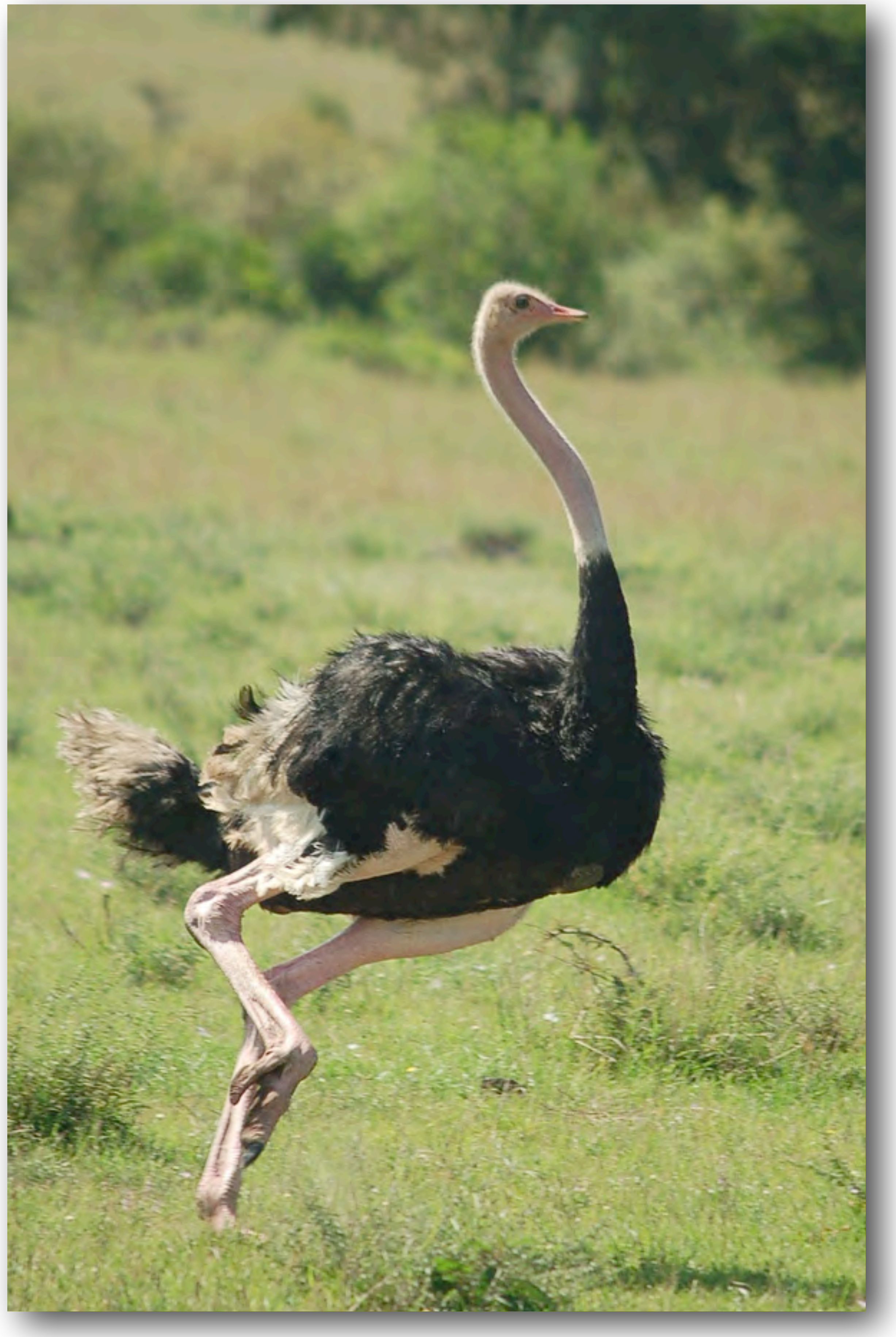
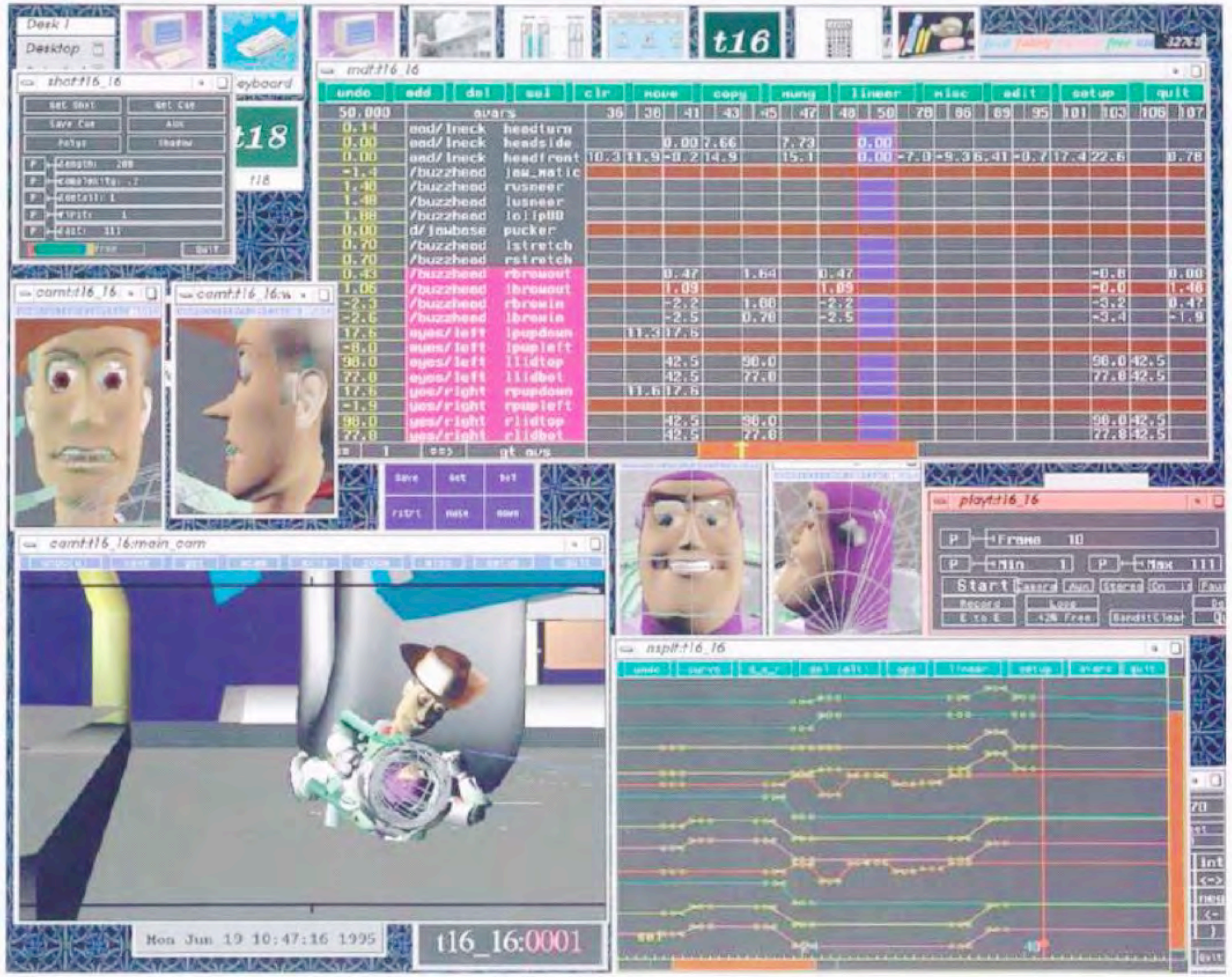
Biomechanics for Computer Animation and Vision

Aaron Hertzmann
Adobe Research







Keyframing

Motion capture

Half-Life 2 cap from Marco da Silva’s webpage

Brand and Hertzmann, SIGGRAPH 2000


It might
look goofy ...

Why care about physics in animation and vision?

Create realistic motion

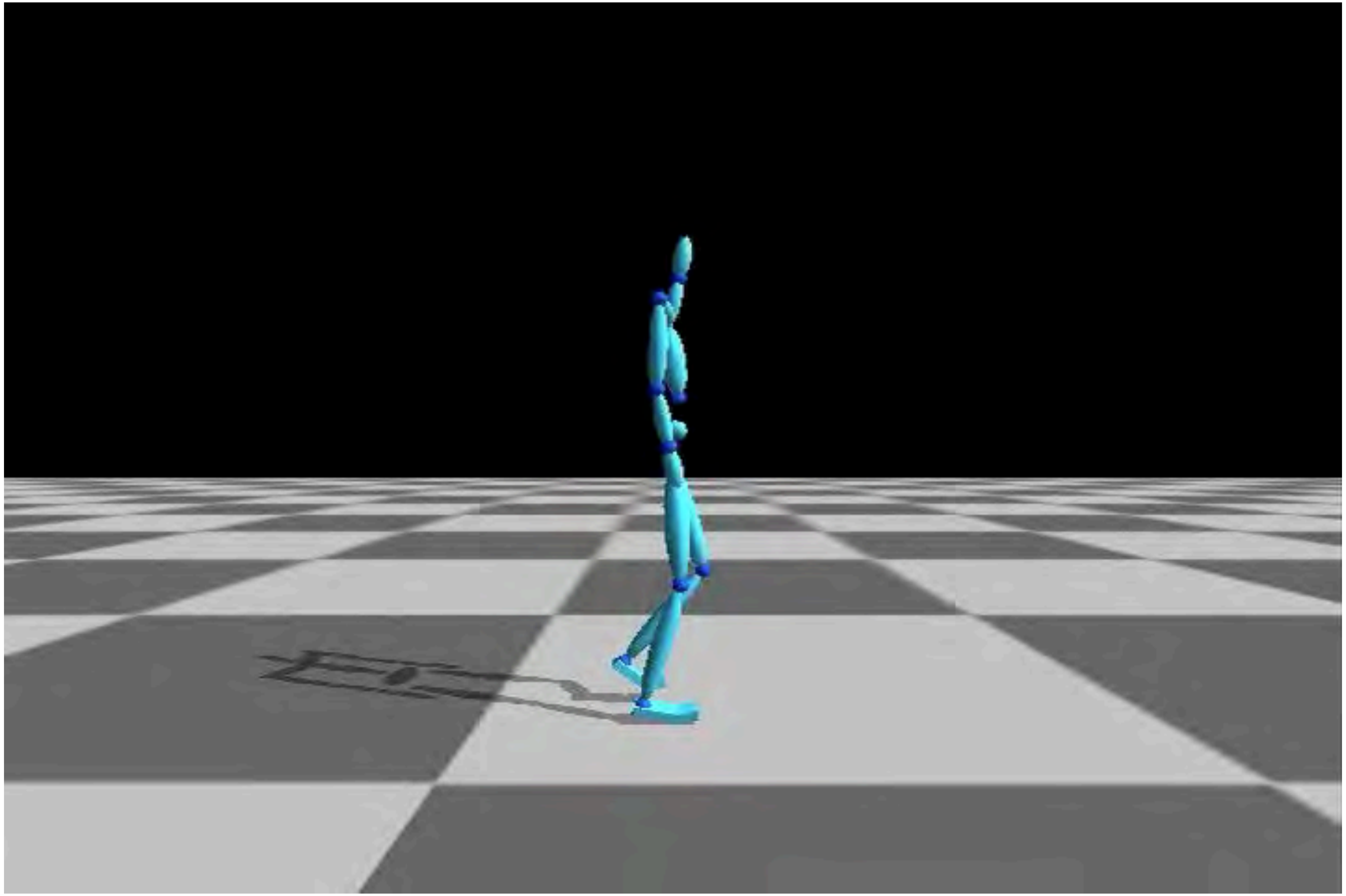
Generalize from small datasets

Understand how to evaluate results

Natural parameterization for style

Artificial creatures

The problem of control



Not covered today

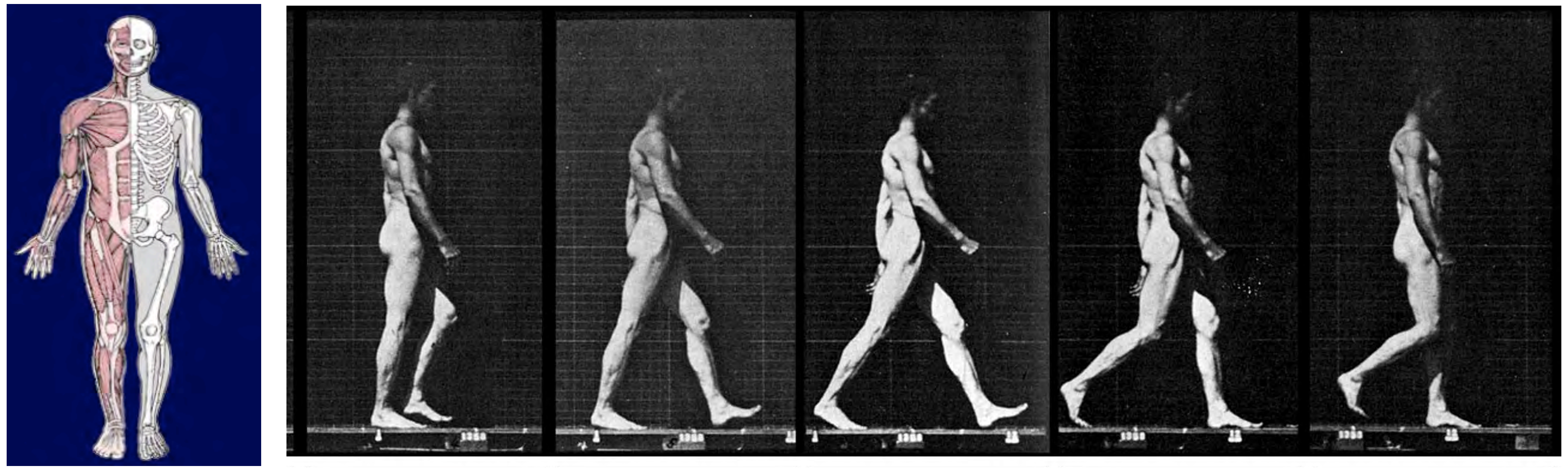
Physics/Mechanics

Simulation algorithms

Optimization algorithms

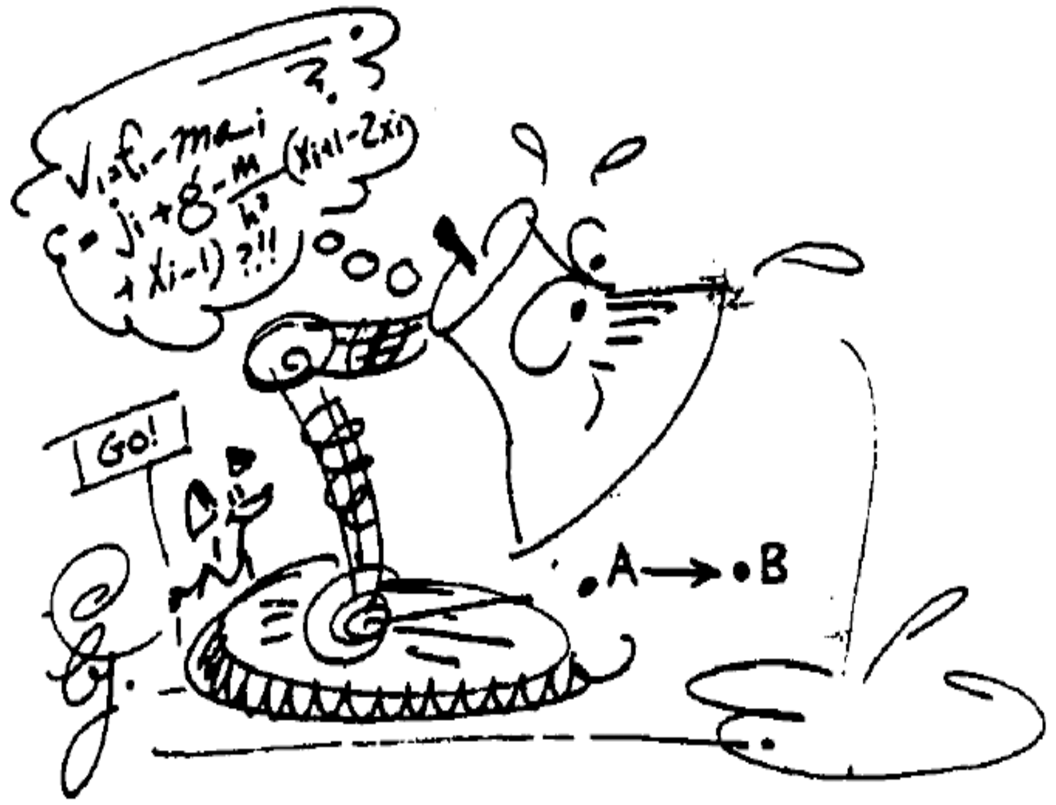
Learning algorithms

Outline



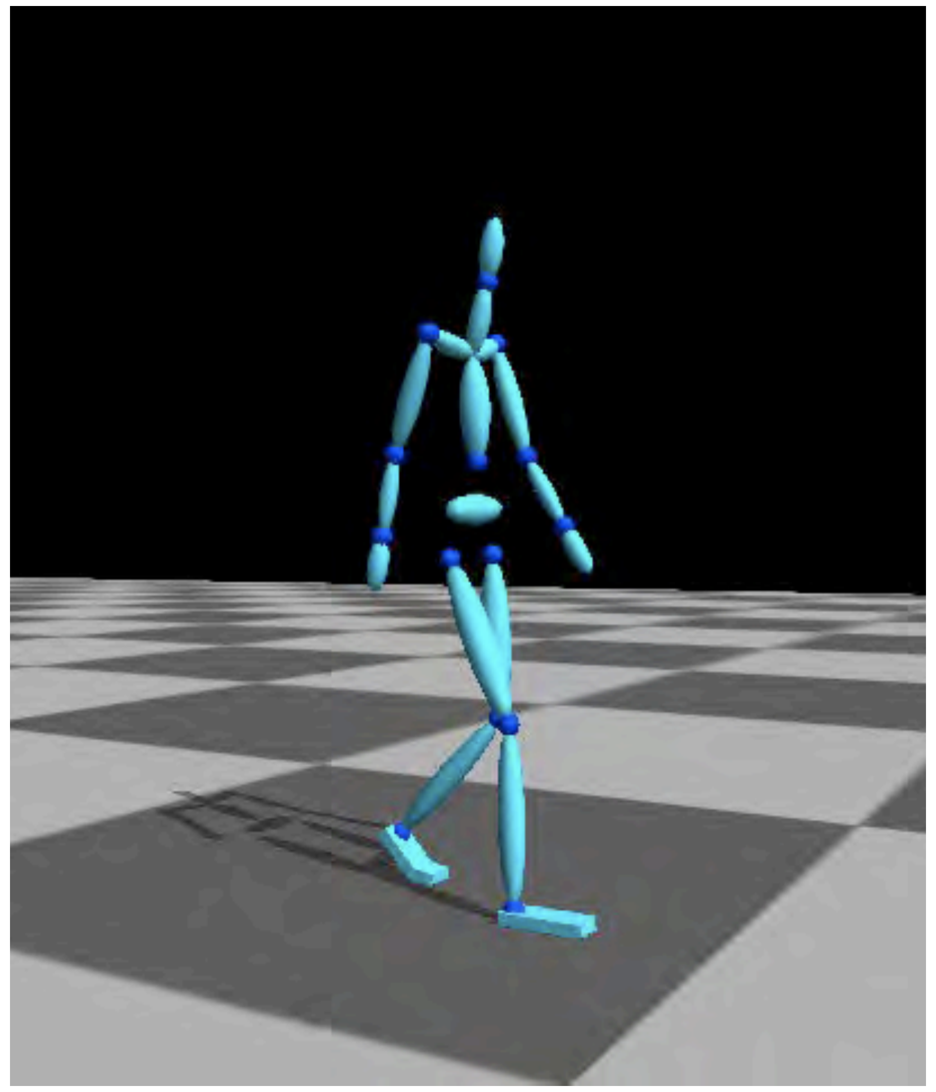
Basics of body and gait

Ballistic motion and balance



Optimality

Simplified models



Controllers

Basics of body and gait

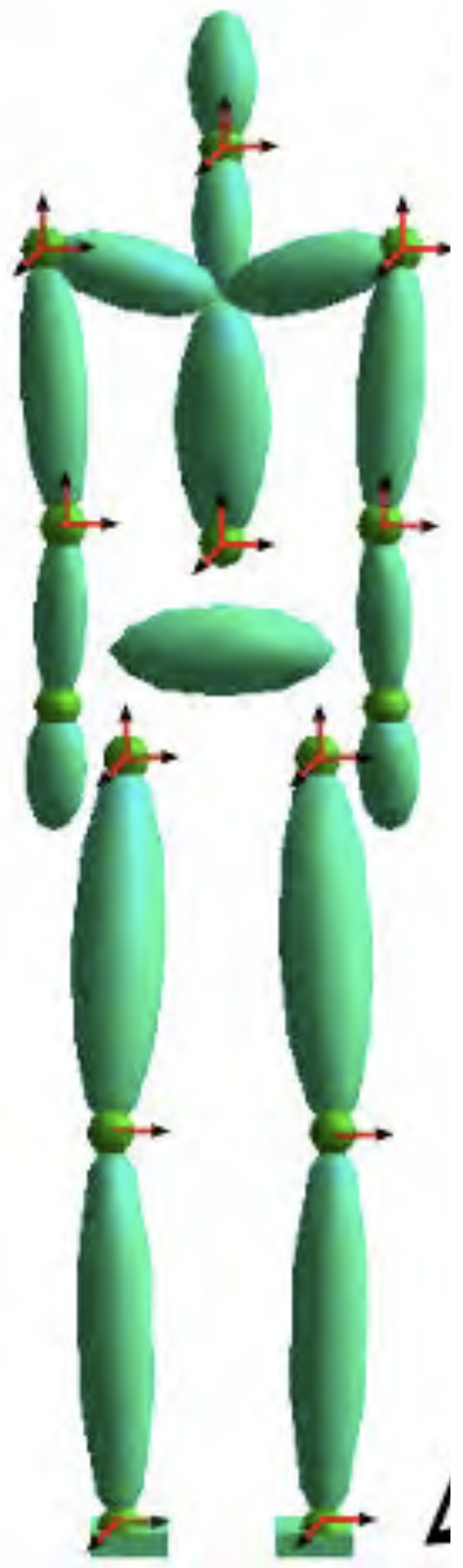
Kinematics

Degrees-of-Freedom (DOFs):

- Root position (XYZ)
- Root orientation (3D)
- Joint angles (up to 3D each)

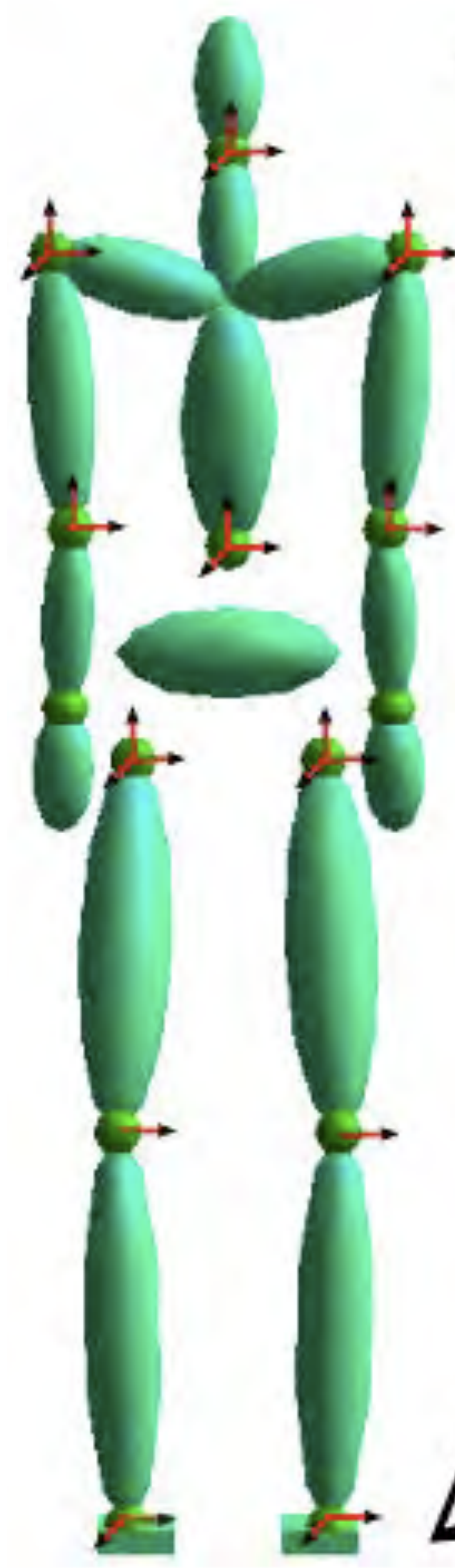
Generalized coordinates:

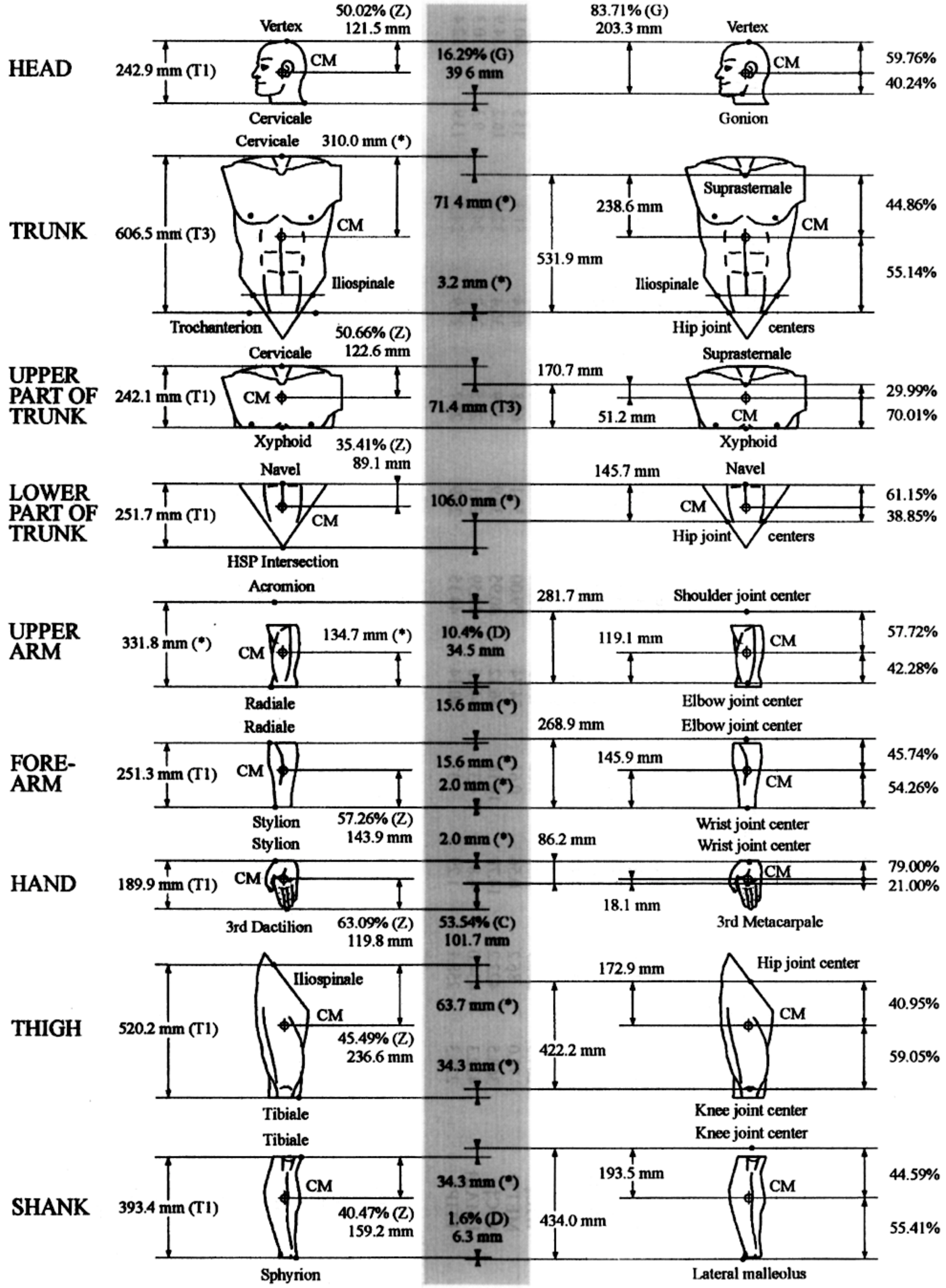
$$\mathbf{q} = [x, y, z, \theta_1, \theta_2, ..., \theta_N]^T$$



