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On the dynamics of human locomotion and co-design of lower limb assistive devices

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Supervisor: prof. Auke Jan Ijspeert

PhD public defense, June 27, 2014

INTRODUCTION

Source: youtube.com

INTRODUCTION

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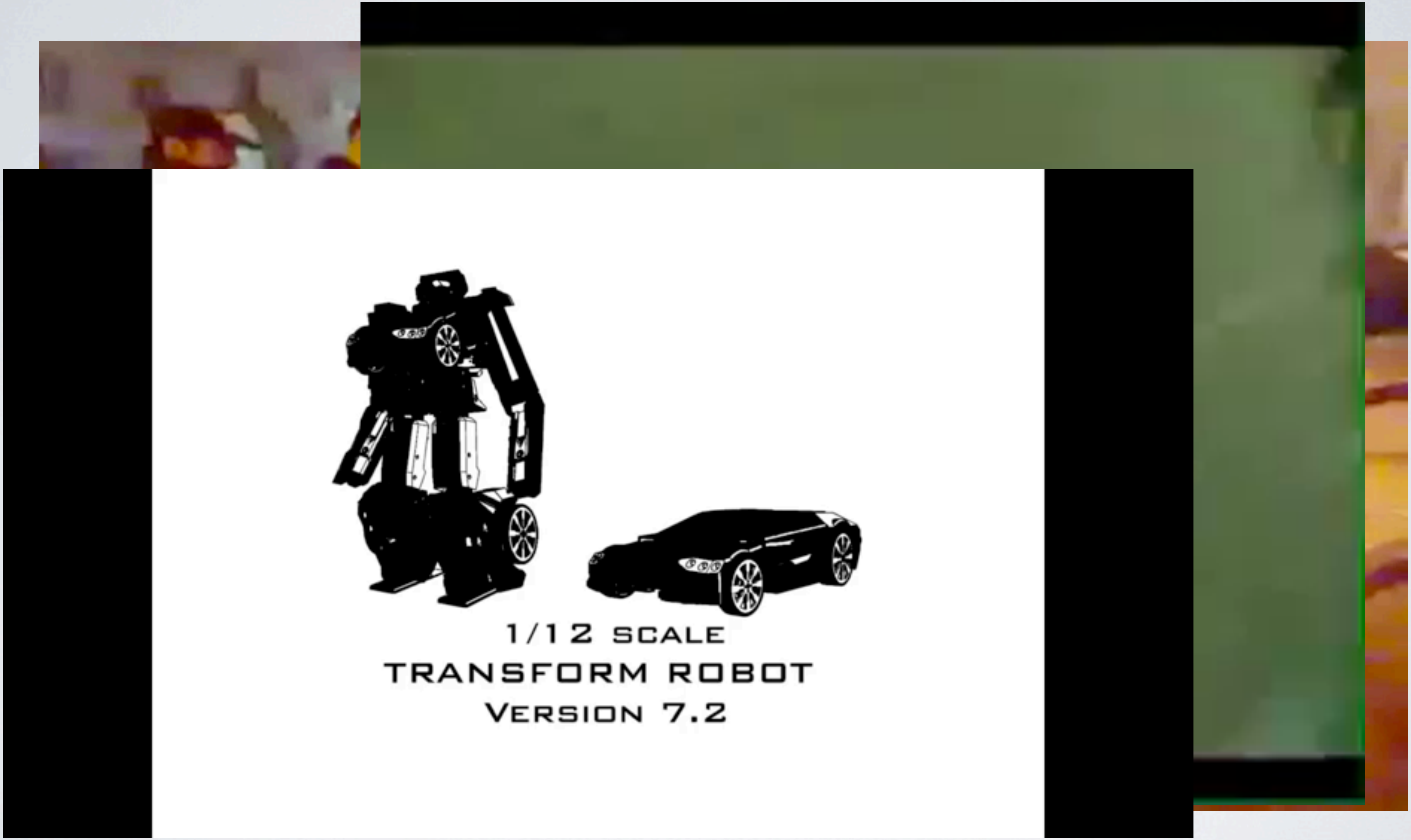
INTRODUCTION



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INTRODUCTION

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INTRODUCTION

Motivation

- Body versus mind, embodied intelligence
- Strong notion in natural systems
- Adaptation of morphology is a product of natural evolution
- Take inspiration from natural processes for engineering processes

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INTRODUCTION

Topics

- Development of a methodology for the co-design of bipedal machines, with a case study in wearable lower limb devices

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- Development of a methodology for the co-design of bipedal machines, with a case study in wearable lower limb devices
- Study of principles of human gait optimization and control

INTRODUCTION

Topics

- Development of a methodology for the co-design of bipedal machines, with a case study in wearable lower limb devices
- Study of principles of human gait optimization and control
- Rigorous modeling of coupled dynamical systems and rigid body dynamics suitable for locomotion and co-design

OVERVIEW

1. Introduction
2. Dynamical systems
3. Human gait optimization
4. Co-design methodology for wearable devices
5. Conclusion

Dynamical systems

DYNAMICAL SYSTEMS

- Generally: a system which changes over time
- Interested in simulation of:
  - Control dynamics
  - Articulated rigid body dynamics
  - Coupled dynamics

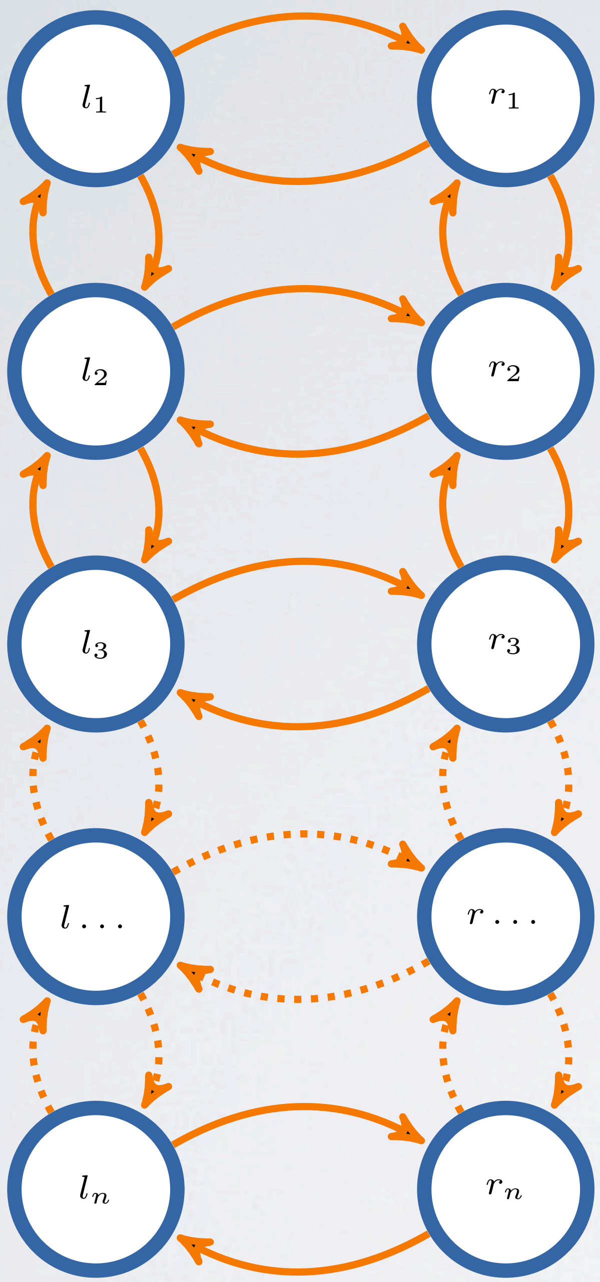
DYNAMICAL SYSTEMS

codyn - ***co***upled ***dyn***amical systems

- A framework for modeling and integrating multi-domain, coupled dynamical systems
- Motivations

1. Free/open
2. Expressive, strong focus on modeling
3. Good performance
4. Educational

DYNAMICAL SYSTEMS



Run

```
defines {
  n = 10
}

node "{r,l}{1:@n}" {
     R = 1

     p' = "2 * pi"
     r' = "(R - r)"

     x = "r * cos(p)"
}

<bidirectional>
edge from "r{1:@n}" to "l@1" {
     p' = "sin(input.p - output.p - pi)"
}

<bidirectional>
edge from "{r,l}{1:@n}" to "@1$(@2 + 1)" {
     bias = "0.1 * pi"
     p' = "sin(input.p - output.p - bias)"
}
```

Modeled after IJspeert et al. (2007)

DYNAMICAL SYSTEMS

codyn - Rigid Body Dynamics

- Articulated rigid body dynamics essential tool in robotics research (modeling, simulation, control)
- Hard problem, a variety of simulators existing today
- Accuracy vs. performance vs. modeling effort

DYNAMICAL SYSTEMS

codyn - Rigid Body Dynamics

- General purpose, 3D articulated rigid body dynamics
- Entirely user extensible, customized joint models, contact models
- State of the art: Availability of inverse, forward, closed chain, hard contacts, Jacobians, etc.

DYNAMICAL SYSTEMS

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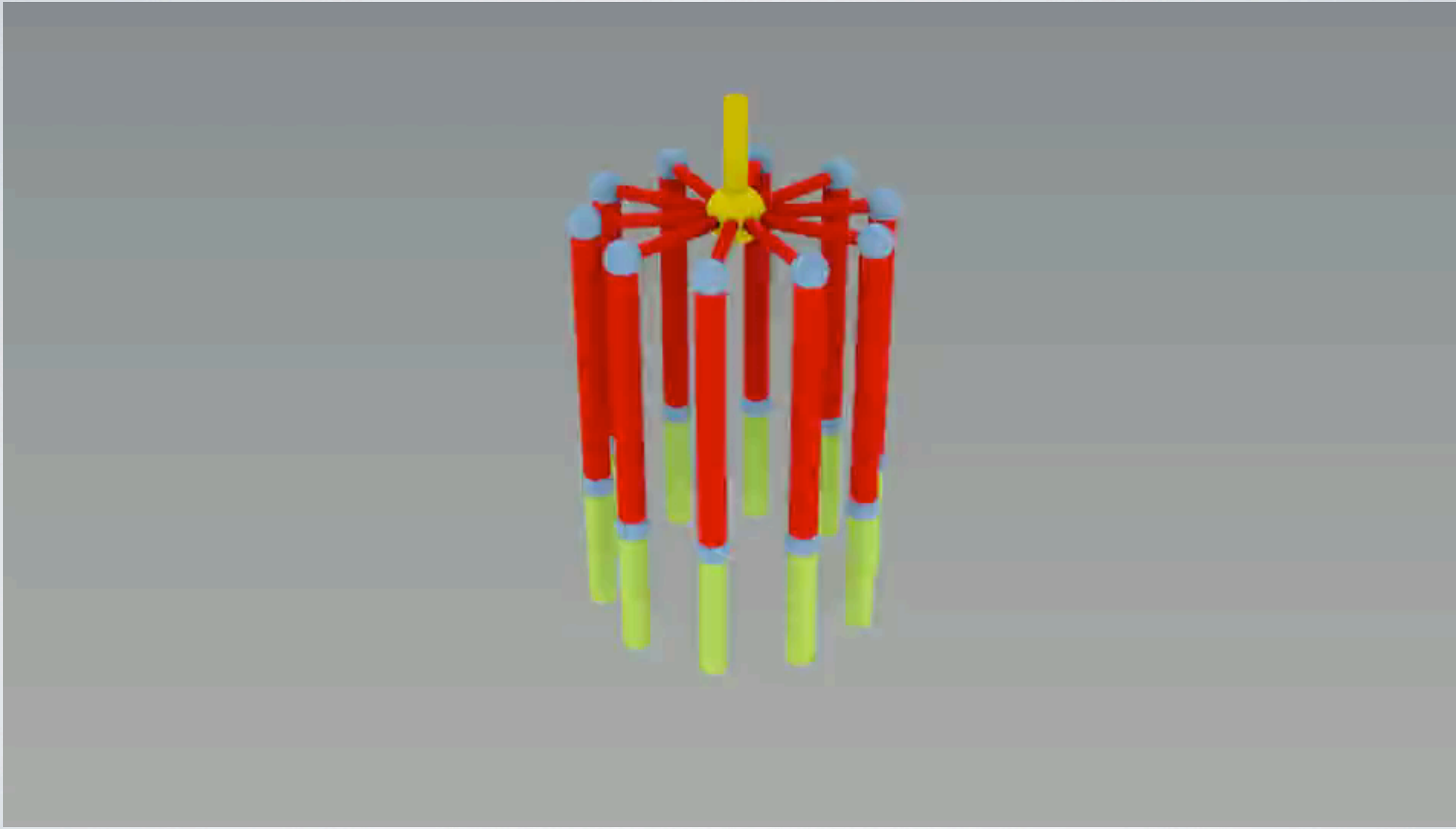
DYNAMICAL SYSTEMS



DYNAMICAL SYSTEMS

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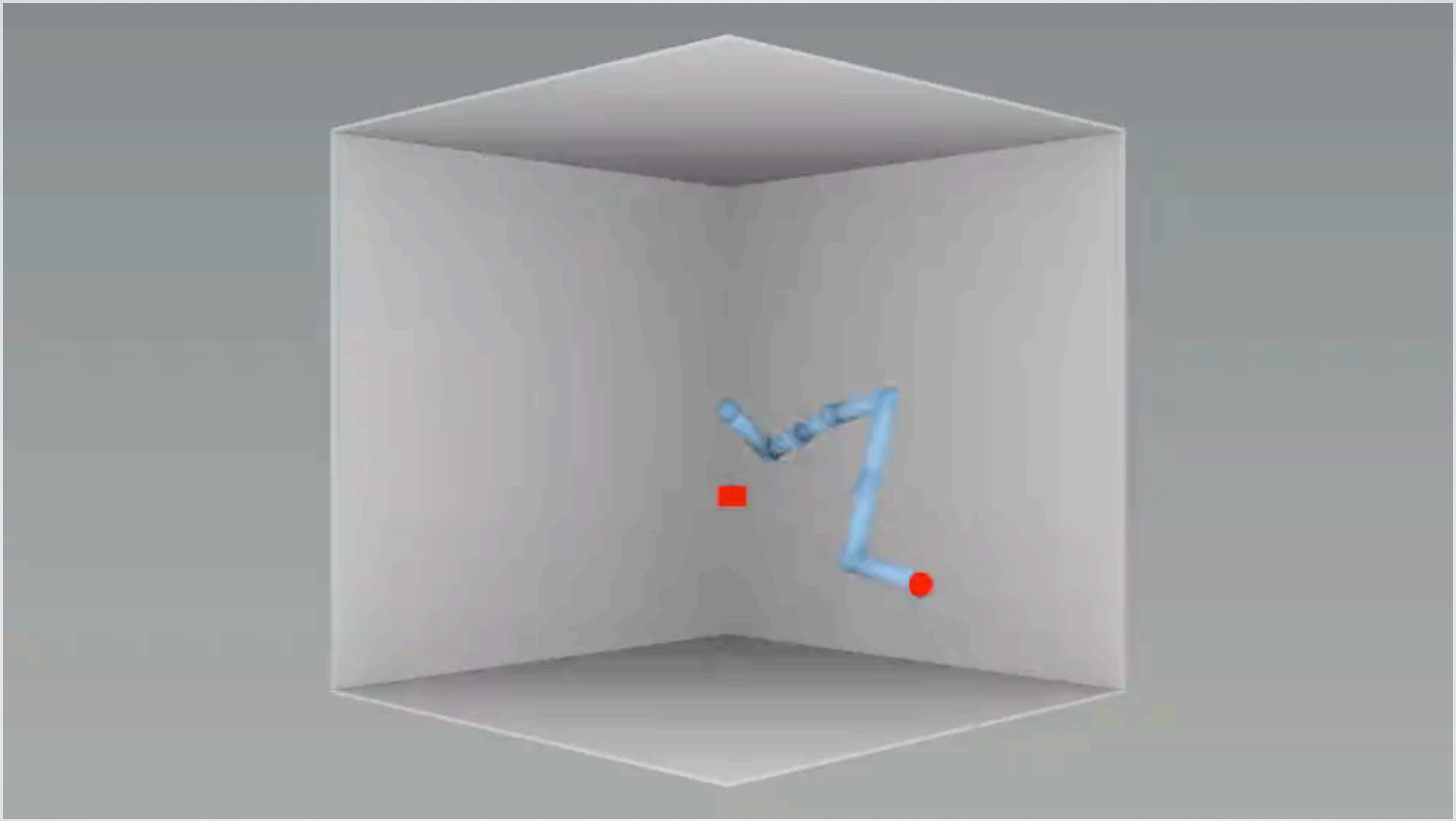
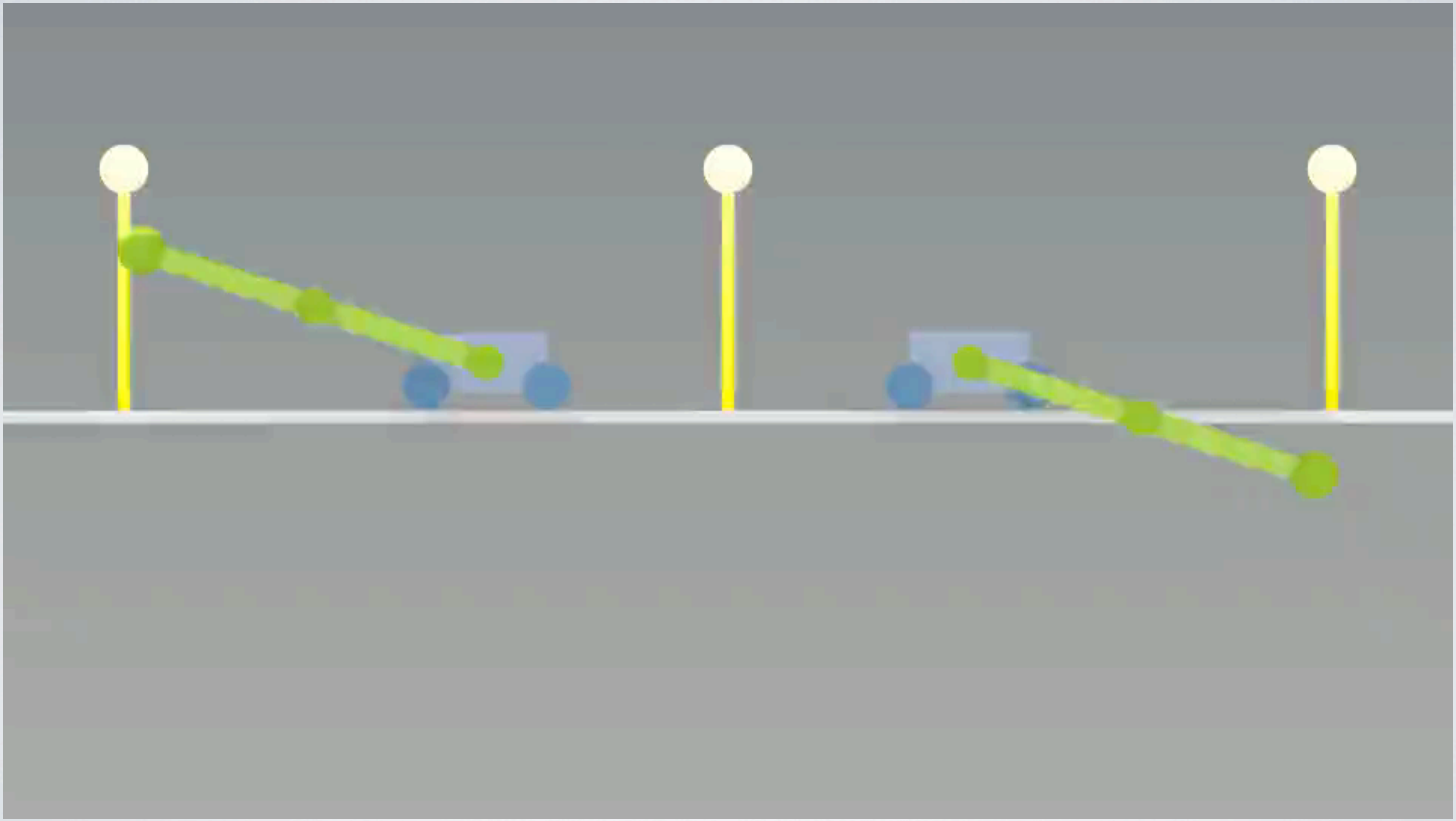


