Chair of Applied Mechanics
TUM School of Engineering and Design
Technical University of Munich

Comparison of Controllers for Trunk Stabilization in a Bipedal Robot

Final Presentation, Master's Thesis

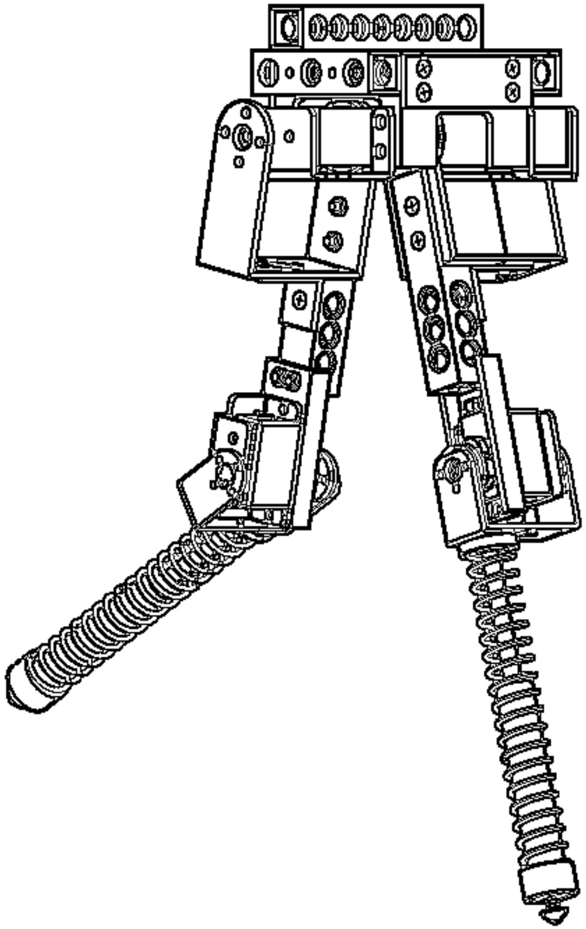
Felix Schausberger

March 21, 2023

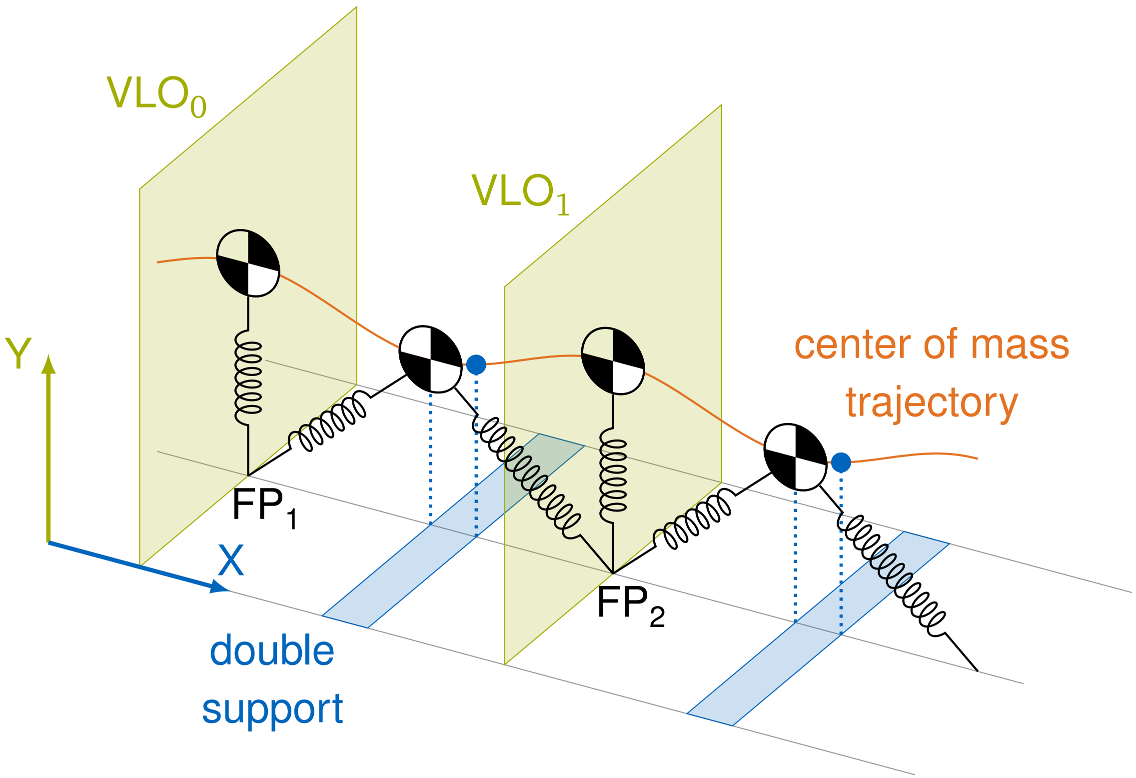
Supervisor: *Dr.-Ing. Daniel Renjewski*
Examiner: *Dr.-Ing. Daniel Renjewski*

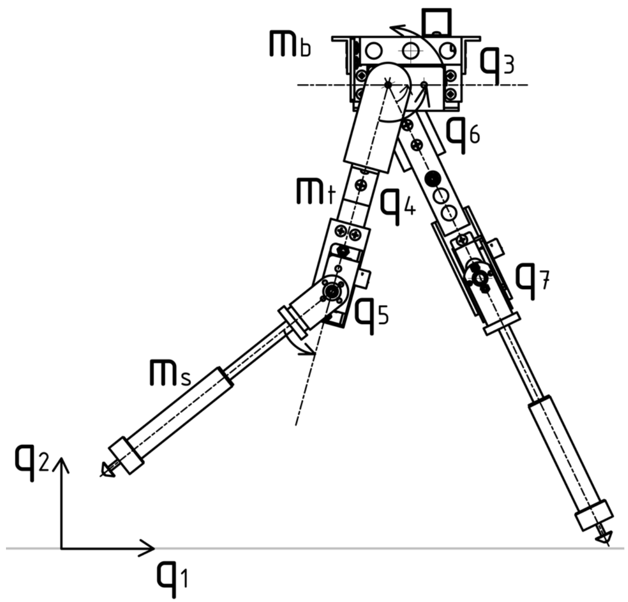
Introduction

1. Objective: Stabilize torso
2. Goal: Quantify correlations of parameters that influence periodic gait
3. Implementation: Neural network controller, trajectory optimization, vertical leg orientation
4. Evaluation: Mechanical cost analysis, stability analysis