Skeleton and mass parameters

[P. de Leva 1996]

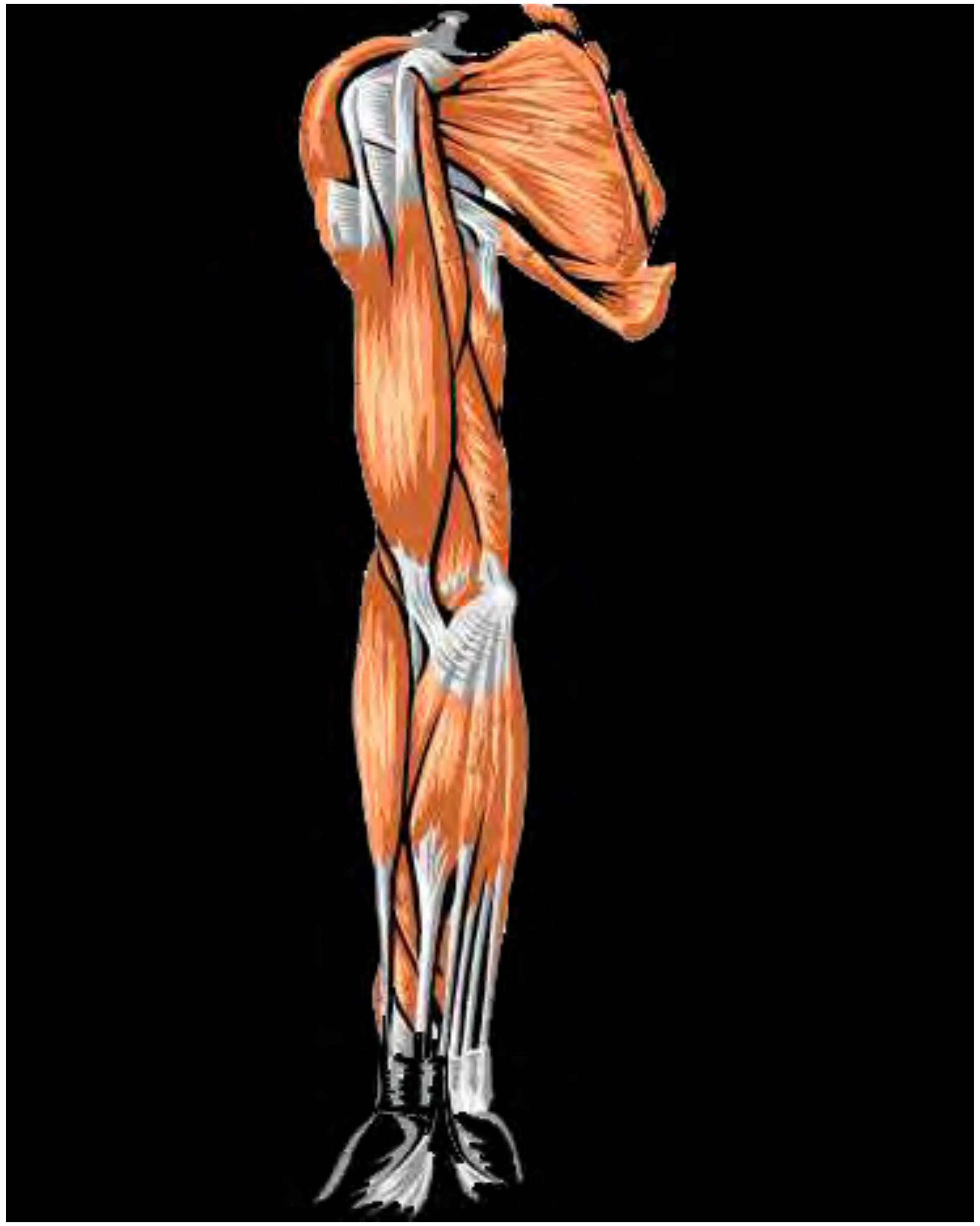




Muscles

Supply active torques

Simple model: just add torque at joints



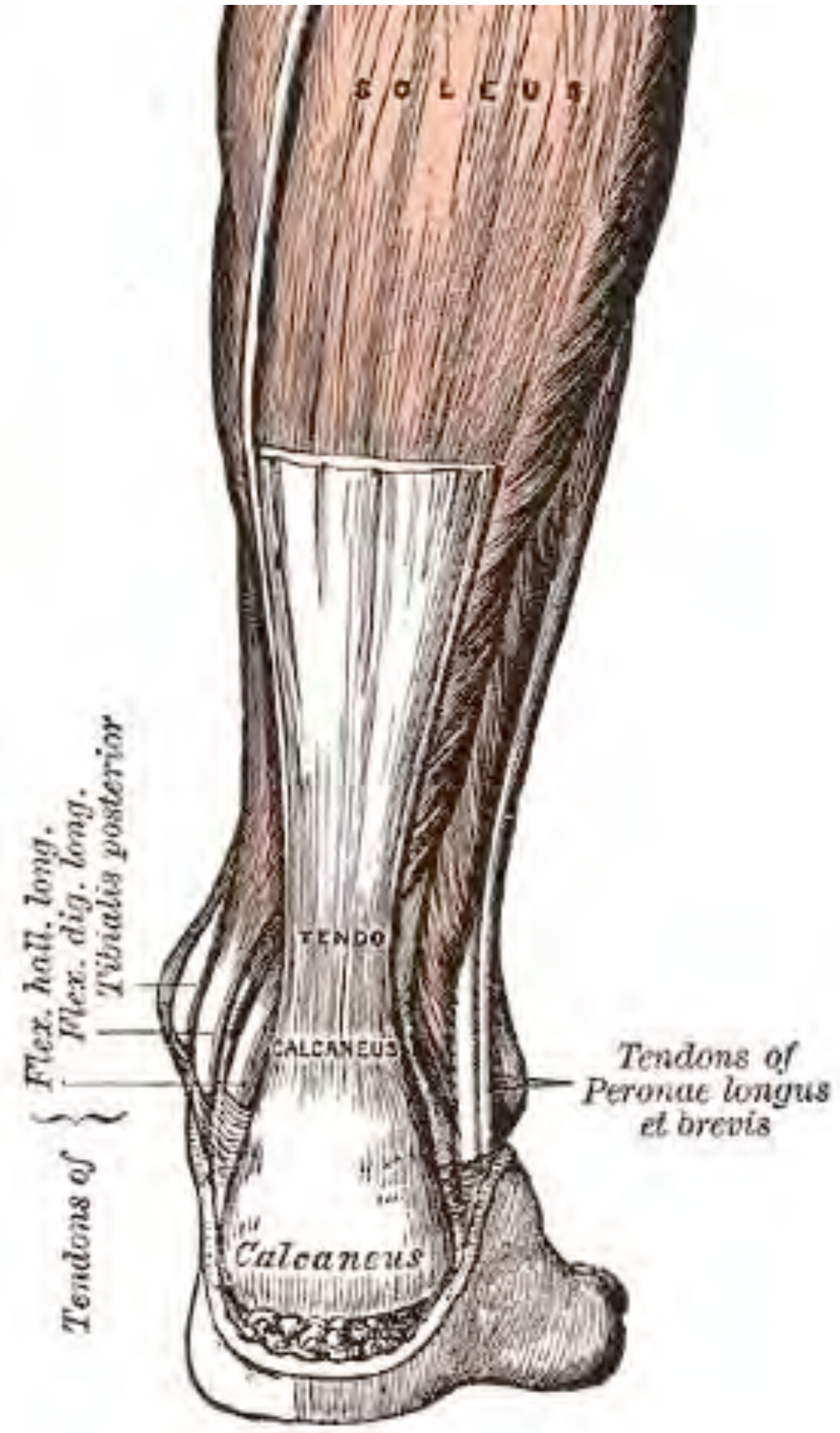
Passive elements

Tendon: connects muscle to bone

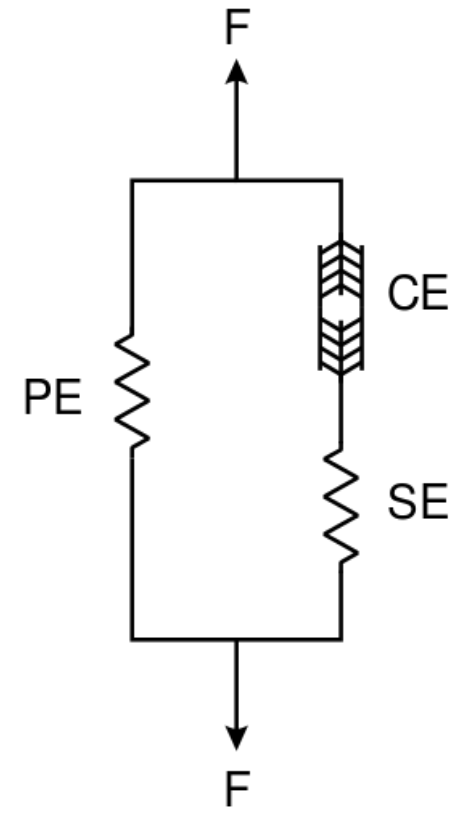
Ligaments: connect bone to bone

Fascia: connect muscle to muscle

Passive elements store 20-30% of energy during running

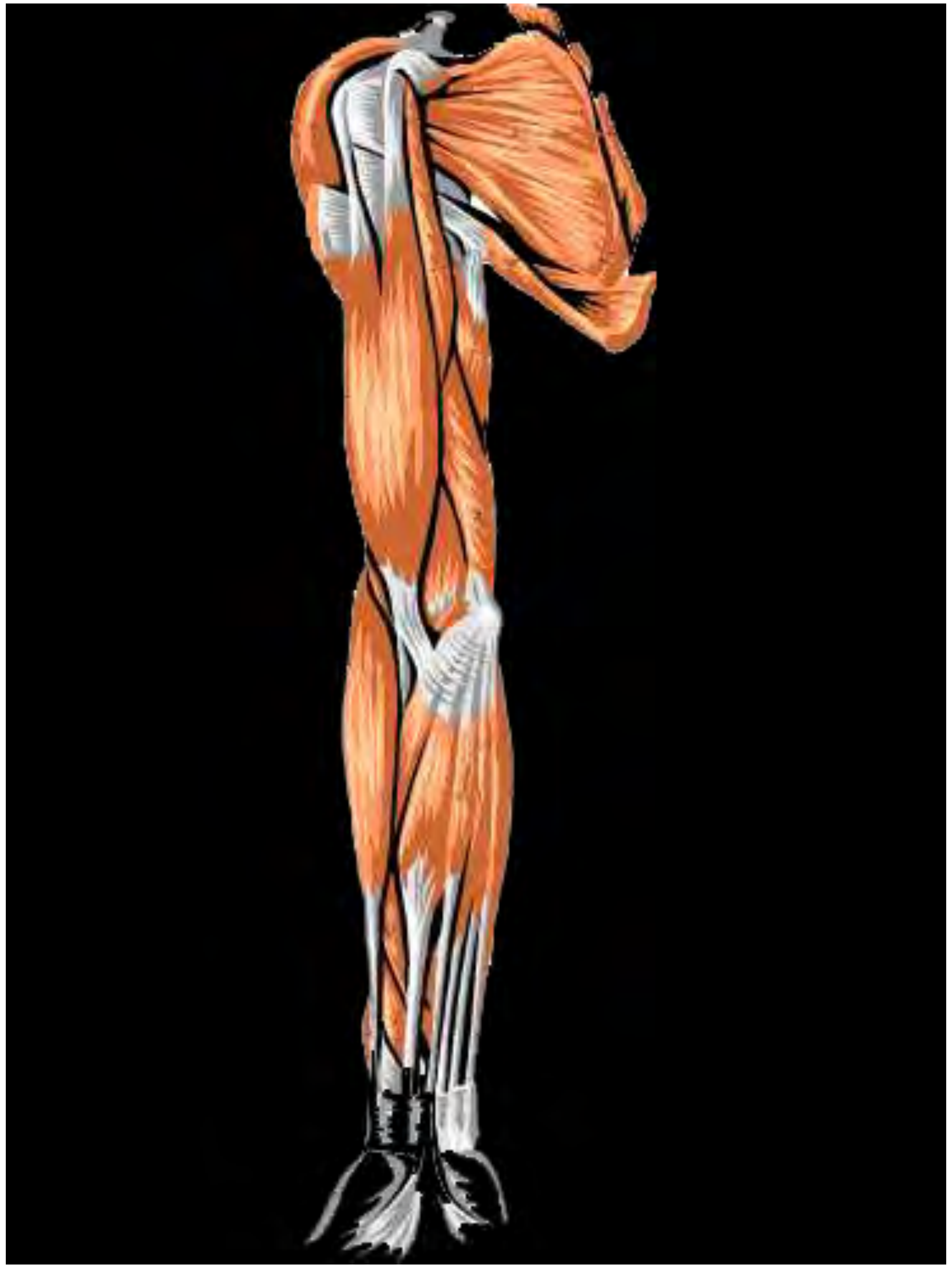


Hill model

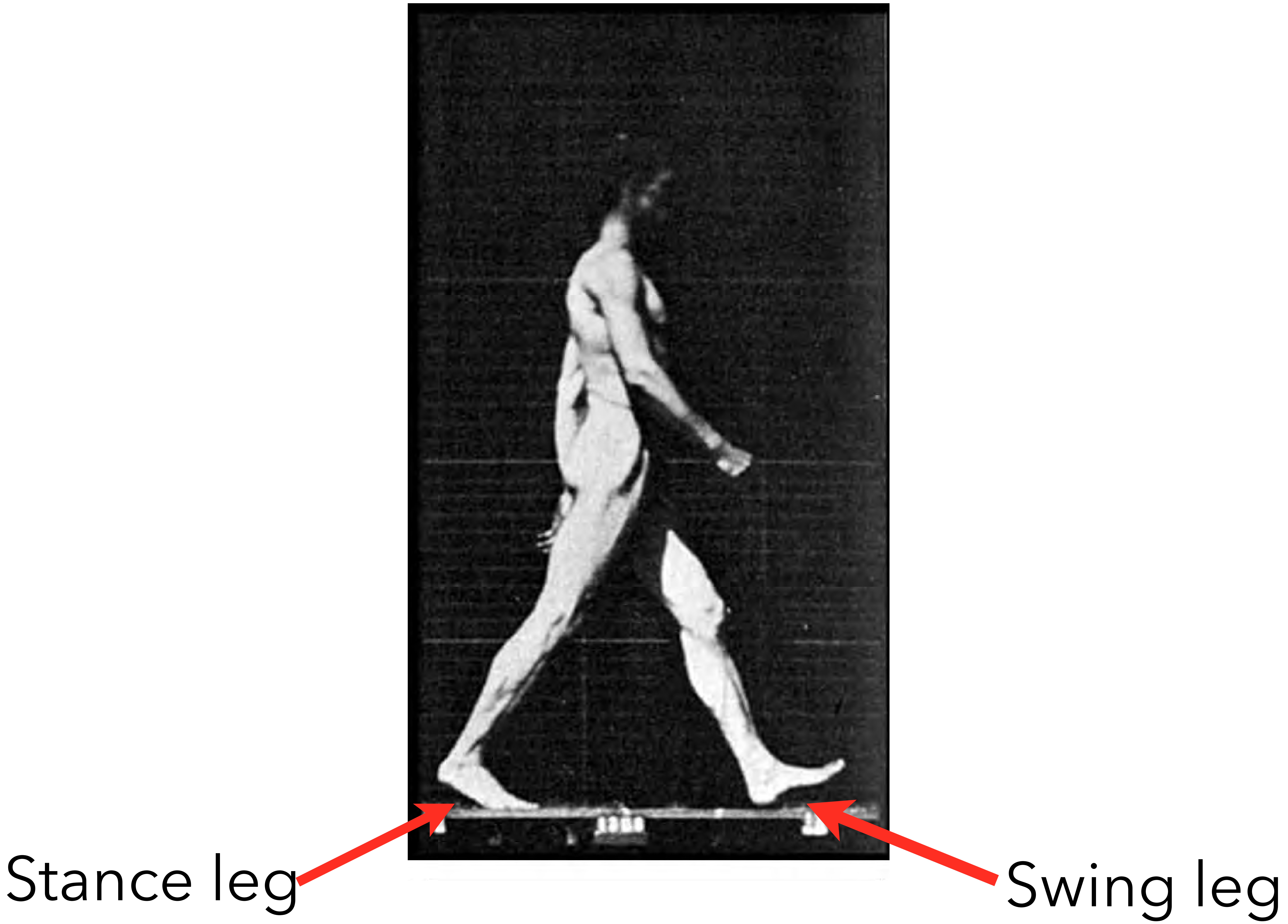


Agonist and antagonist muscles

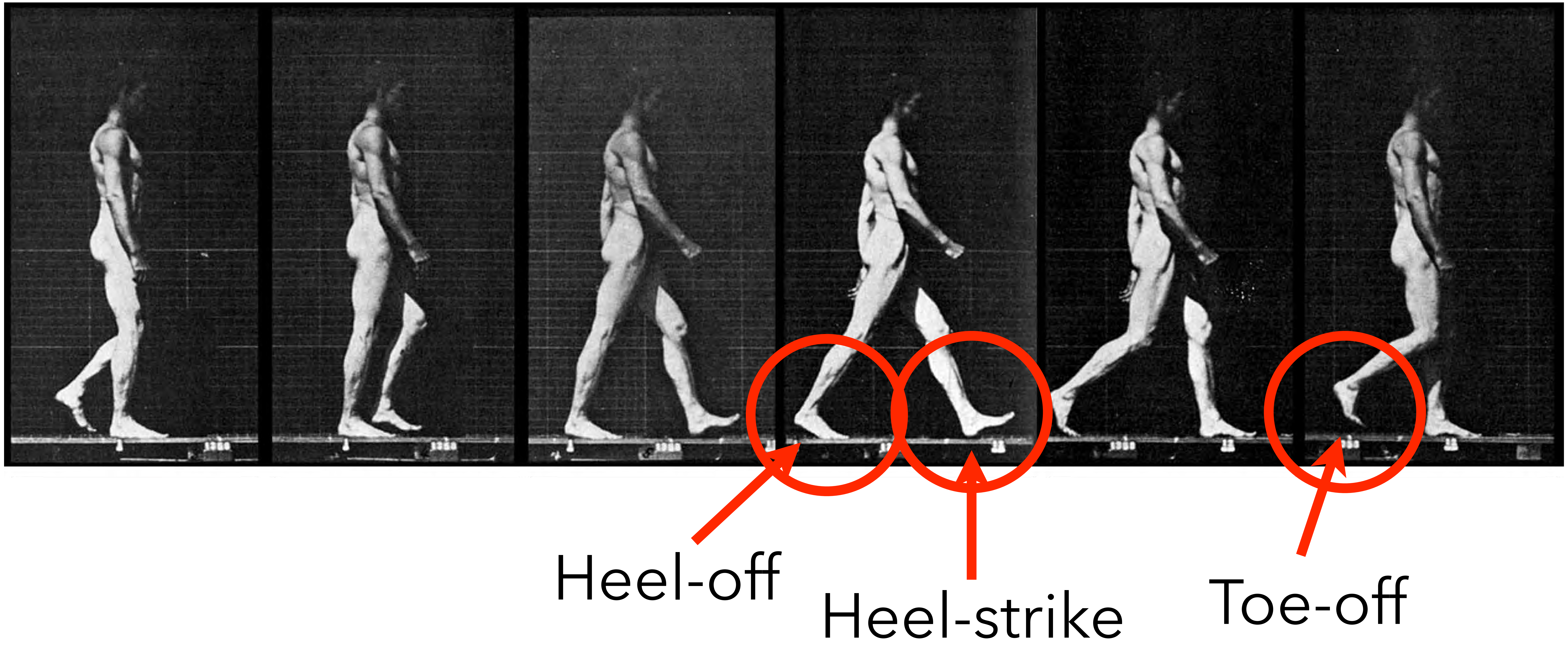
Tension level affects style [Neff 2002]

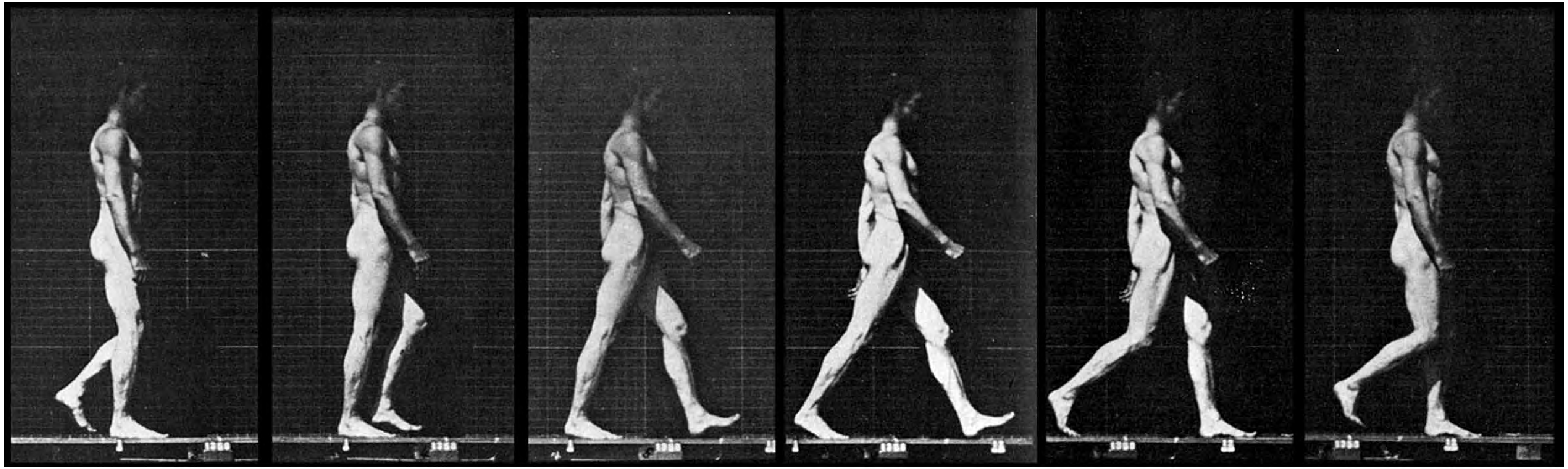


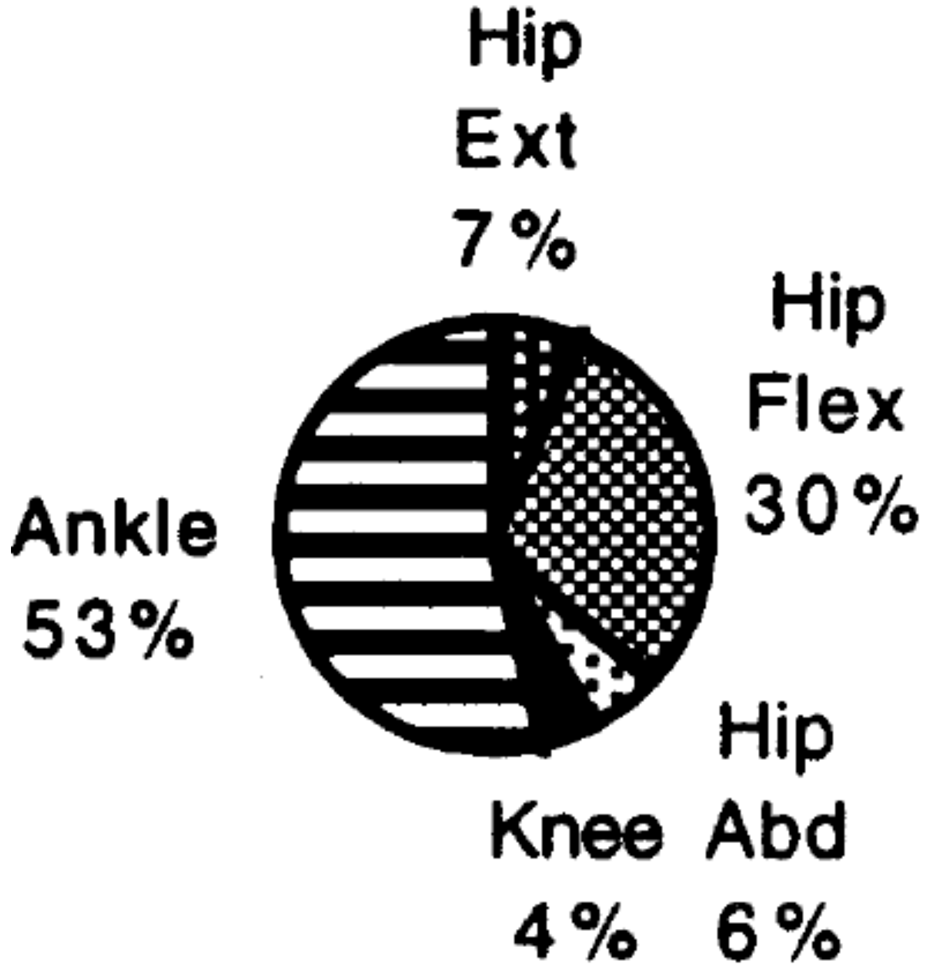
In walking, when your foot hits the ground, does the front or back hit first?