DYNAMICAL SYSTEMS

DYNAMICAL SYSTEMS



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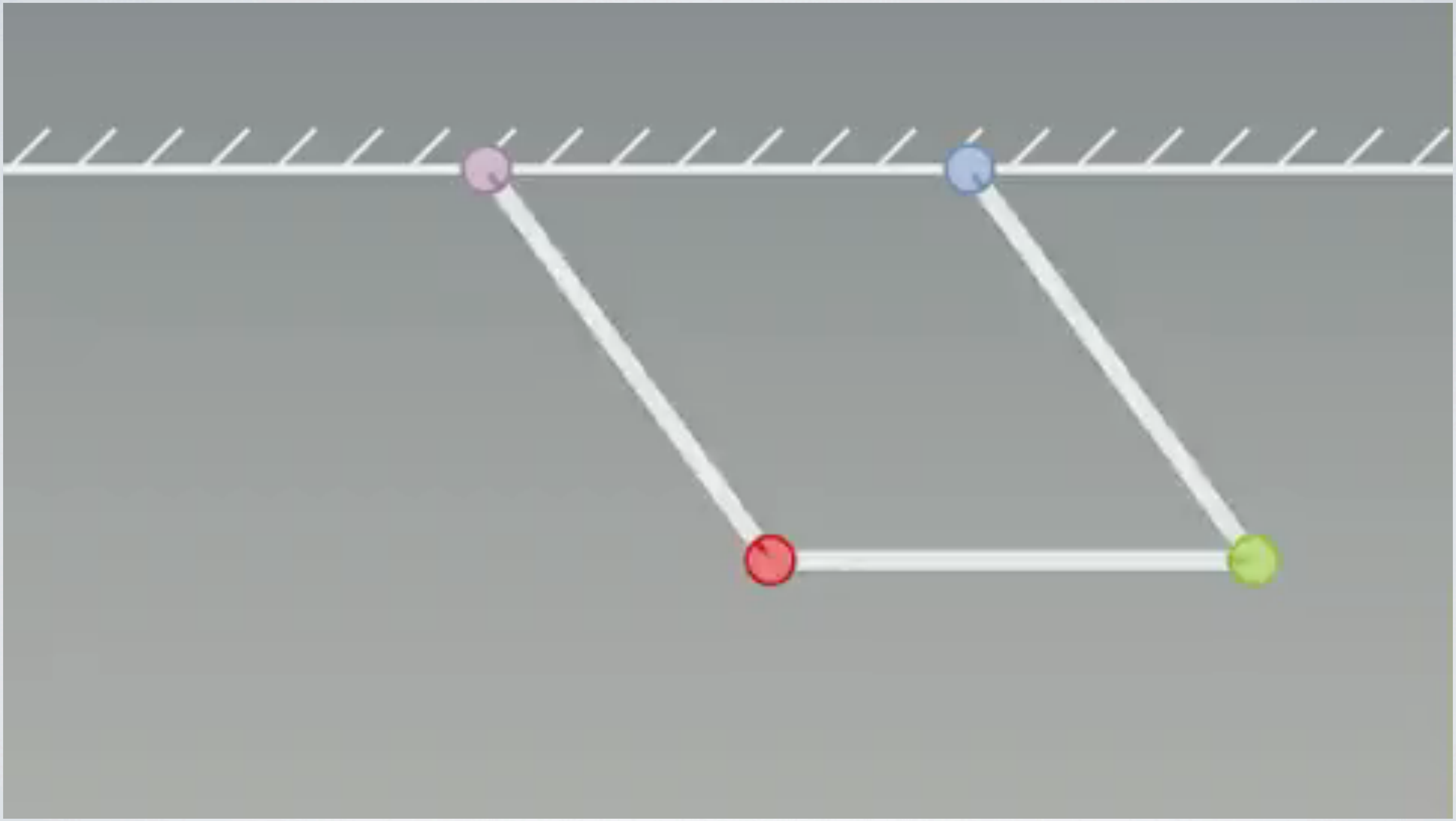
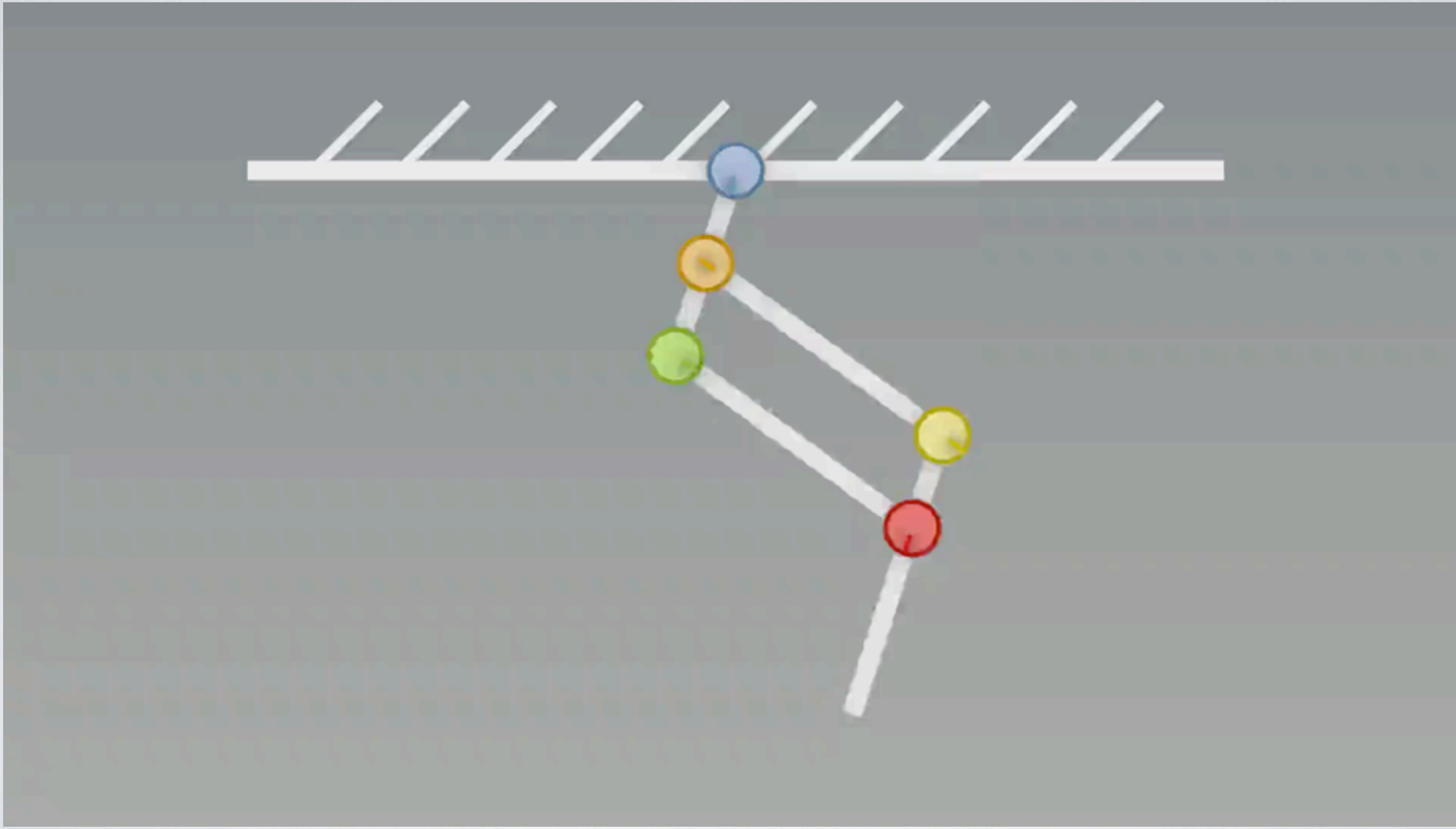


DYNAMICAL SYSTEMS



DYNAMICAL SYSTEMS

codyn - Performance

- Naive implementations of RBD have very poor performance
- Automatically translate models to an efficient representation
  - Fast, optimized code
  - Suitable for Real Time systems
  - Suitable for low-resource, embedded systems (for example micro-controllers)

DYNAMICAL SYSTEMS

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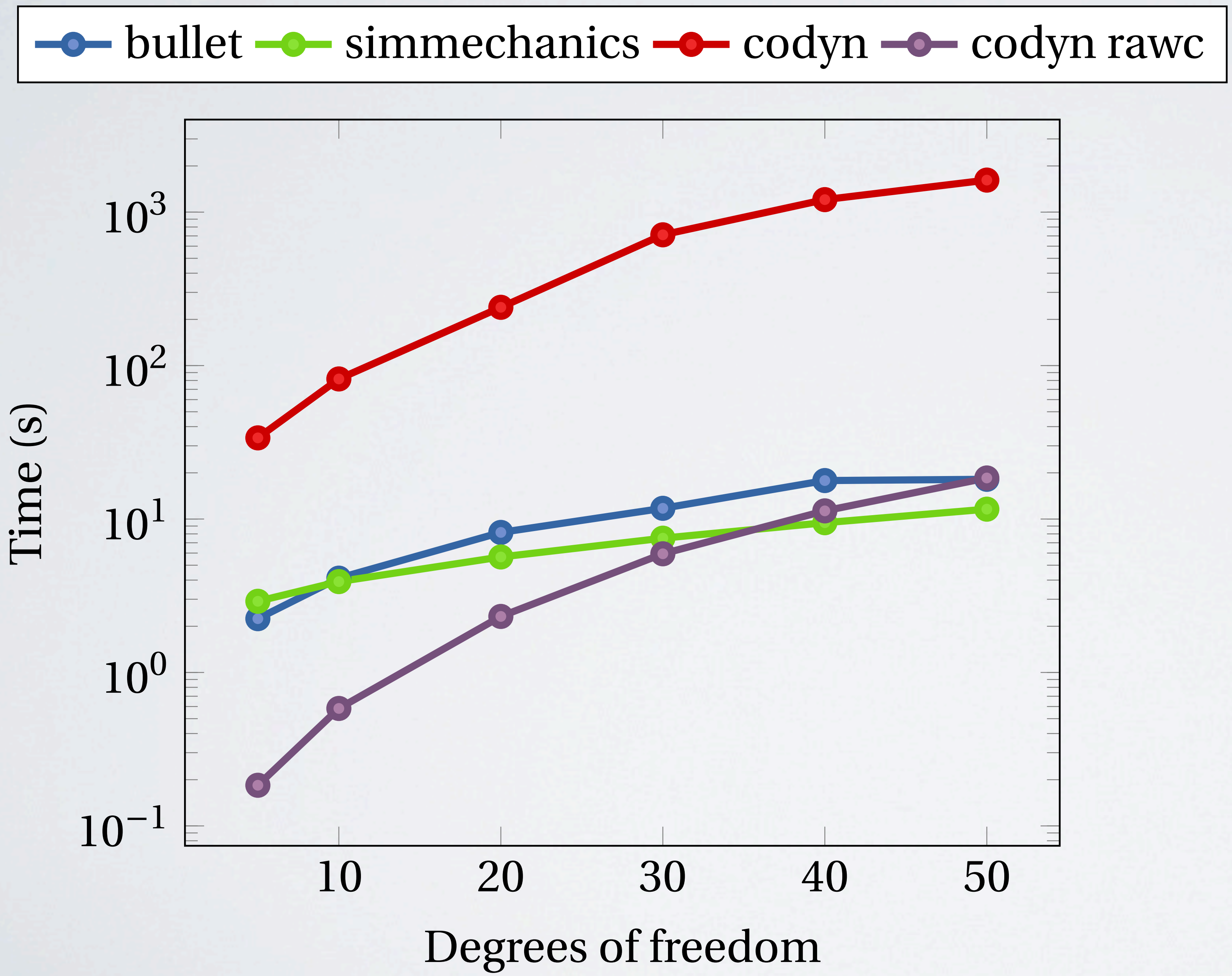
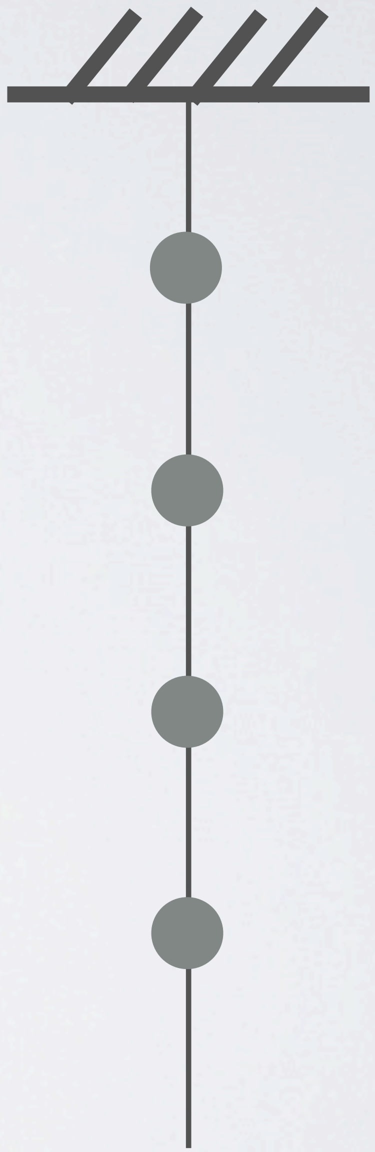
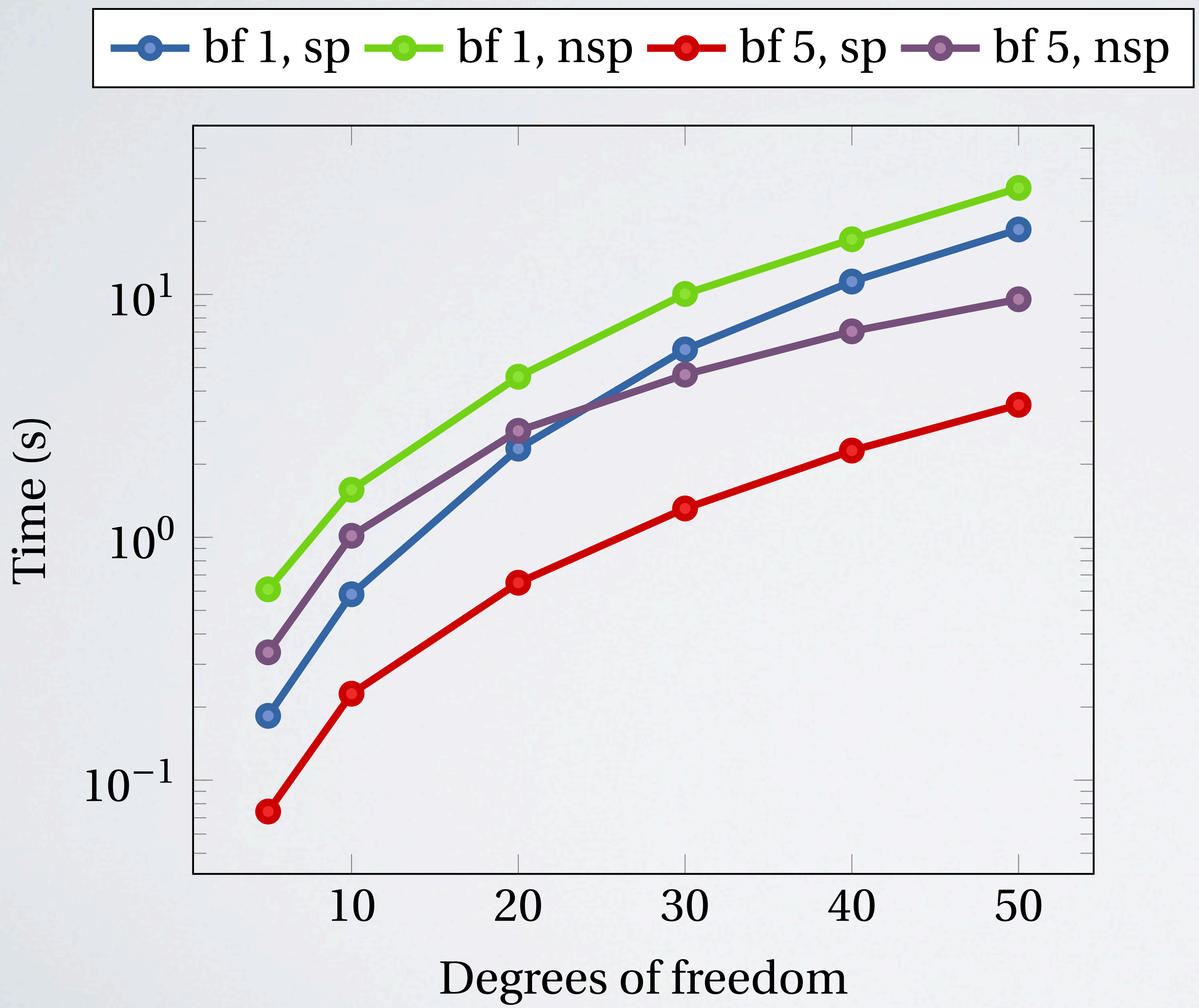
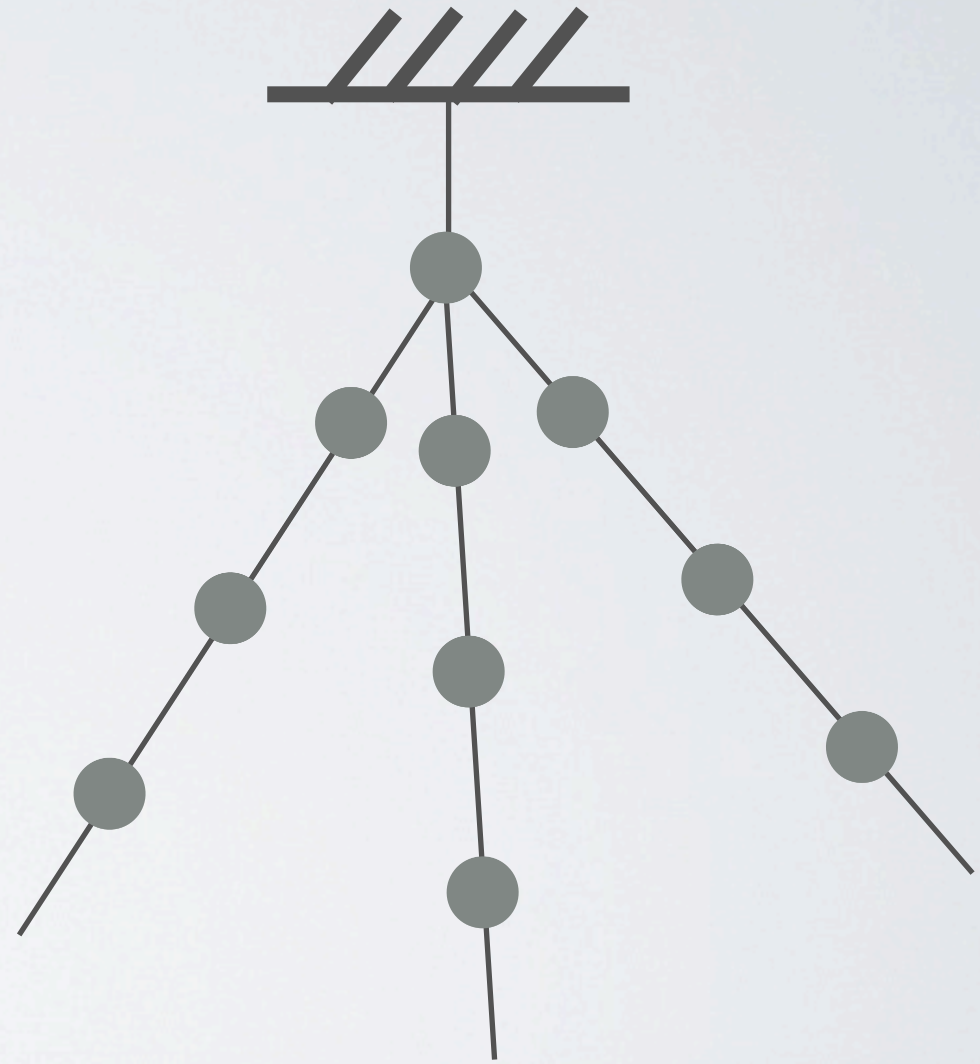
codyn - Performance