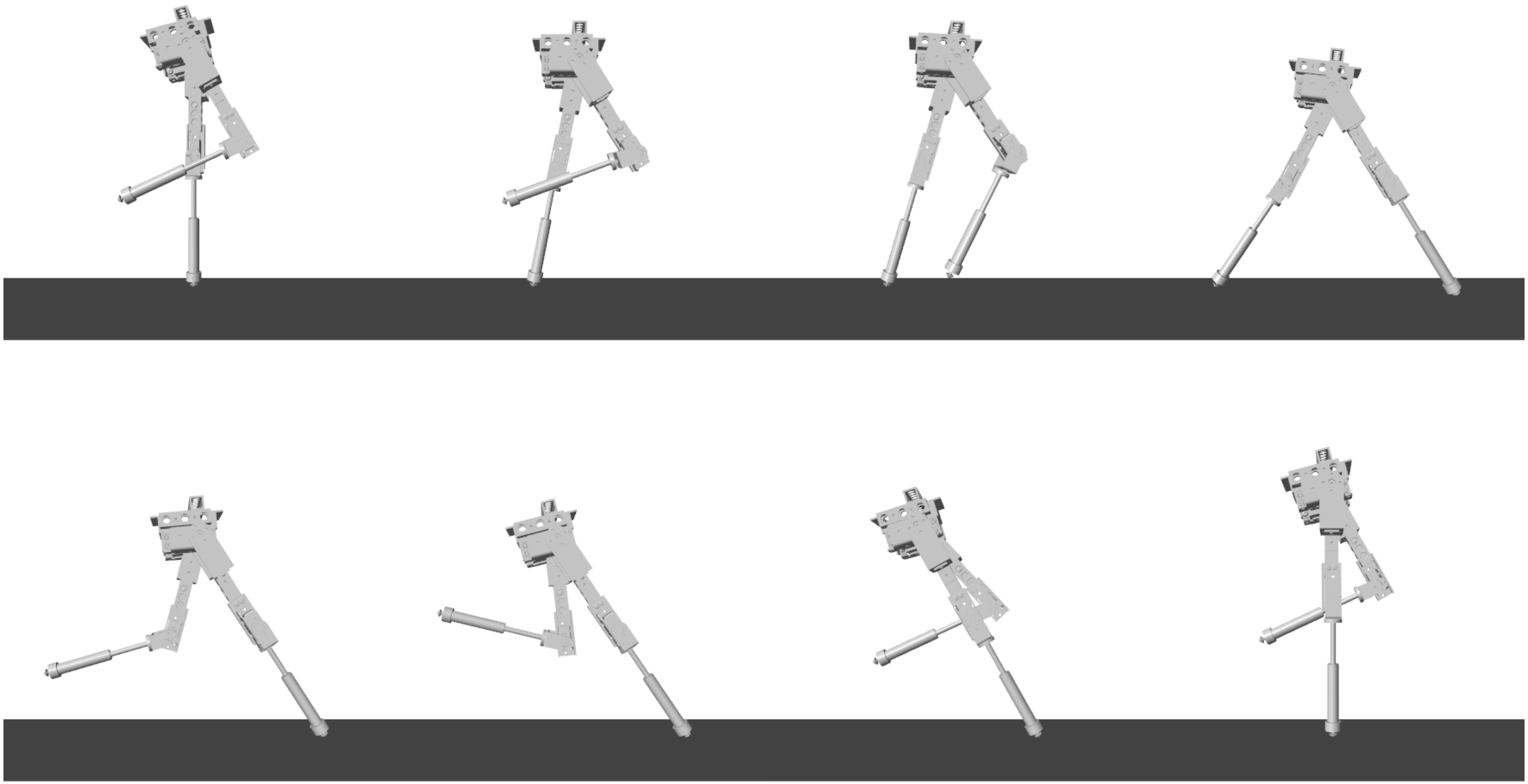
Trajectory optimization [Rum+10] [Ren13]





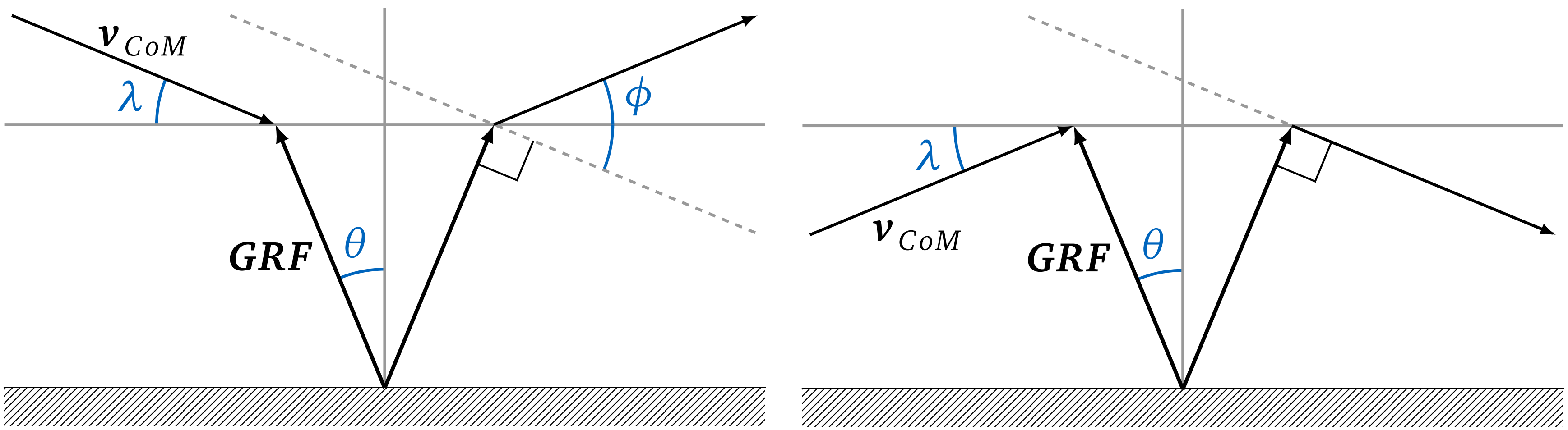
$$f = \sum_{i=3}^{7} |\, q_i(VLO_1) - q_i(VLO_0)\,| + |\, \dot{q}_i(VLO_1) - \dot{q}_i(VLO_0)\,|$$