[Muybridge 1887]


Heel-off
Heel-strike
Toe-off





[Novacheck 1998]

MENU

nature
International journal of science

Letter | Published: 27 January 2010

Foot strike patterns and collision forces in habitually barefoot versus shod runners

Daniel E. Lieberman, Madhusudhan Venkadesan, William A. Werbel, Adam I. Daoud, Susan D'Andrea, Irene S. Davis, Robert Ojiambo Mang'Eni & Yannis Pitsiladis

Nature **463**, 531–535 (28 January 2010) | Download Citation

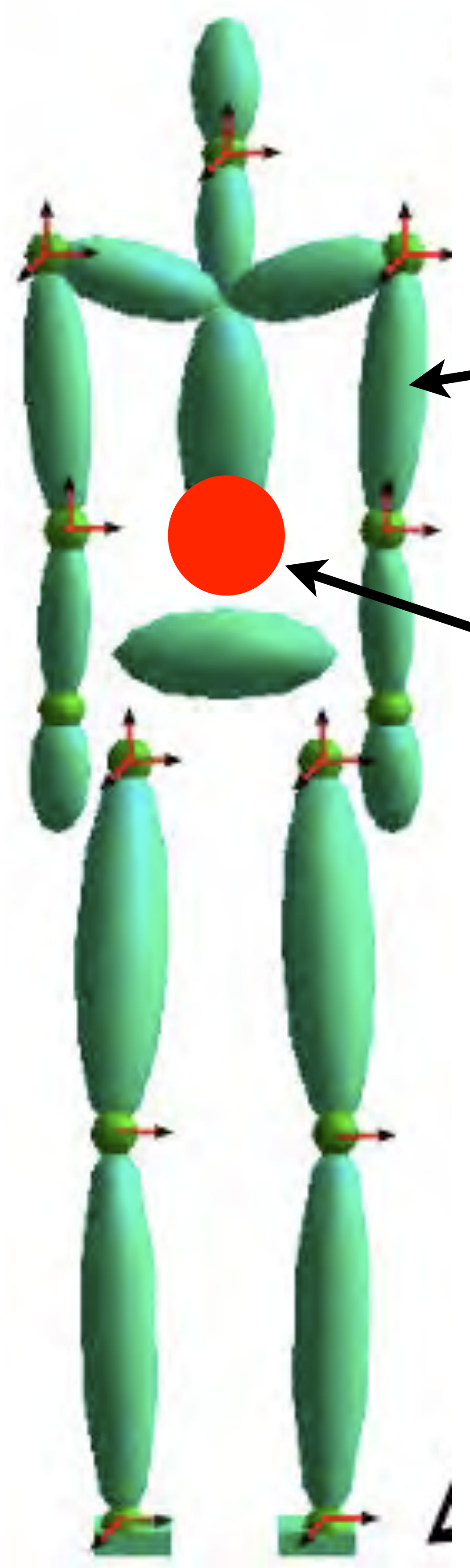
Abstract

Humans have engaged in endurance running for millions of years[1], but the modern running shoe was not invented until the 1970s. For most of

Ballistic Motion and Balance

Much of the analysis of locomotion and control is in terms of low-dimensional *features*

Center-of-mass (COM)



$\mathbf{x}_i$

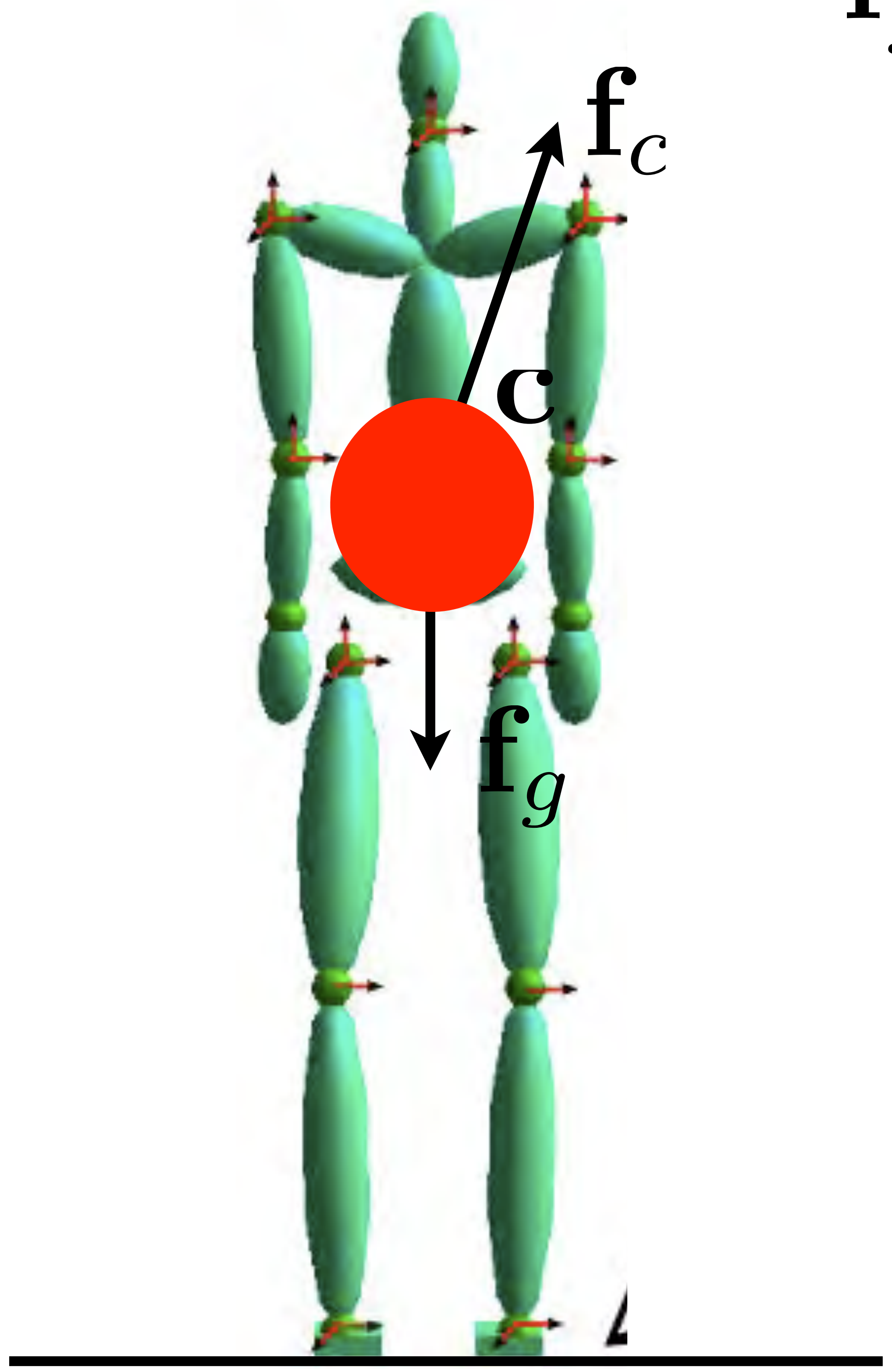
$$\mathbf{c} = \frac{\sum_i \mathbf{x}_i m_i}{\sum_i m_i}$$

COM motion

Newton's 2nd Law: $\mathbf{f} = m\ddot{\mathbf{x}}$

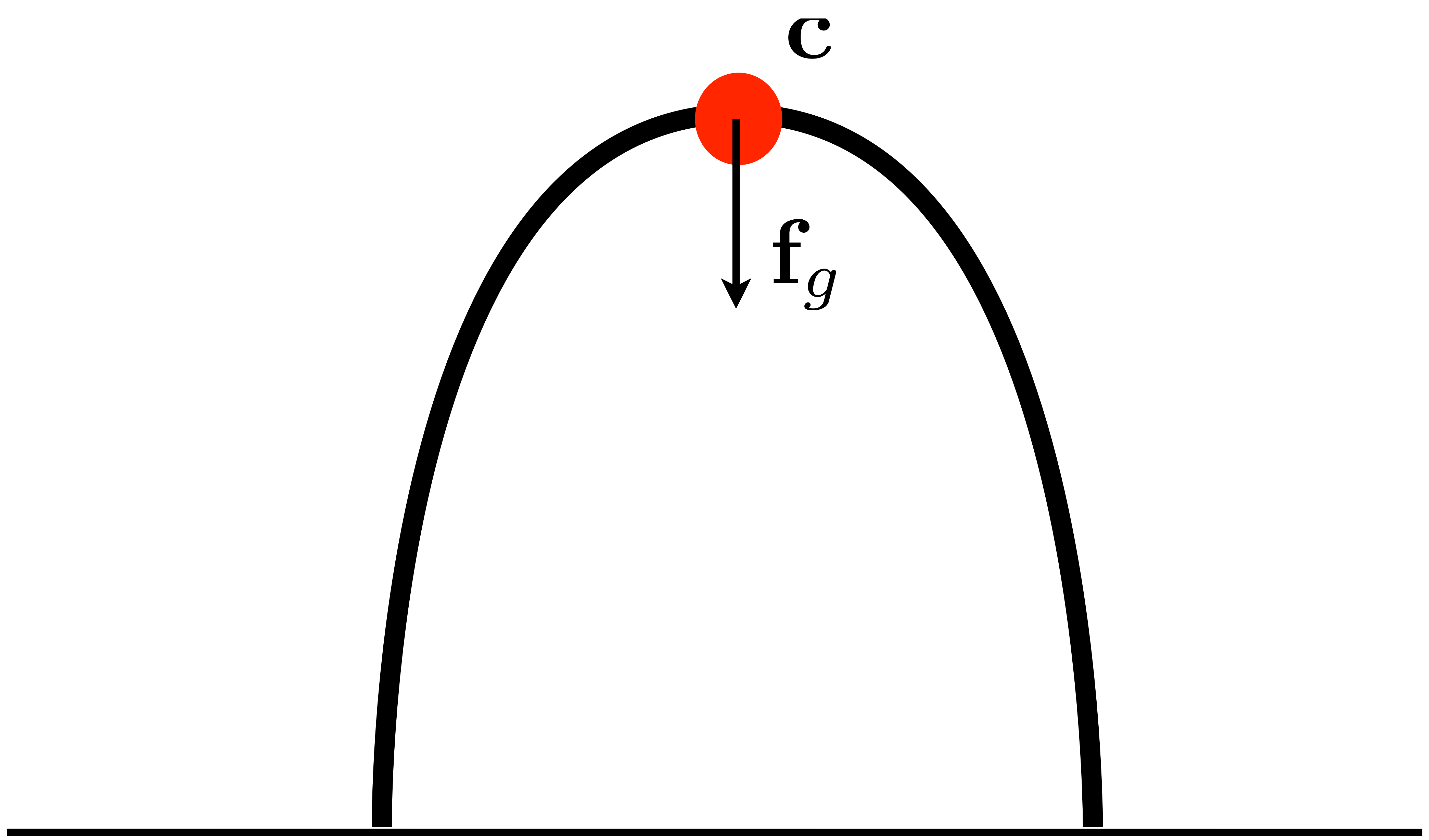
$$\mathbf{f} = m\ddot{\mathbf{c}} \qquad \mathbf{f} = \mathbf{f}_g + \mathbf{f}_c$$

$$\mathbf{f}_g = -mg\mathbf{u}$$



Ballistic motion

$$
\begin{aligned}
m\ddot{\mathbf{c}} &= \mathbf{f}_g \\
&= -mg\mathbf{u} \\
\ddot{\mathbf{c}} &= -g\mathbf{u}
\end{aligned}
$$

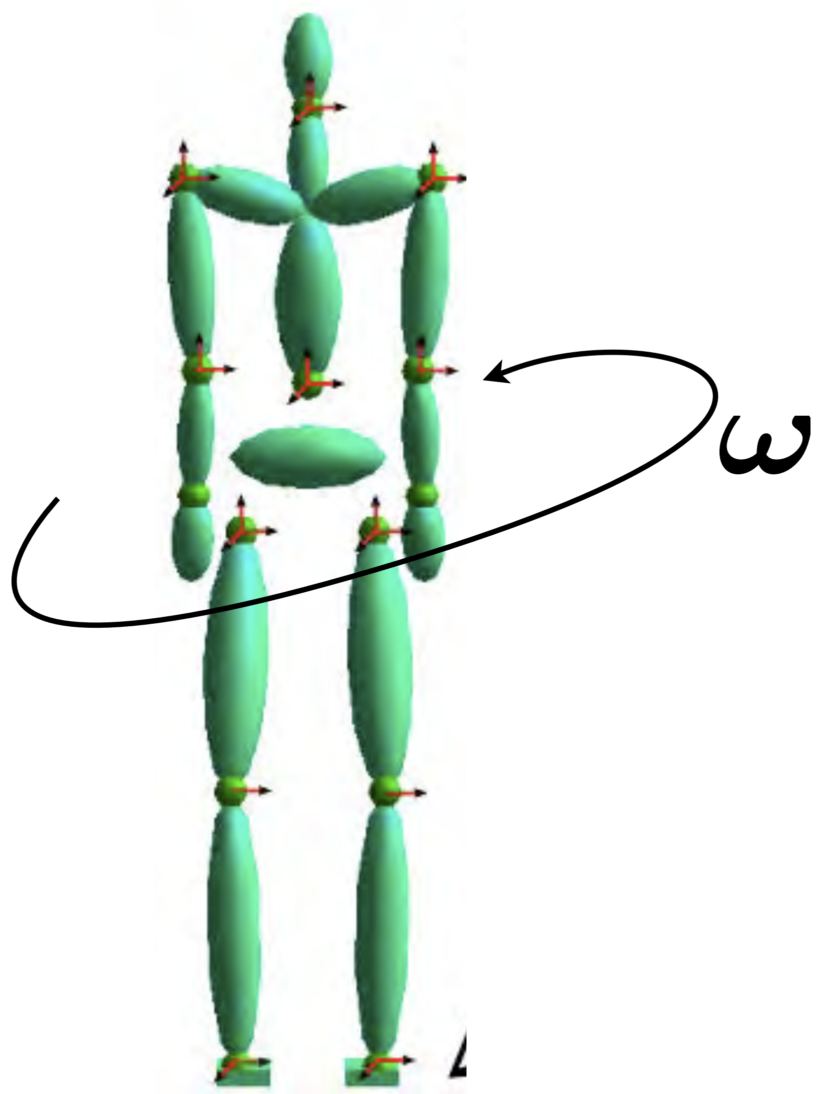


Hence, a character in flight must follow a parabolic arc.

Angular momentum

$$\boldsymbol{\tau} = \mathbf{I}\dot{\boldsymbol{\omega}}$$

$$\boldsymbol{\tau} = \boldsymbol{\tau}_c$$

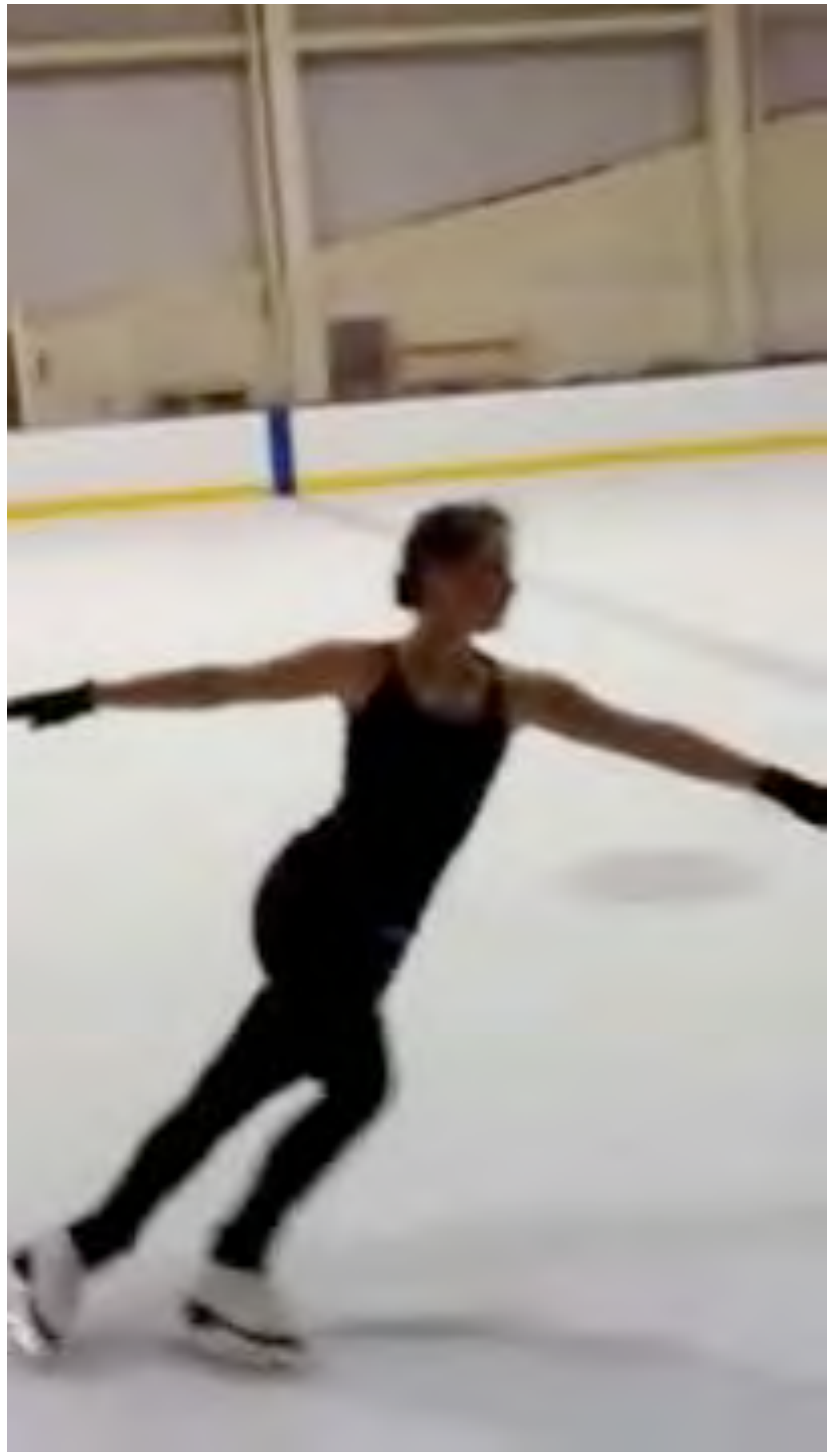


In ballistic motion, $\boldsymbol{\tau} = 0$

A character in flight has constant angular momentum.

$$\mathbf{L} = \mathbf{I}\omega$$

Conservation of Angular momentum



$$\mathbf{L} = \mathbf{I}\omega$$

$$\mathbf{I}_1\omega_1 = \mathbf{I}_2\omega_2$$

EXHIBITS

Bicycle Wheel Gyro

Let this gyroscope take you for a spin.

Tilt a spinning bicycle wheel while you're sitting in a swivel chair and—surprise—you'll start spinning in circles, too. You can also witness the same phenomenon here by hanging a spinning wheel from its axle.

Where: Crossroads: Getting Started
Exhibit Developers: Exploratorium Founder Frank Oppenheimer and Tom Tompkins, 1975

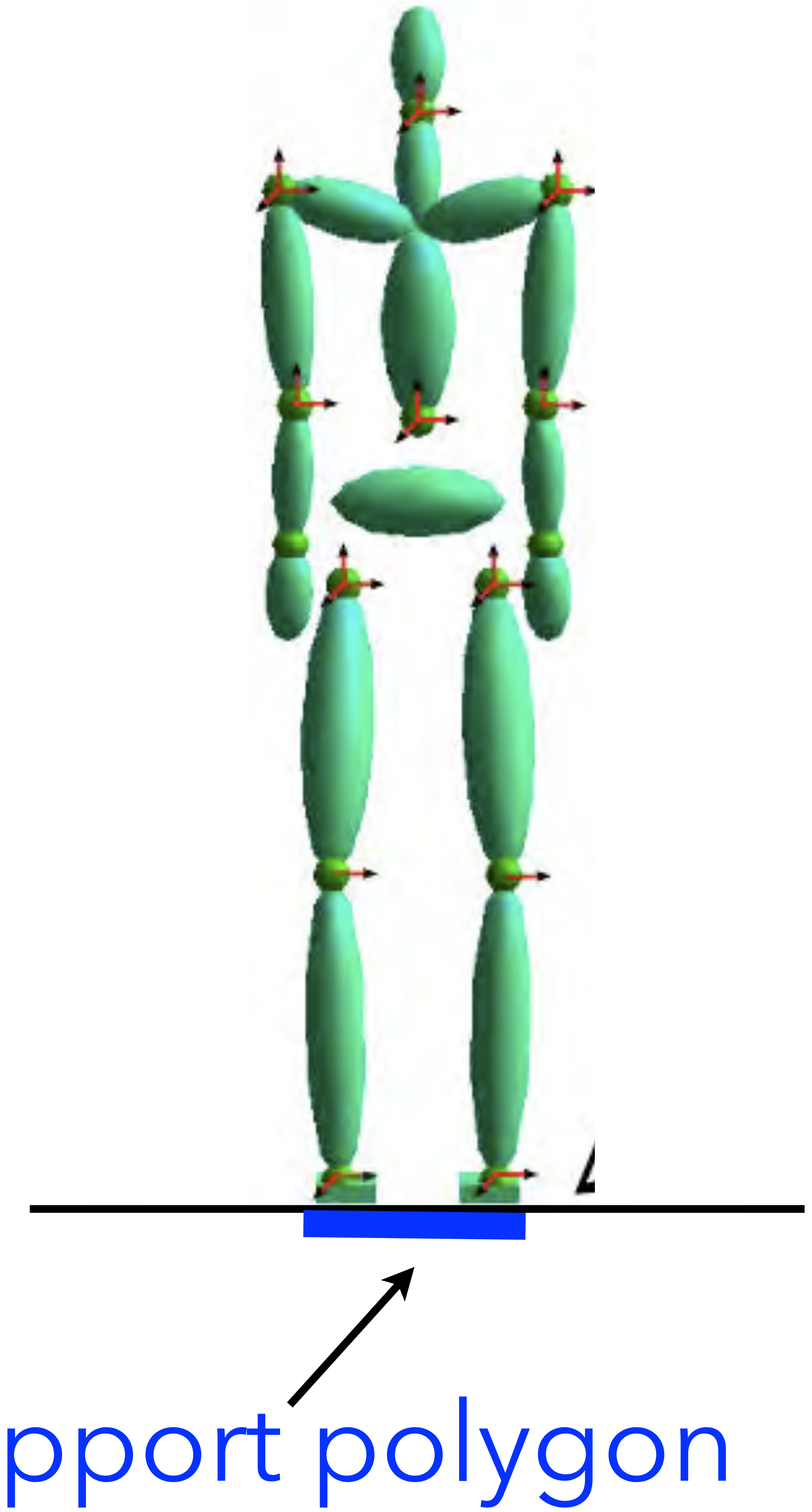
What's going on?

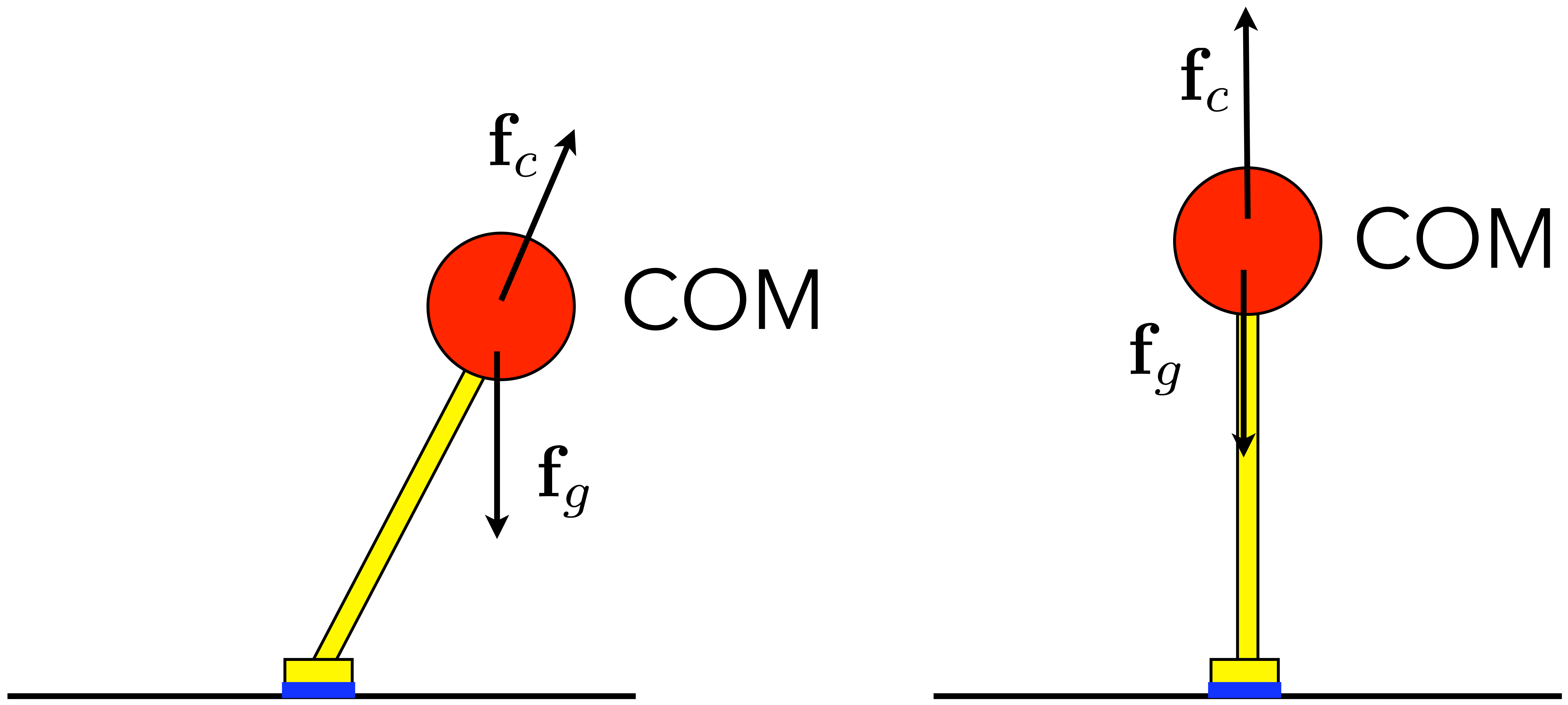
A spinning wheel has *angular momentum*, which gives it a natural tendency to keep spinning at the same speed in the same direction. When you tilt the gyroscope, you change its angular momentum. The spinning wheel resists this change, pushing back and causing you to spin in the chair.