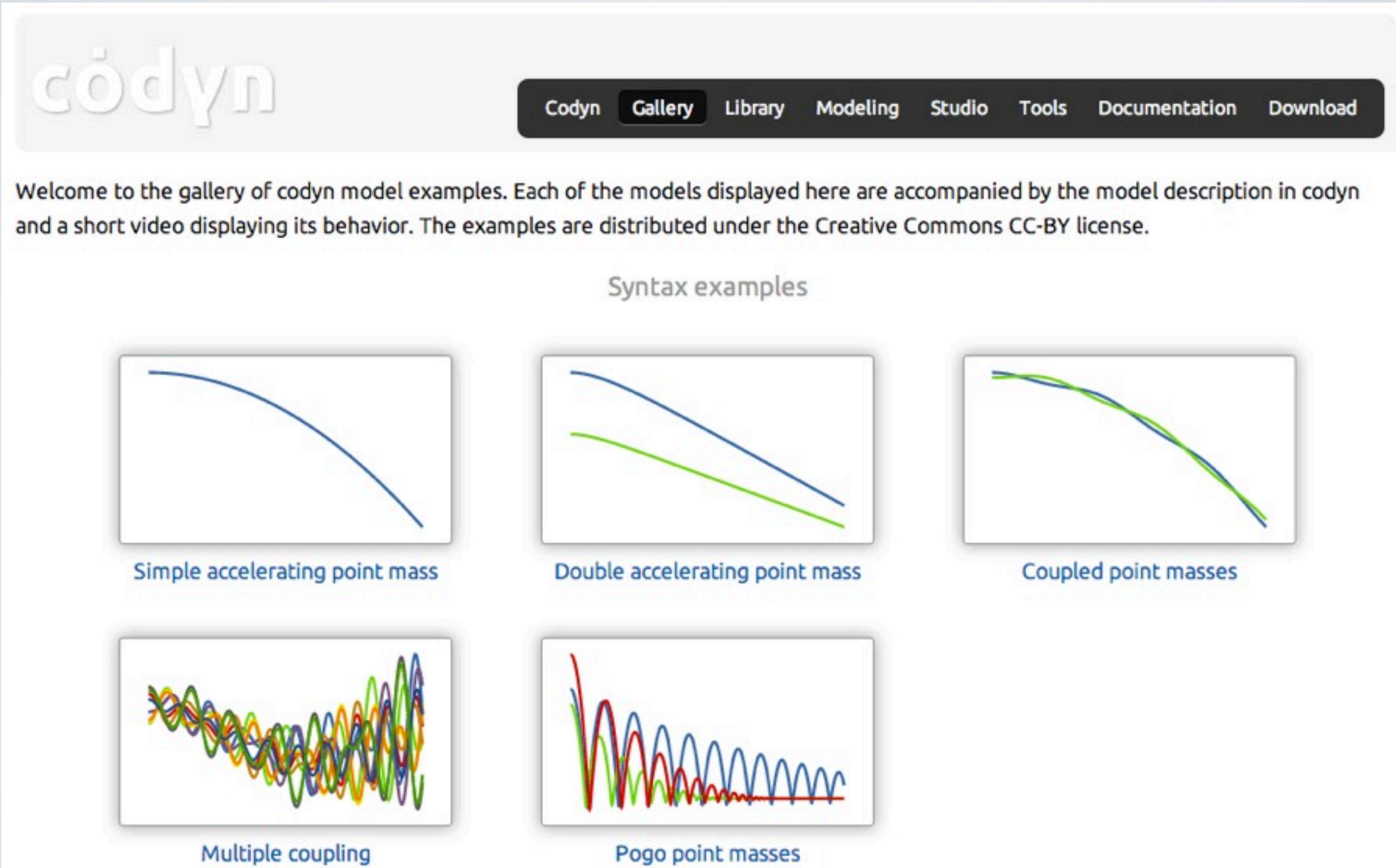
codyn - Performance





DYNAMICAL SYSTEMS

http://www.codyn.net/



Human gait optimization

HUMAN GAIT OPTIMIZATION

- Given a physical (articulated rigid body) structure
- Use automated processes to find how to control this structure to perform a specified task
- Generally called "Optimization"
- We used Particle Swarm Optimization (Kennedy, Eberhart; 1995)

HUMAN GAIT OPTIMIZATION

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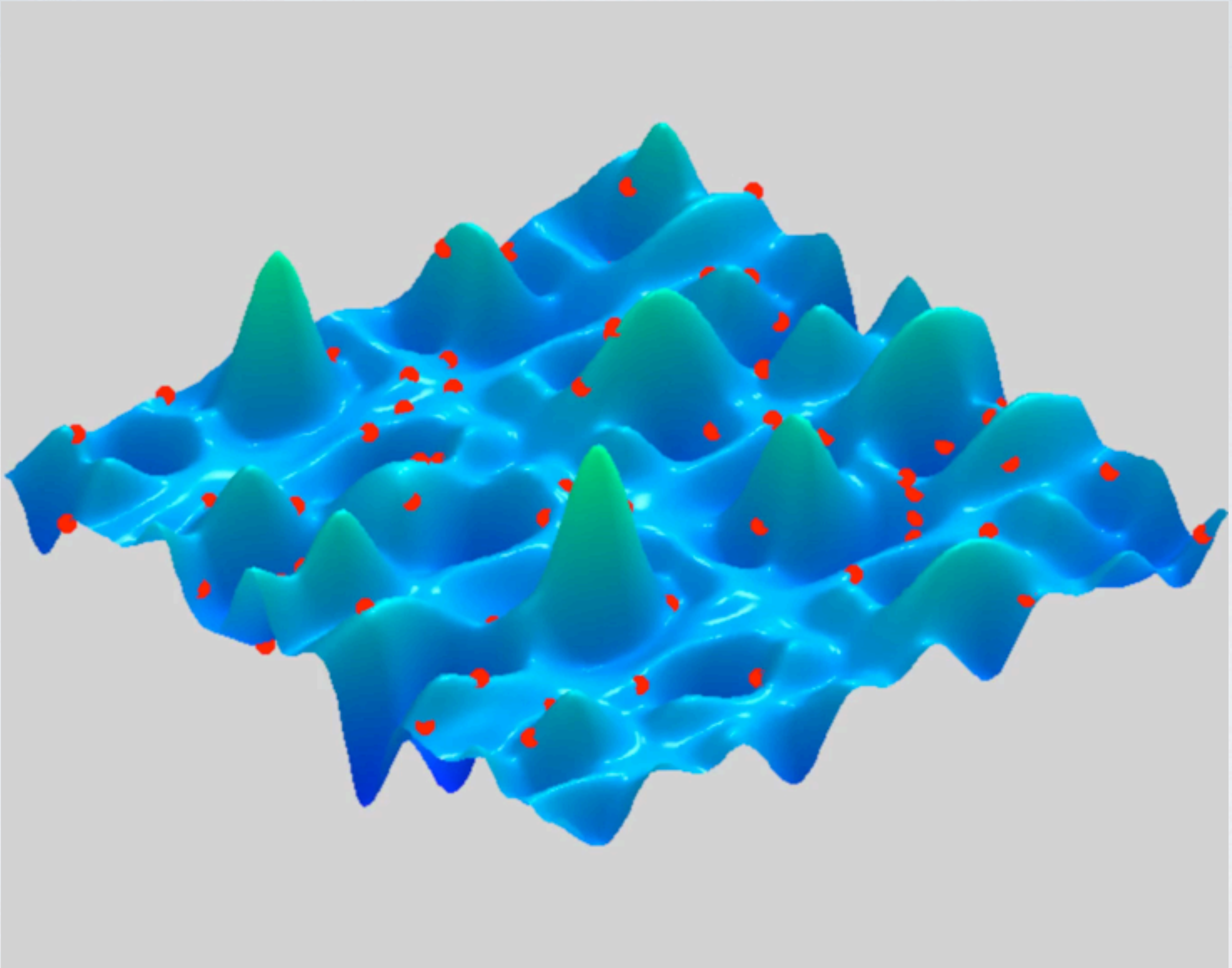
HUMAN GAIT OPTIMIZATION



HUMAN GAIT OPTIMIZATION

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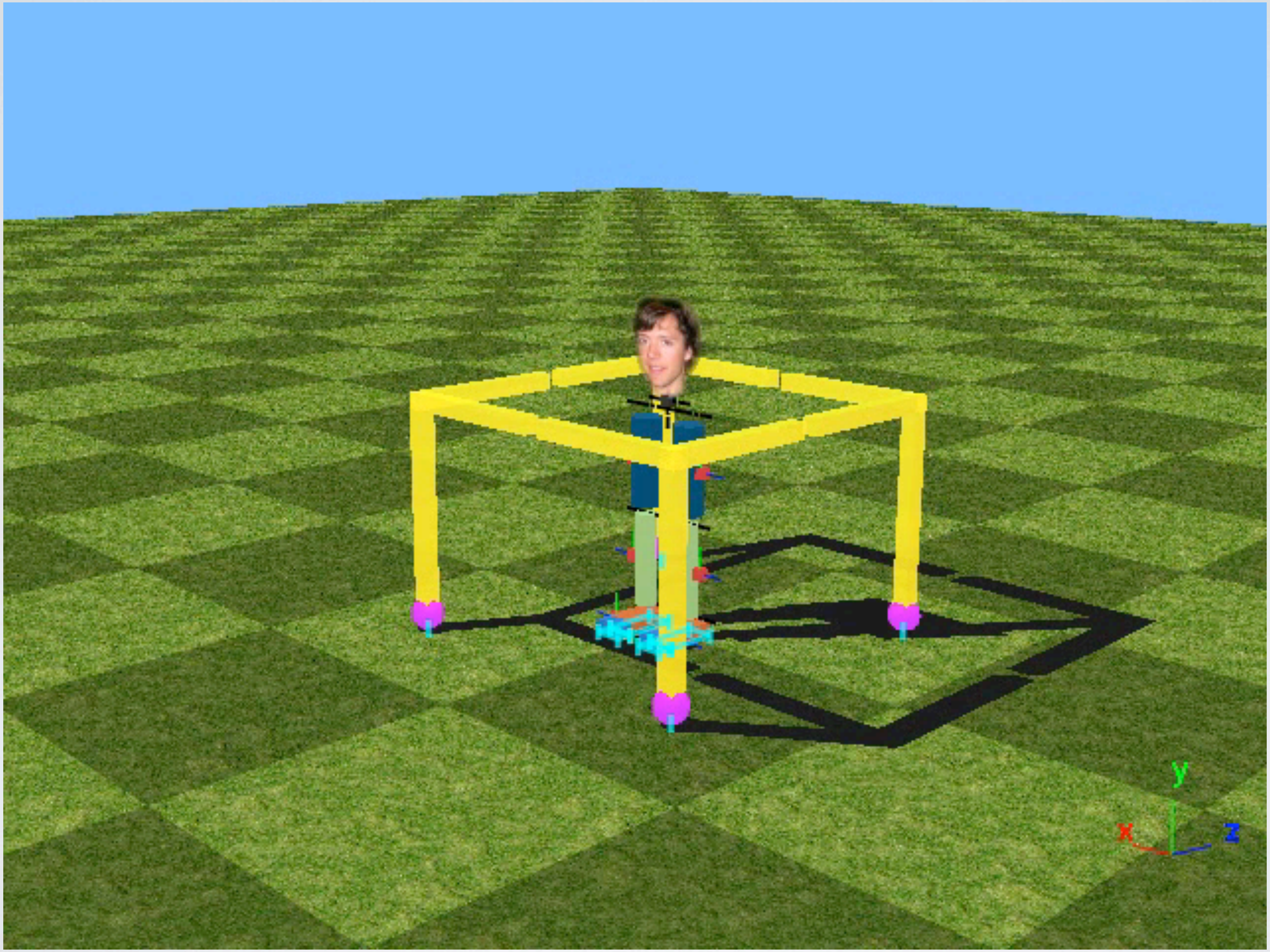
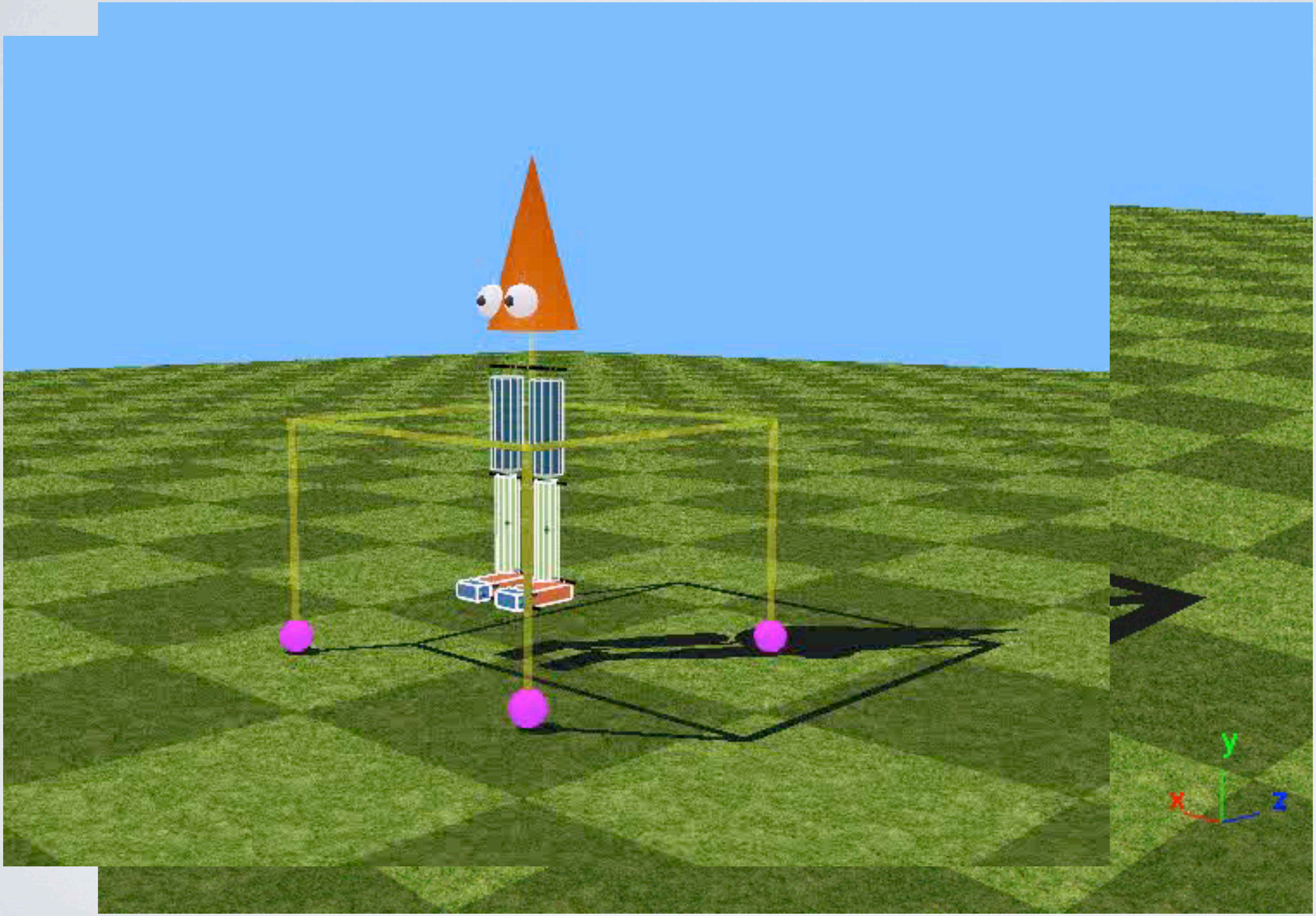