Vertical leg orientation



Mechanical Cost Analysis [Lee+11]

$\phi = \lambda + \theta \neq 0$: $\phi = |\lambda - \theta| = 0$:



$$\phi = \arcsin\left(\frac{|\boldsymbol{GRF} \cdot \boldsymbol{v}_{CoM}|}{|\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|}\right)$$

$$\lambda = \arccos\left(\frac{|\boldsymbol{v}_{CoM_x}|}{|\boldsymbol{v}_{CoM}|}\right),\ \theta = \arccos\left(\frac{|\boldsymbol{GRF}_y|}{|\boldsymbol{GRF}|}\right)$$

Collision fraction [Lee+11]

$$\kappa = \frac{\sum |\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|\ (\phi/(\theta+\lambda))}{\sum |\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|} = \frac{\Phi}{\Theta + \Lambda}$$

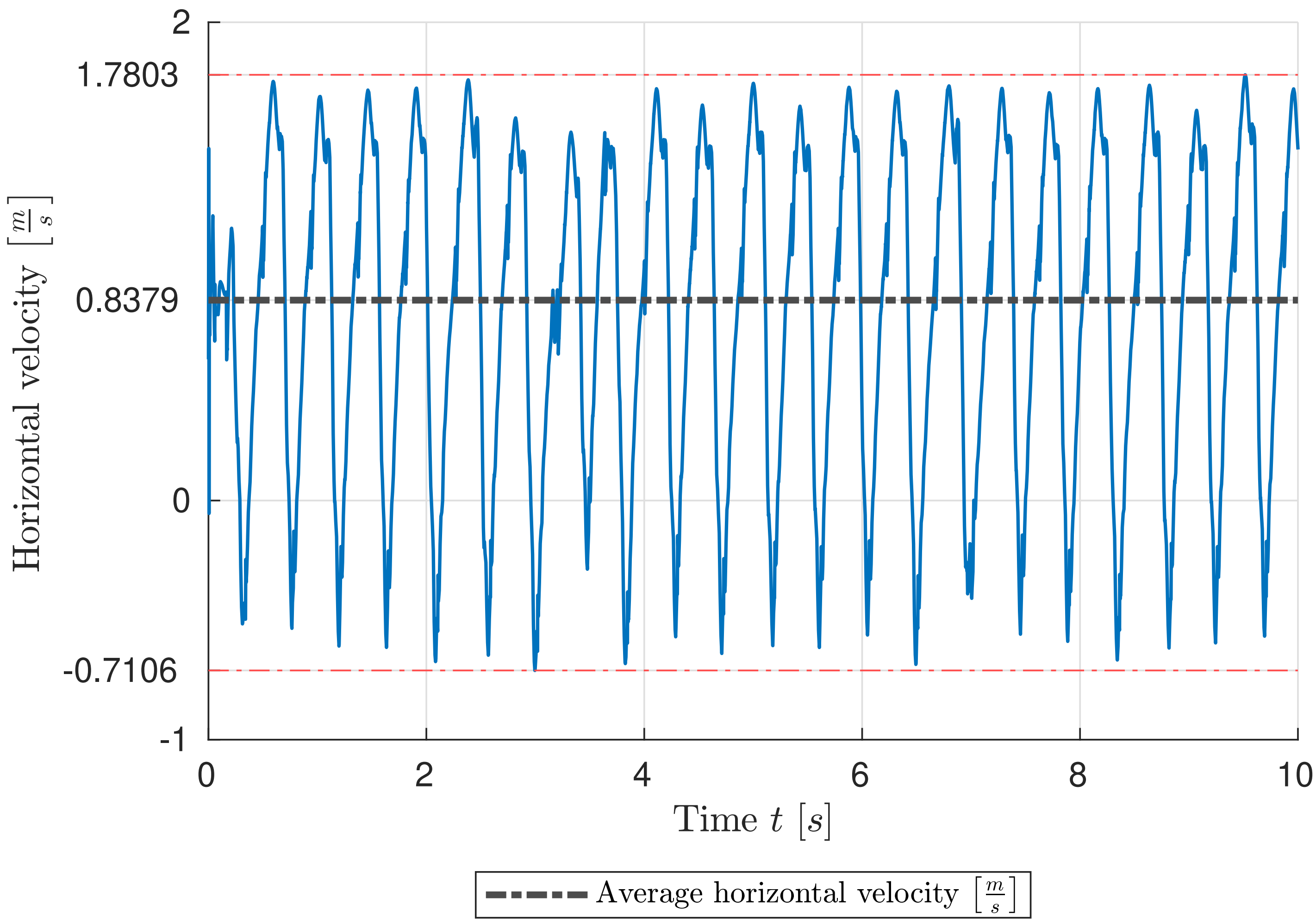
$$\Phi = \frac{\sum |\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|\ \phi}{\sum |\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|}$$

$$\Lambda = \frac{\sum |\boldsymbol{v}_{CoM}|\ \lambda}{\sum |\boldsymbol{v}_{CoM}|}$$