Going further

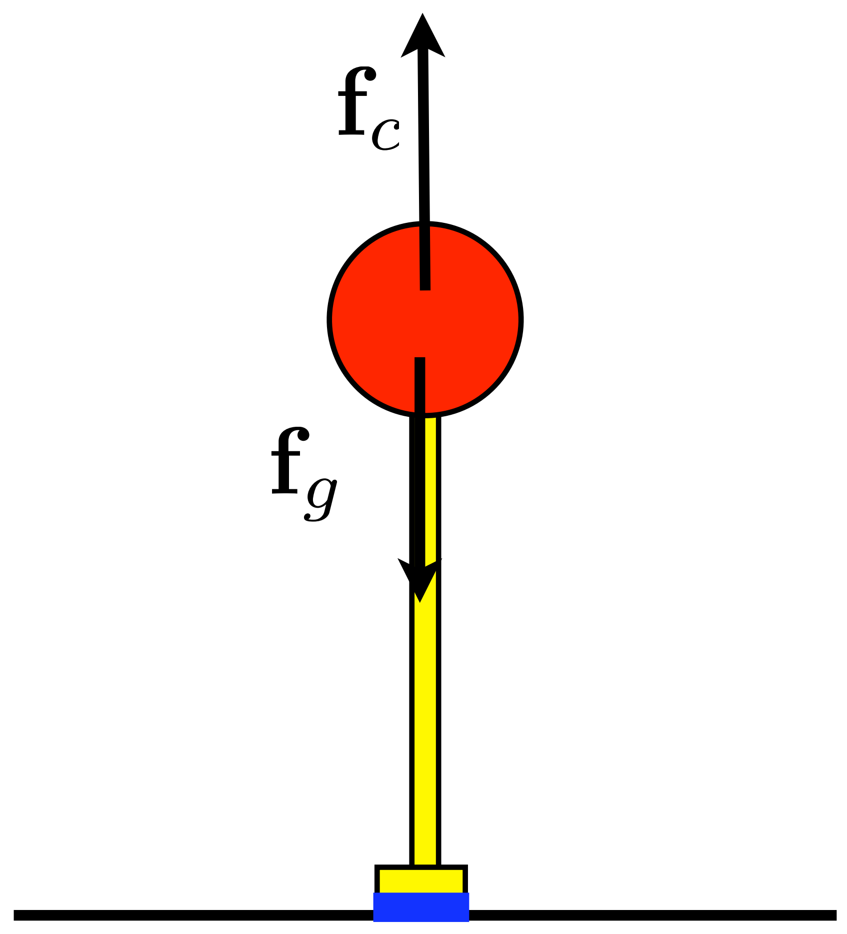
Spider-Man (2002)

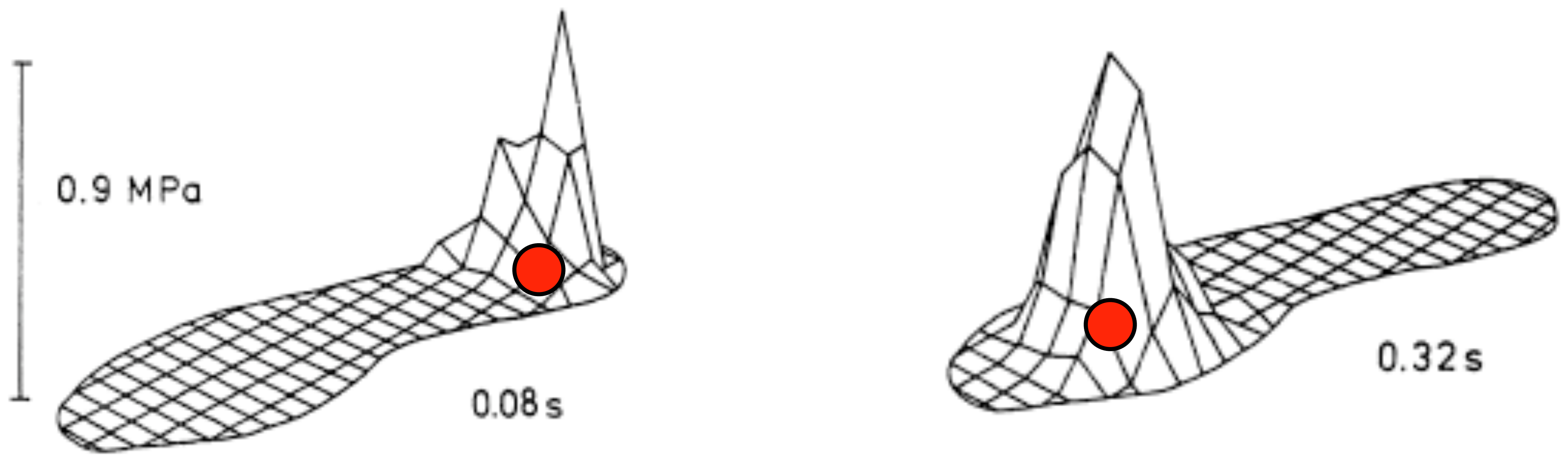
Balance





Keeping the COM over the support aids balance





Pressure

<u>Center-of-pressure (COP):</u>

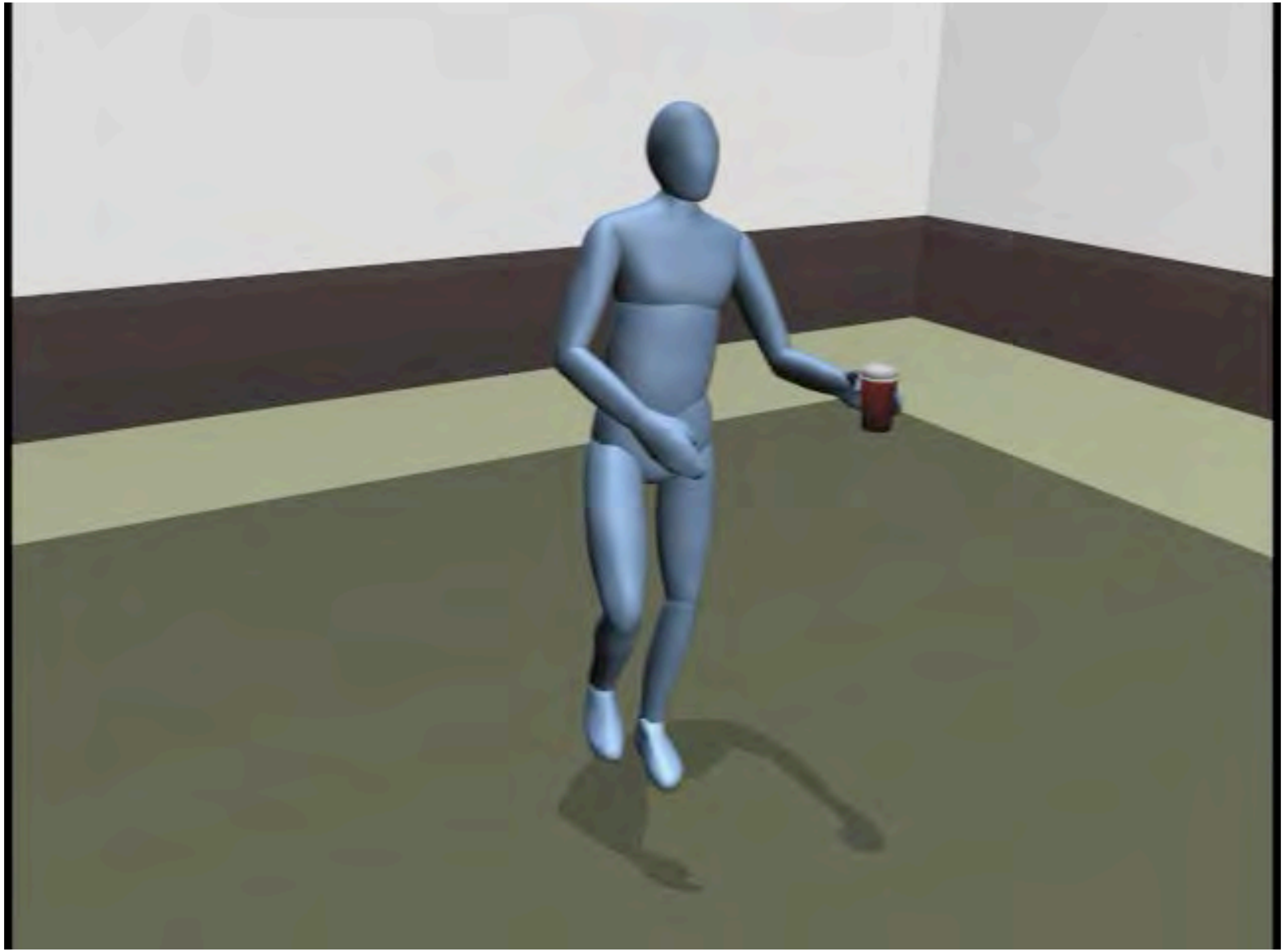
Weighted average position of forces on foot

If the COP reaches the edge of support, the body may tip

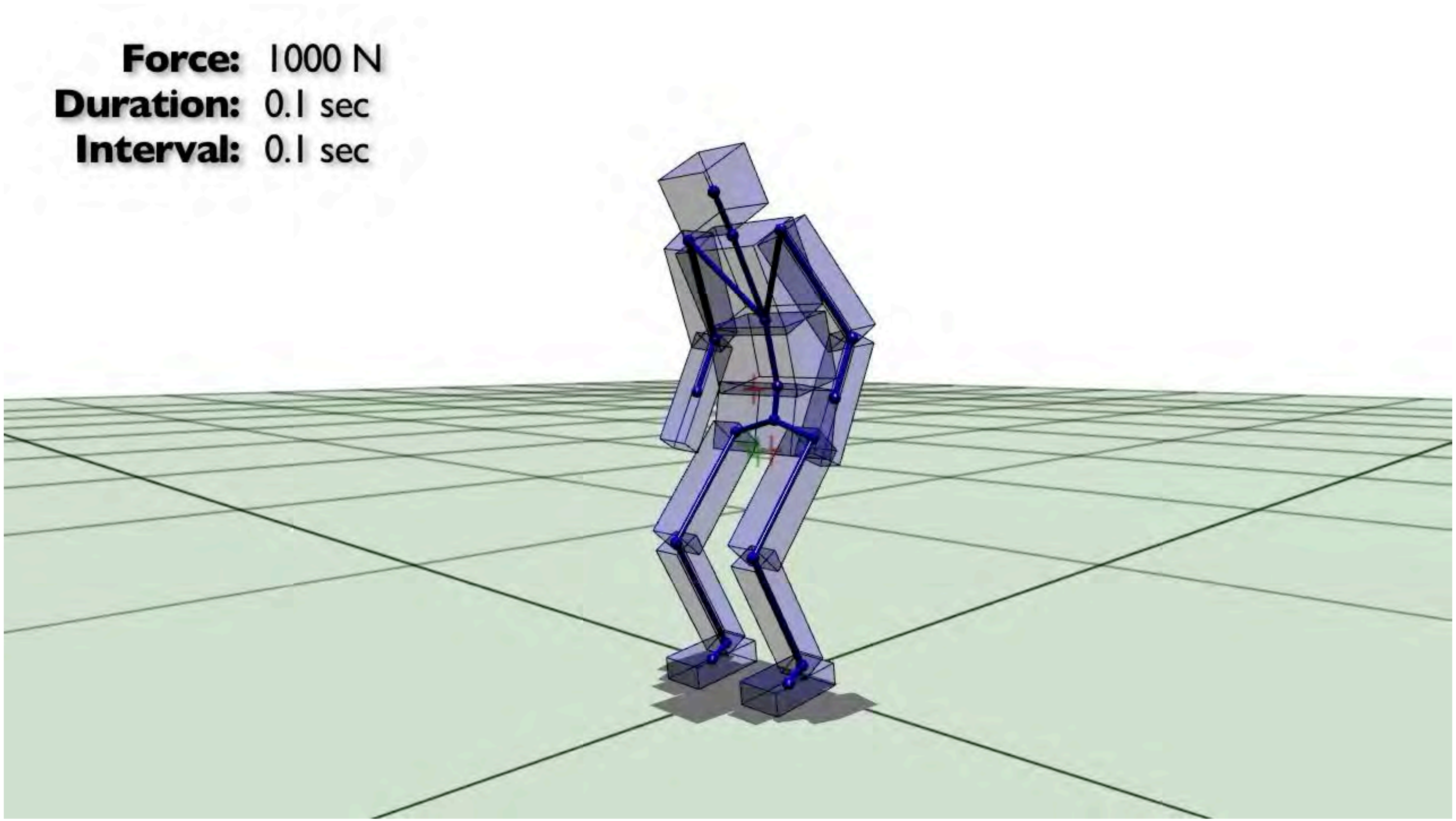
Kudoh et al. Dynamic Postural Adjustment. IROS 2002
Macchietto. Momentum Control for Balance. SIGGRAPH 2009

Balancing objective terms:

1. Keep COM above support
2. Regulate COP or angular momentum
3. Reach target pose

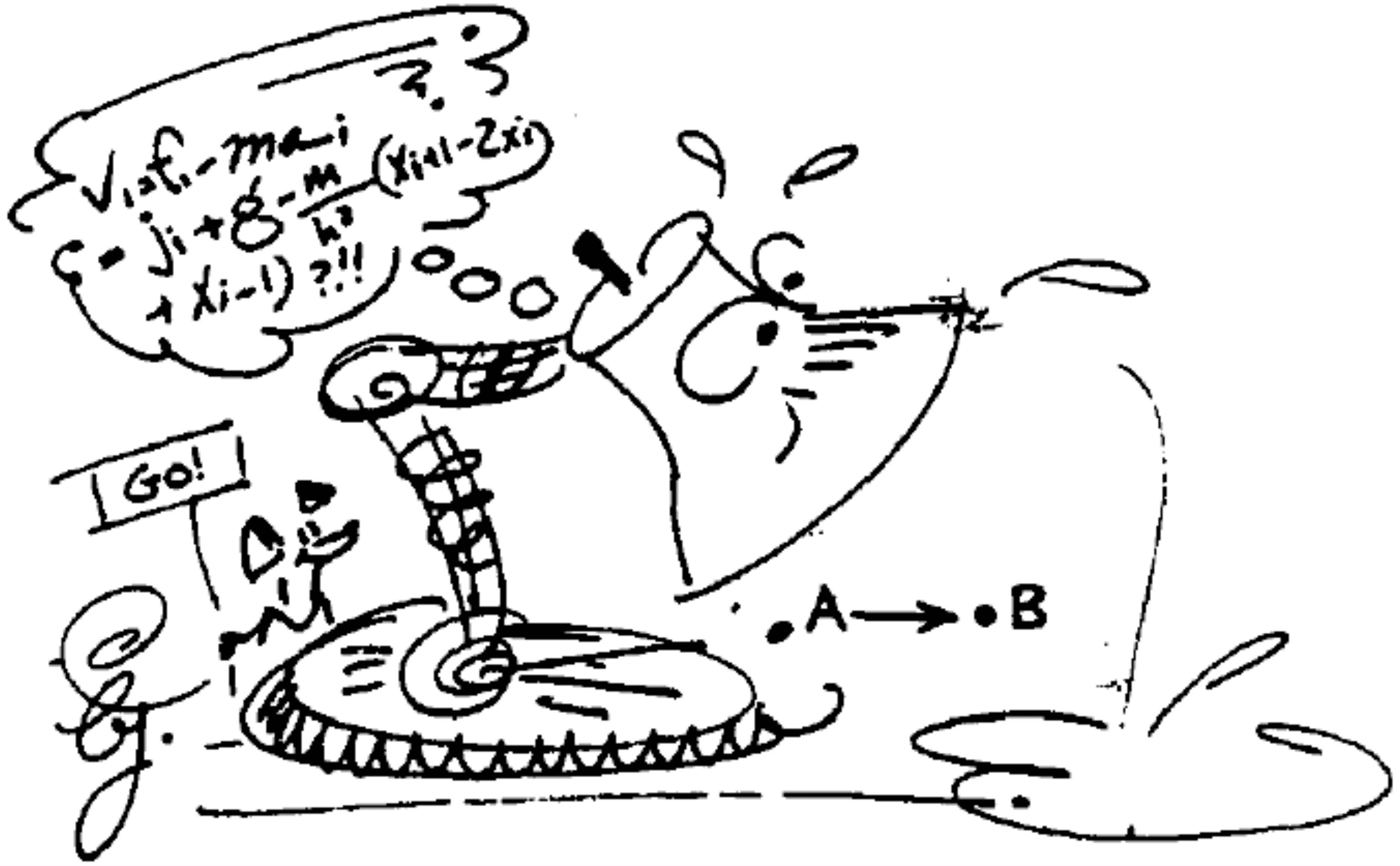


Macchietto et al. SIGGRAPH 2009



de Lasa, Mordatch, Hertzmann. SIGGRAPH 2010

Optimal movements



Hypothesis:

Animals move optimally, for some objective function, as a result of evolution

This has been controversial in biology.

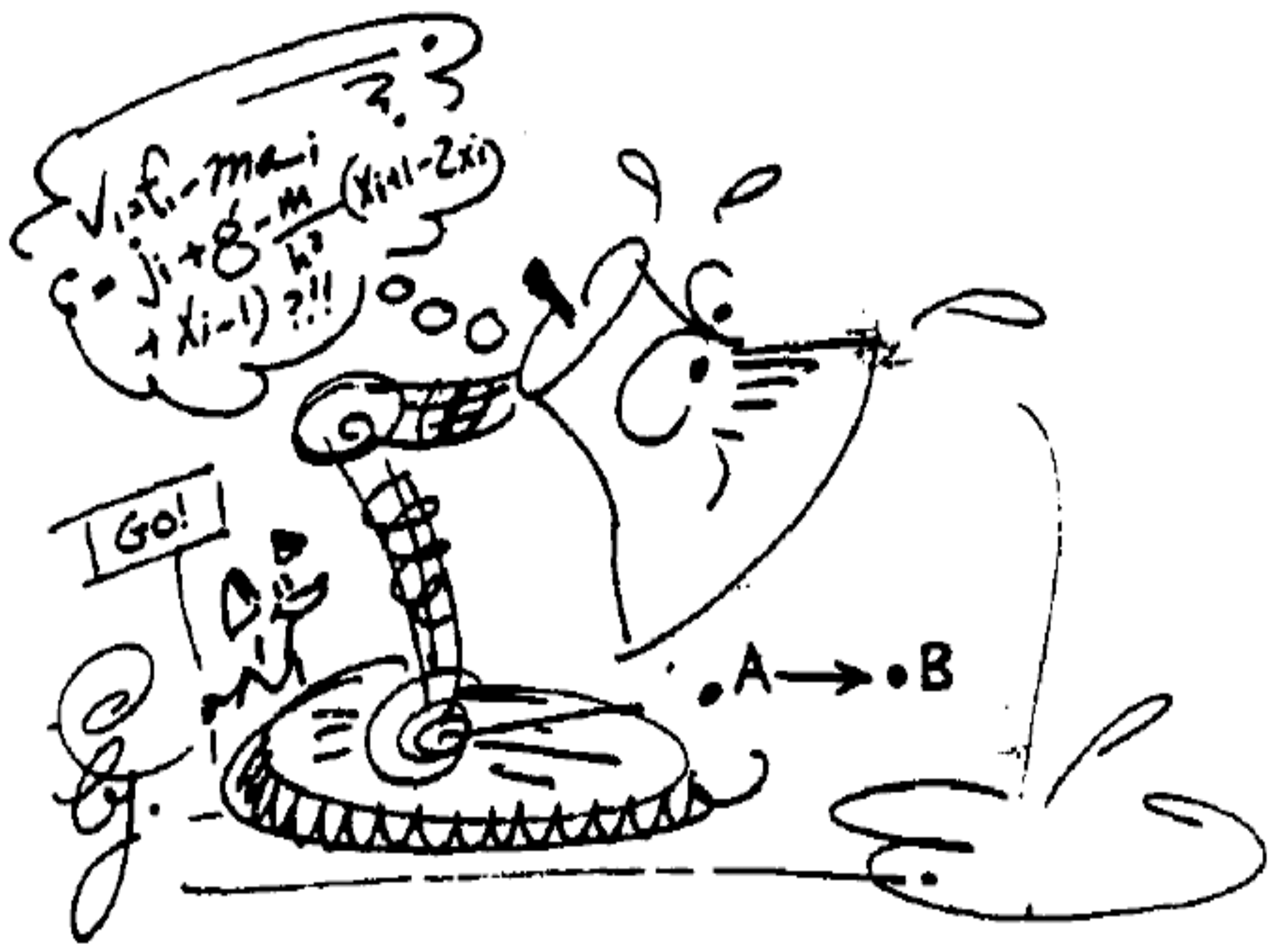
We’re probably not globally optimal.

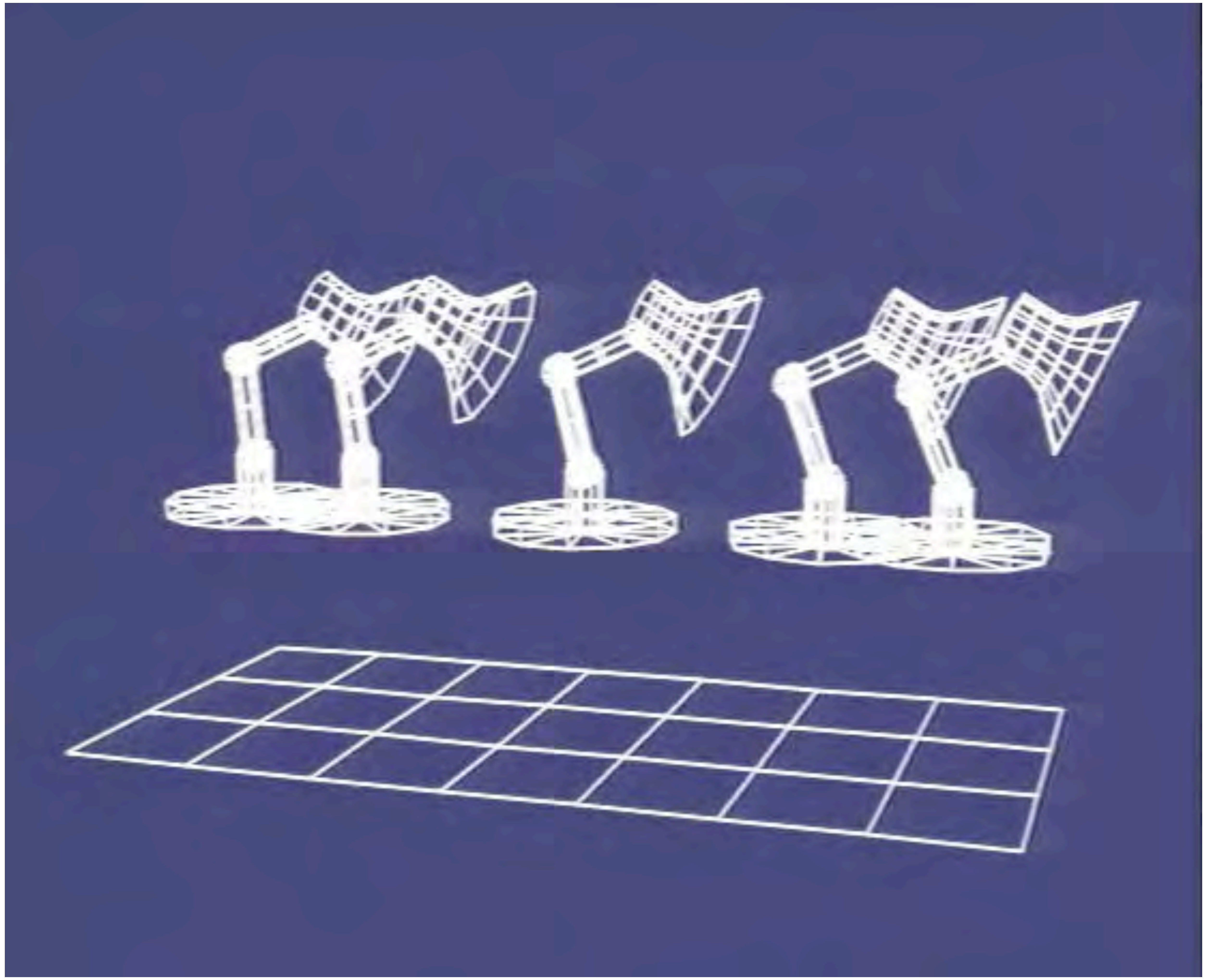
- Evolution and mutation are random
- The objective function constantly changes
- We never really converge

Optimality is a *model*, not reality

Captures some phenomena, omits others

Allows us to reason about goals without considering the mechanisms





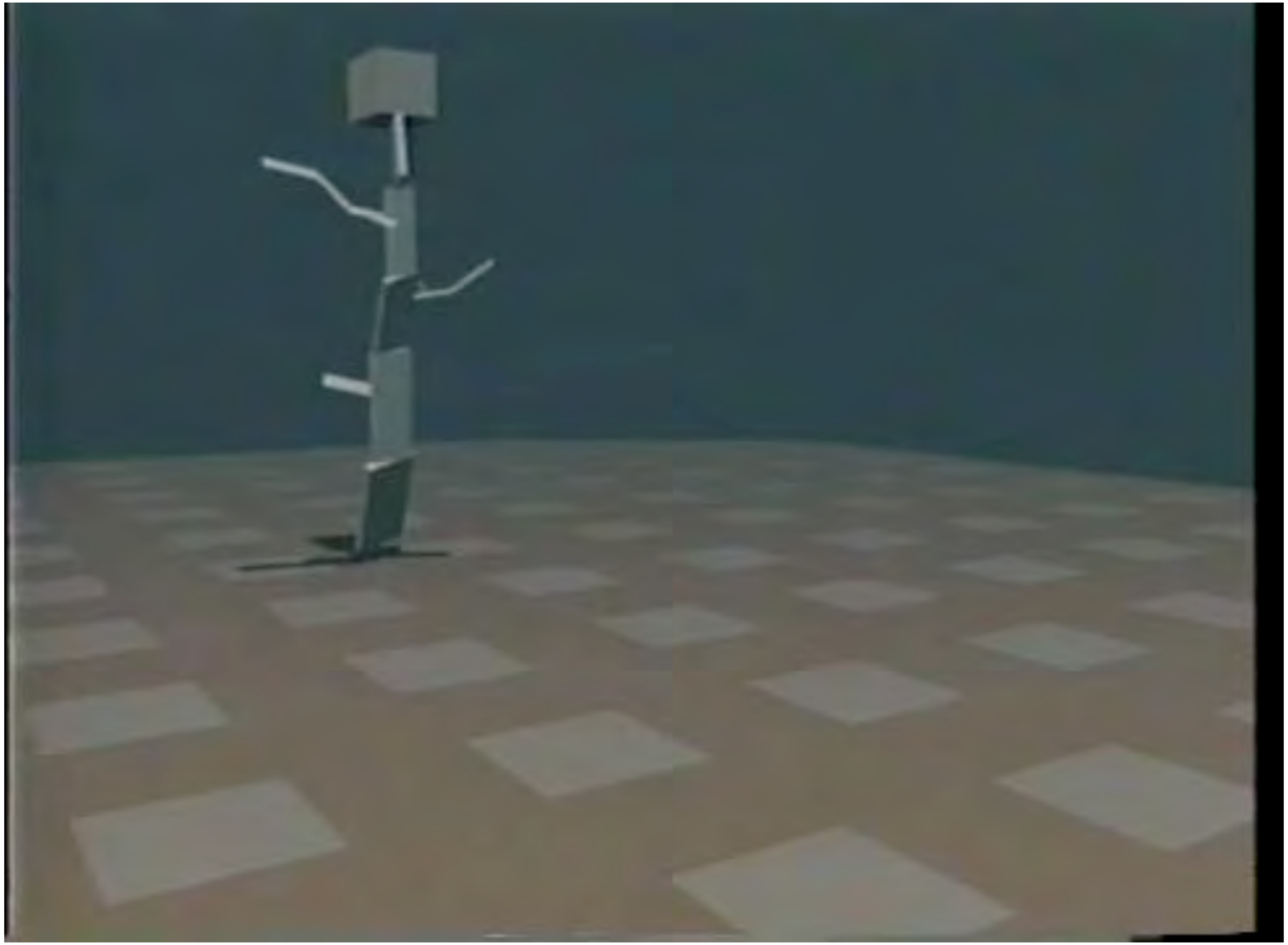
Witkin, Kass. Spacetime Constraints. SIGGRAPH 1988.