HUMAN GAIT OPTIMIZATION



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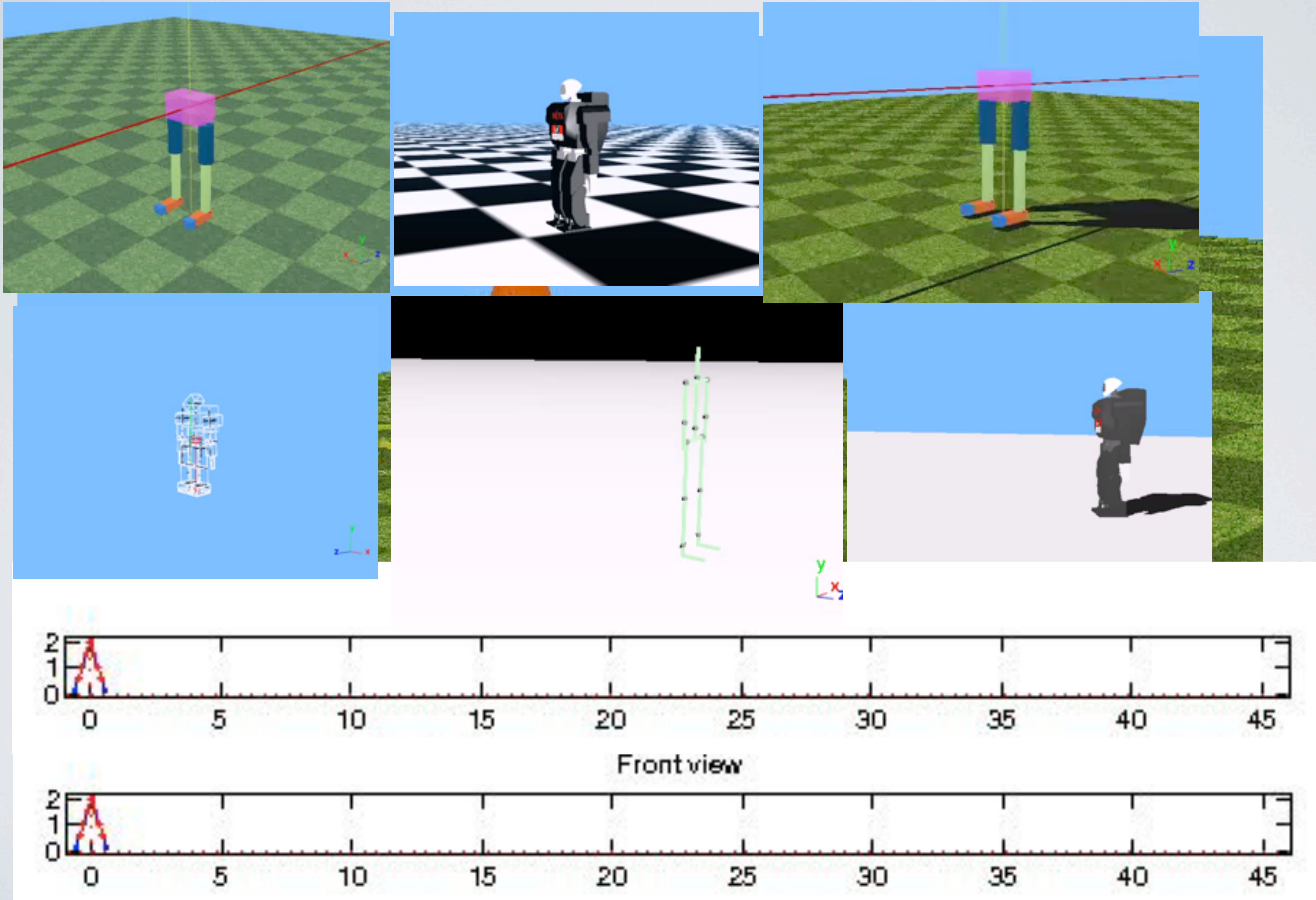
HUMAN GAIT OPTIMIZATION



HUMAN GAIT OPTIMIZATION

Why?

HUMAN GAIT OPTIMIZATION

HUMAN GAIT OPTIMIZATION

HUMAN GAIT OPTIMIZATION

1. What is the minimal, sufficient model for human gait optimization?

2. What are the objectives leading to stable, human gait?

HUMAN GAIT OPTIMIZATION

HUMAN GAIT OPTIMIZATION

Demonstration

HUMAN GAIT OPTIMIZATION

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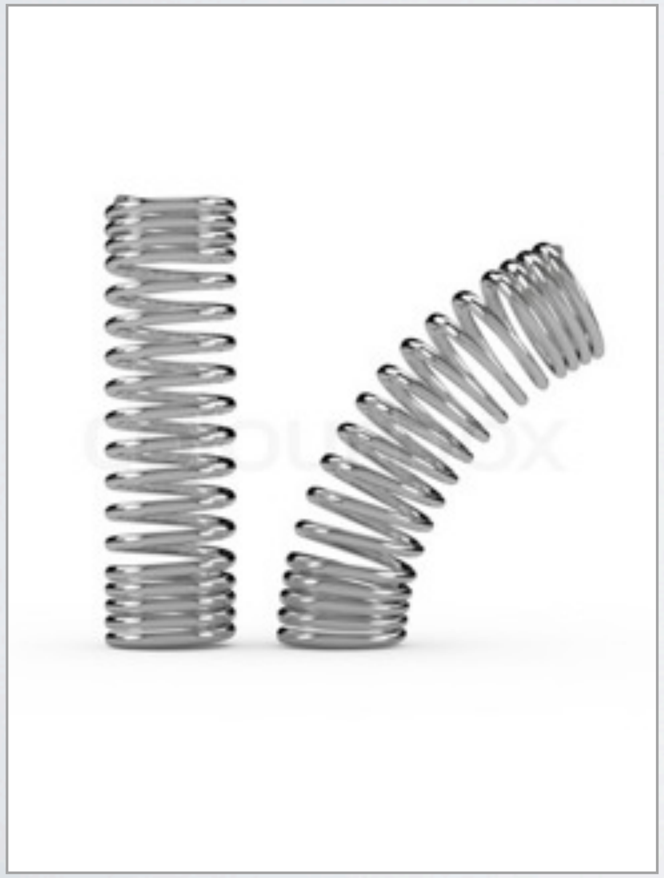
HUMAN GAIT OPTIMIZATION

Impedance control

$$\tau_i(t) = \underbrace{k_i(t)(\bar{q}_i(t) - q_i(t))}_{\text{Spring}} - \underbrace{b_i(t)\dot{q}_i}_{\text{Damper}}$$



HUMAN GAIT OPTIMIZATION

Objectives

1. Walk at a specific speed
2. Walk without falling over
3. Minimize energy

HUMAN GAIT OPTIMIZATION

HUMAN GAIT OPTIMIZATION

Exploiting Natural Dynamics in Biped Locomotion using Variable Impedance Control

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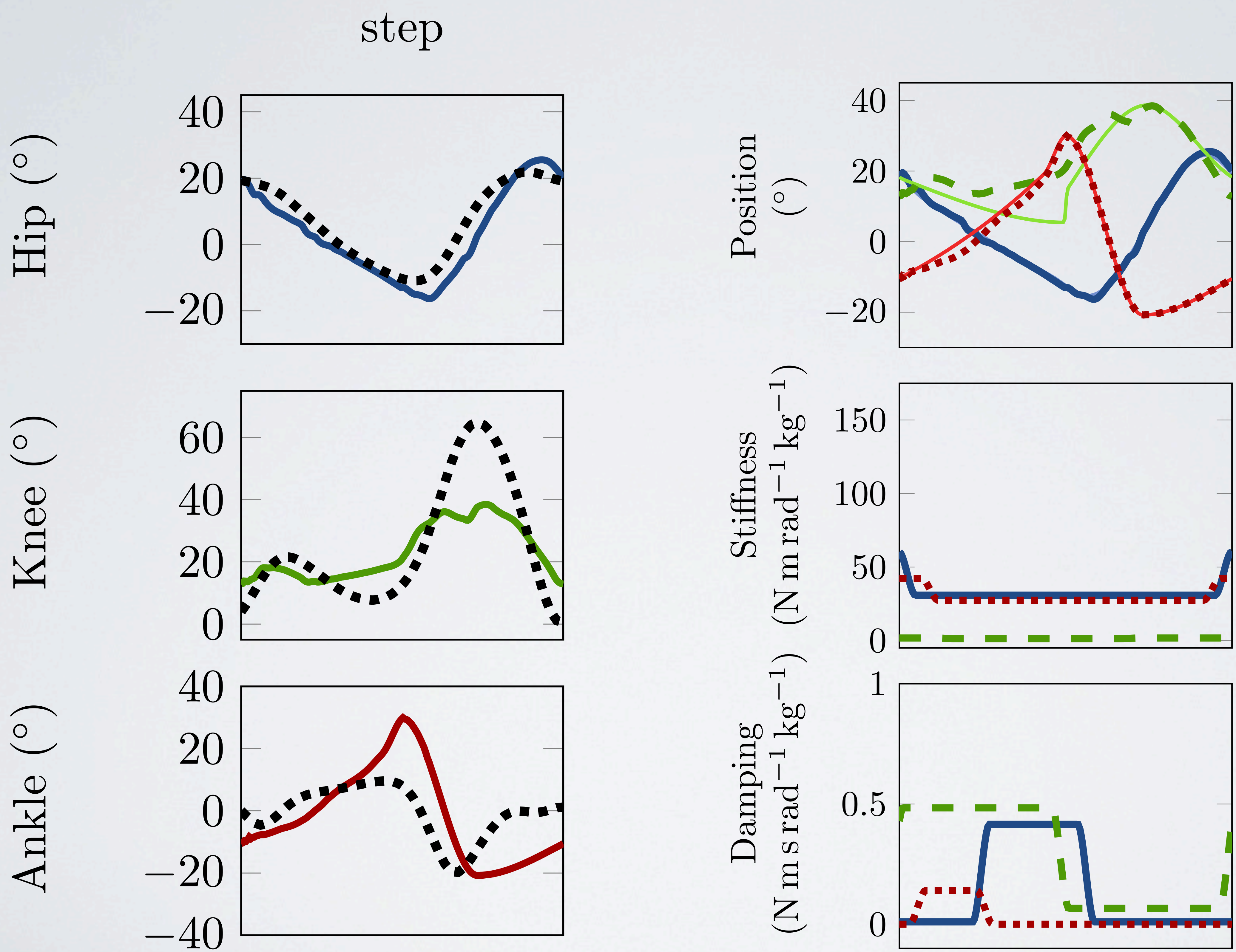
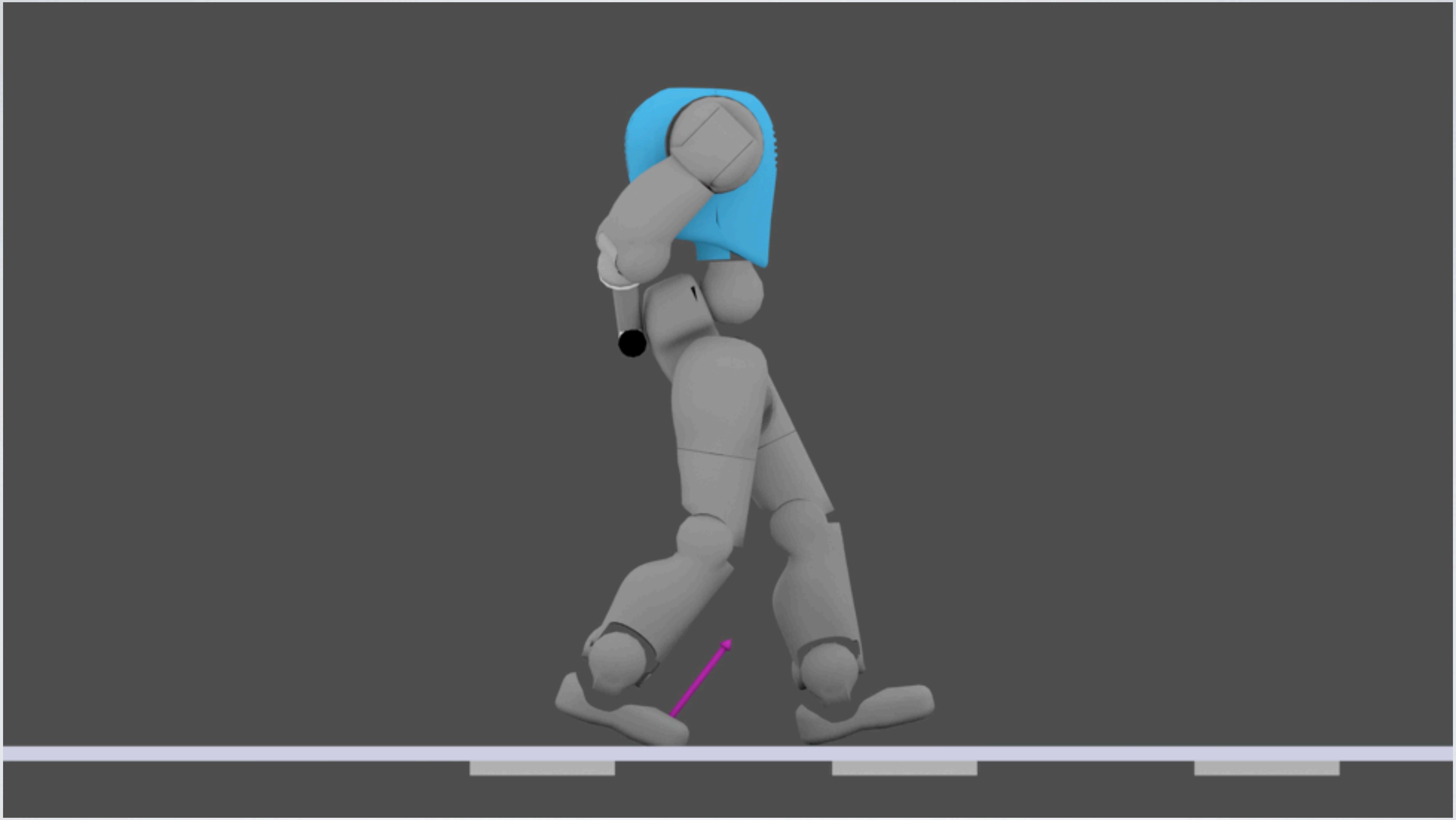
HUMAN GAIT OPTIMIZATION



HUMAN GAIT OPTIMIZATION

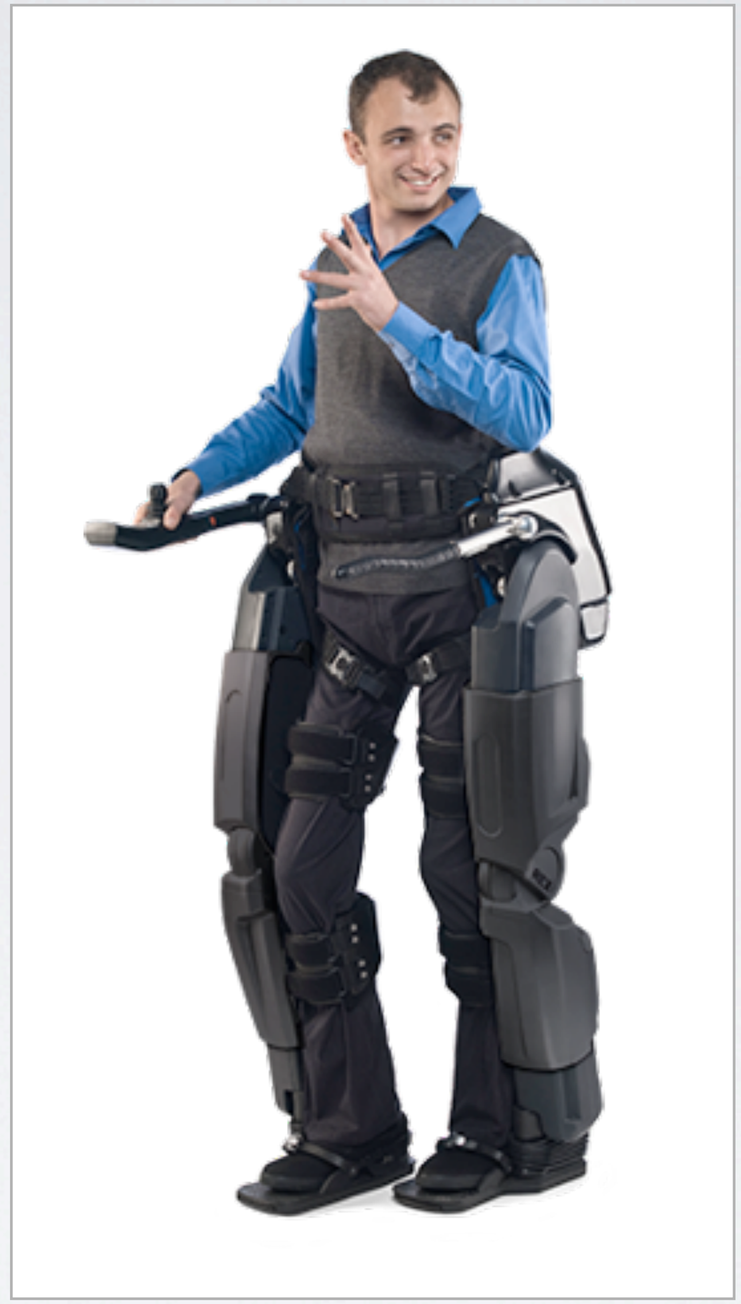
HUMAN GAIT OPTIMIZATION



Morphology/control co-design

CO-DESIGN

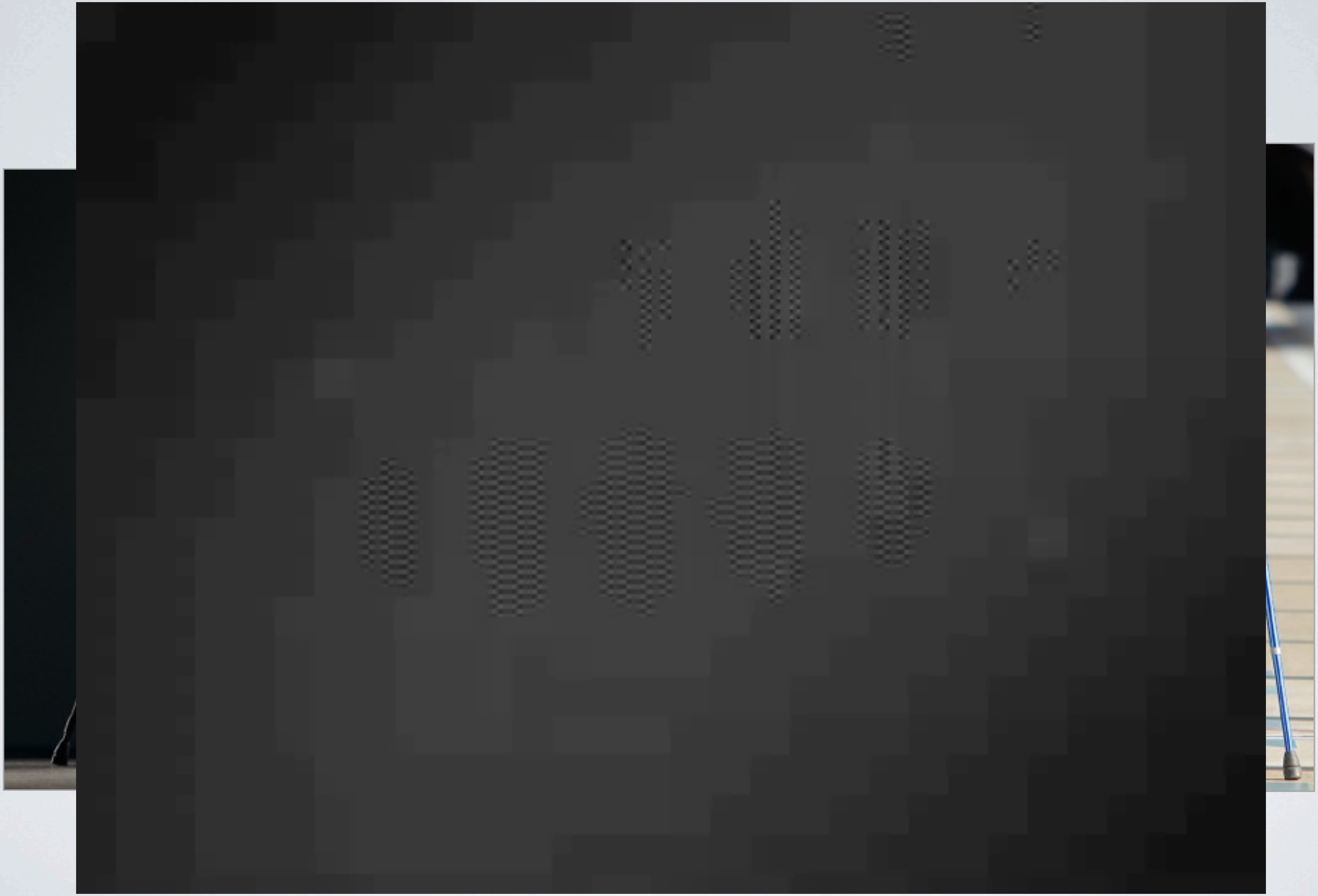
Ekso



Rex

ReWalk

CO-DESIGN



CO-DESIGN

Problem domain

- Development of a co-design methodology, using evolutionary inspired processes
- EVRYON: use case for a non-anthropomorphic, lower limb wearable device for locomotion
- A framework for the iterative co-design of wearable devices, focussing on open-ended **exploration** of solutions