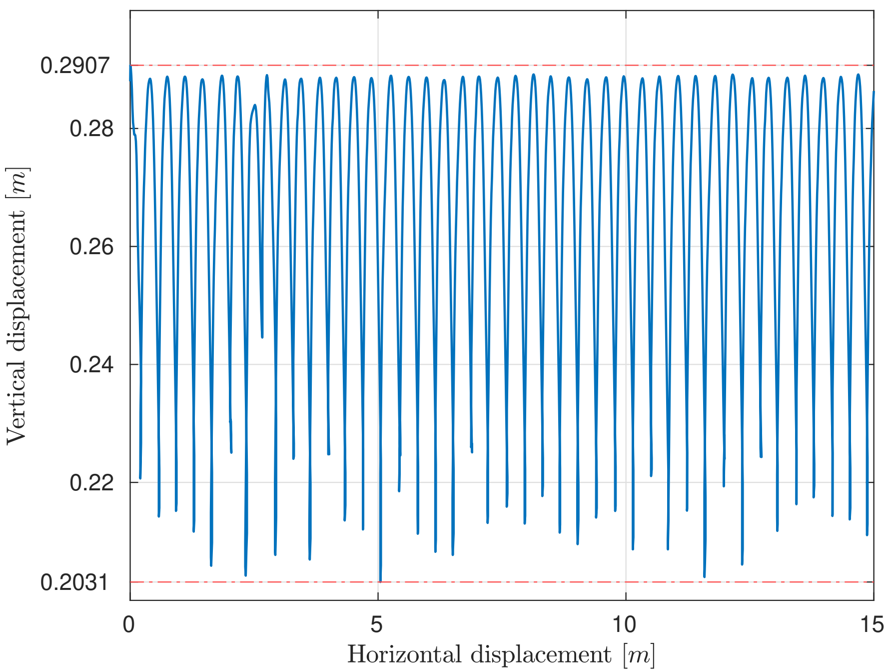
$$\Theta = \frac{\sum |\boldsymbol{GRF}|\ \theta}{\sum |\boldsymbol{GRF}|}$$

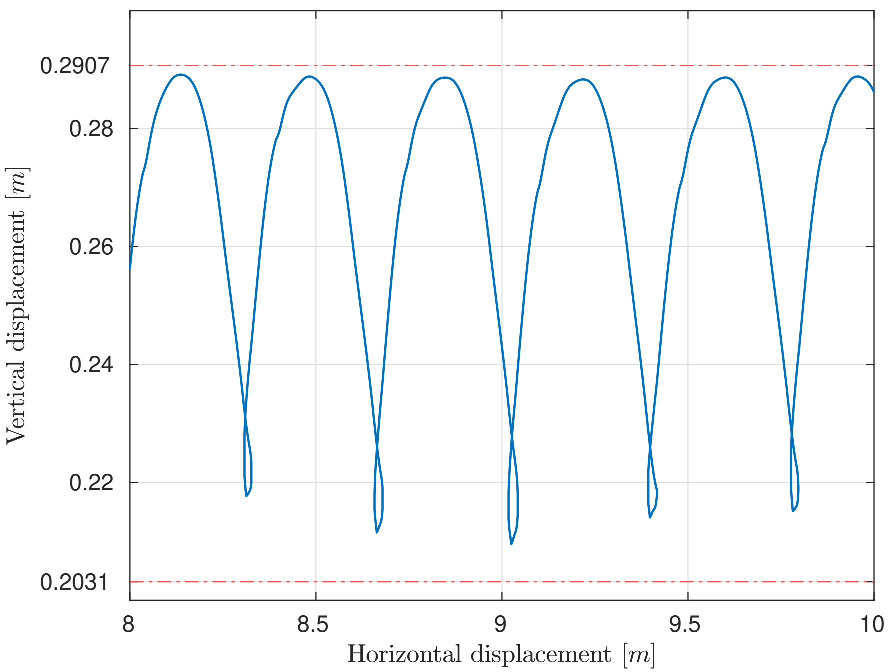
$$\Phi \approx \frac{\sum |\boldsymbol{GRF} \cdot \boldsymbol{v}_{CoM}|}{\sum |\boldsymbol{GRF}|\ |\boldsymbol{v}_{CoM}|} \approx \mathrm{CoT}_{\mathrm{mech}} = \frac{\sum |\boldsymbol{GRF} \cdot \boldsymbol{v}_{CoM}|}{\overline{\boldsymbol{v}_{CoM_x}}\ m\ g}$$