K. Sims. Evolving Virtual Creatures. SIGGRAPH 1994

Genetic algorithm optimizing morphology and controller

Unexpected outcomes: “Maximize ground velocity in 2 seconds”

Unexpected outcomes: “Maximize ground velocity in 2 seconds”



arXiv.org > cs > arXiv:1803.03453

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Computer Science > Neural and Evolutionary Computing

The Surprising Creativity of Digital Evolution: A Collection of Anecdotes from the Evolutionary Computation and Artificial Life Research Communities

Joel Lehman, Jeff Clune, Dusan Misevic, Christoph Adami, Lee Altenberg, Julie Beaulieu, Peter J. Bentley, Samuel Bernard, Guillaume Beslon, David M. Bryson, Patryk Chrabaszcz, Nick Cheney, Antoine Cully, Stephane Doncieux, Fred C. Dyer, Kai Olav Ellefsen, Robert Feldt, Stephan Fischer, Stephanie Forrest, Antoine Frénoy, Christian Gagné, Leni Le Goff, Laura M. Grabowski, Babak Hodjat, Frank Hutter, Laurent Keller, Carole Knibbe, Peter Krcah, Richard E. Lenski, Hod Lipson, Robert MacCurdy, Carlos Maestre, Risto Miikkulainen, Sara Mitri, David E. Moriarty, Jean-Baptiste Mouret, Anh Nguyen, Charles Ofria, Marc Parizeau, David Parsons, Robert T. Pennock, William F. Punch, Thomas S. Ray, Marc Schoenauer, Eric Shulte, Karl Sims, Kenneth O. Stanley, François Taddei, Danesh Tarapore, Simon Thibault, Westley Weimer, Richard Watson, Jason Yosinski

(Submitted on 9 Mar 2018 (v1), last revised 14 Aug 2018 (this version, v3))

Biological evolution provides a creative fount of complex and subtle adaptations, often surprising the scientists who discover them. However, because evolution is an algorithmic process that transcends the substrate in which it occurs, evolution's creativity is not limited to

Measuring effort

Want to measure metabolic energy

Mechanical power: $Power = Force \cdot Velocity$

$$= \tau \dot{q}$$

$$E = \sum \tau \dot{q}$$

Squared torques: $E = \sum \tau^2$

More accurate muscle+effort models:

Jack M. Wang et al. SIGGRAPH 2012

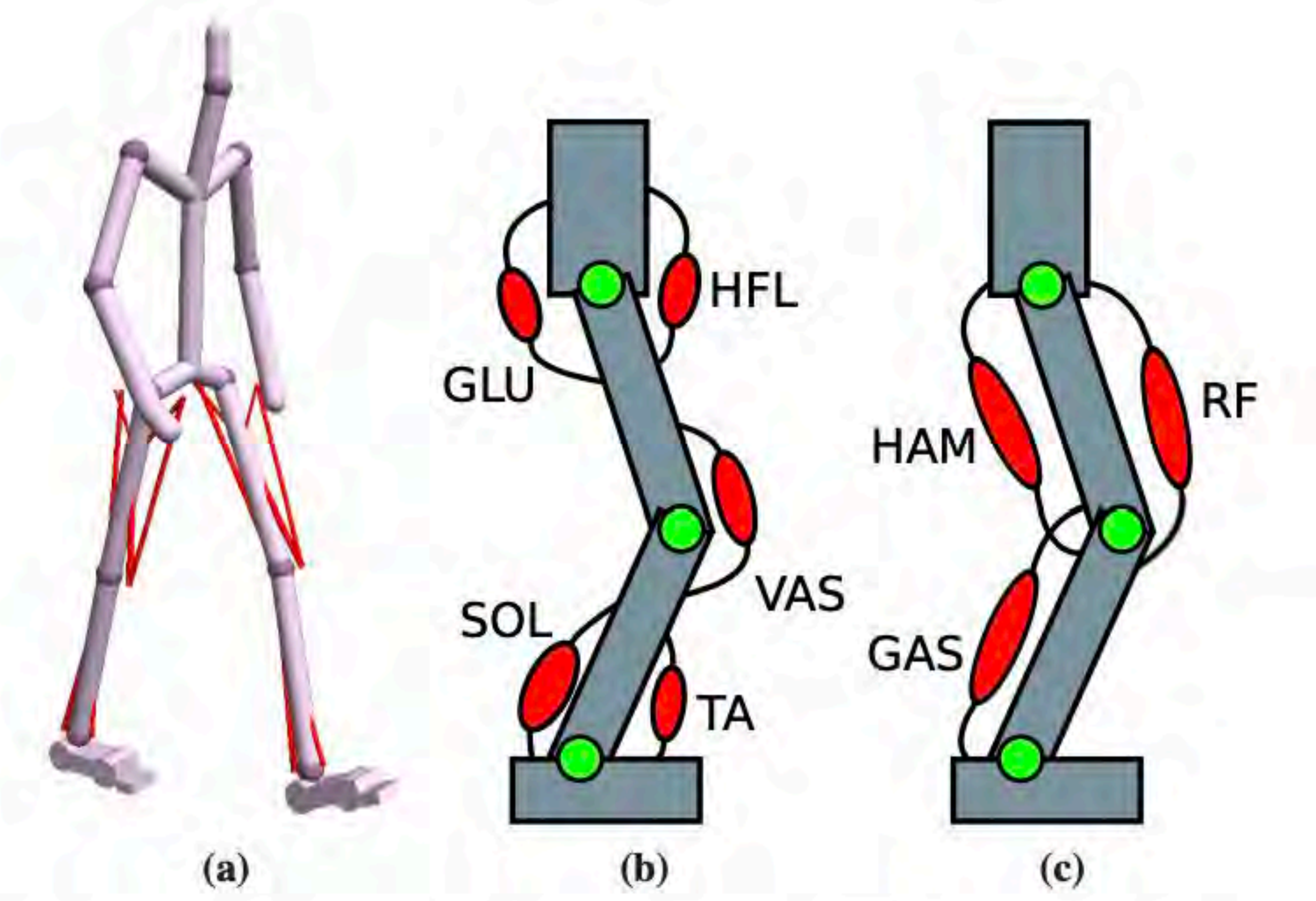


Figure 1: *Humanoid model. (a) Sixteen Hill-type MTUs, shown in red, generate torques for the hips, knees, and ankles. Note that the back joint is not rendered for aesthetic reasons. (b) Five uniarticular muscles in each leg produce flexion or extension torques at single joints. (c) Three biarticular muscles in each leg generate torques at pairs of joints. See Section 3 for details.*

5.1 Effort Term

The main contribution to our effort measurement is the total rate of metabolic energy expenditure ($\dot{E}$) over all MTUs. To quantify $\dot{E}$, we implement a model described by Anderson [1999], which is later expanded by Bhargava et al. [2004]. The rate of metabolic energy expenditure for a given muscle can be modeled as the sum of heat released and mechanical work done by the muscle:

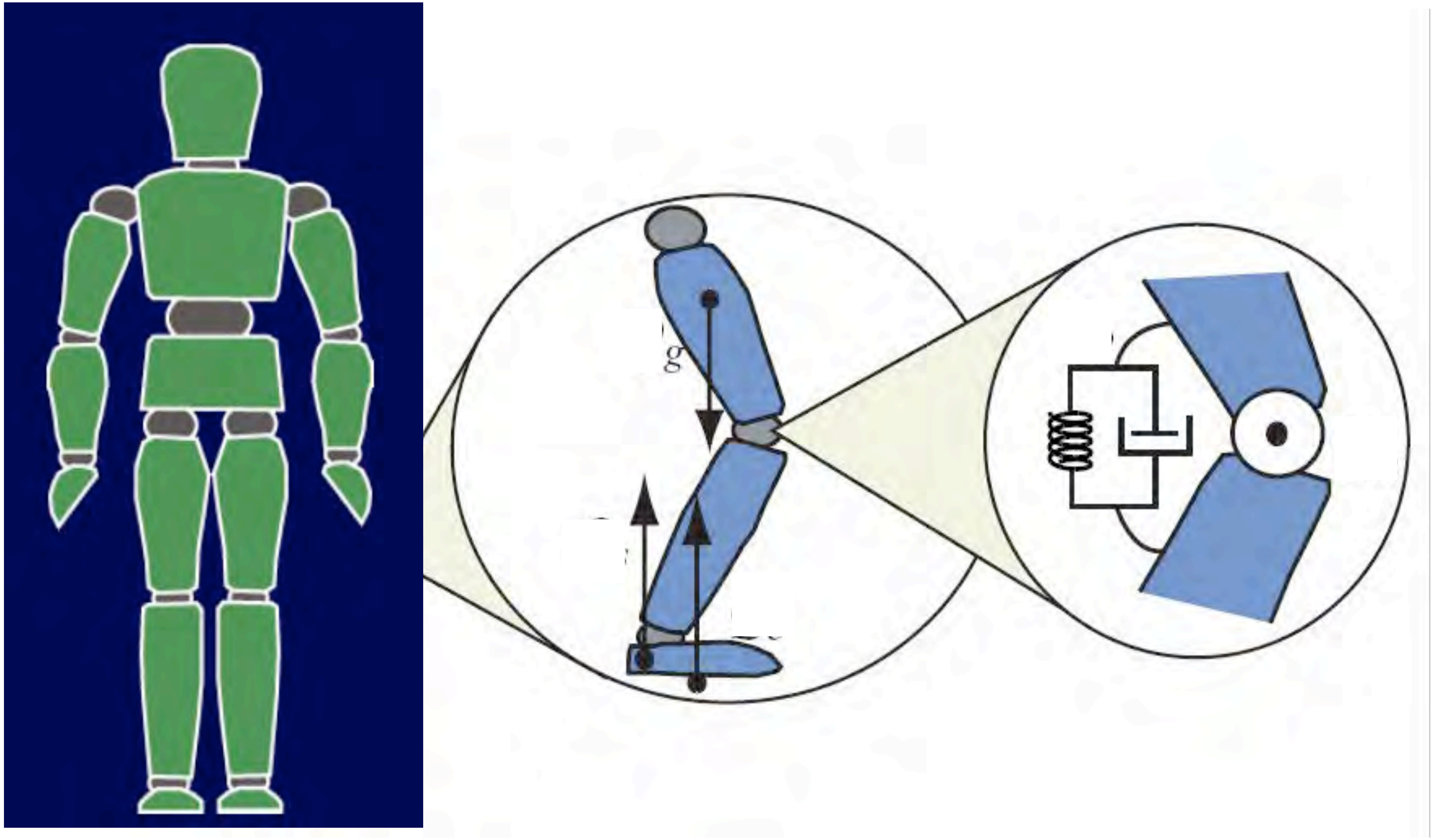
$$\dot{E} = \dot{A} + \dot{M} + \dot{S} + \dot{W},$$

where $\dot{A}$ is the muscle activation heat rate, $\dot{M}$ is the muscle maintenance heat rate, $\dot{S}$ is the muscle shortening heat rate, and $\dot{W}$ is the positive mechanical work rate.

Learning motion style

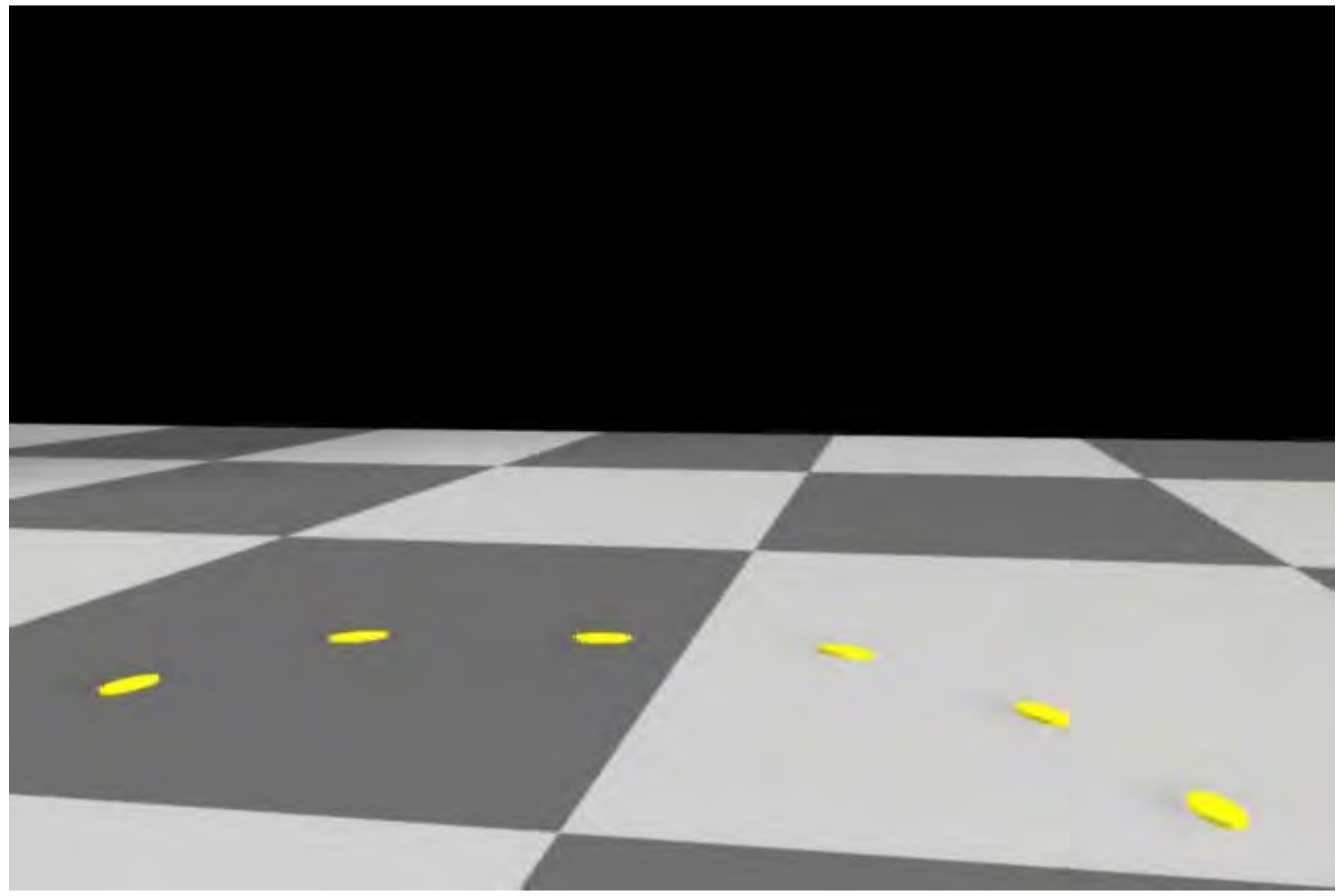
with Karen Liu, Zoran Popovic

SIGGRAPH 2005



$$\tau = \tau_m + \tau_p$$

$$E(\mathbf{Q}) = \sum_{ti} \alpha_i \tau_{ti}^2$$



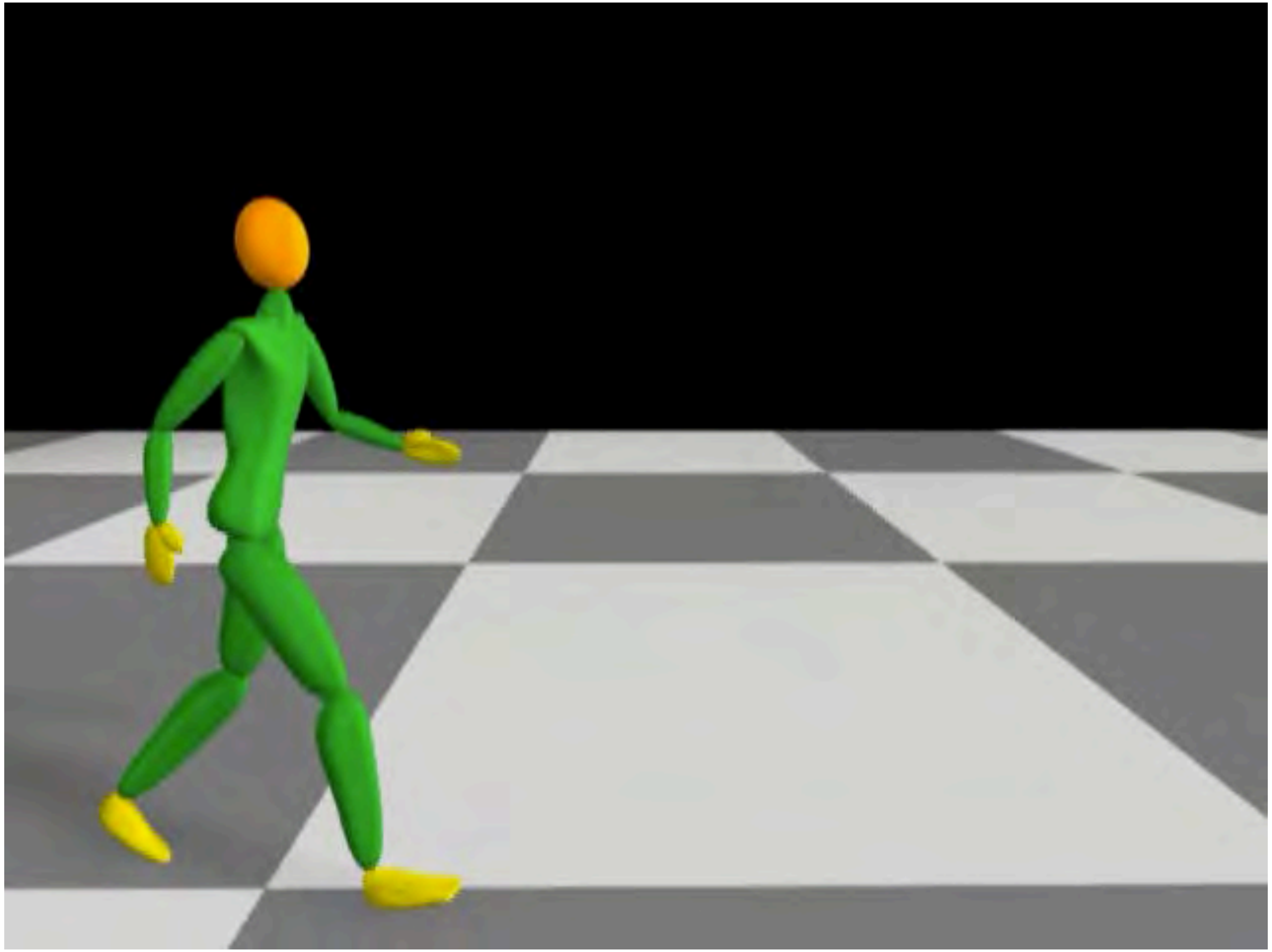
Constraints **C**

$$\mathbf{Q}^* = \arg\min_{\mathbf{Q}} E(\mathbf{Q})$$
$$s.t.\ \mathbf{C}(\mathbf{Q}) = 0$$