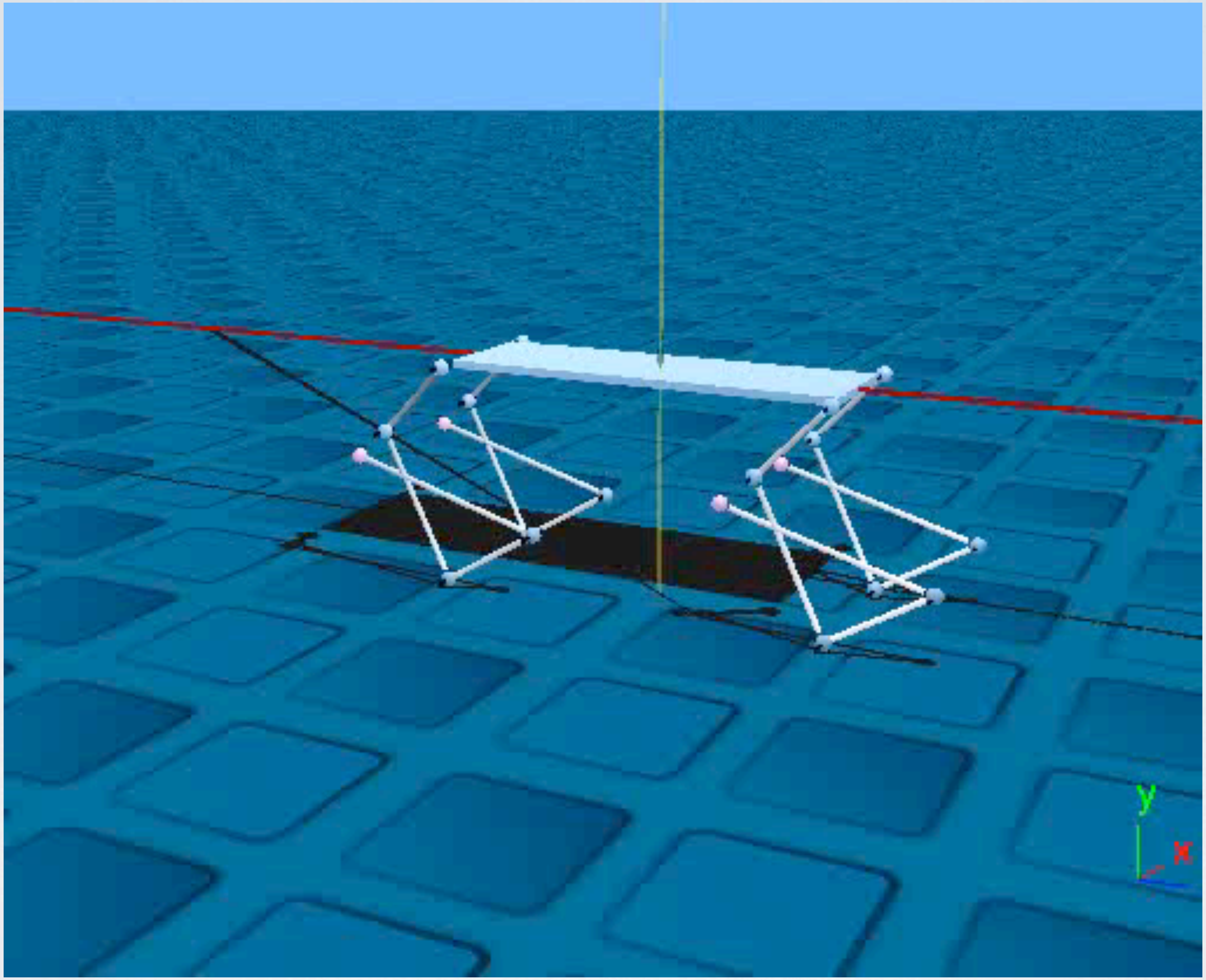
CO-DESIGN

CO-DESIGN

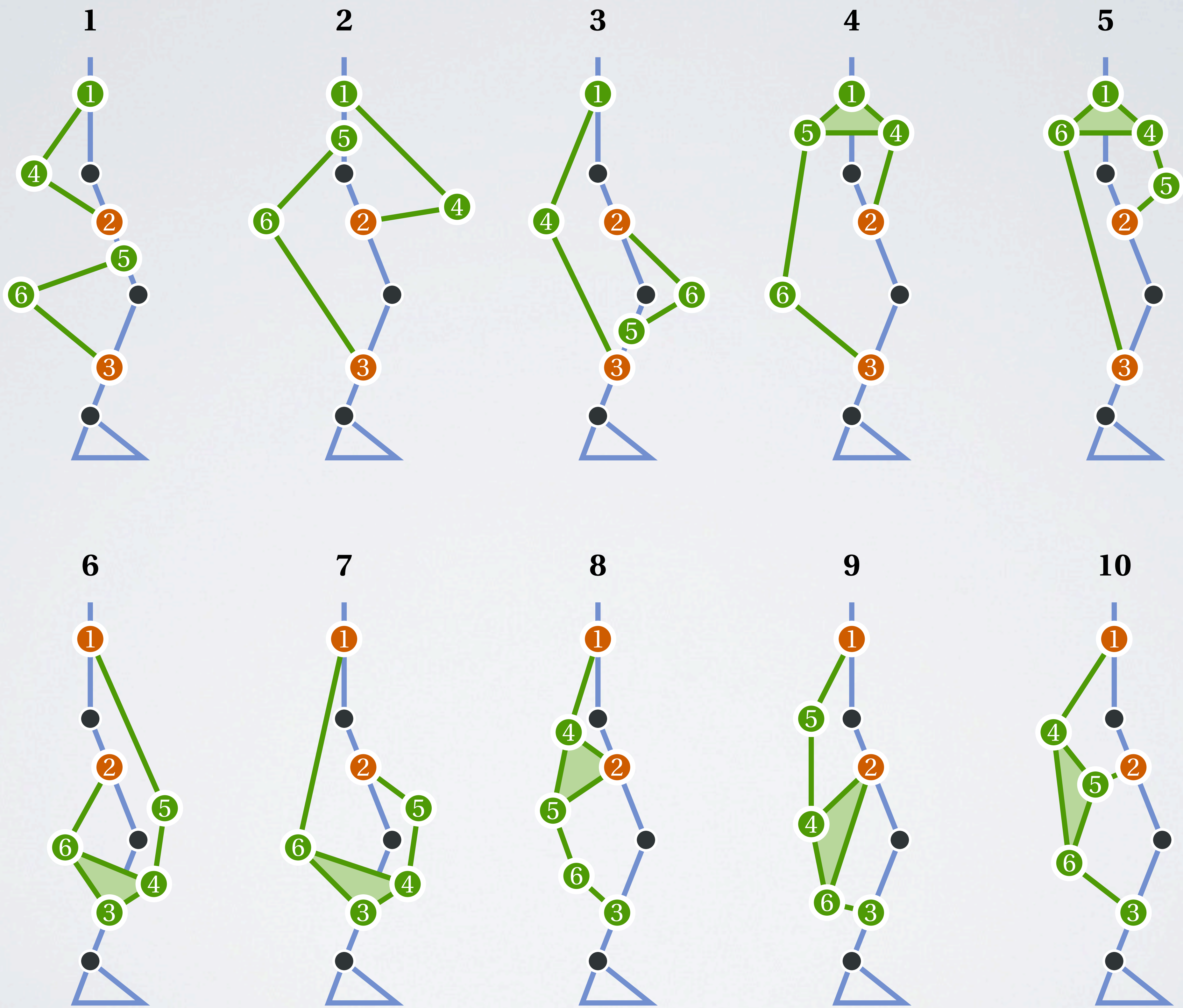
CO-DESIGN

CO-DESIGN

CO-DESIGN

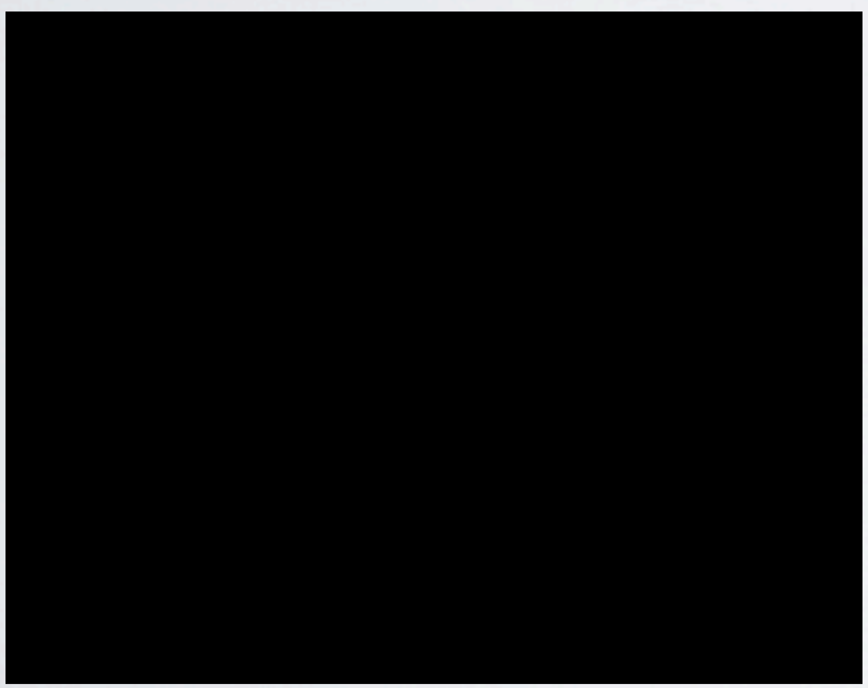


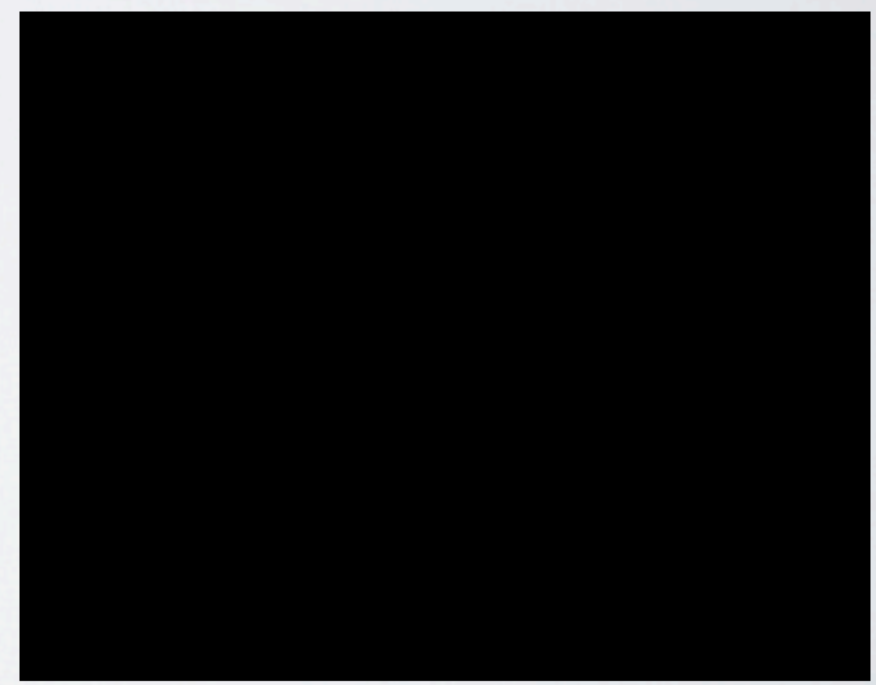
CO-DESIGN



CO-DESIGN



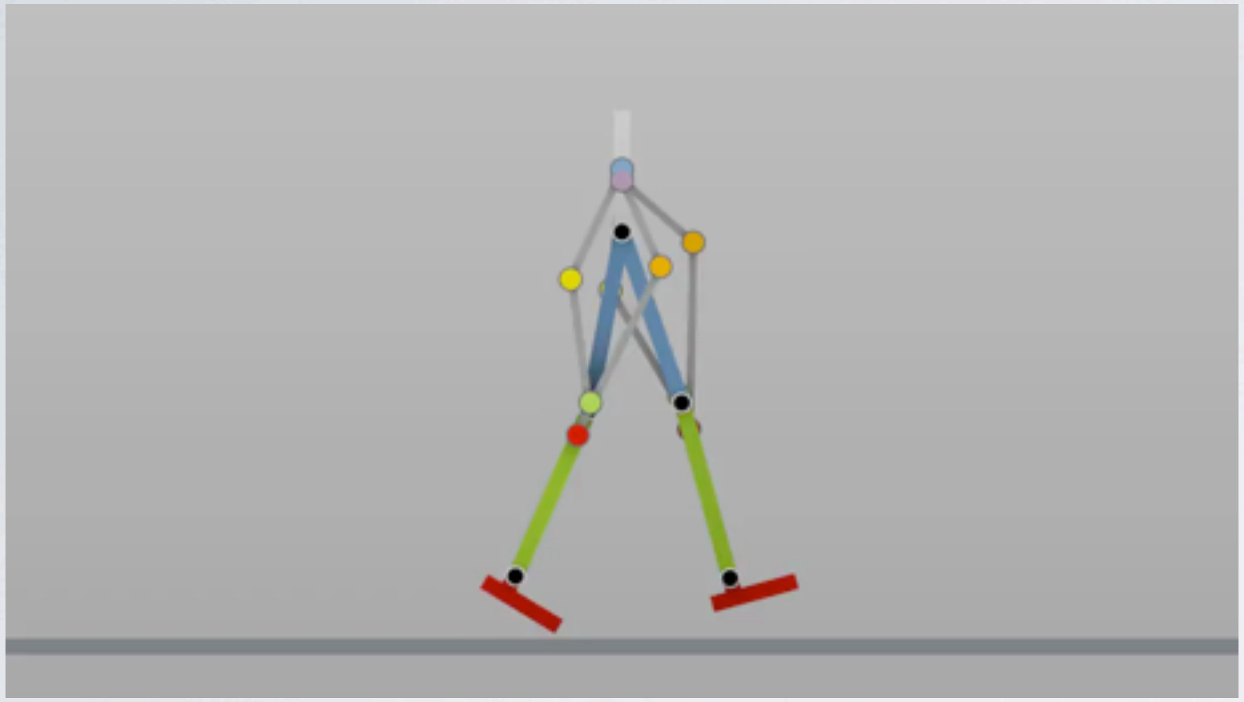



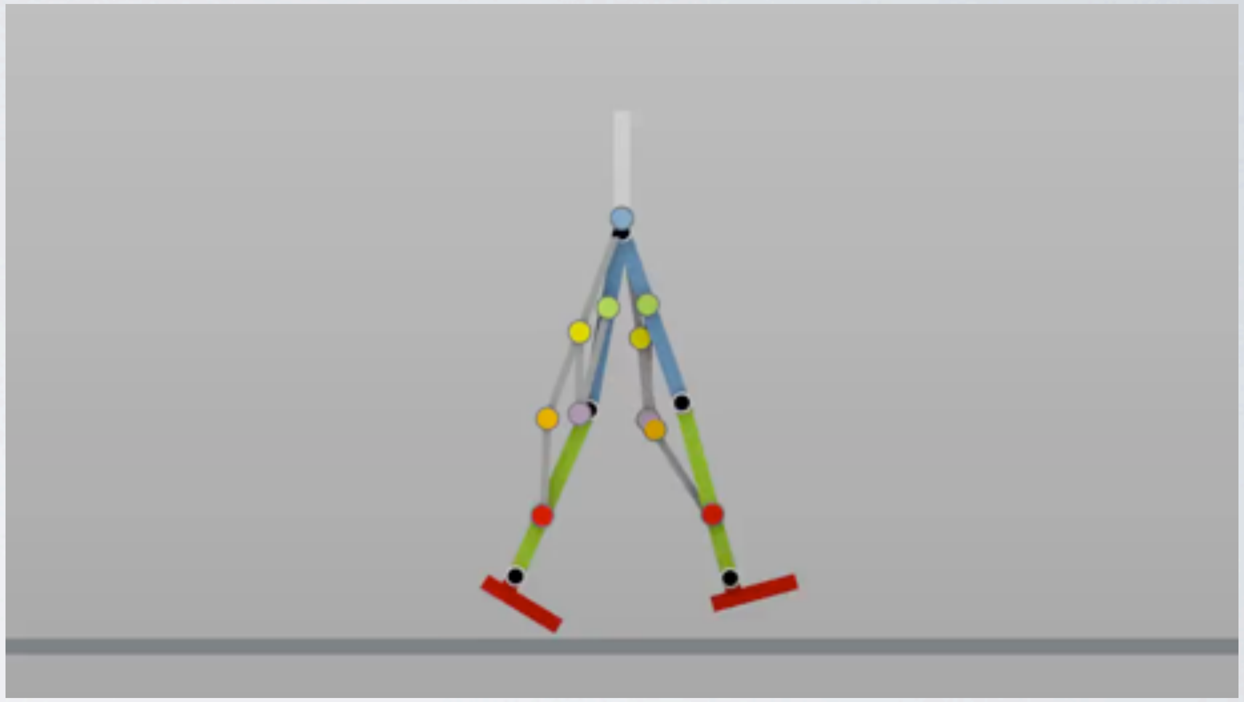


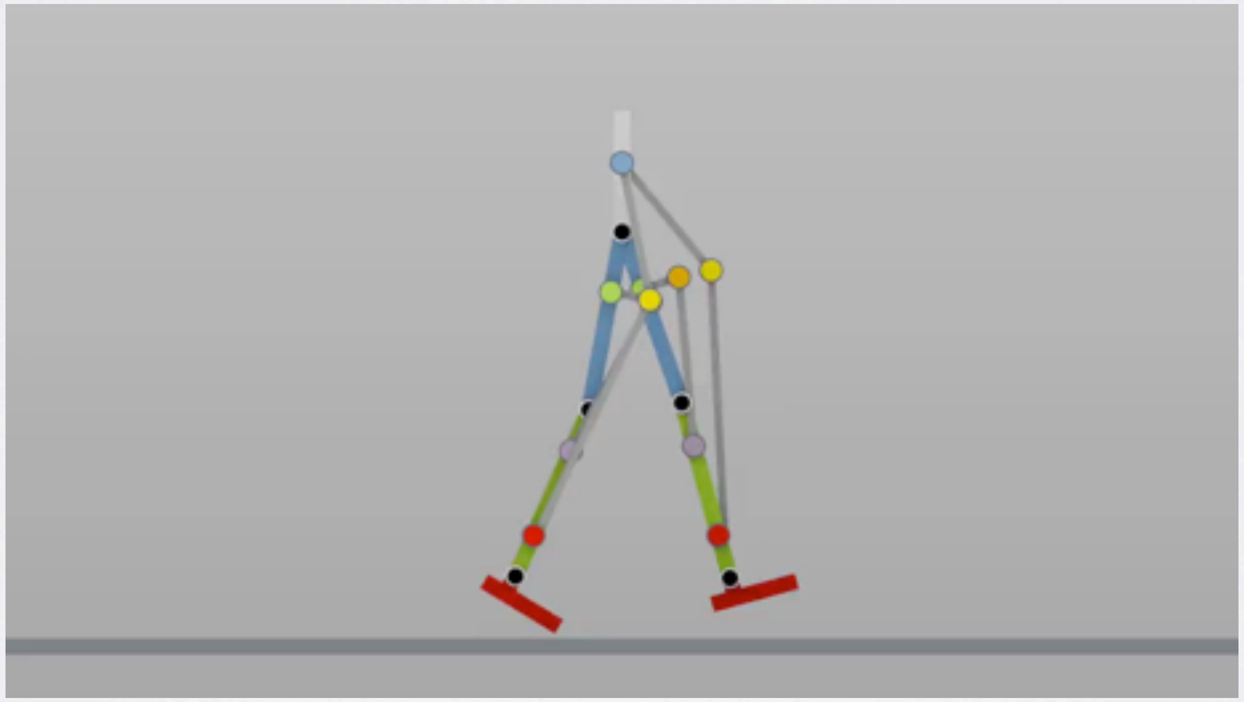
CO-DESIGN

- Various problems with this first attempt
  - Not self-stable
  - Artifacts due to contact modeling
  - Use of singularities
  - No reliable method to determine interaction forces

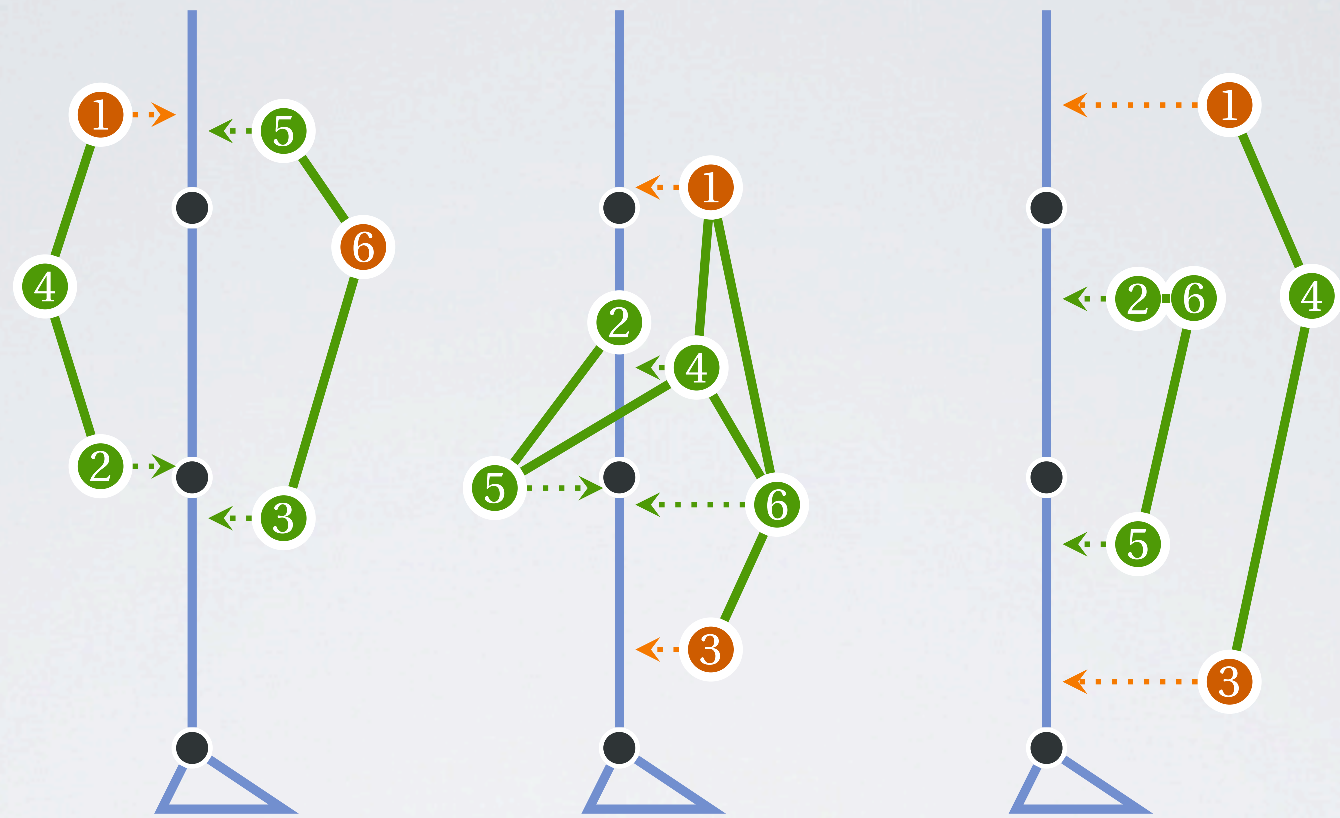
CO-DESIGN







CO-DESIGN



Topo	Mass	CoM (up)	Segment size
2	83.3 (+13.3)	1.07 (-0.03)	0.3 - 0.46
5	83.9 (+13.9)	1.02 (-0.08)	0.2 - 0.52
3	83.5 (+13.5)	1.03 (-0.07)	0.1 - 0.64

CO-DESIGN

- Development of a complete framework for co-design (dynamics/control, optimization, simulation)
- Successfully optimize human like gaits with parallel structures
- Automatic and simultaneous exploration of solution structures and their parameters