Horizontal velocity

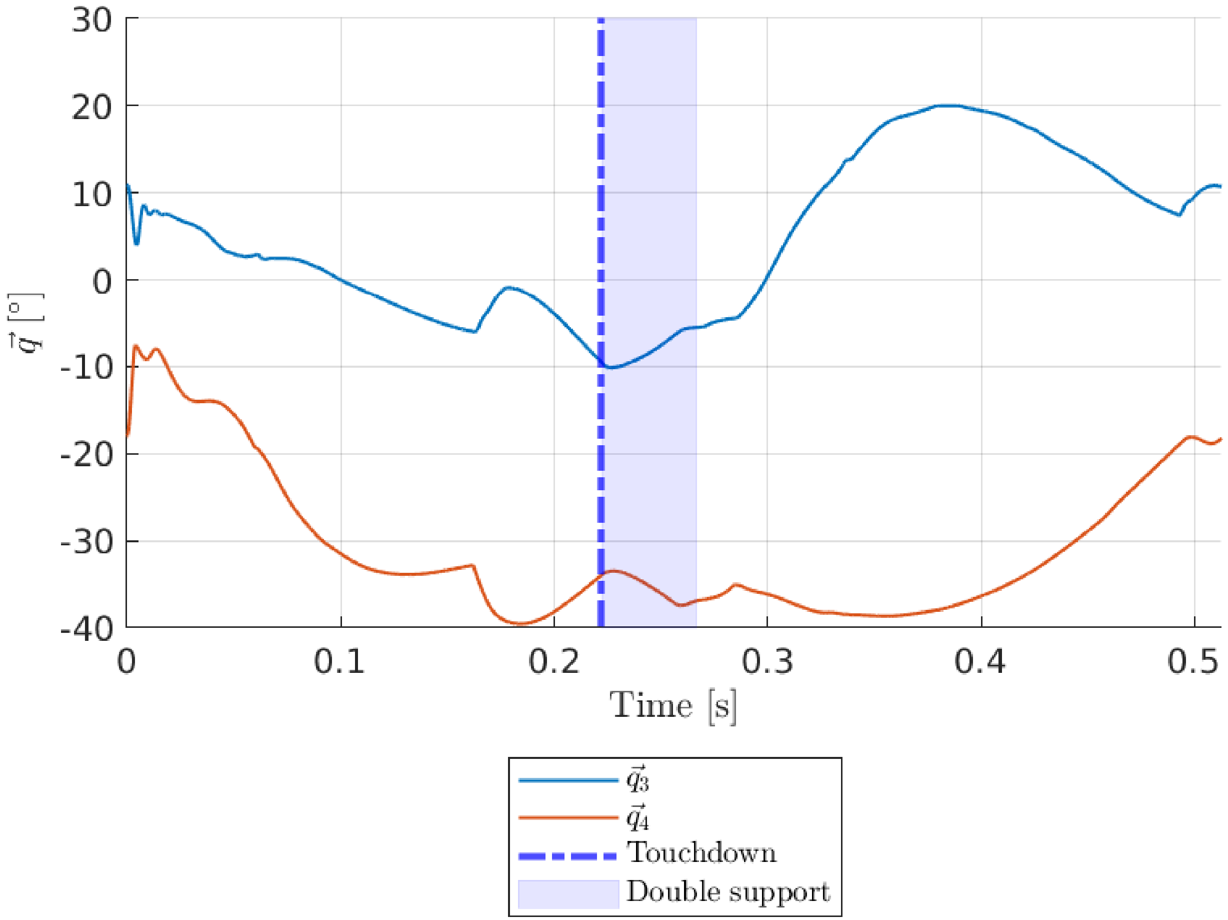


Displacement

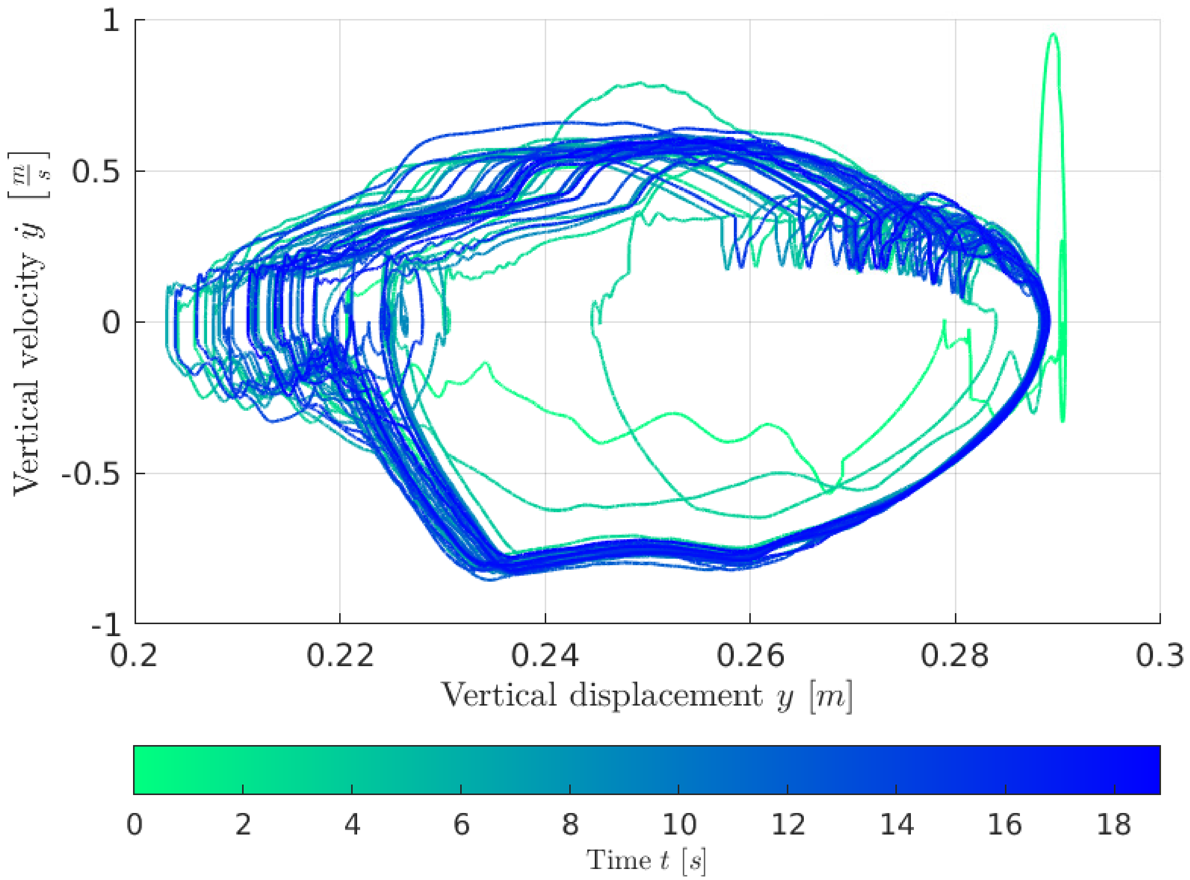




Torso and hip angle



Phase plot over time



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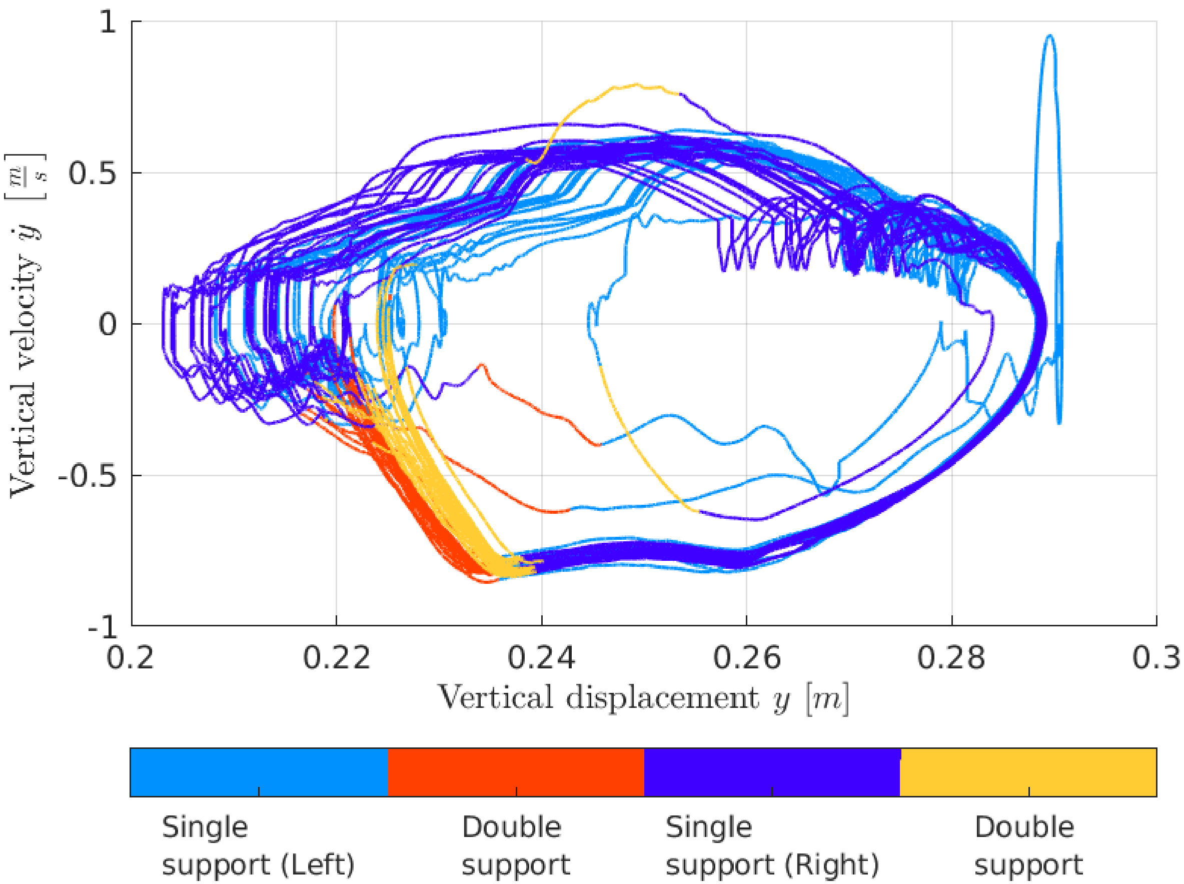
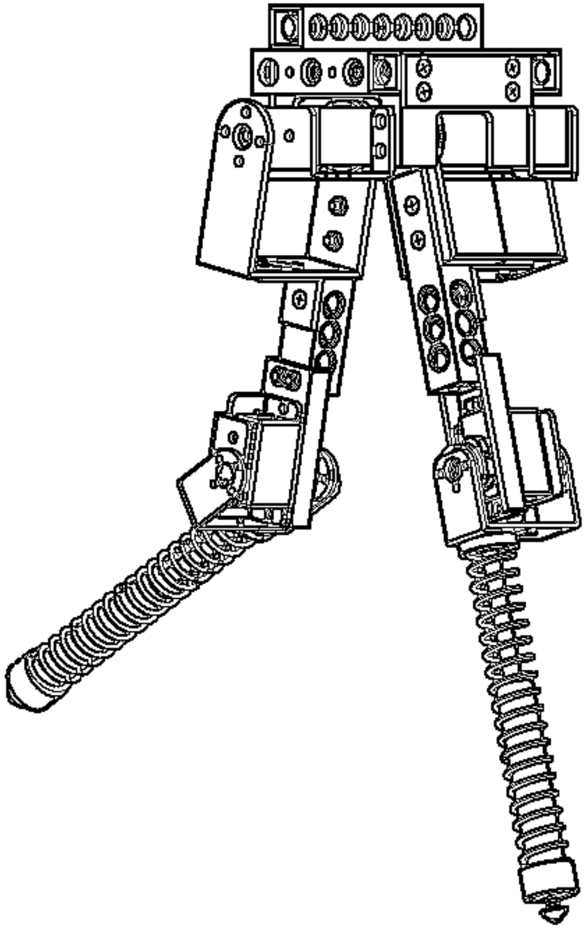
Phase plot with ground-state



Summary

1. Objective: Stabilize torso
2. Goal: Quantify correlations of parameters that influence periodic gait
3. Implementation: Neural network controller, trajectory optimization, VLO, MCA
4. Result: Asymptotically stable gait found
5. Evaluation: Not energy efficient