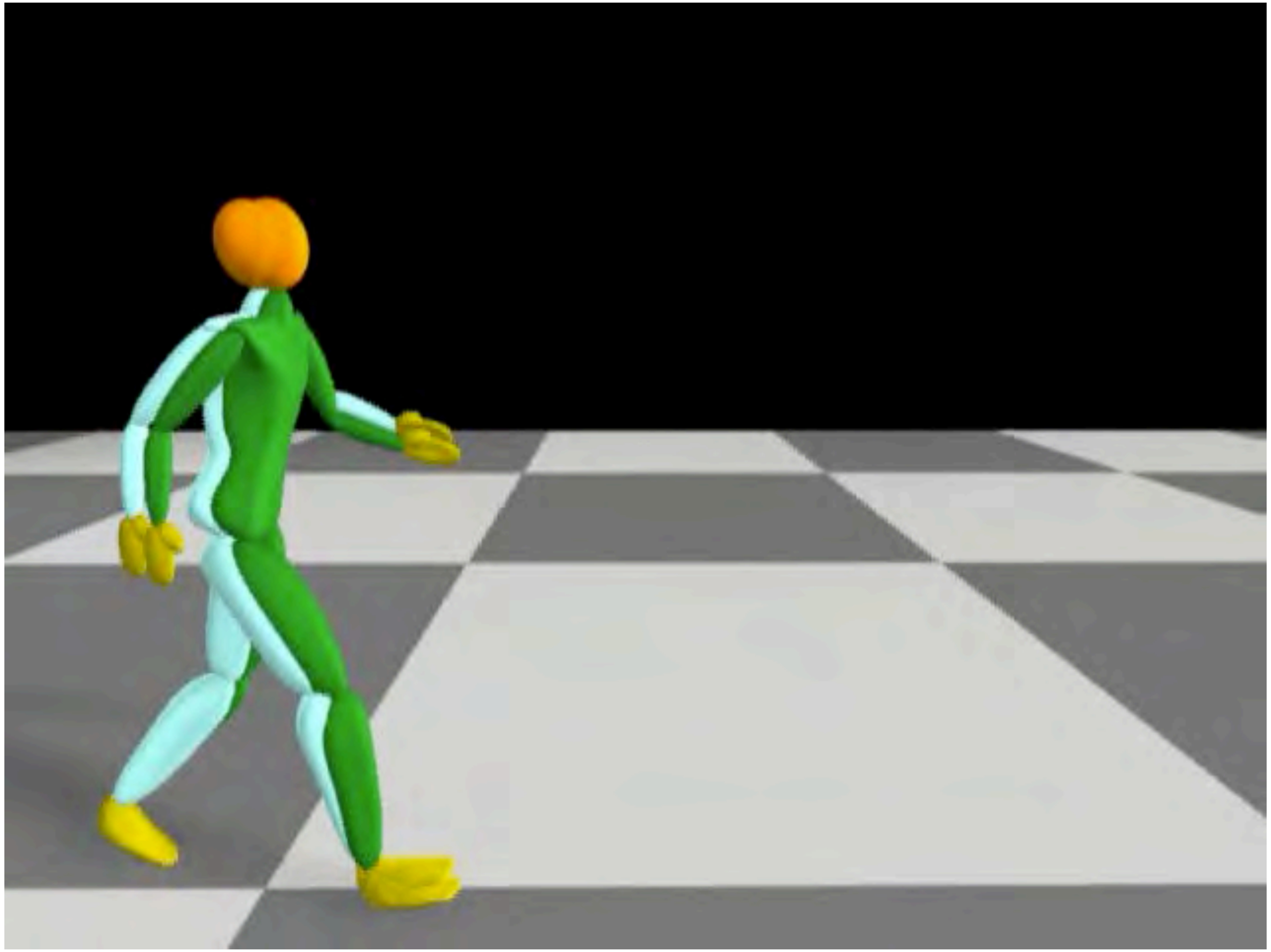
147 model parameters, very hard to set

Inverse optimization

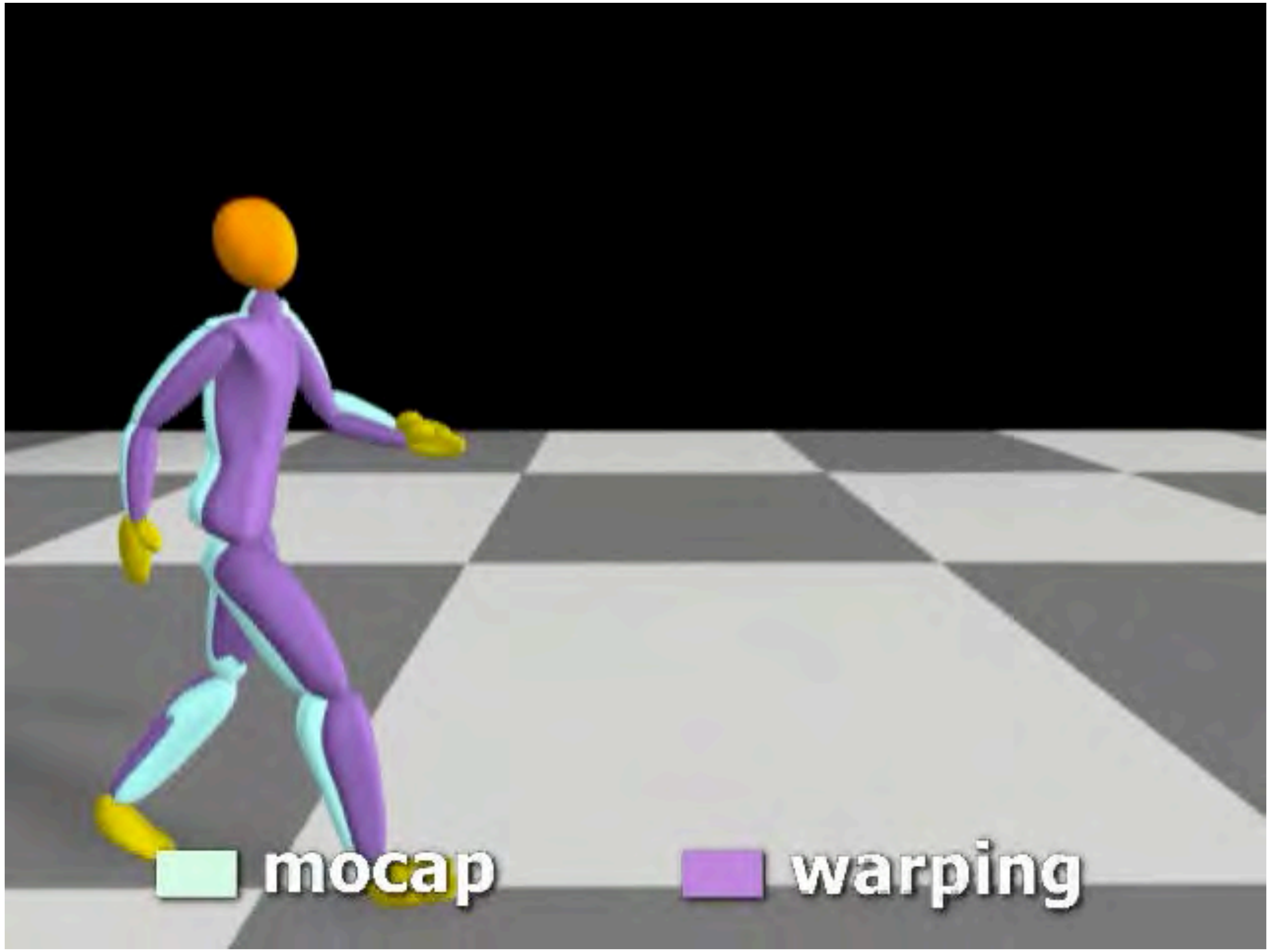
Synthesis



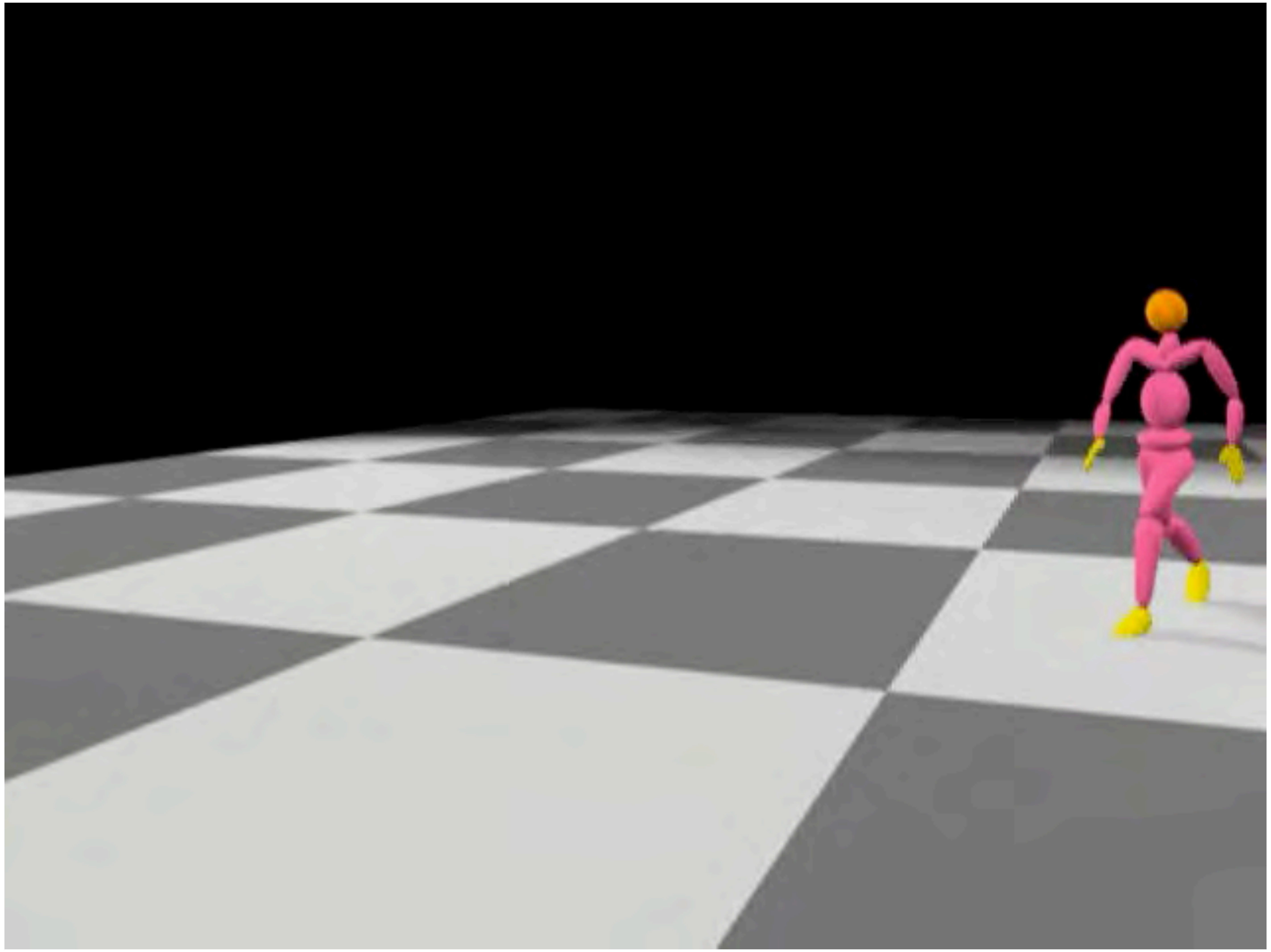
Validation



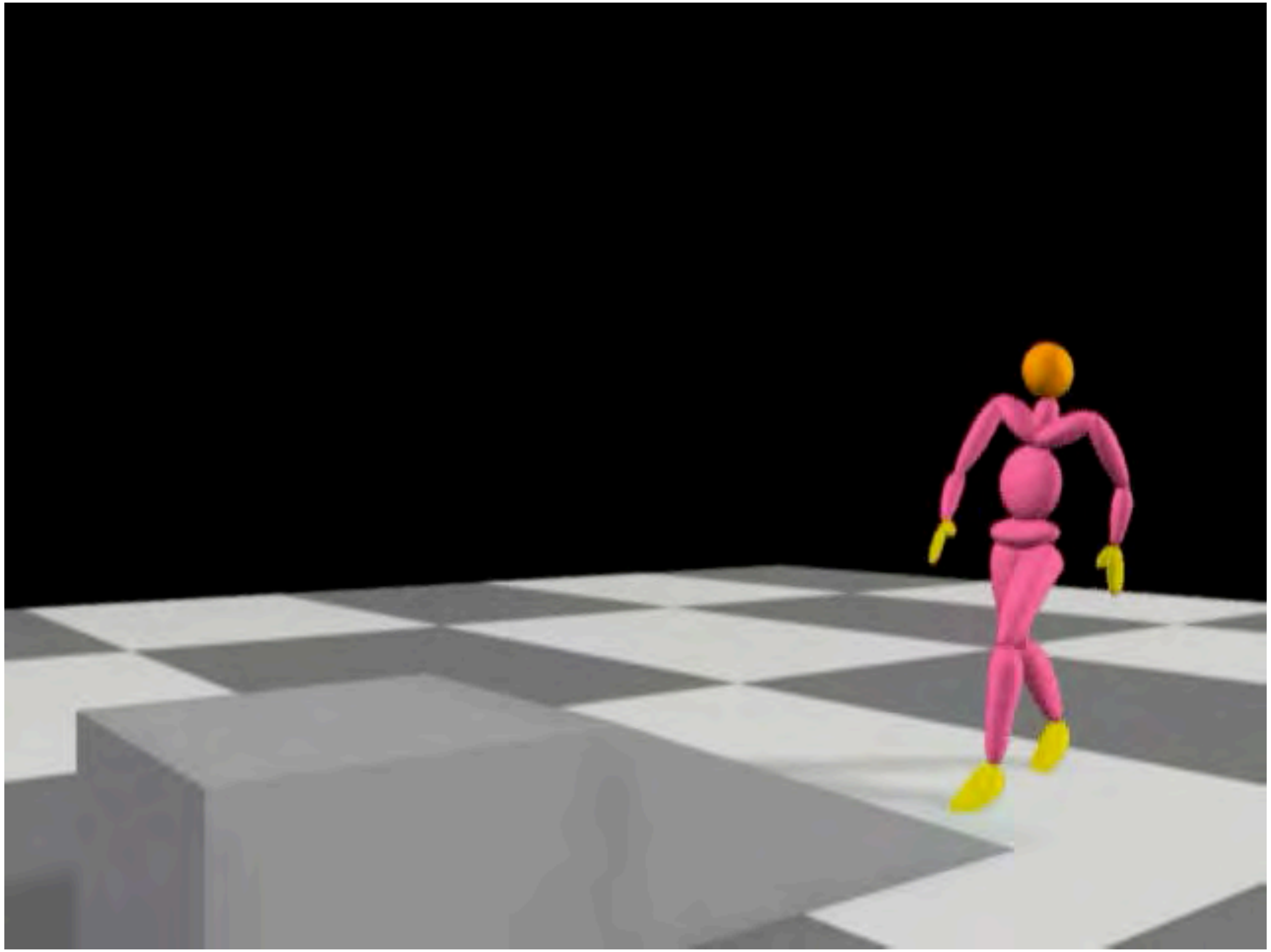
Motion warping



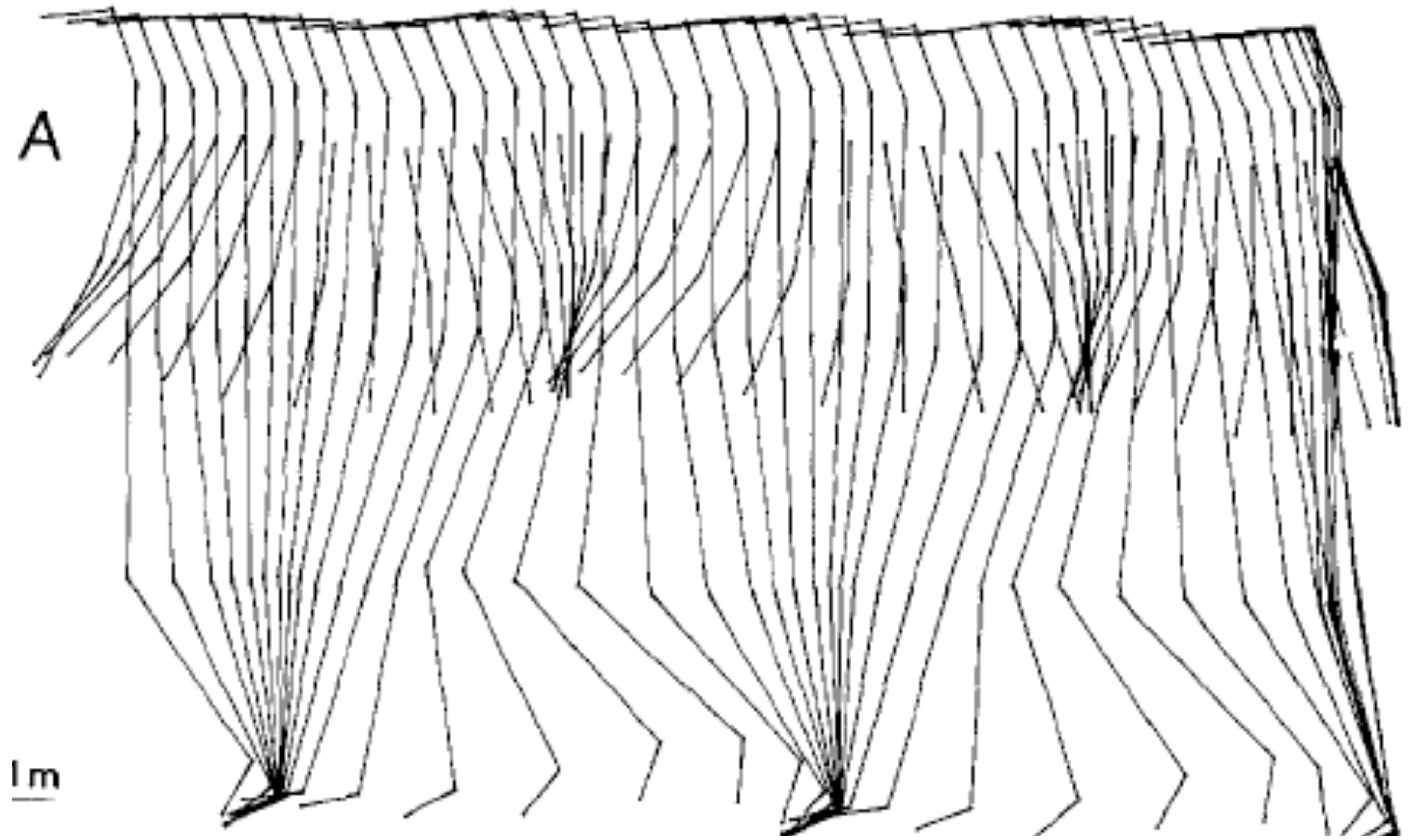
Training data



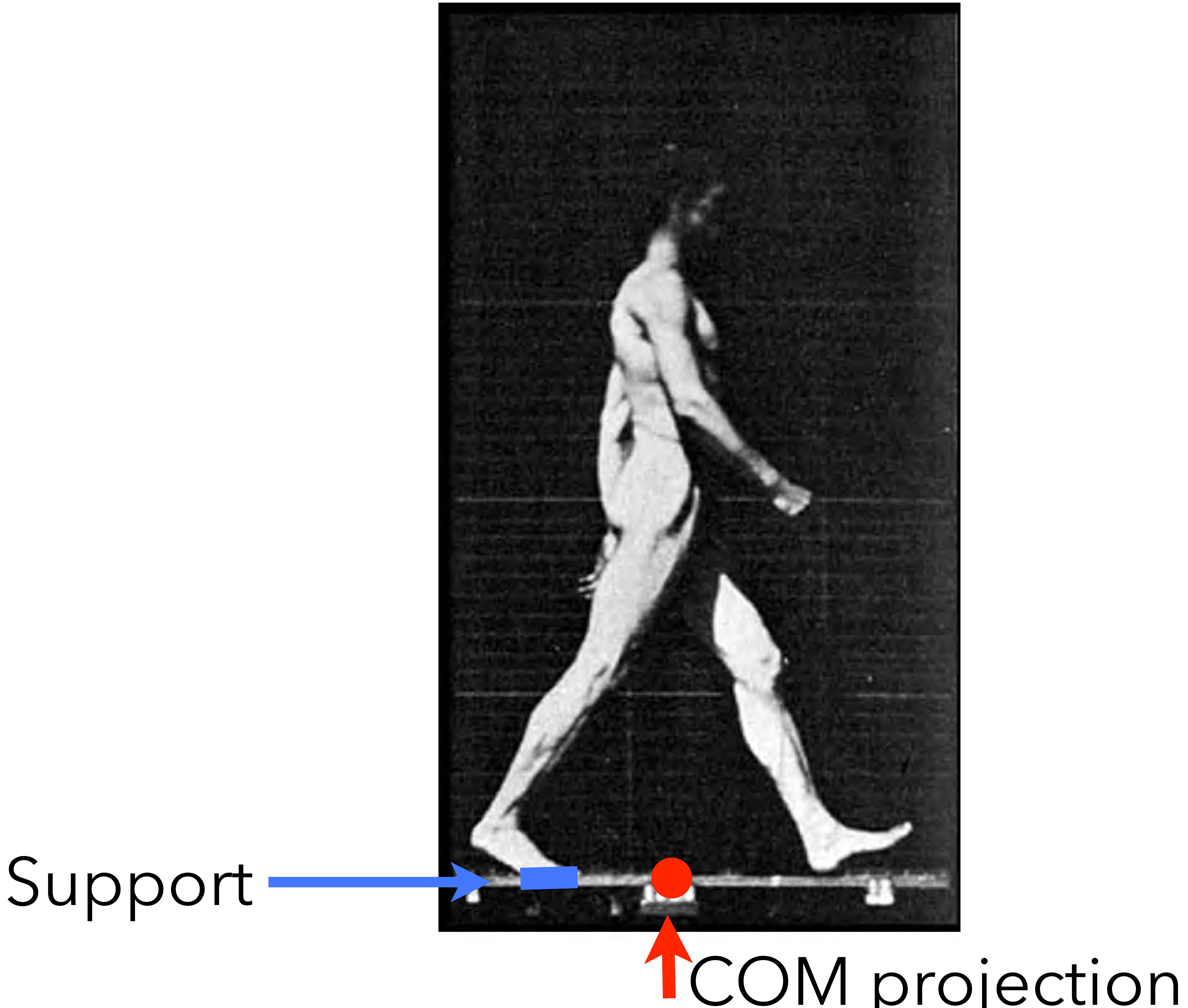
Synthesized motion



Features in walking

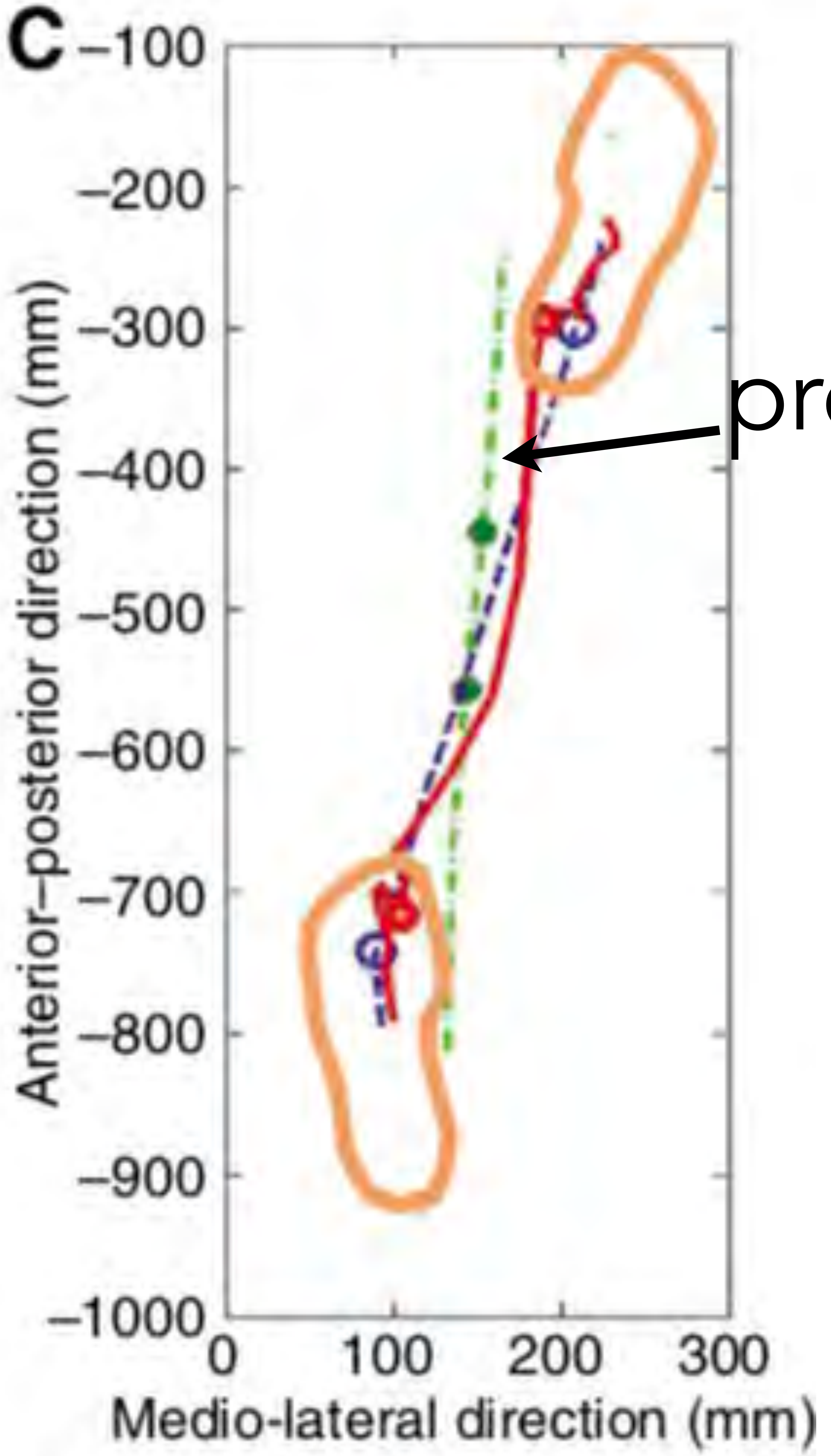


Humans don't keep static balance in walking



Center-of-Mass (COM)

Propel forward, shift weight to maintain balance

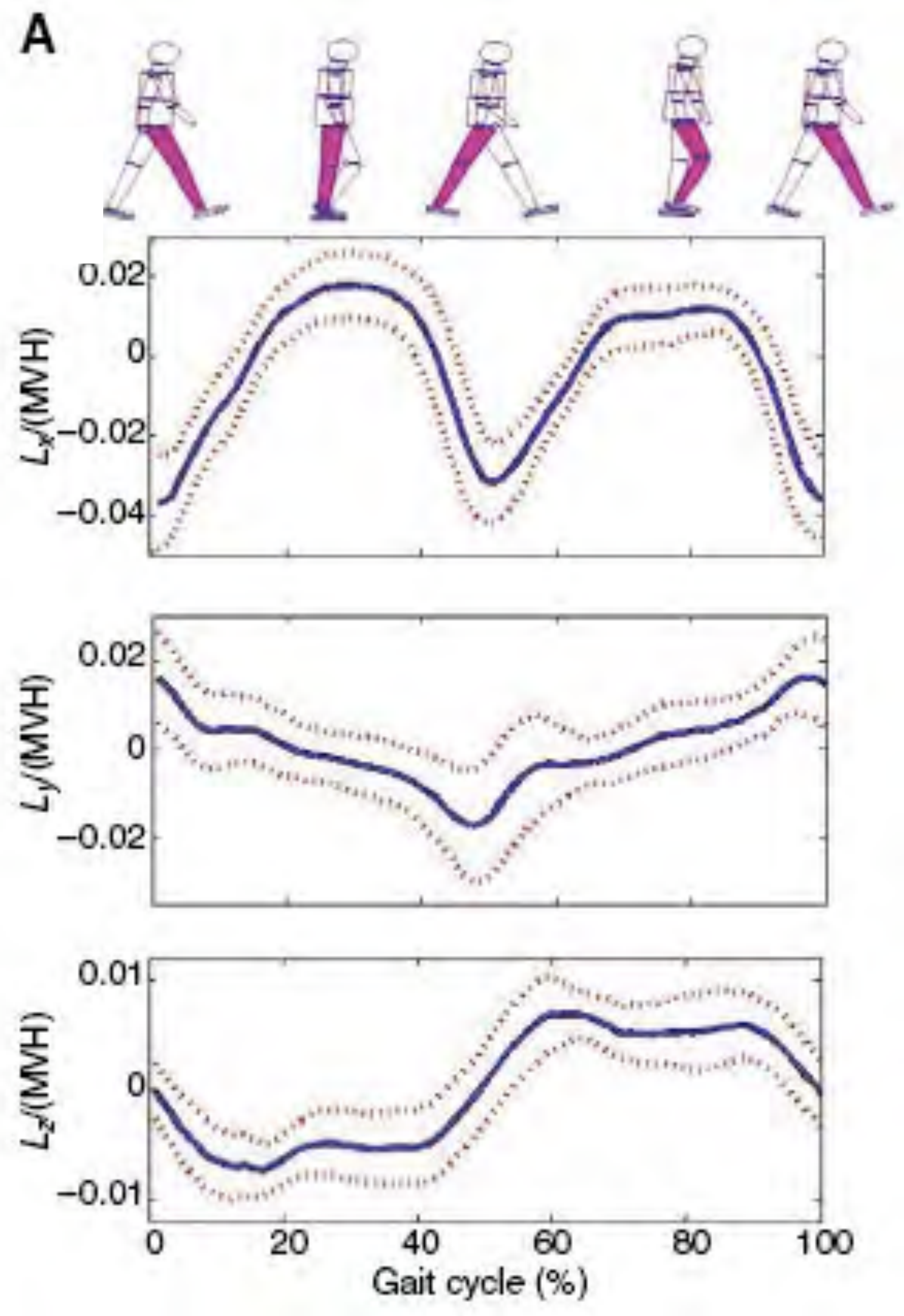


COM projection

M. Popovic et al 2004

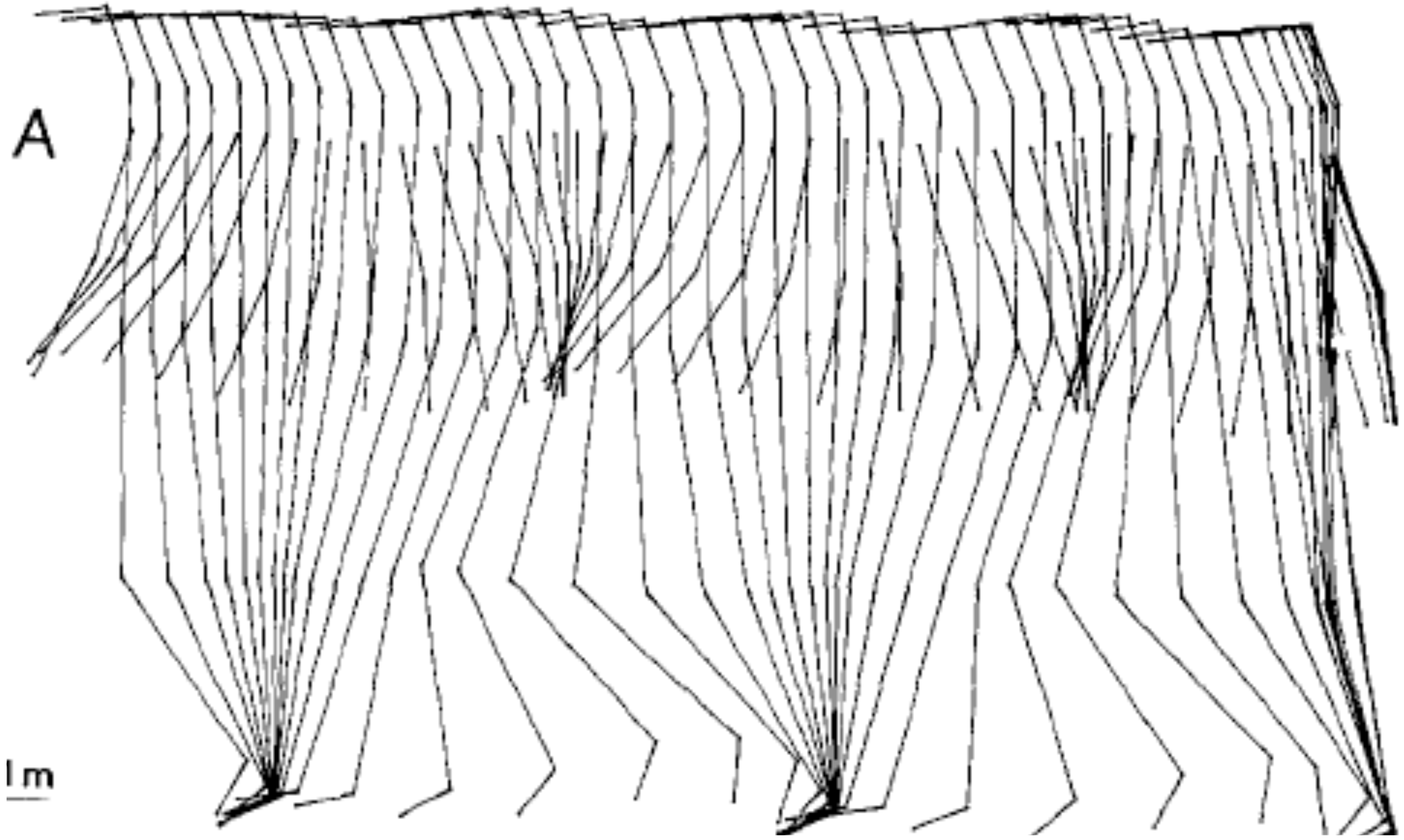
Angular momentum in walking

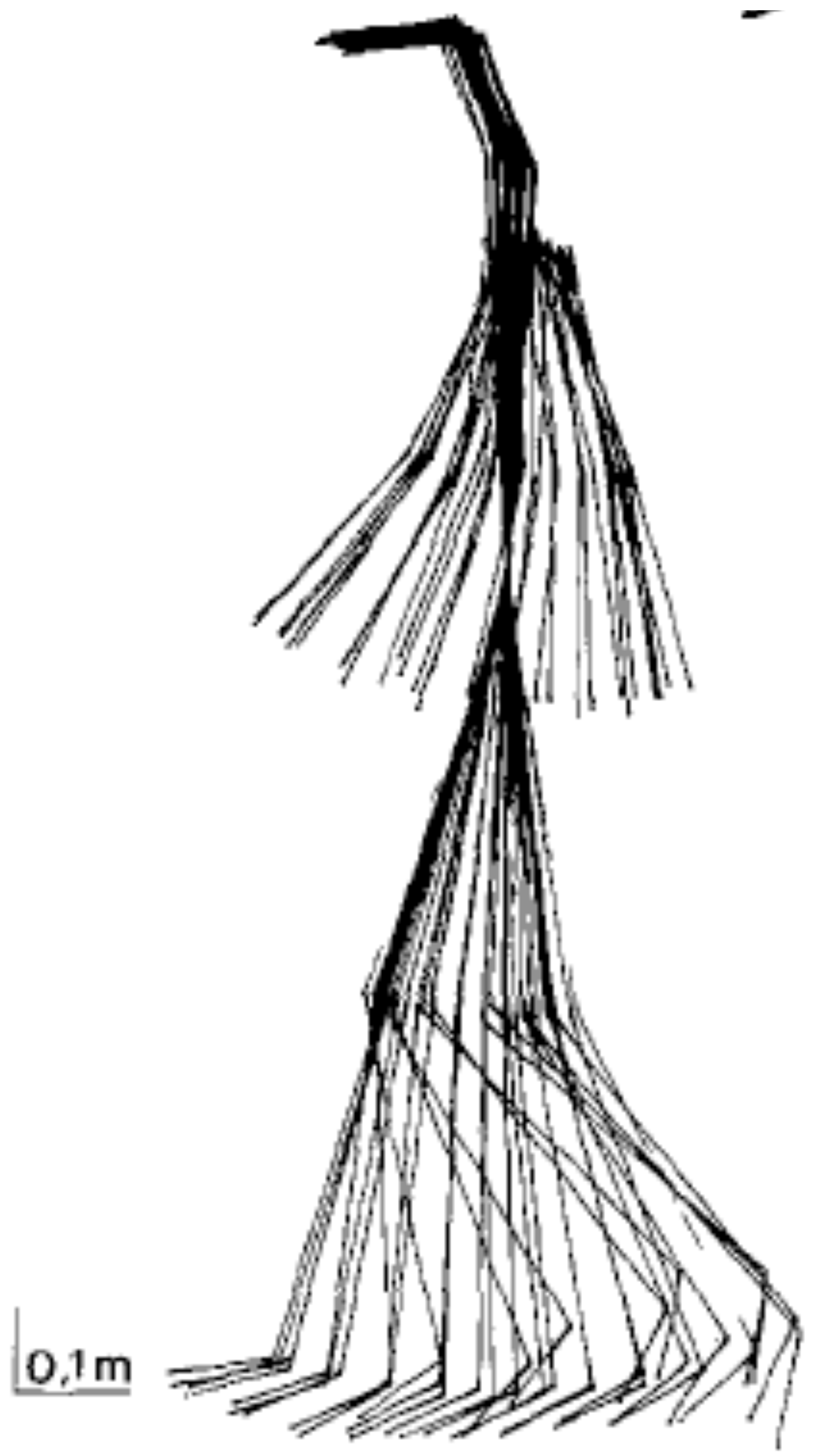
Herr and Popovic. Angular momentum in human walking. *J. Exp. Biol.* 2008.



Head stabilization

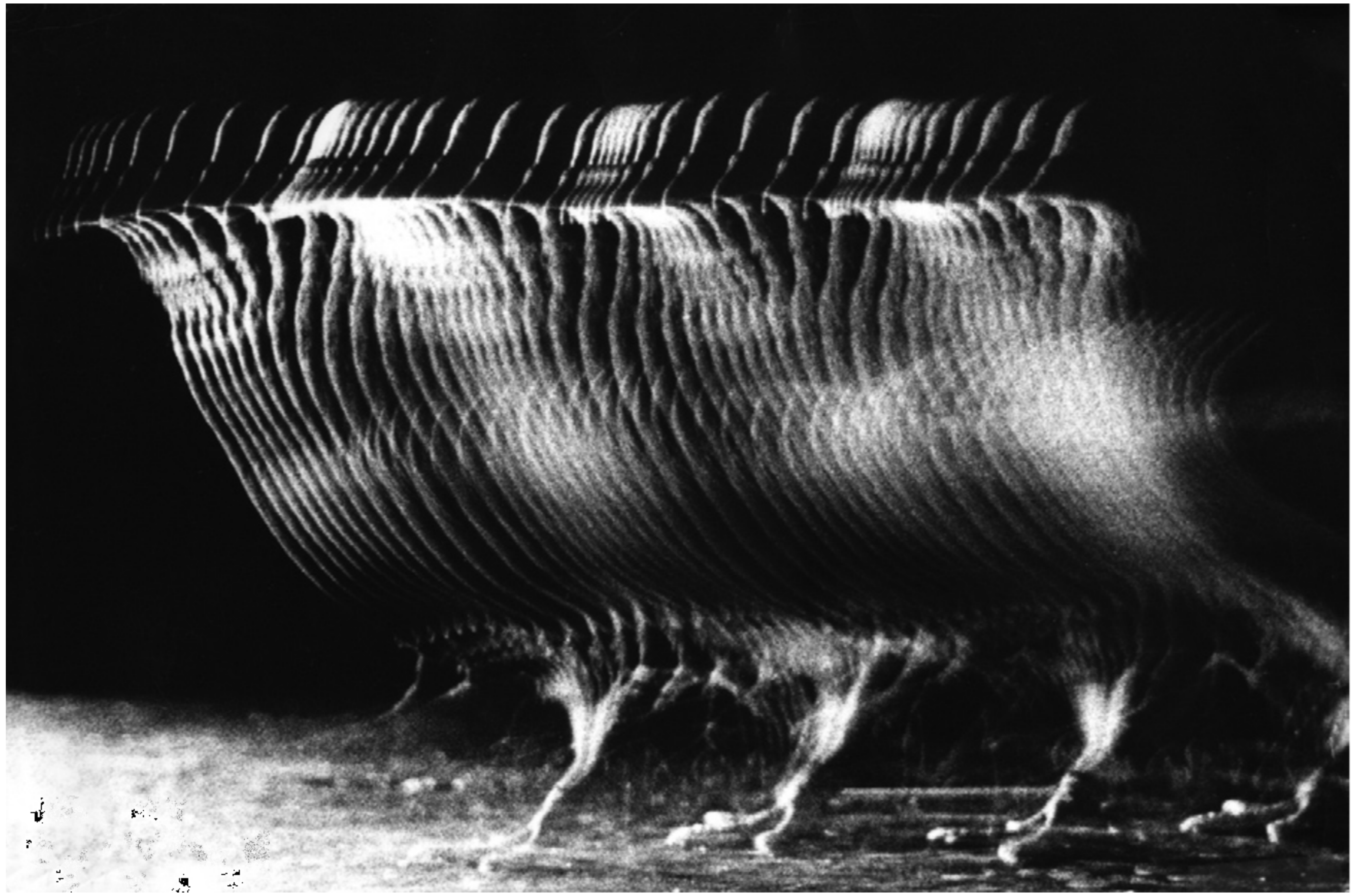
T. Pozzo et al. Head stabilization during various locomotor tasks in humans. *J. Exp. Brain Res.* 1990.