- Mass distribution particularly important

Conclusion

CONCLUSION

Main contributions

1. Open and freely available, framework for modeling of multi-domain coupled dynamics systems

2. State of the art, competitive rigid body dynamics simulator

3. Novel particle swarm optimization based algorithm for co-optimization of solution structures and their parameters

4. Robust optimization of human gait from global objectives using simple, local impedance control

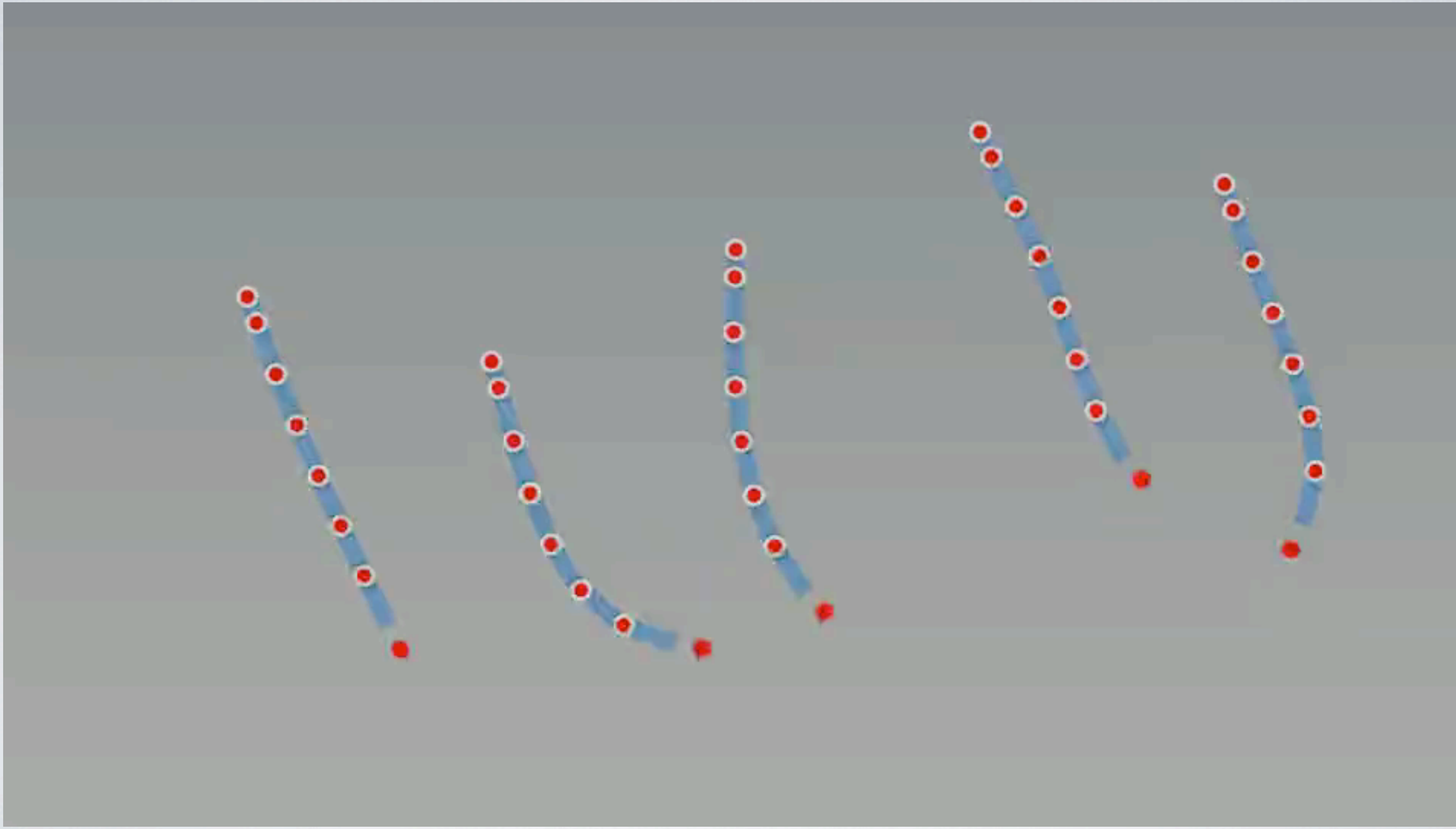
5. Front-to-end framework for the co-design of morphology and control of robotic structures

CONCLUSION

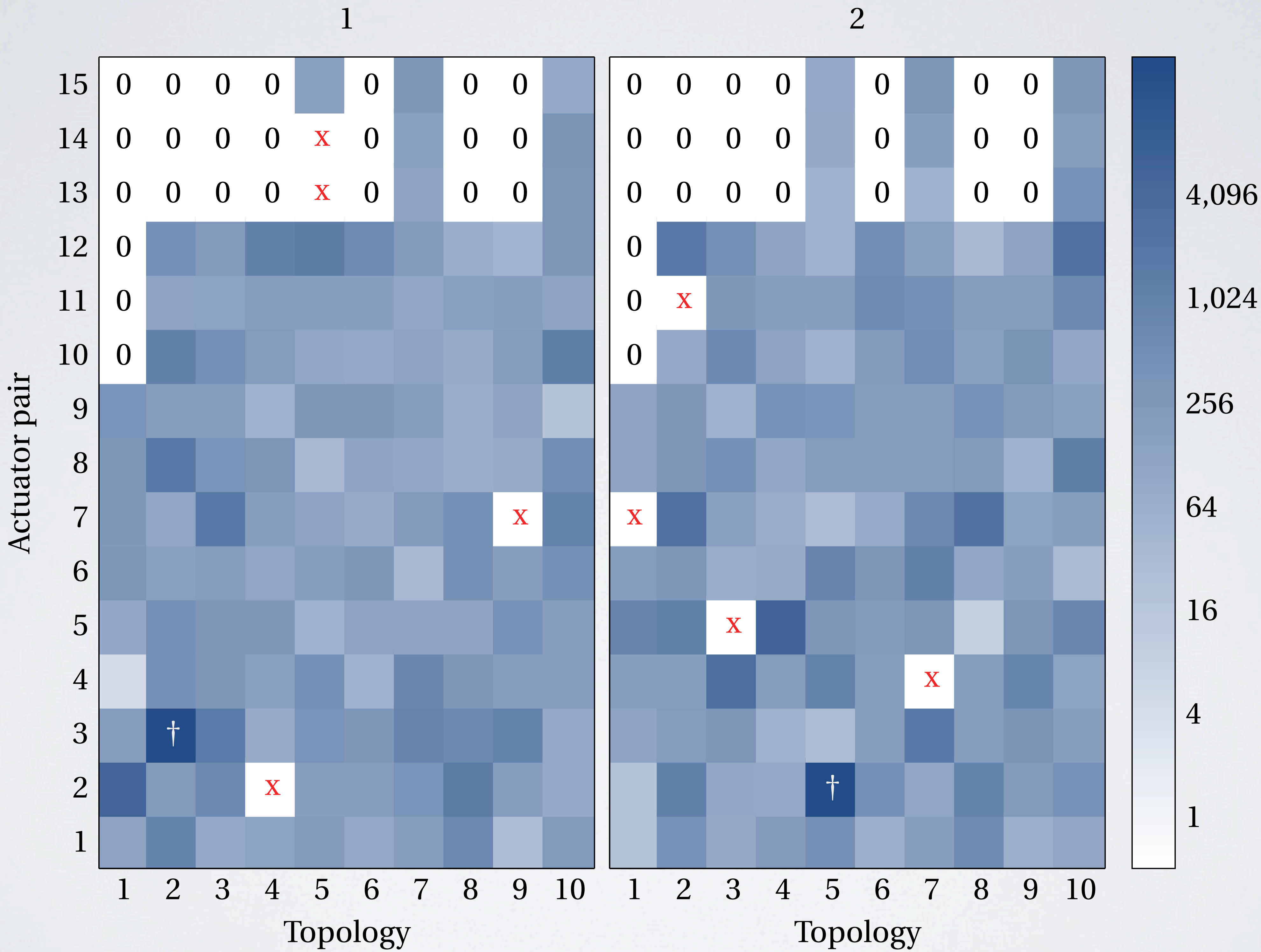
Co-design

- Methodology shown to be feasible
- Should provide input in a larger, iterative design process
- Open-ended search does not provide *complete* solutions

QUESTIONS



CO-DESIGN



Sunday, June 29, 14

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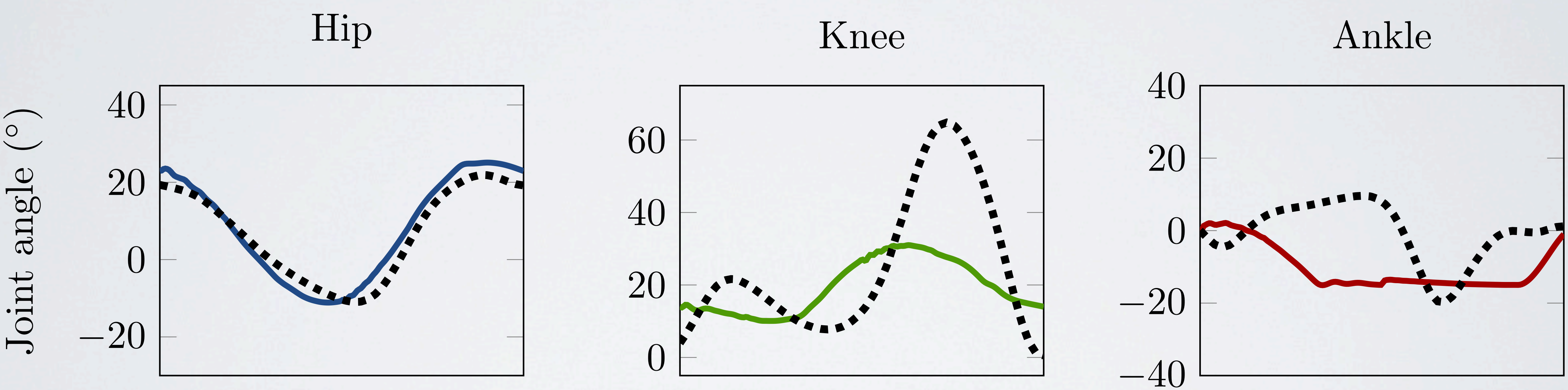
14. **Featherstone, R.** (2008). Rigid body dynamics algorithms. *Springer New York*,*49*.

