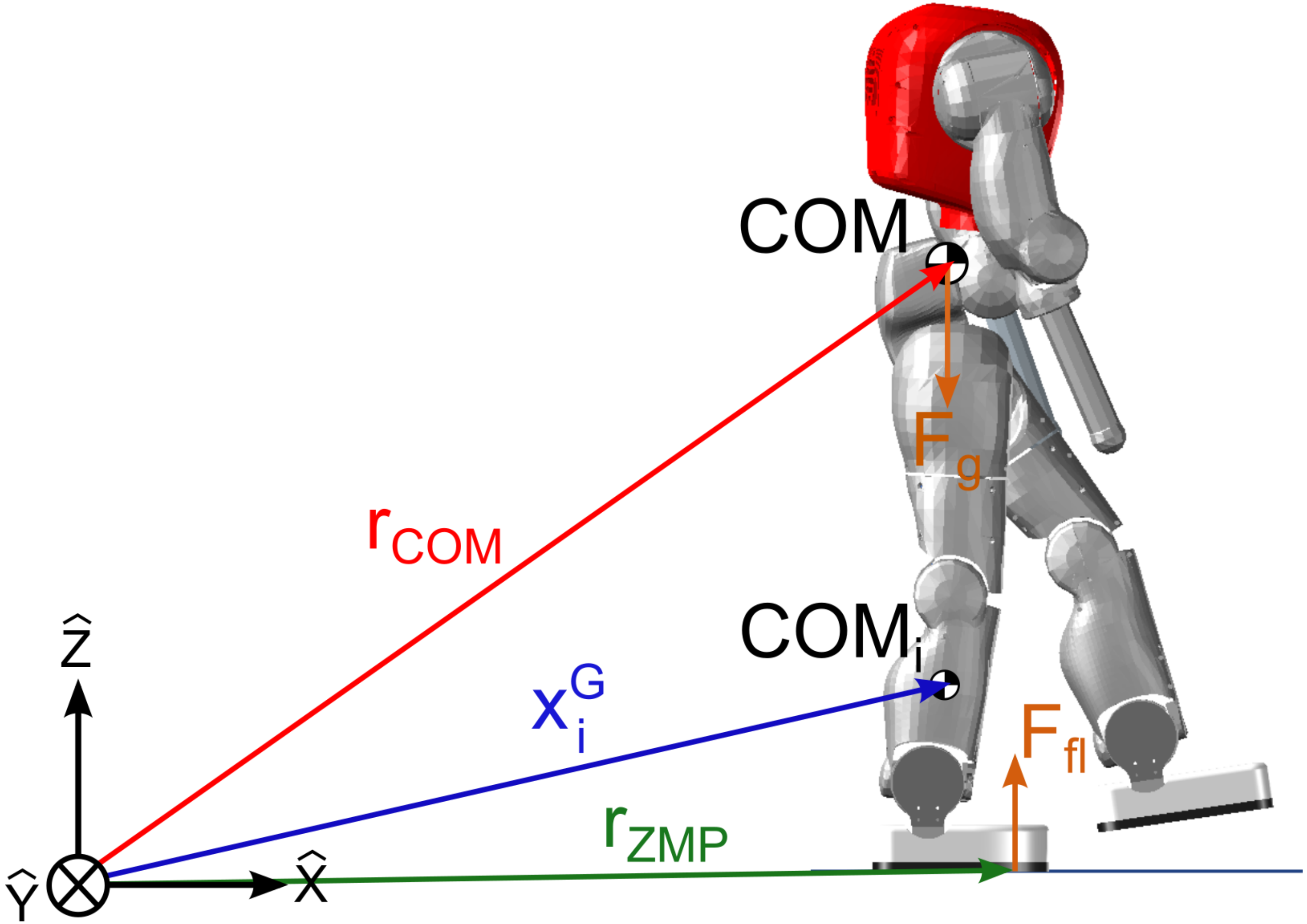




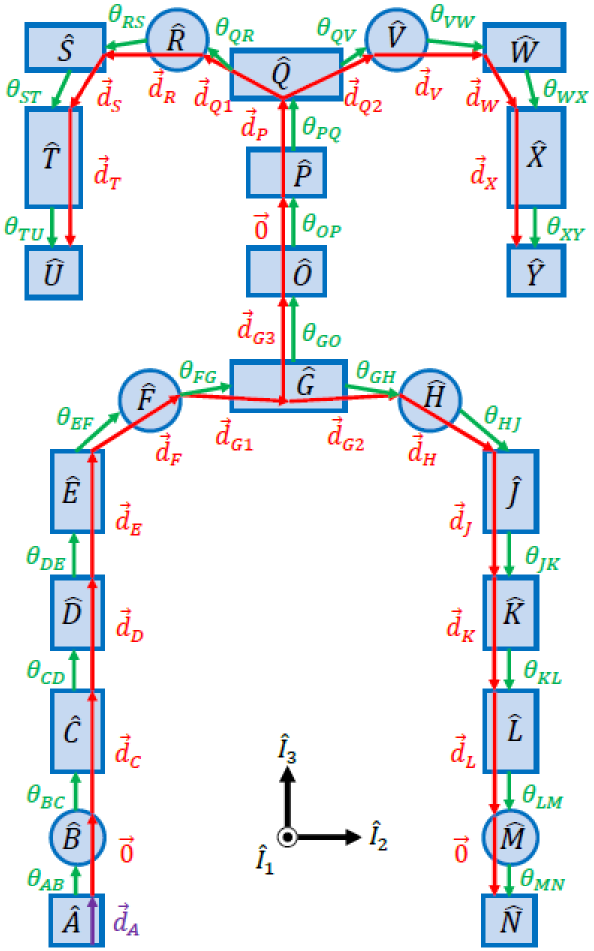
Single Support

Double Support

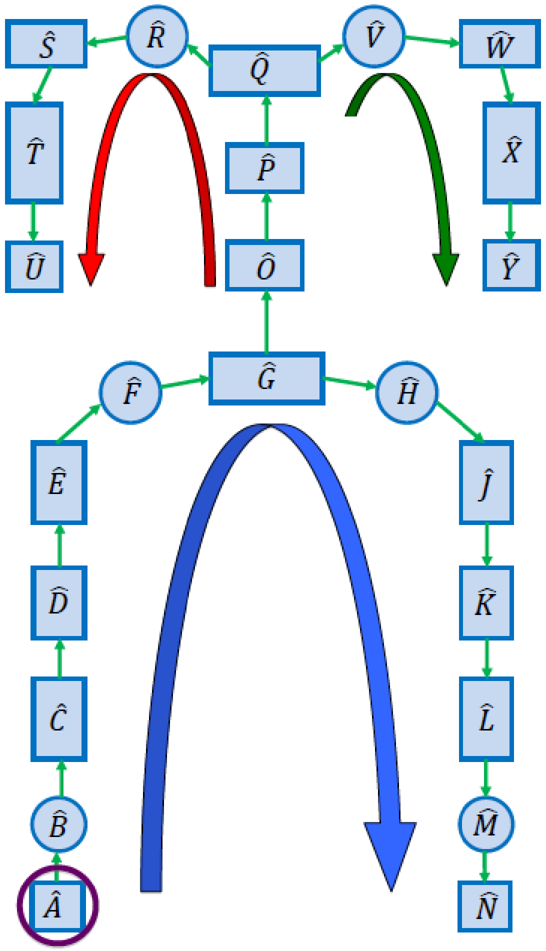
Zero-moment point computation



Zero-moment point: recursion