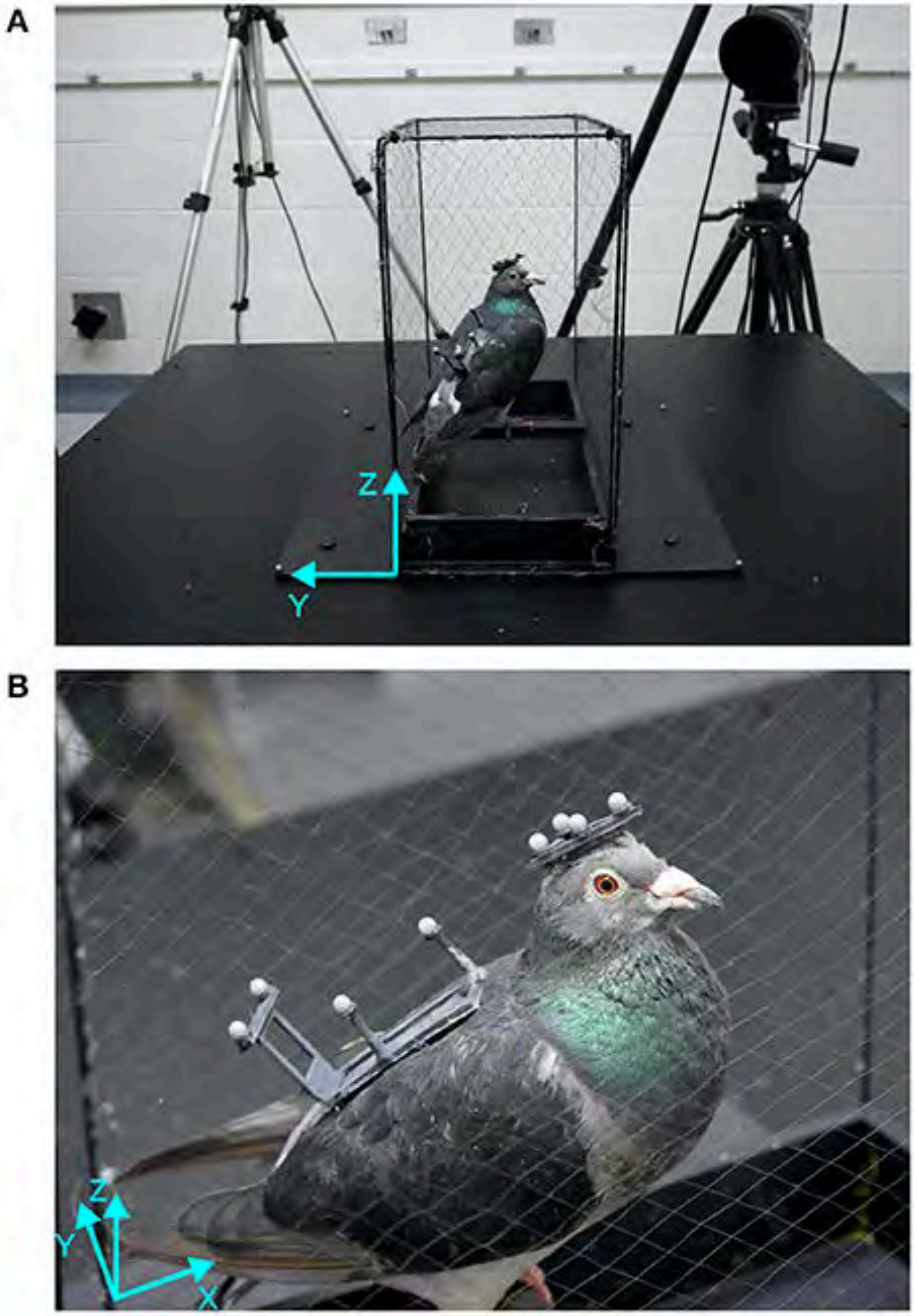


Money and Correia. The Vestibular System of the Owl.
Comparative Biochemistry and Physiology. 1972.

LG Commercial

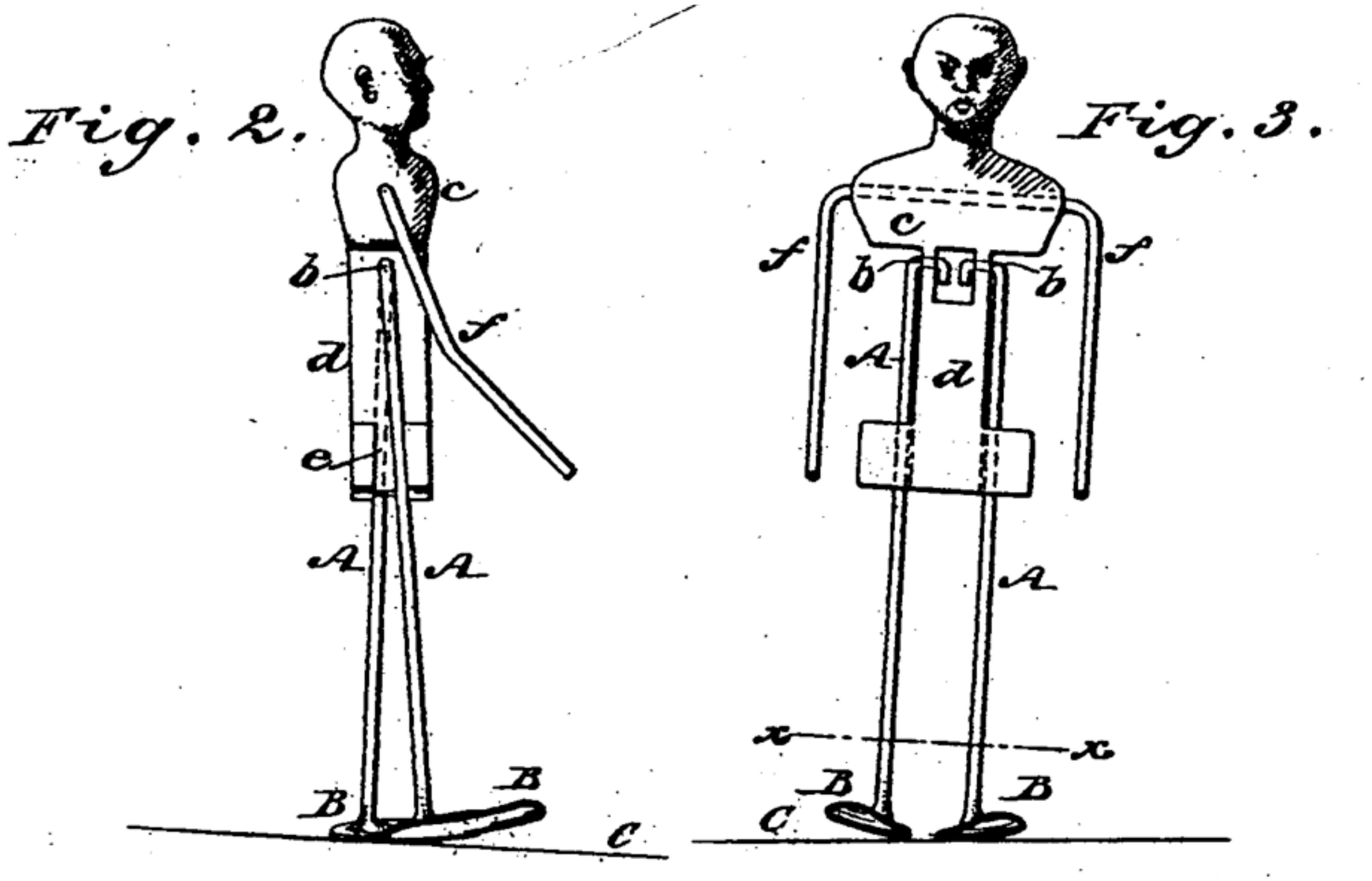


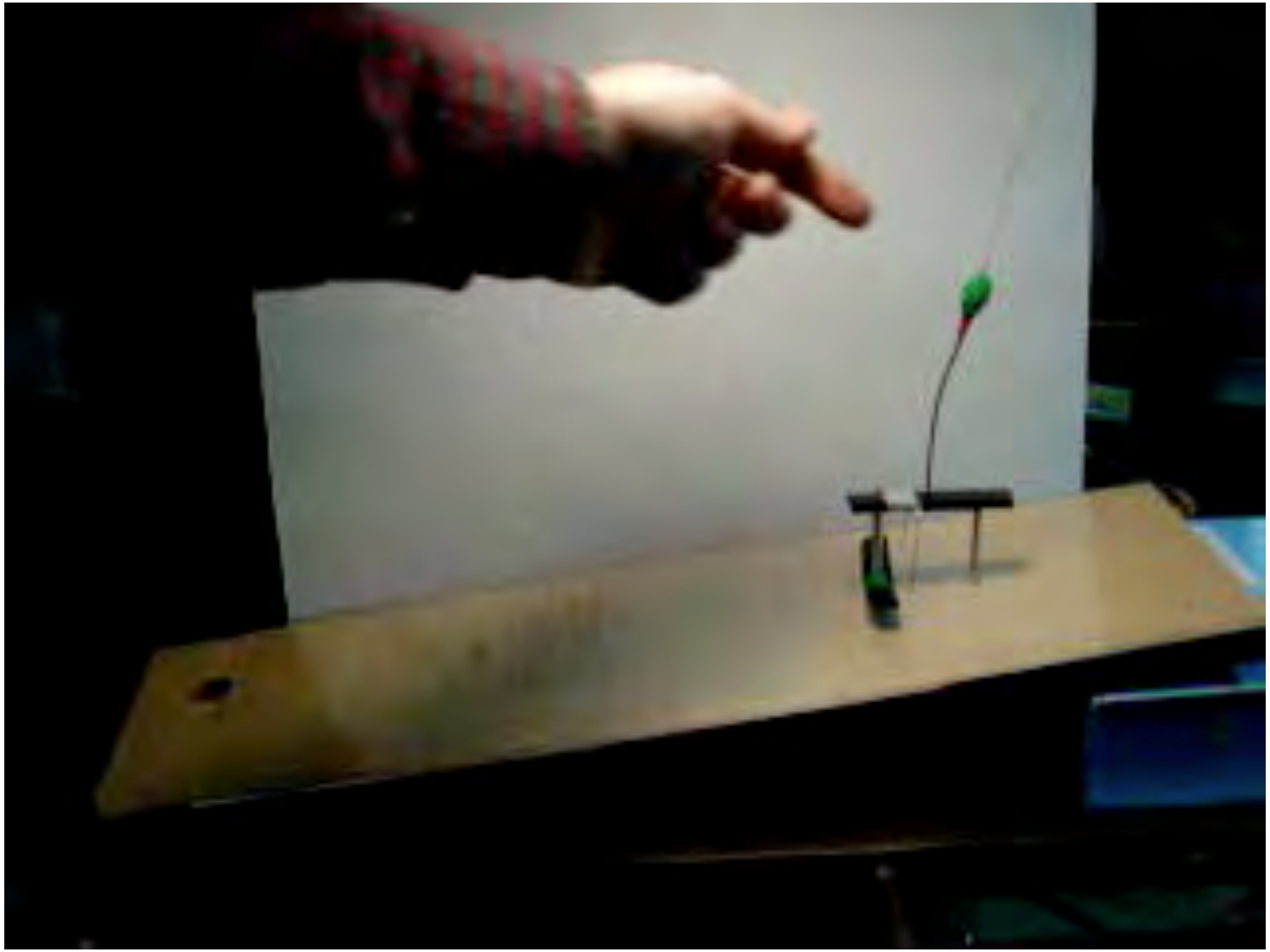
Pigeon movement



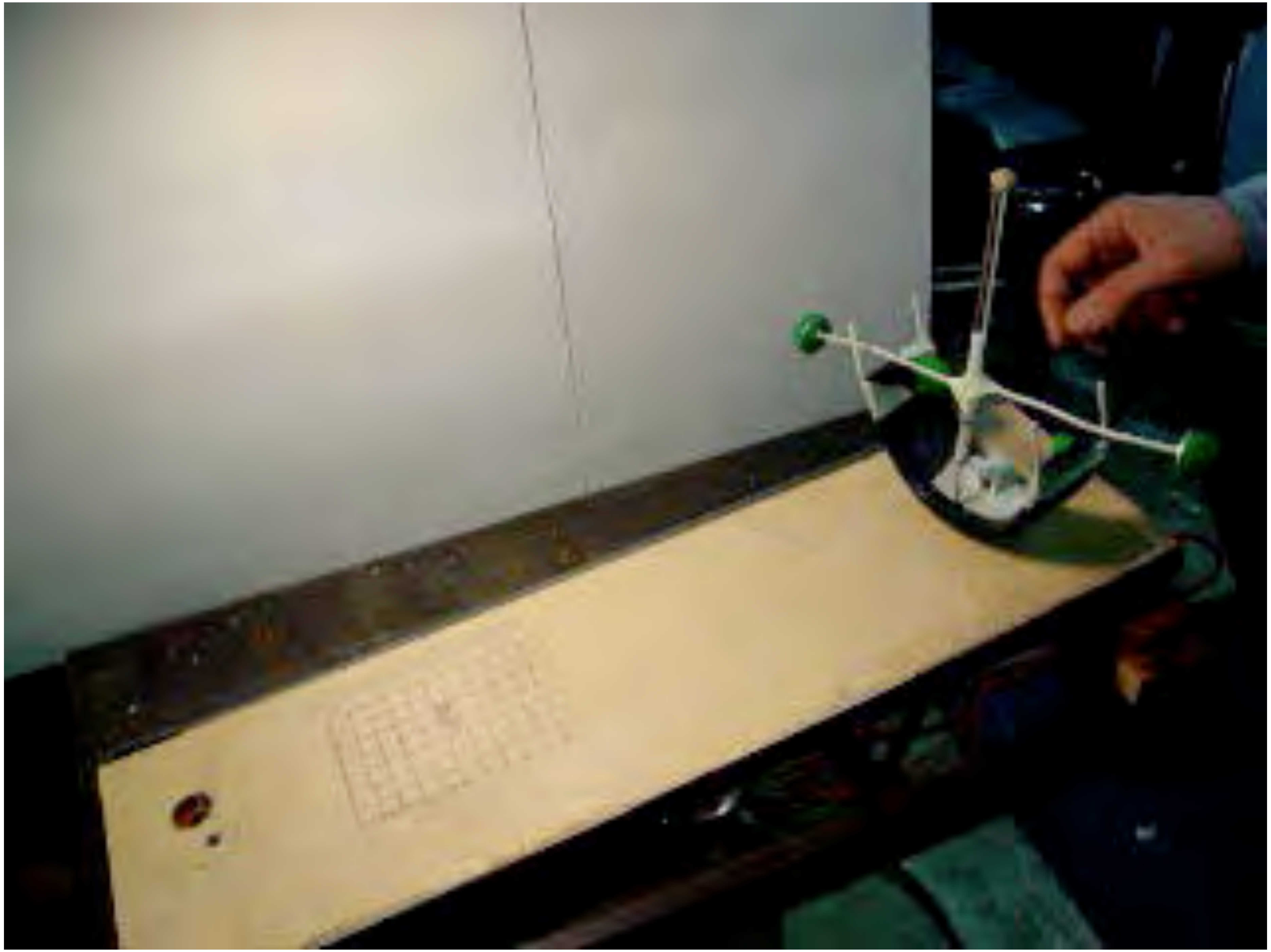
Theunissen and Troje. Head Stabilization in the Pigeon: Role of Vision to Correct for Translational and Rotational Disturbances. Front. Neurosci. 2007

Simplified Models





Passive toys by Peter Steinkamp



Passive toys by Peter Steinkamp

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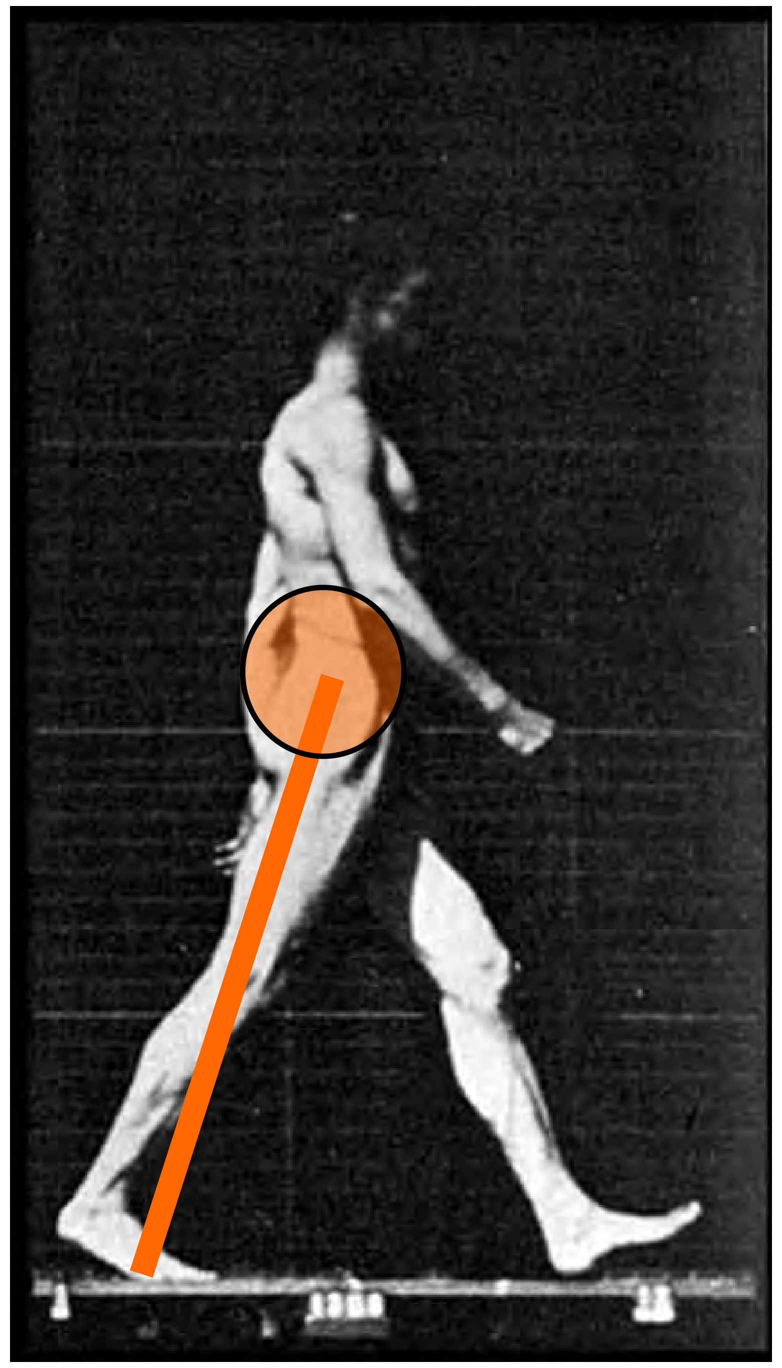
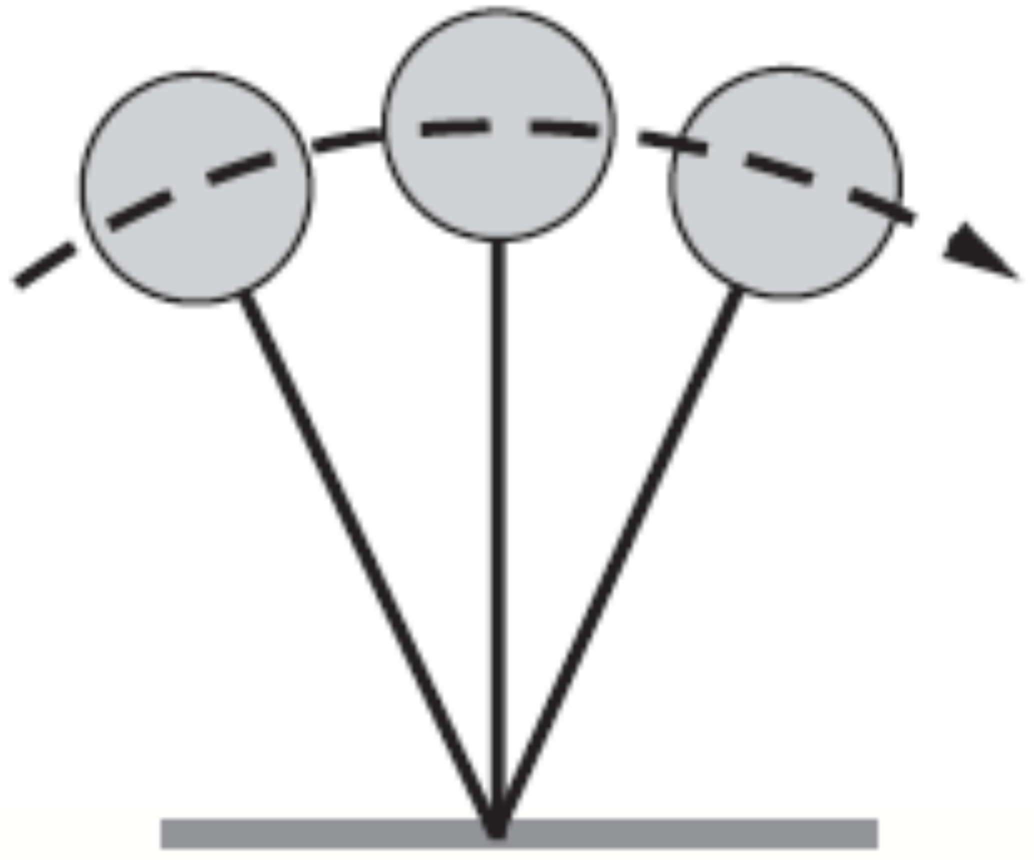
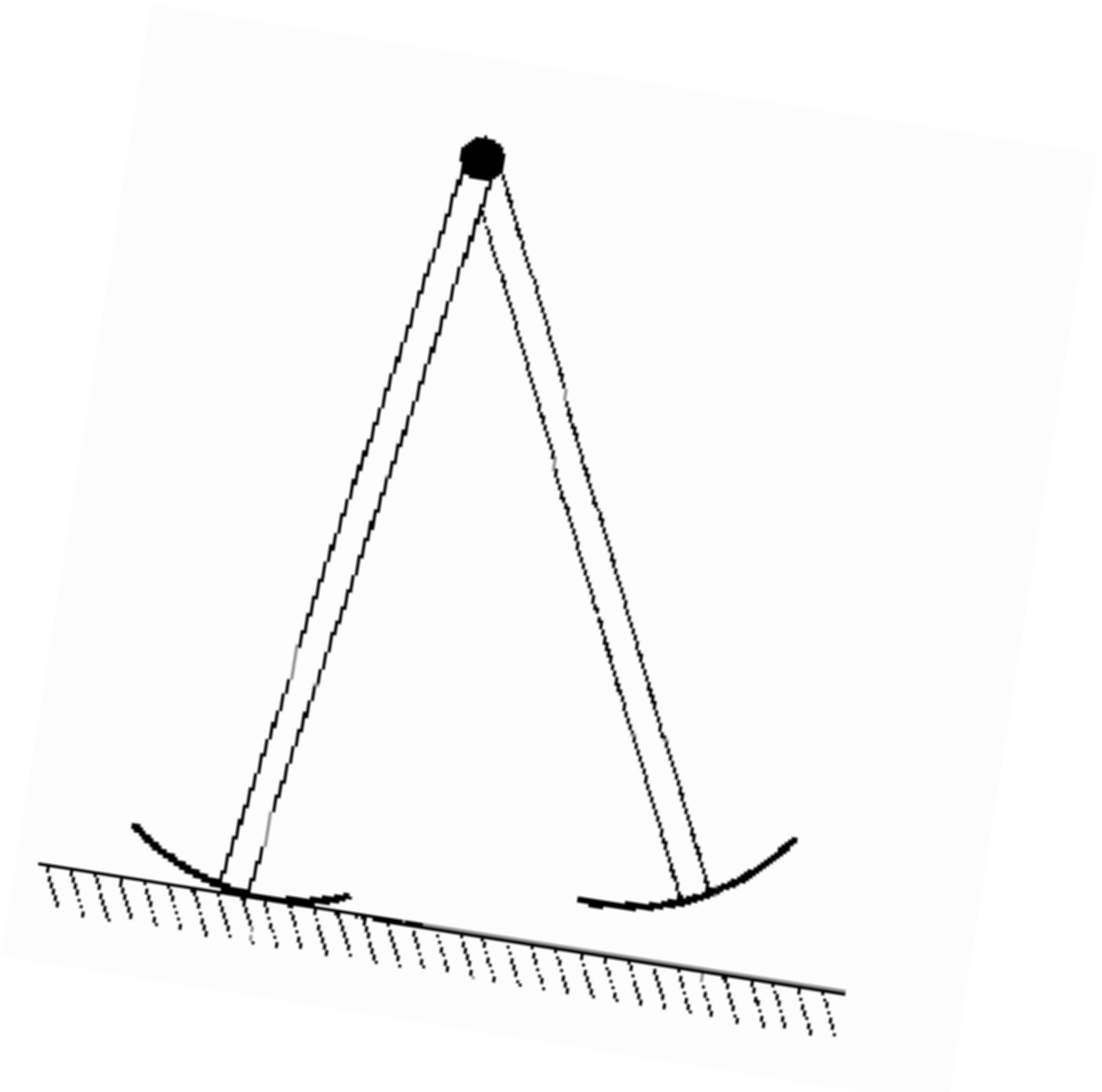




Inverted Pendulum

Passive Dynamic Walker

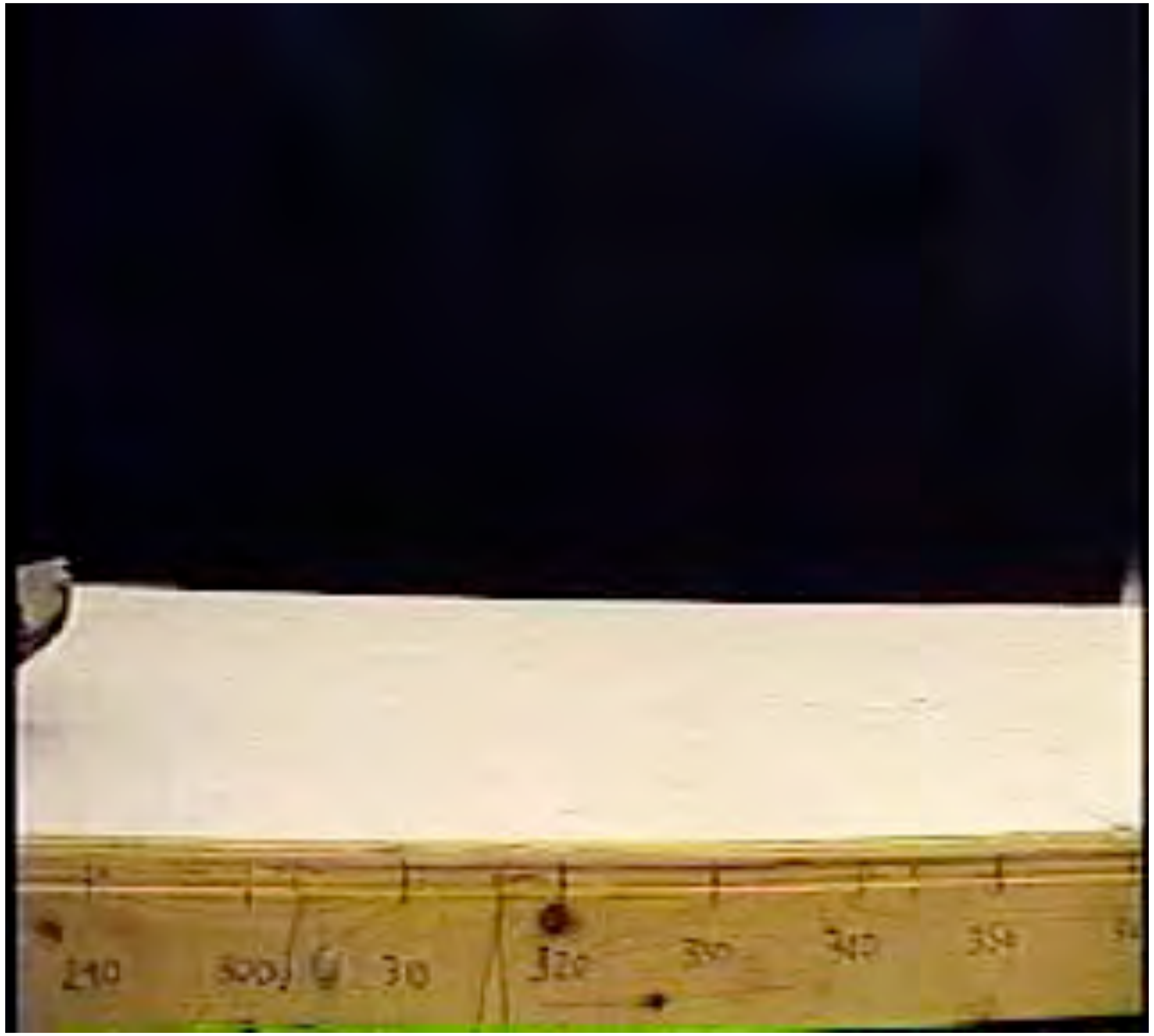
McGeer. Passive Dynamic Walking. *Int J. Robotics Research*. 1990



Kneed Passive Walker

Collins et al. Efficient Bipedal Robots Based on Passive-Dynamic Walkers. *Science* 2005.