HUMAN GAIT OPTIMIZATION

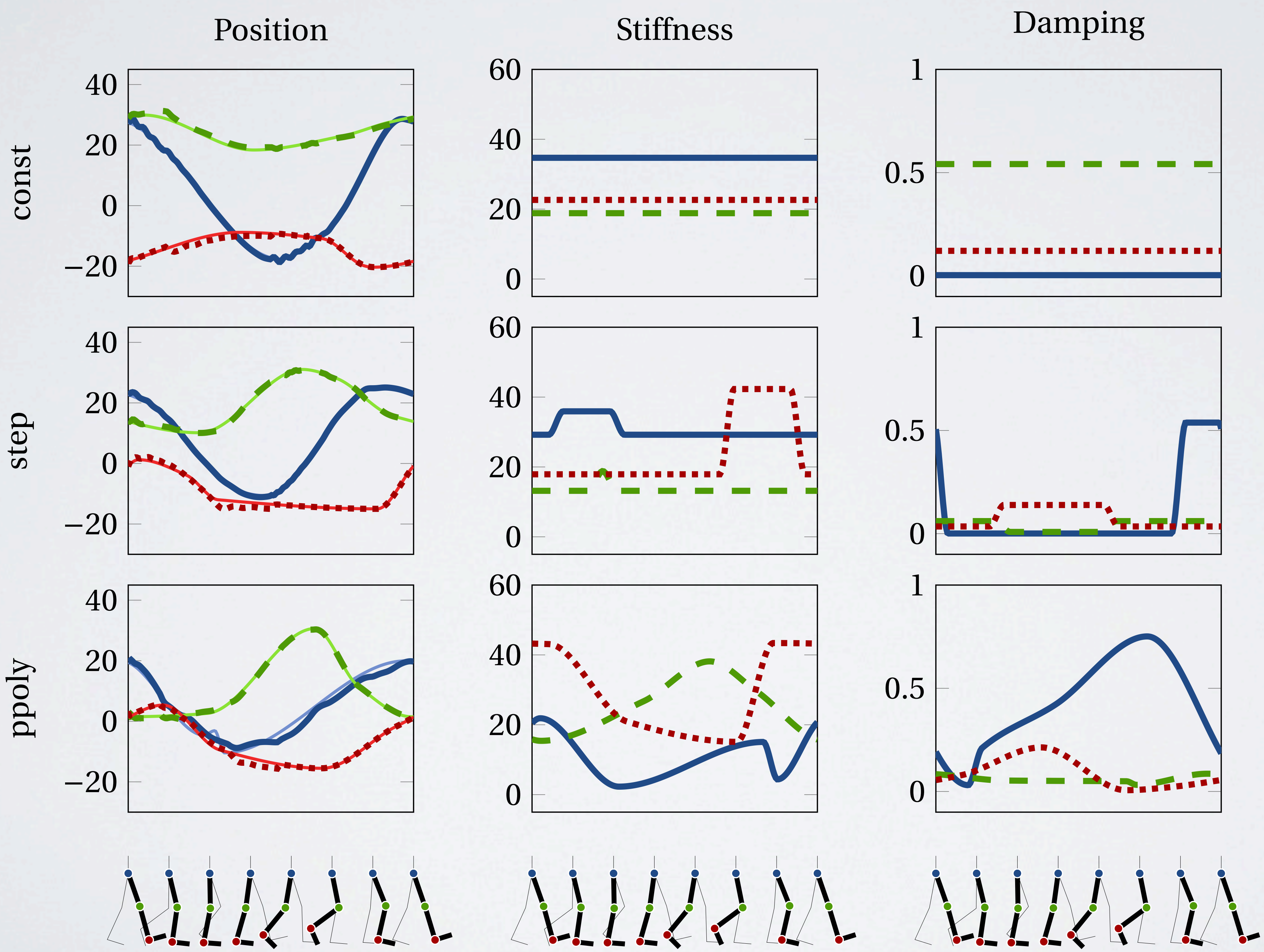
Transfer of methodology to a human-like platform

Step controller kinematics

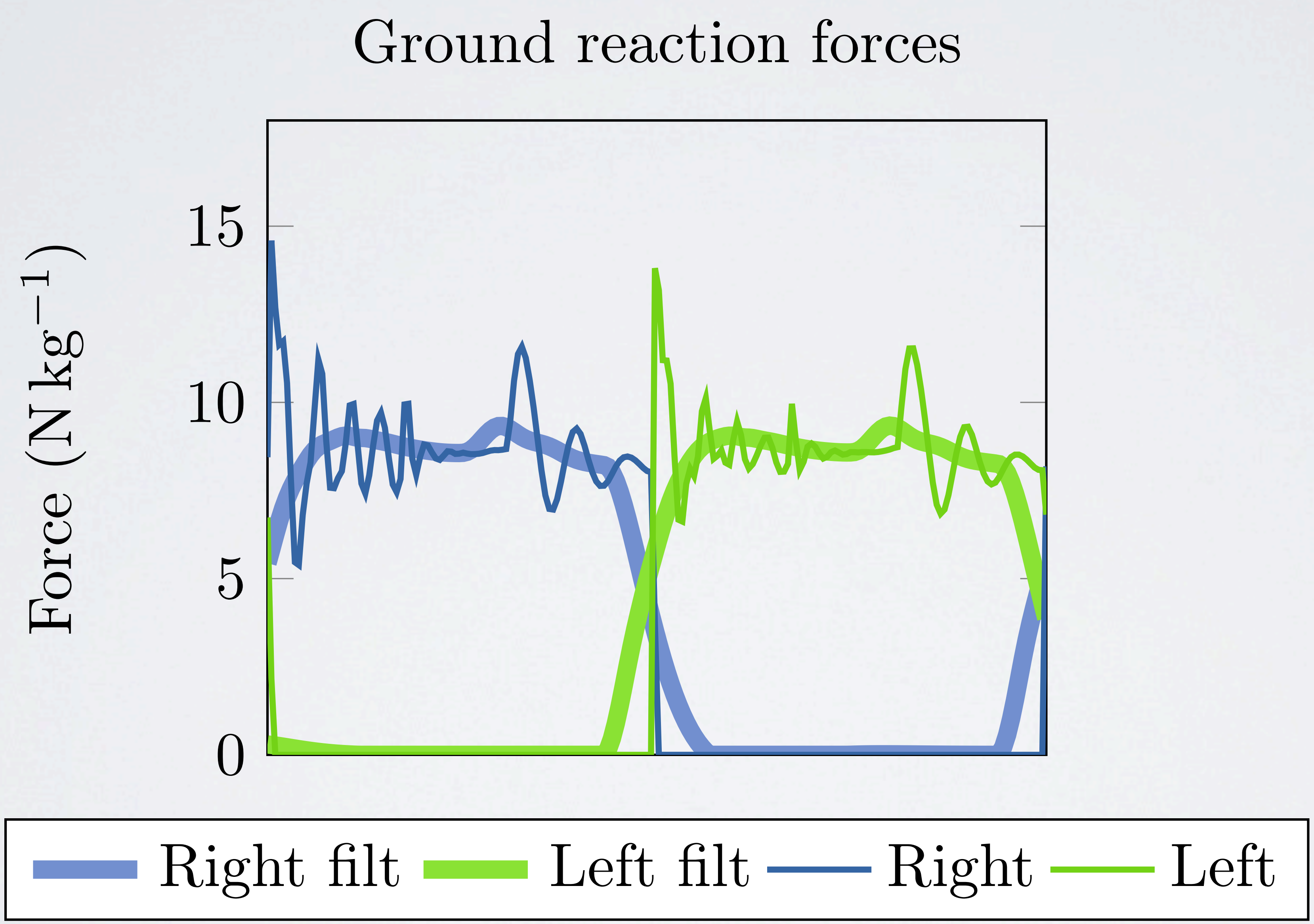


Single step (stance to stance)

Transfer of methodology to a human-like platform



Transfer of methodology to a human-like platform



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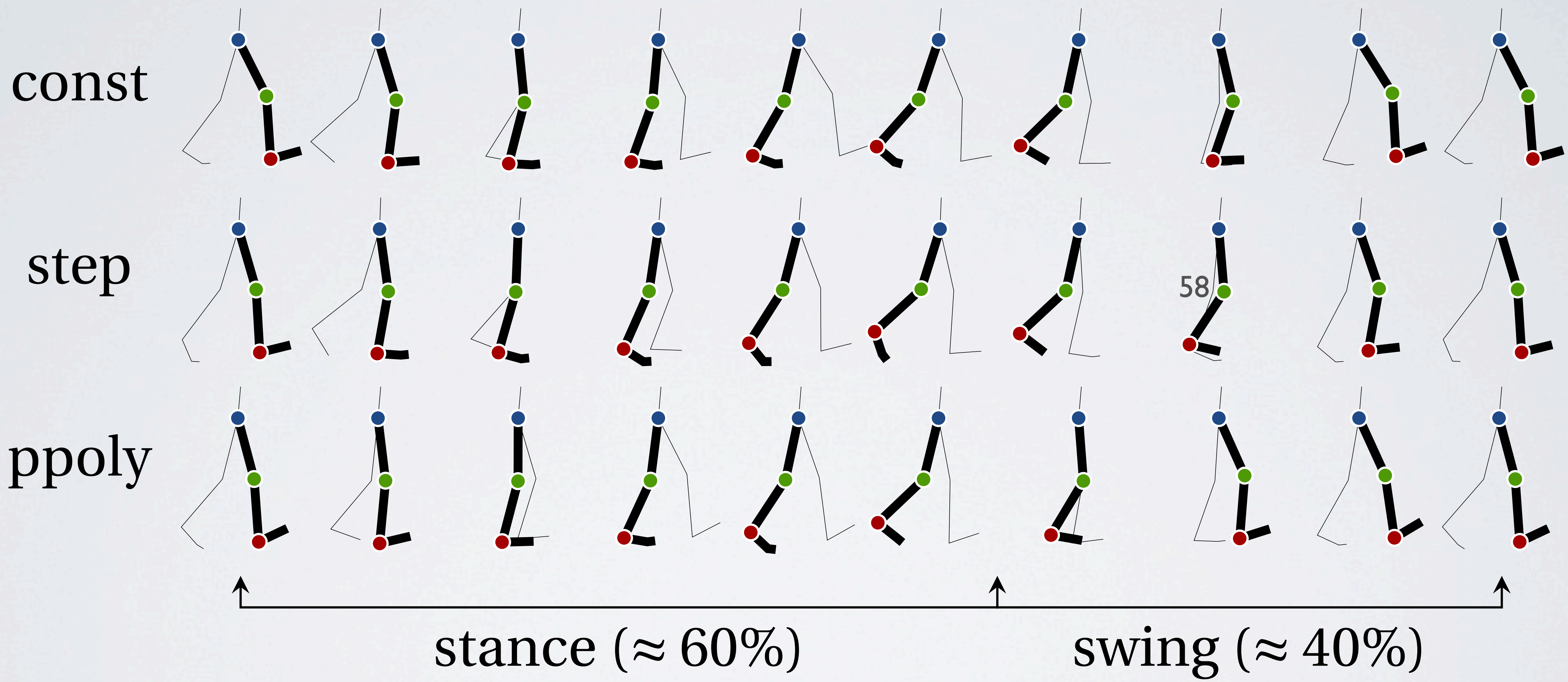

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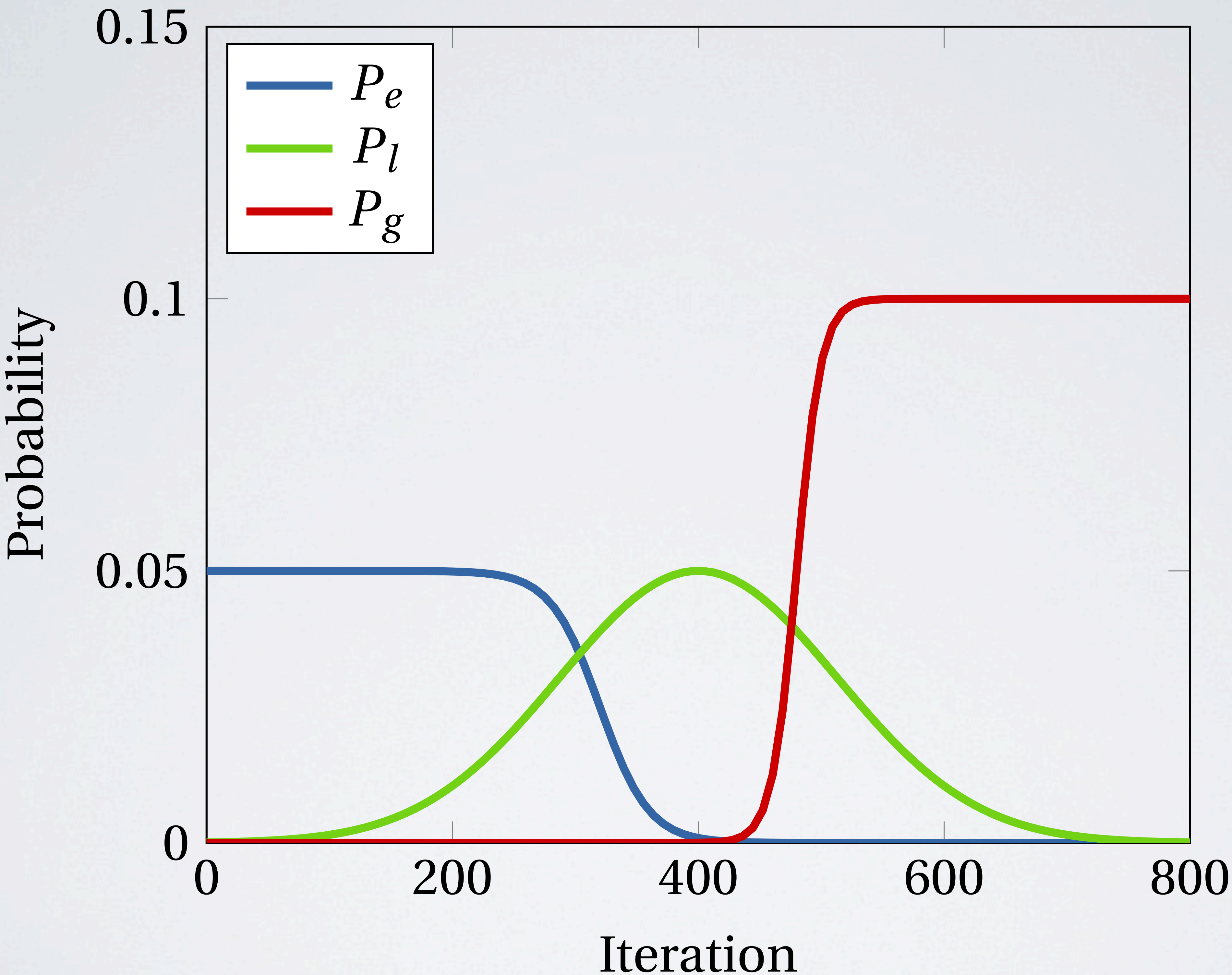
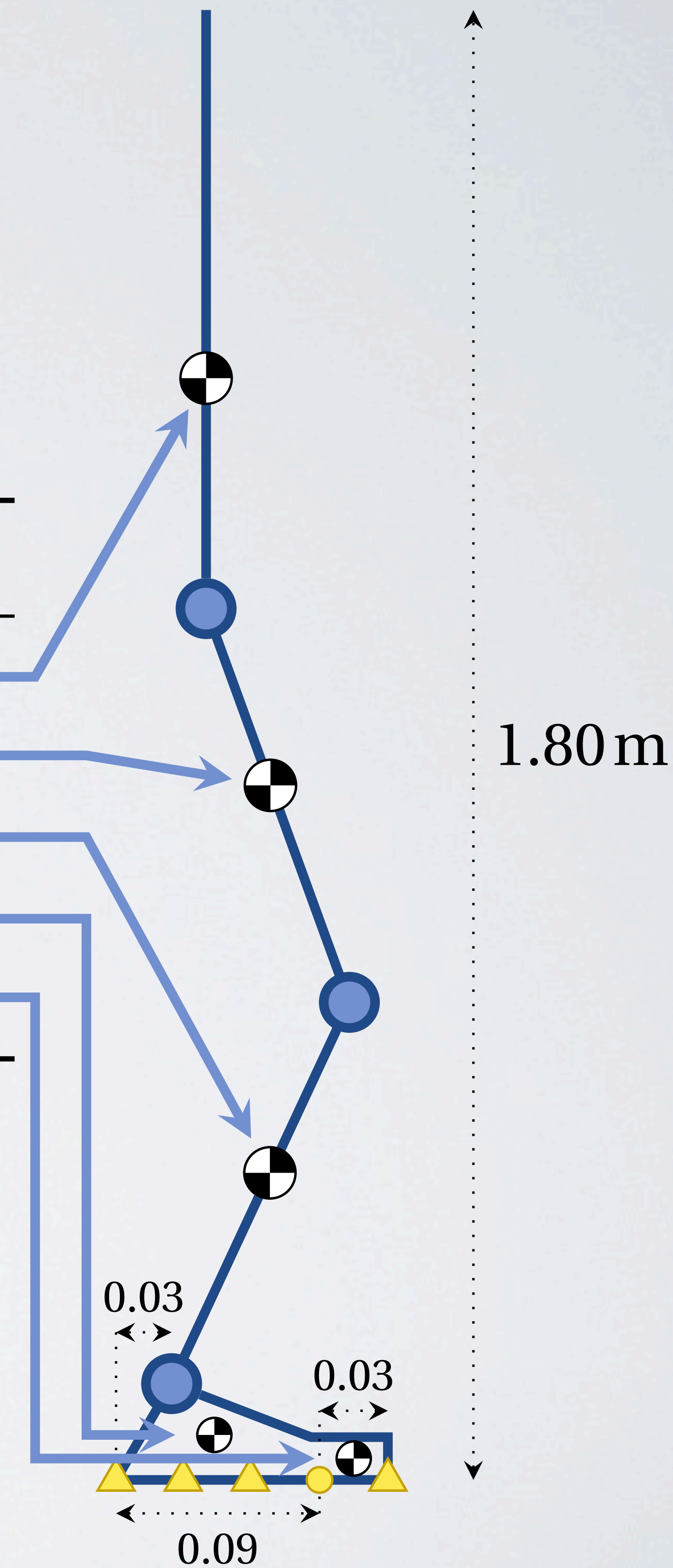
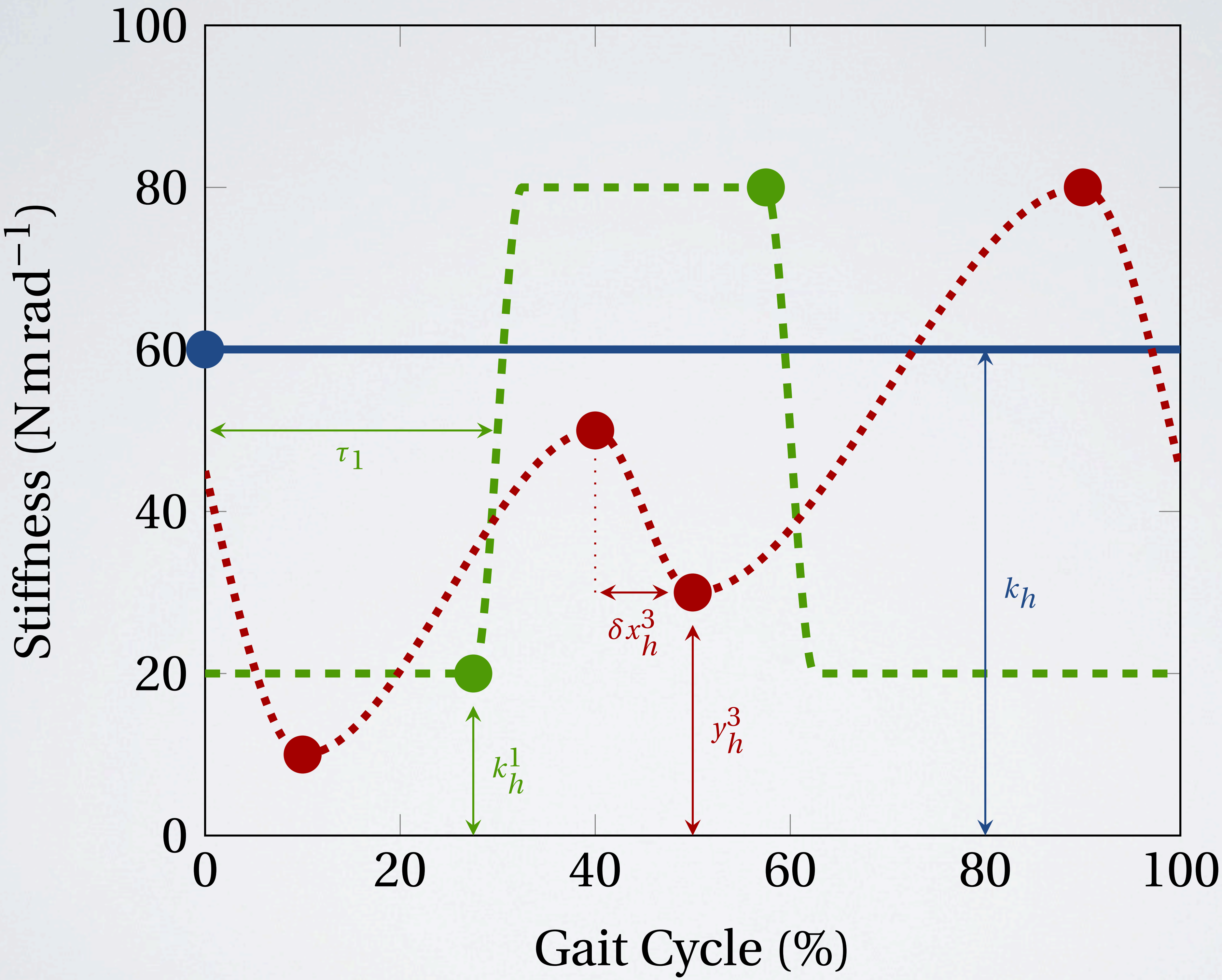
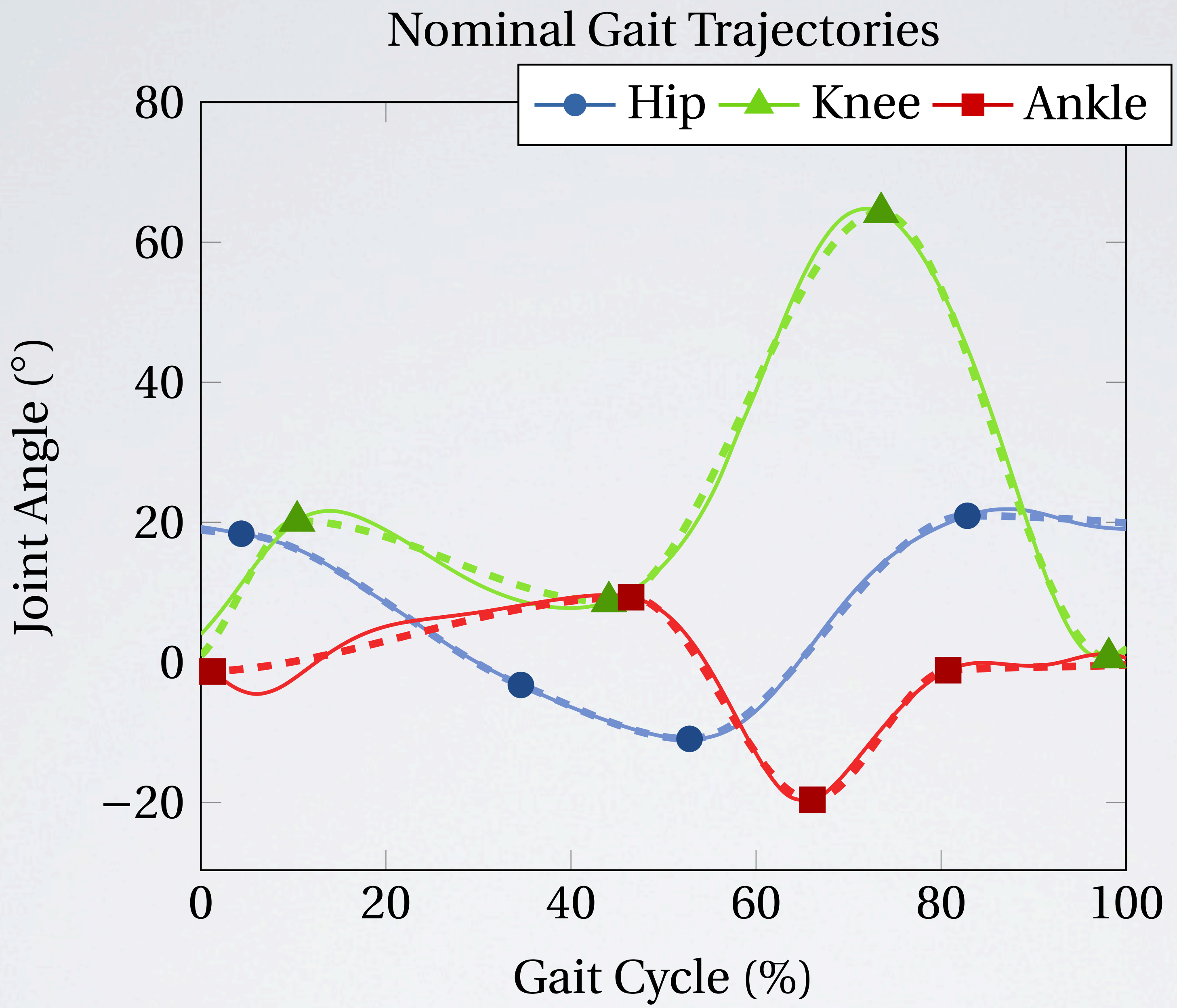
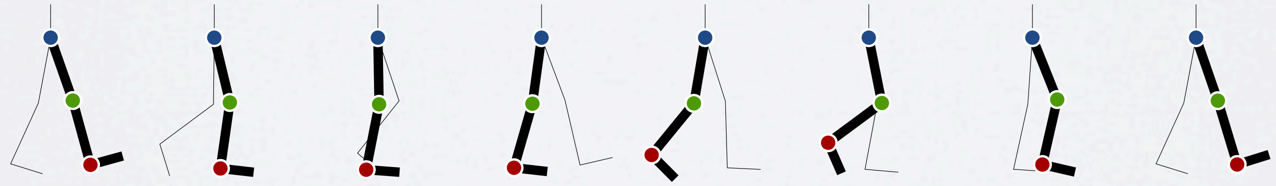