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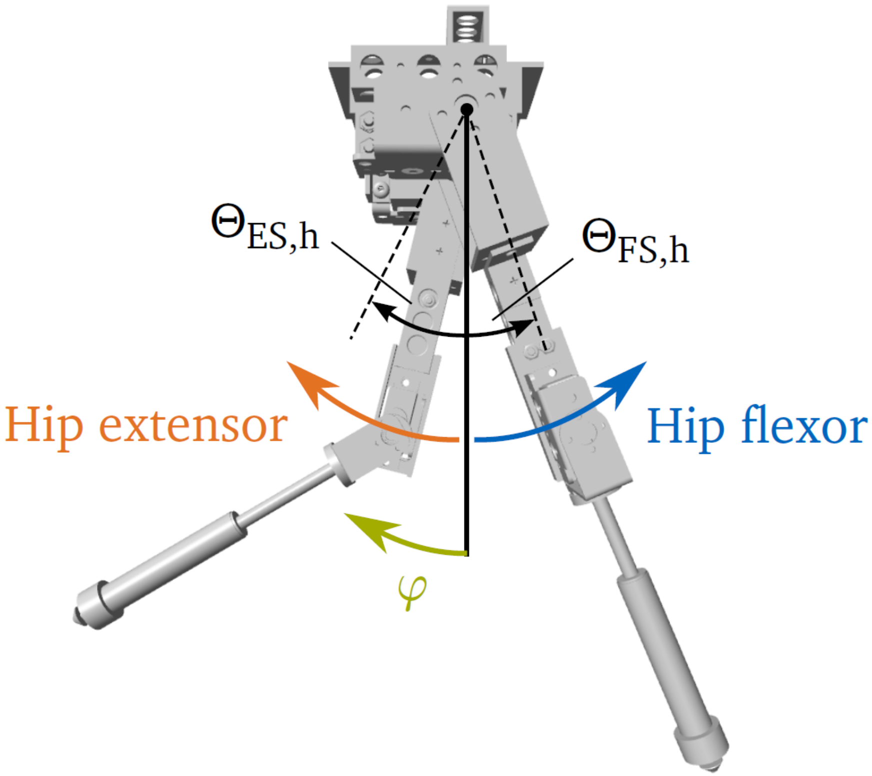
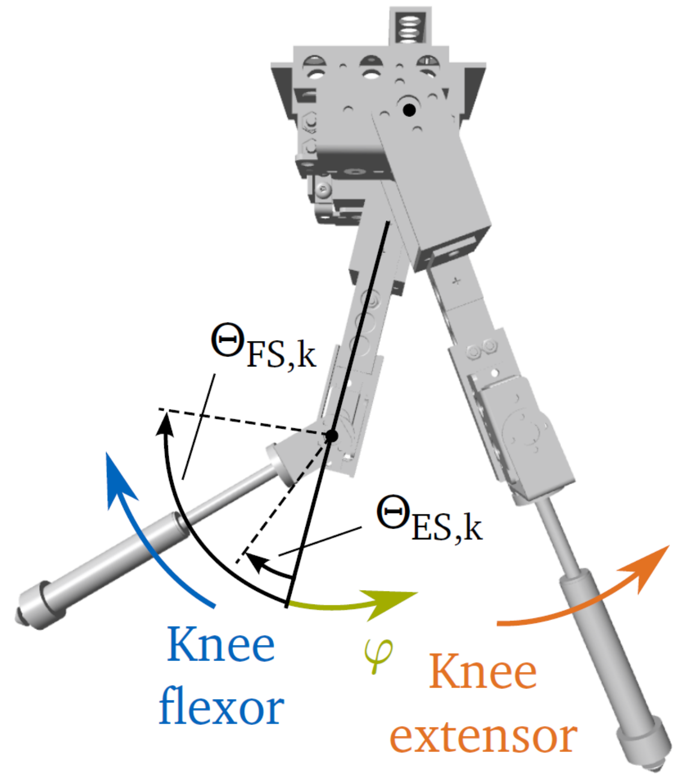
Control parameters [Ren]