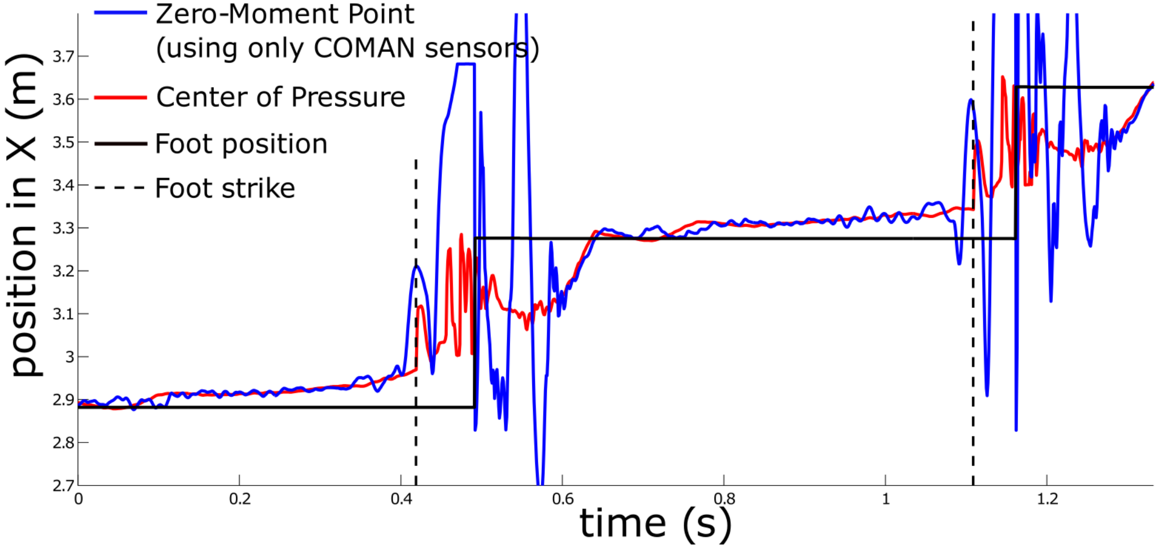
(a) Joint and positions



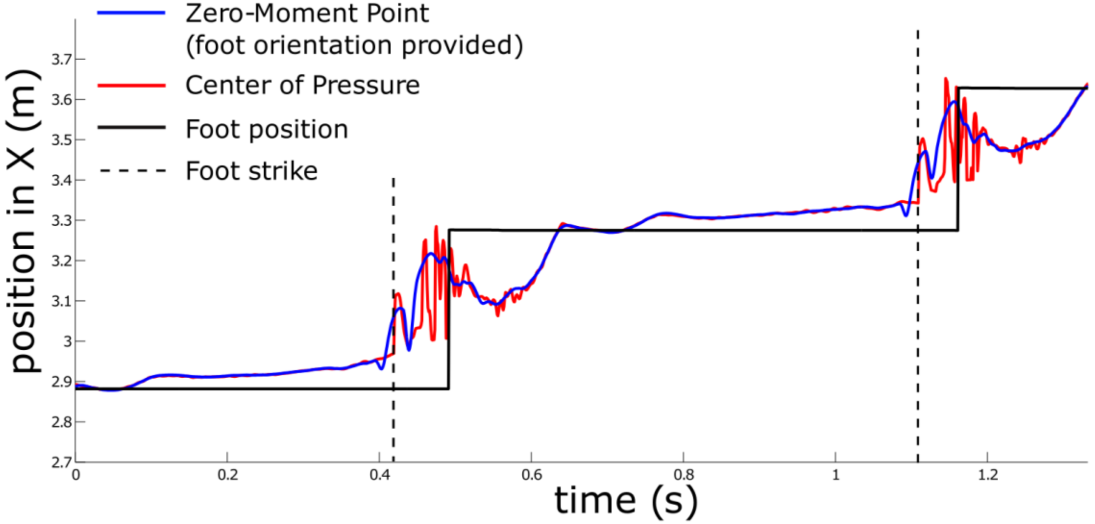
(b) Forward kinematics path

Zero-moment point results: 2D walking

**No foot information,
no post-process filtering**