0.15
0.1
0.05
0
Probability
P_e
P_l
P_g
0
200
400
600
800
Iteration

Joint	CoM_x	CoM_y	l	m	r_g
torso	0.000	0.030	$n.a$	0.678	0.90
up leg	0.000	−0.108	0.25	0.100	0.32
low leg	0.000	−0.108	0.25	0.047	0.30
ankle	0.004	−0.002	0.04	0.011	0.48
toe	0.001	0.000	0.03	0.003	0.10

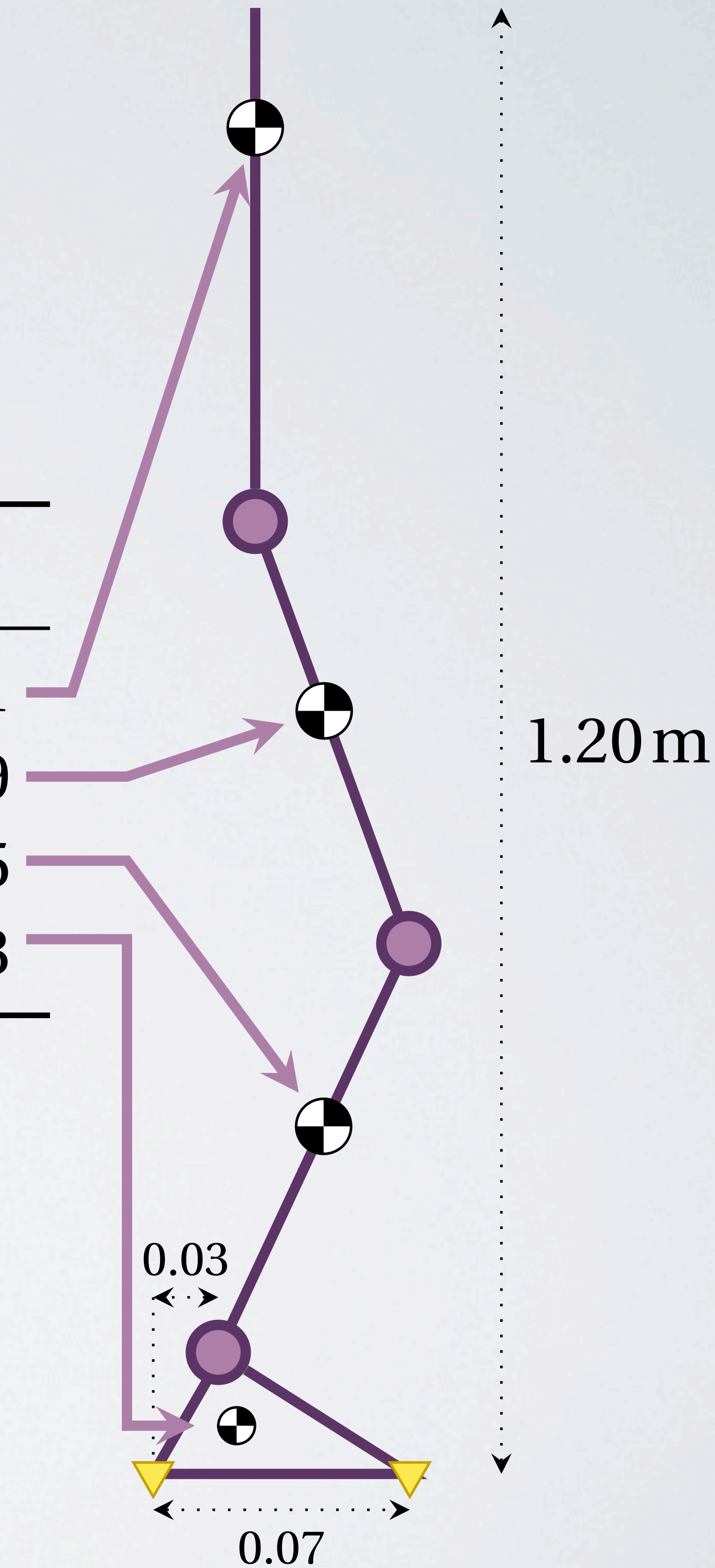


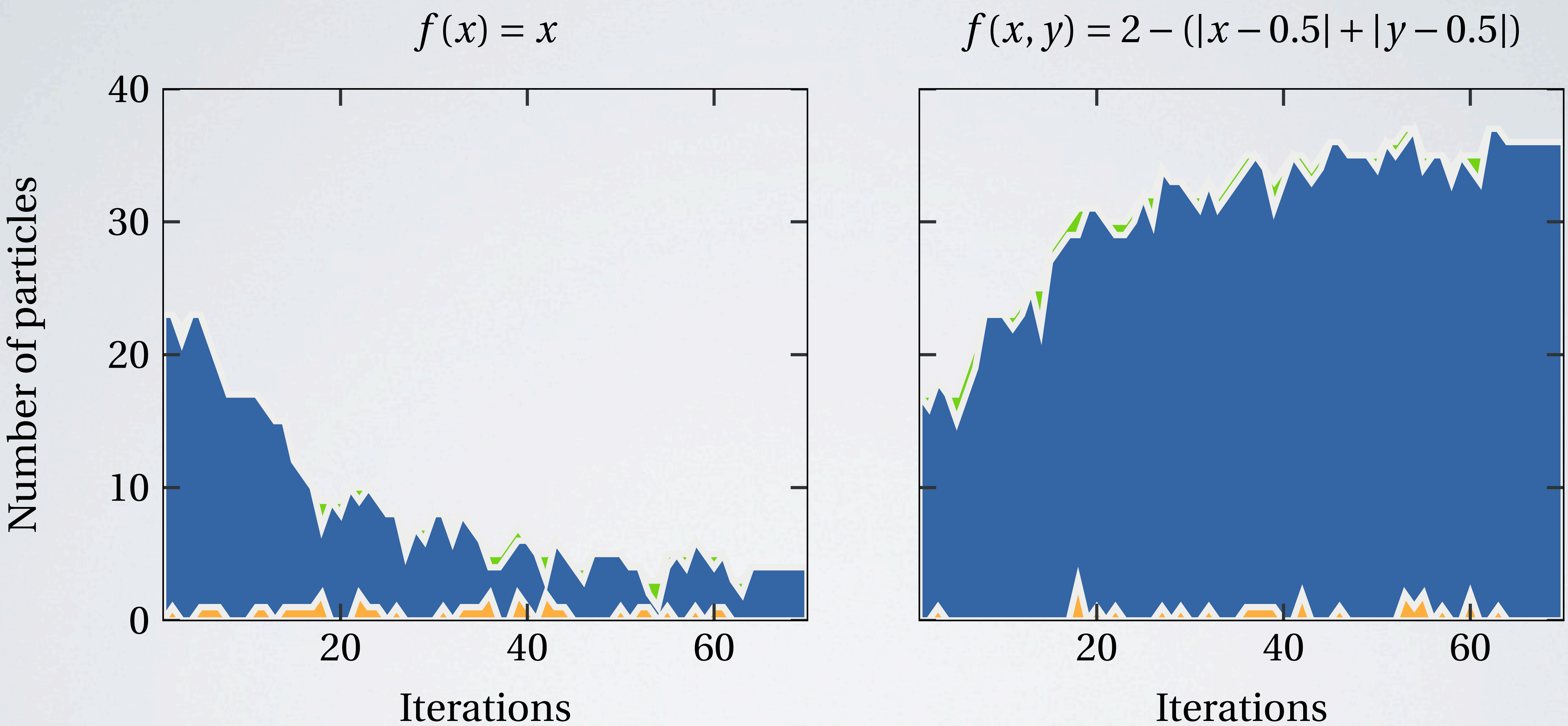

100
80
60
40
20
0
Stiffness (N m rad^{-1})
0
20
40
60
80
100
Gait Cycle (%)
τ_1
k_h^1
δx_h^3
y_h^3
k_h

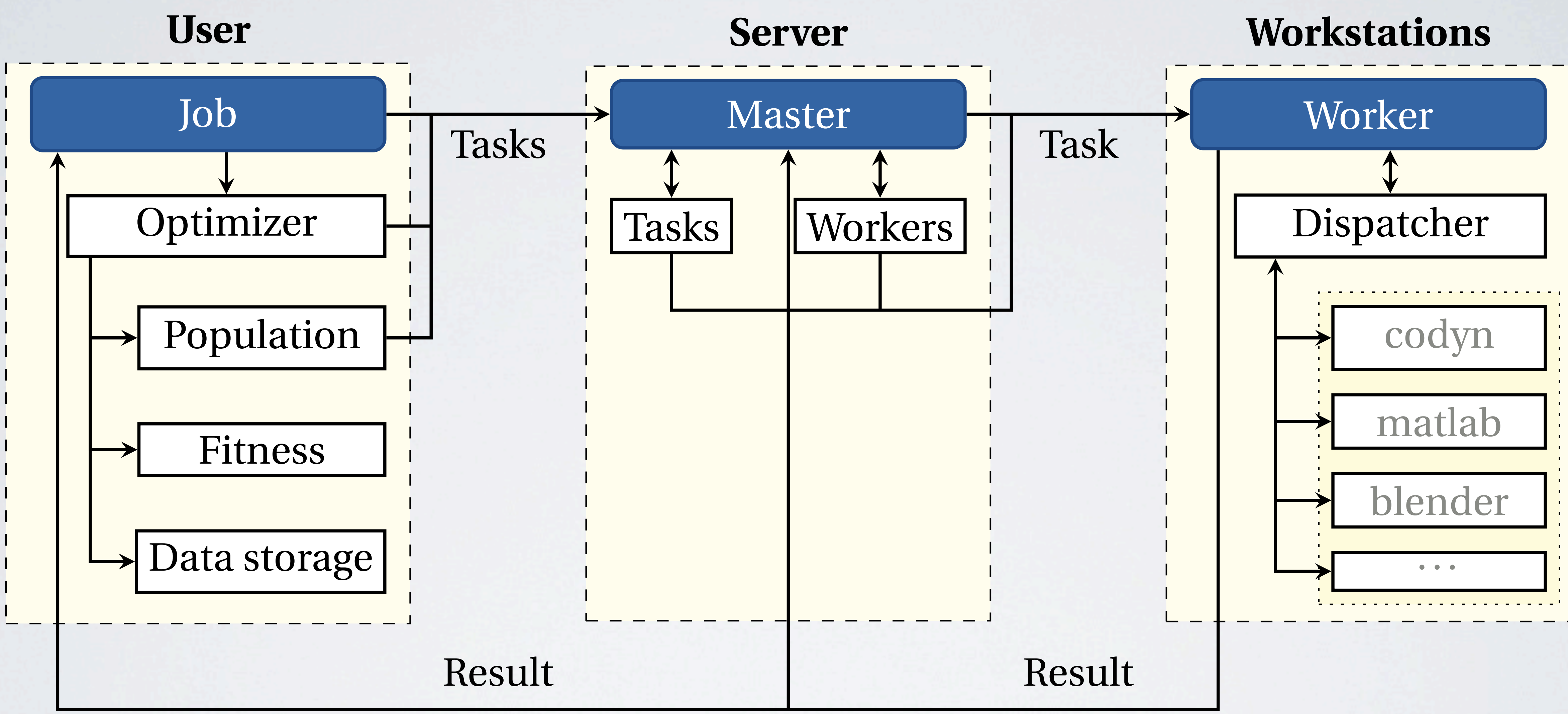

Nominal Gait Trajectories
Hip
Knee
Ankle
Joint Angle (°)
Gait Cycle (%)
80
60
40
20
0
−20
0
20
40
60
80
100



Joint	CoM_x	CoM_y	l	m	r_g
torso	0.00	0.18	$n.a$	0.530	0.11
up leg	0.00	−0.08	0.19	0.132	0.09
low leg	0.00	−0.07	0.17	0.052	0.05
ankle	0.00	−0.02	0.08	0.051	0.03




f(x) = x
f(x, y) = 2 − (|x − 0.5| + |y − 0.5|)
Number of particles
0
10
20
30
40
20
40
60
Iterations
Iterations


User
Server
Workstations
Job
Optimizer
Population
Fitness
Data storage
Tasks
Master
Tasks
Workers
Task
Worker
Dispatcher
codyn
matlab
blender
...
Result
Result