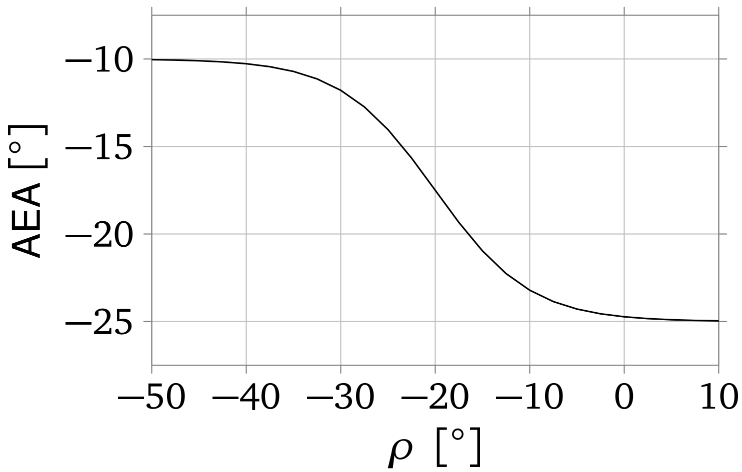


Results

$$\theta_{ES,\ k} = -4.25$$

$$\theta_{FS,\ h} = \text{AEA} = \frac{15}{1 + e^{0.2 \cdot \rho + 4}} - 25$$

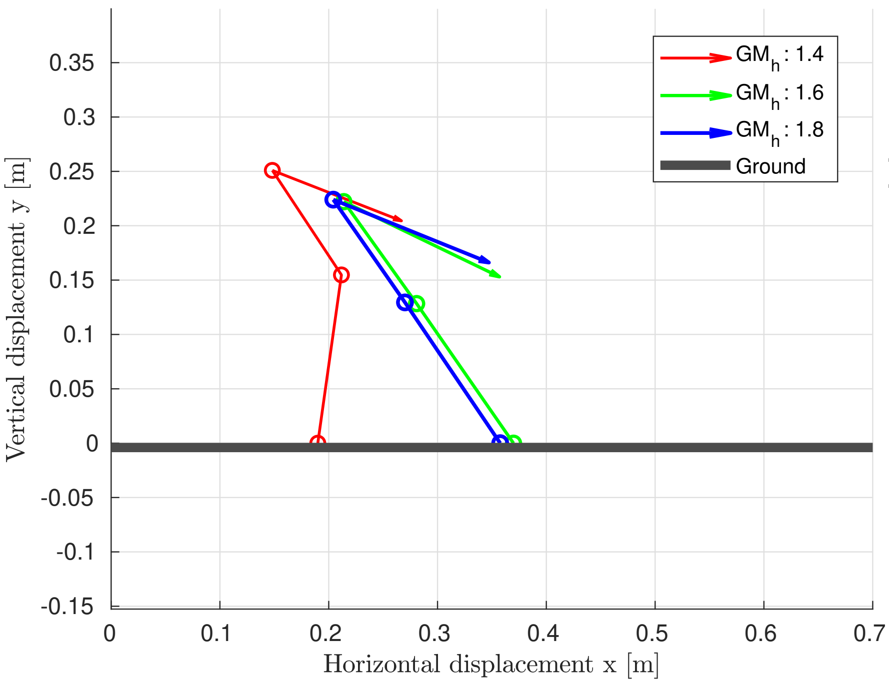
$$GM_h = 1.6$$

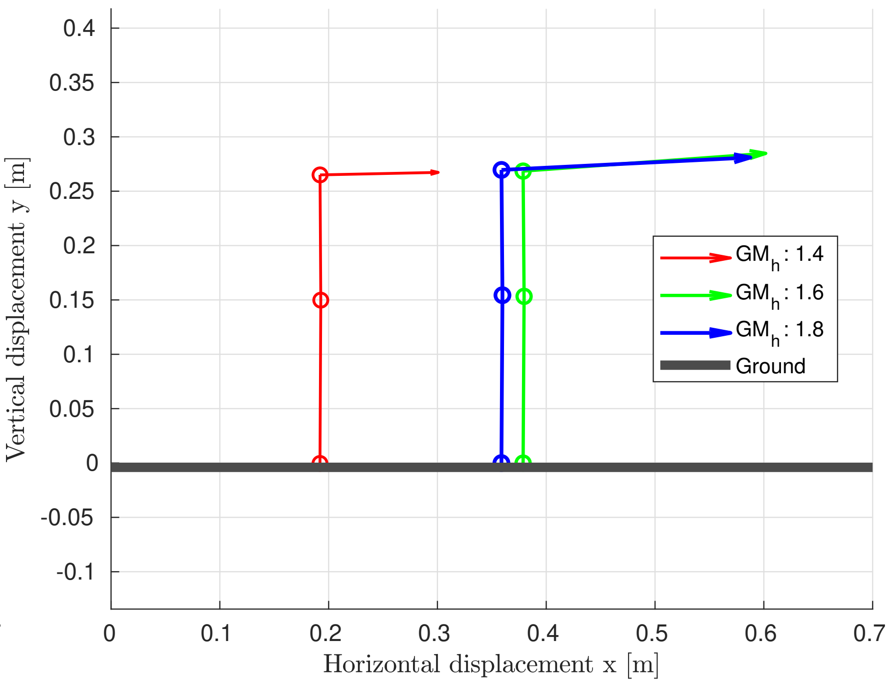


Results II

Symbol	Description	Value	Unit
$x_{CoM,\ end}$	Distance covered	15	$[\mathrm{m}]$
t_{end}	Time required	18.8502	$[\mathrm{s}]$
$\overline{v_{CoM_x}}$	Average forward velocity	0.8379	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
$v_{CoM_x,\ max}$	Maximum instantaneous velocity	1.7803	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
$v_{CoM_x,\ min}$	Minimum instantaneous velocity	-0.7106	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
$y_{CoM,\ max}$	Highest vertical displacement	0.2907	$[\mathrm{m}]$
$y_{CoM,\ min}$	Lowest vertical displacement	0.2031	$[\mathrm{m}]$
Fr	Froude number	0.2468	-
$\sqrt{Fr}$	Dimensionless velocity	0.4986	-
Θ	Average force angle	0.7285	$[\mathrm{rad}]$
Λ	Average velocity angle	0.3704	$[\mathrm{rad}]$
Φ	Average collision angle	0.9855	$[\mathrm{rad}]$
$\mathrm{CoT}_{\mathrm{mech}}$	Mechanical Cost of Transport	0.5226	$\left[\frac{\mathrm{J}}{\mathrm{m\,N}}\right]$
κ	Collision fraction	0.8968	-

Velocity vectors





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[Ren13] Renjewski, D. *An Engineering Contribution to Human Gait Biomechanics*. Verlag Dr. Kovac, 2013, p. 140. ISBN: 9783830068587.

[Rum+10] Rummel, J., Blum, Y., Maus, H. M., Rode, C., and Seyfarth, A. “Stable and robust walking with compliant legs”. In: *2010 IEEE International Conference on Robotics and Automation*. IEEE, May 2010. DOI: 10.1109/robot.2010.5509500.

Glossary I

Fr Froude number. 16

GM Motor gain. 15

Λ Average angle associated with $\boldsymbol{v}_{CoM}$ relative to horizontal $(^\circ)$. 6, 16, 19

Φ Average collision angle $(^\circ)$. 6, 16, 19

Θ Average angle associated with the ground reaction force relative to vertical $(^\circ)$. 6, 16, 19

$\boldsymbol{v}$ Velocity vector $\left(\frac{\mathrm{m}}{\mathrm{s}}\right)$. 5, 6, 16, 19, 20

κ Collision fraction, calculated as the quotient of Φ and the sum of Θ and Λ. 6, 16

λ Instantaneous angle of $\boldsymbol{v}_{CoM}$ relative to horizontal $(^\circ)$. 5, 6

Glossary II

ϕ Instantaneous angle of deviation of perpendicularity of force and velocity vectors (collision angle) $(^\circ)$. 5, 6

ρ Angle of $\boldsymbol{v}_{CH}$ relative to horizontal at touchdown $(^\circ)$. 15

θ Instantaneous angle of the ground reaction force relative to vertical $(^\circ)$. 5, 6

θ_{ES} Control parameter of the extensor for the neural controller $(^\circ)$. 15

θ_{FS} Control parameter of the flexor for the neural controller $(^\circ)$. 15

g Acceleration due to gravity $\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)$. 6

m Mass of the body (kg). 6

t Simulation time (s). 16

x Horizontal displacement (m). 16

Glossary III

y Vertical displacement (m). 16

$\boldsymbol{GRF}$ Ground Reaction Force 5, 6, 19, 20

AEA Anterior Extreme Angle 15

CoM Center of Mass 5, 6, 16, 19

CoT_{mech} Mechanical Cost of Transport 6, 16

MCA Mechanical Cost Analysis 2, 12

VLO Vertical Leg Orientation 2, 3, 12