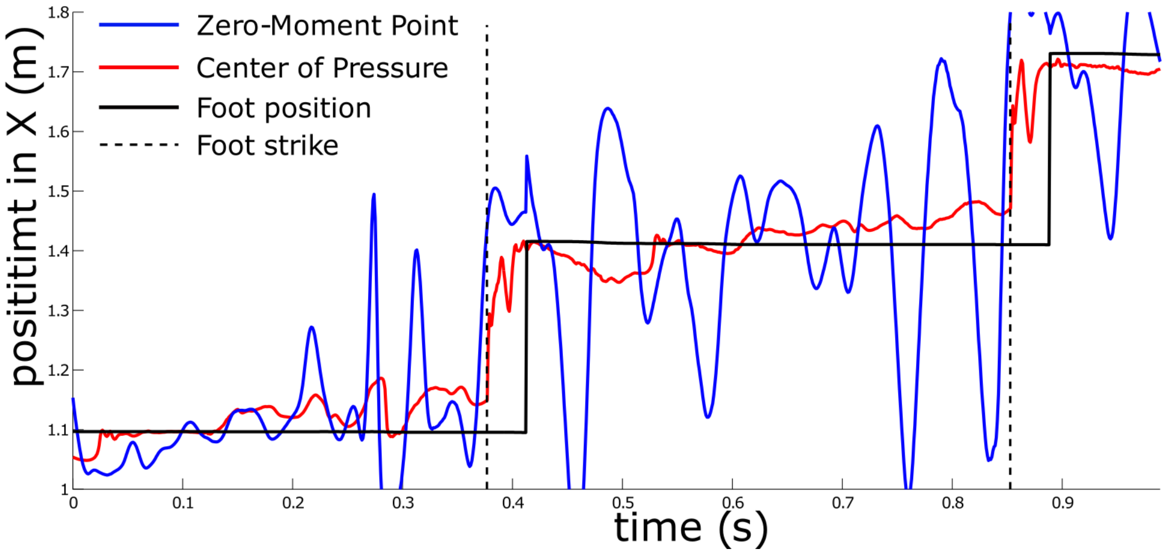


**Foot orientation provided,
no post-process filtering**



Zero-moment point results: 3D walking

Foot orientation provided, no post-process filtering



Foot orientation provided, 100 ms running-average