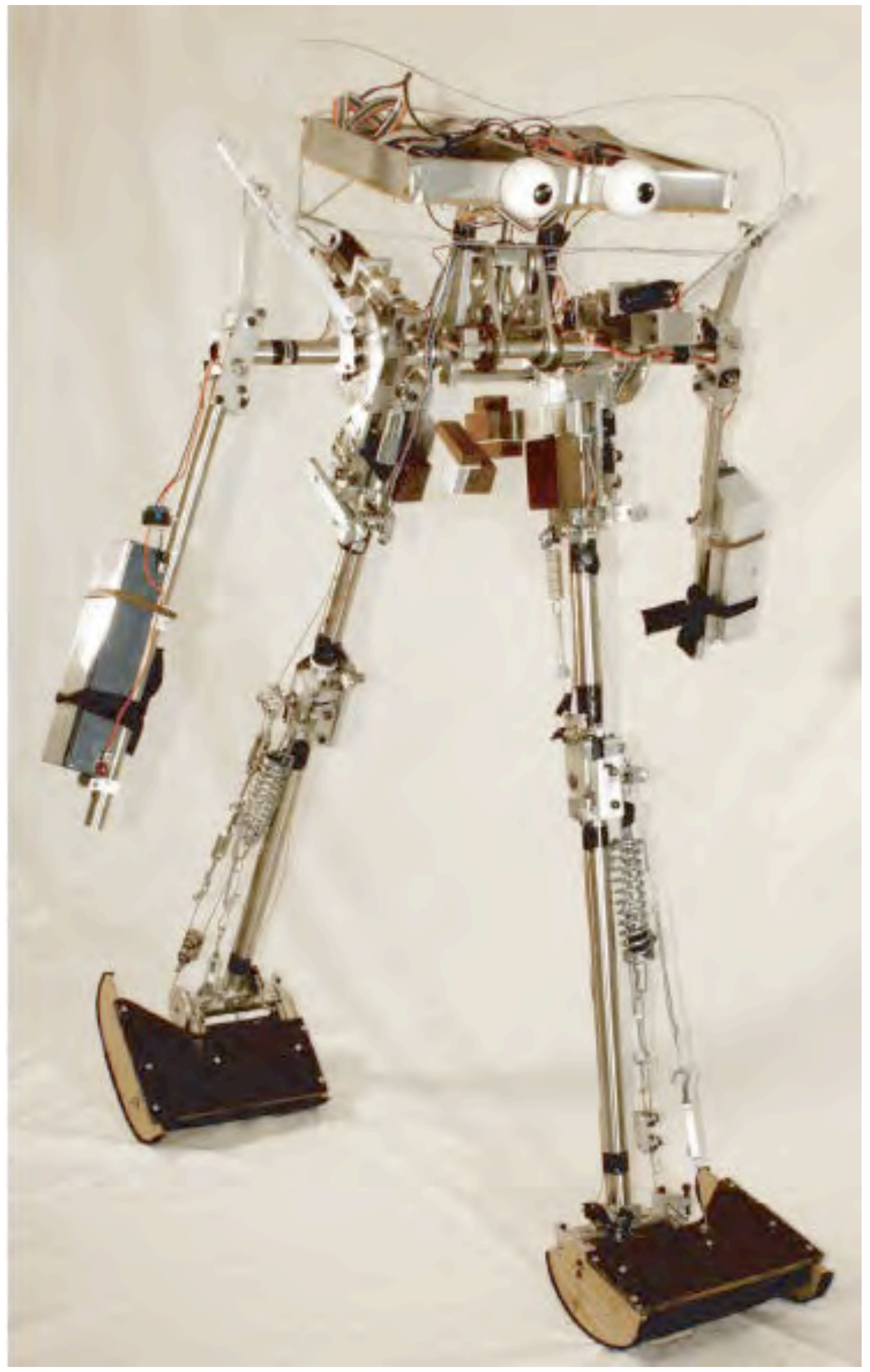
Collins et al. Efficient Bipedal Robots Based on Passive-Dynamic Walkers. *Science* 2005.



Dimensionless Cost of Transport = Energy cost / (Body Weight * Distance)

DCT: 1.6

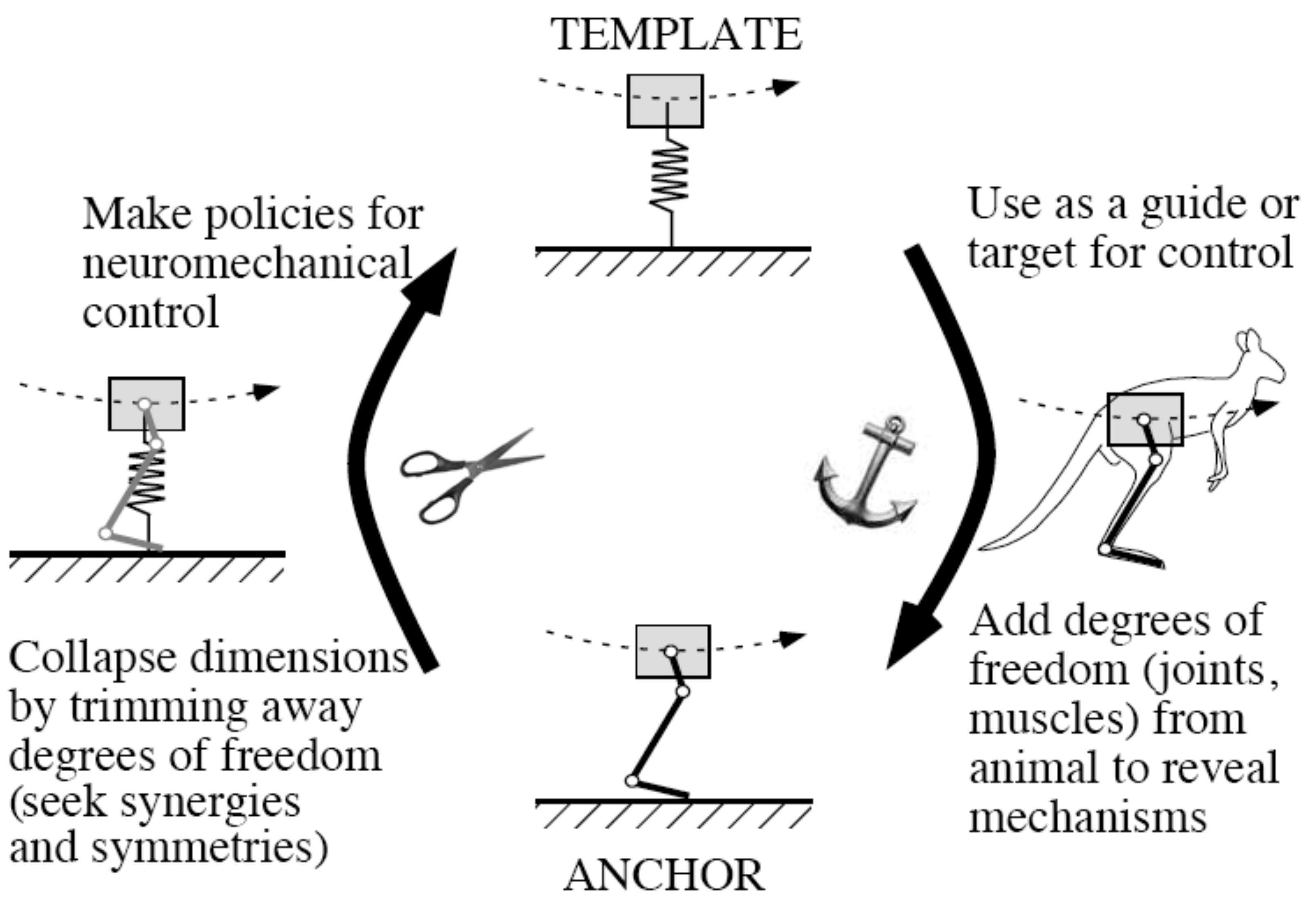
DCT: 0.05

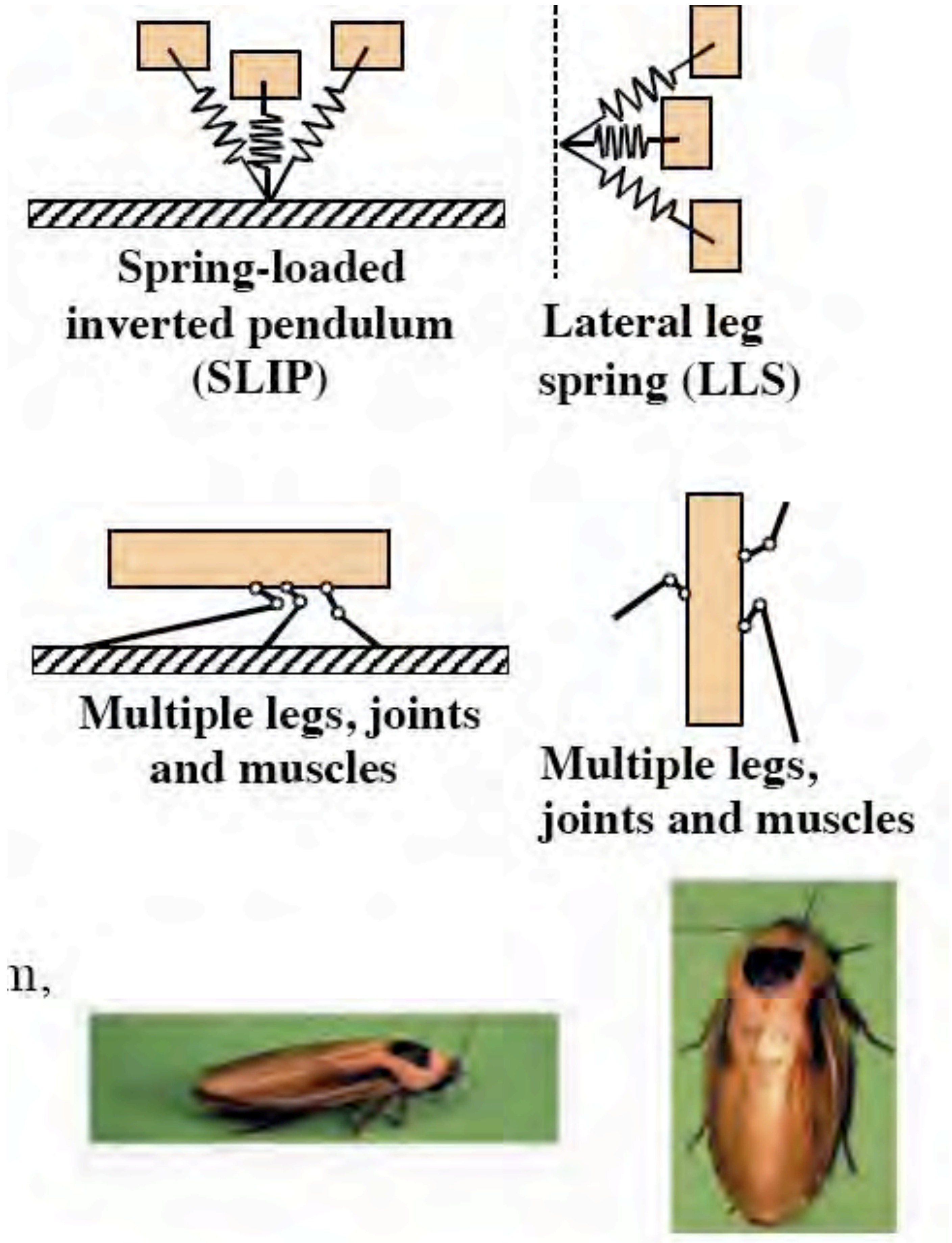


DCT: 0.055

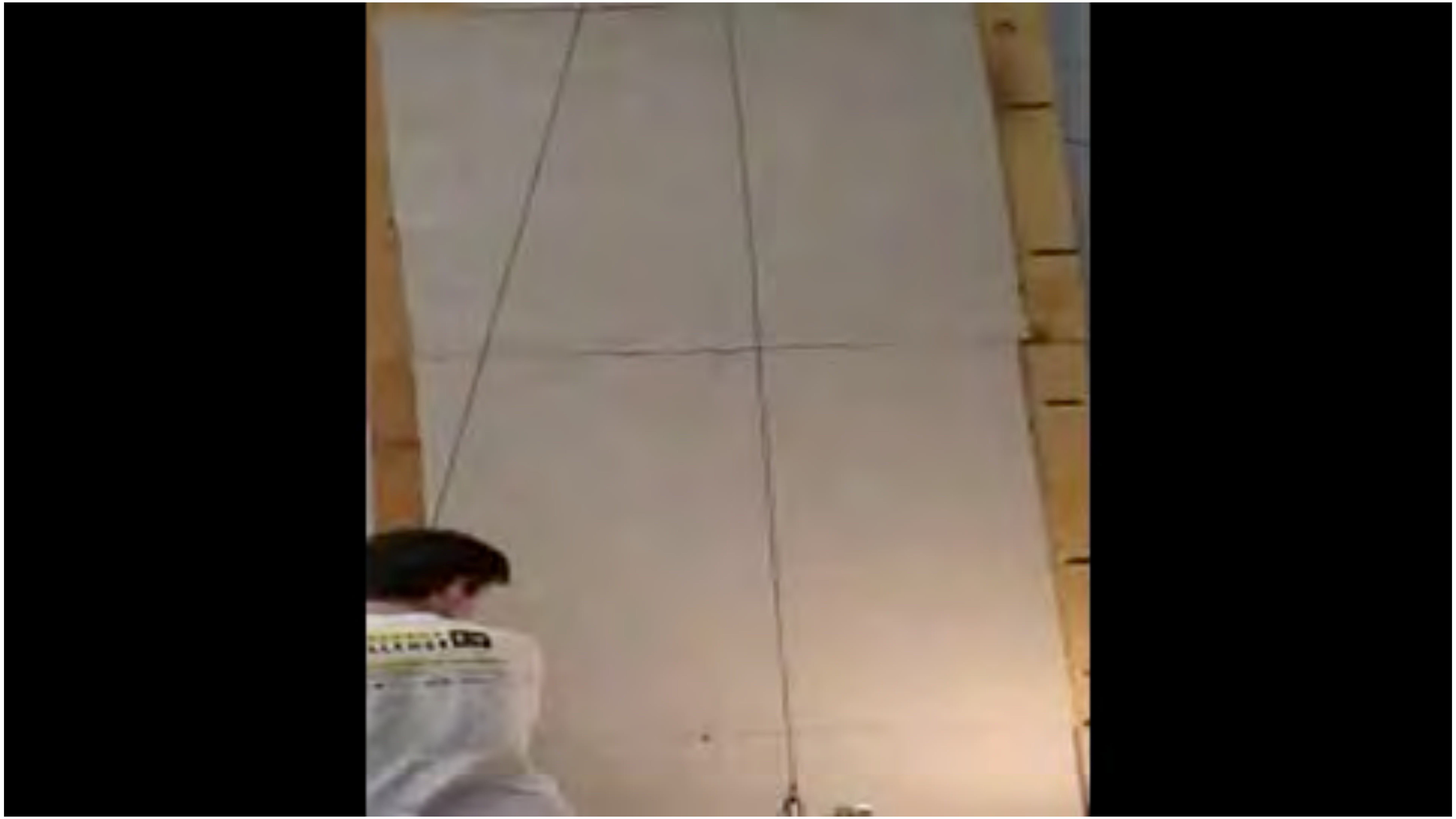
Other simplified models

Full and Koditschek. Templates and Anchors. *J. Exp. Biol.* 1999



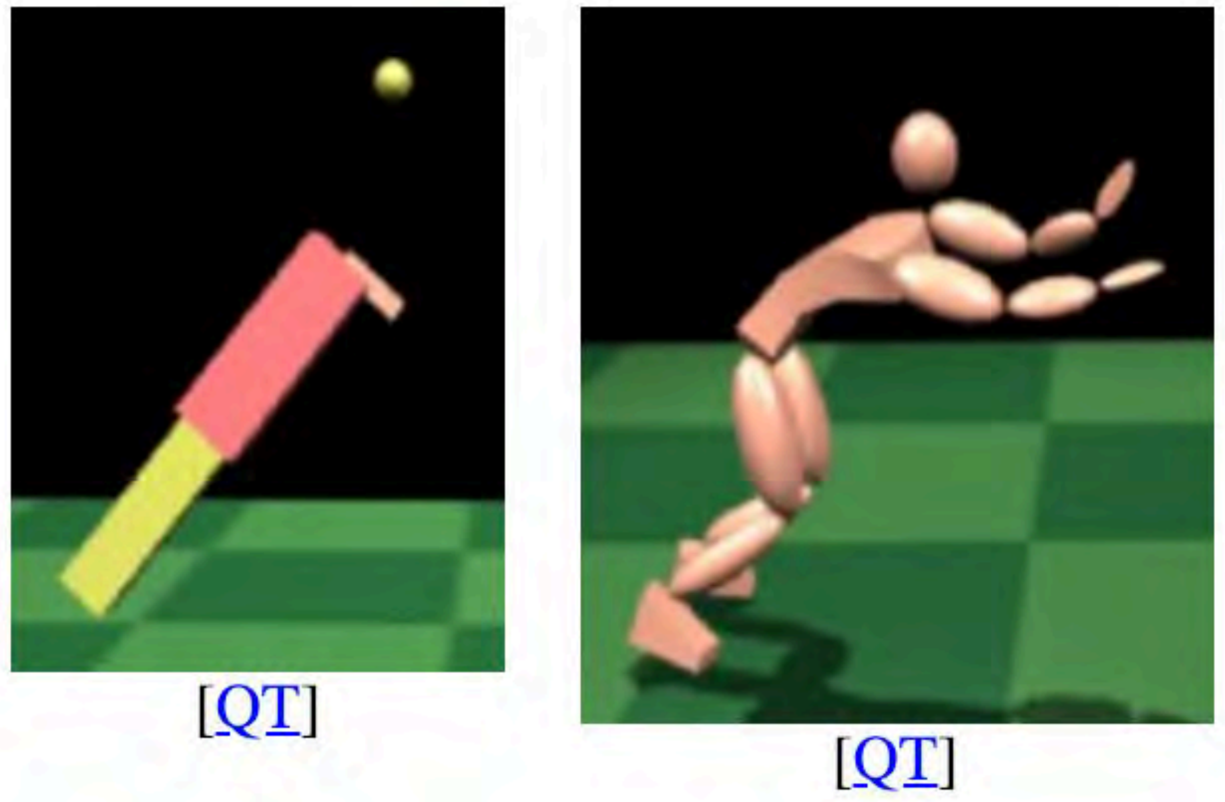


Clark et al. Design of a Bio-inspired Dynamical Vertical Climbing Robot. RSS 2007.

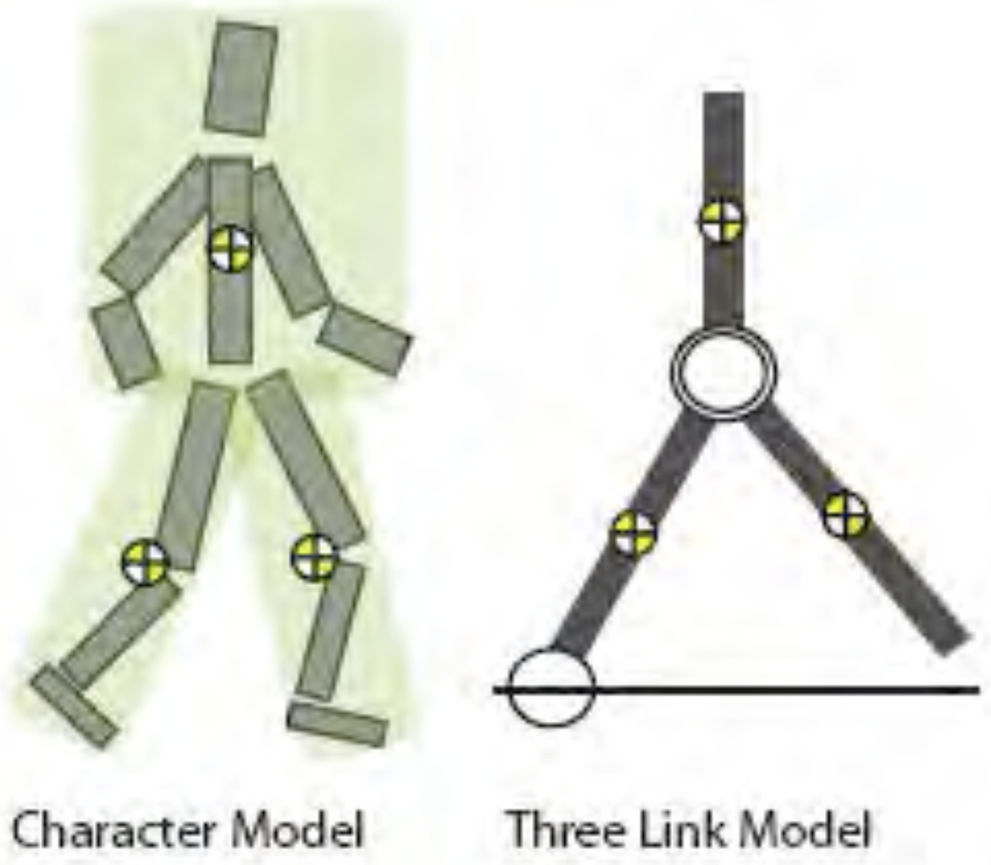


Coupling to full-body kinematics

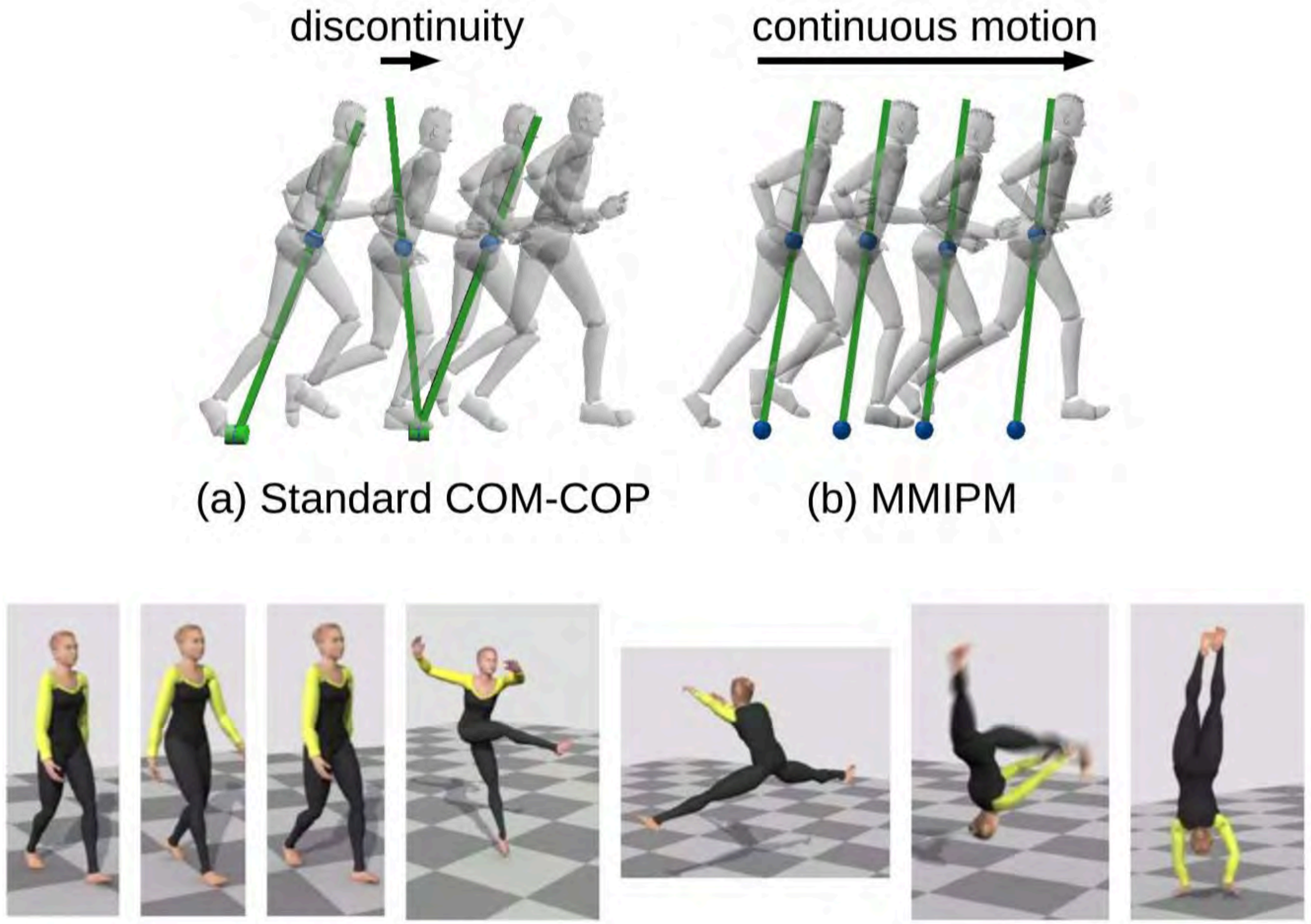
Simplified physics for controlling mocap data



Popovic and Witkin. SIGGRAPH 99



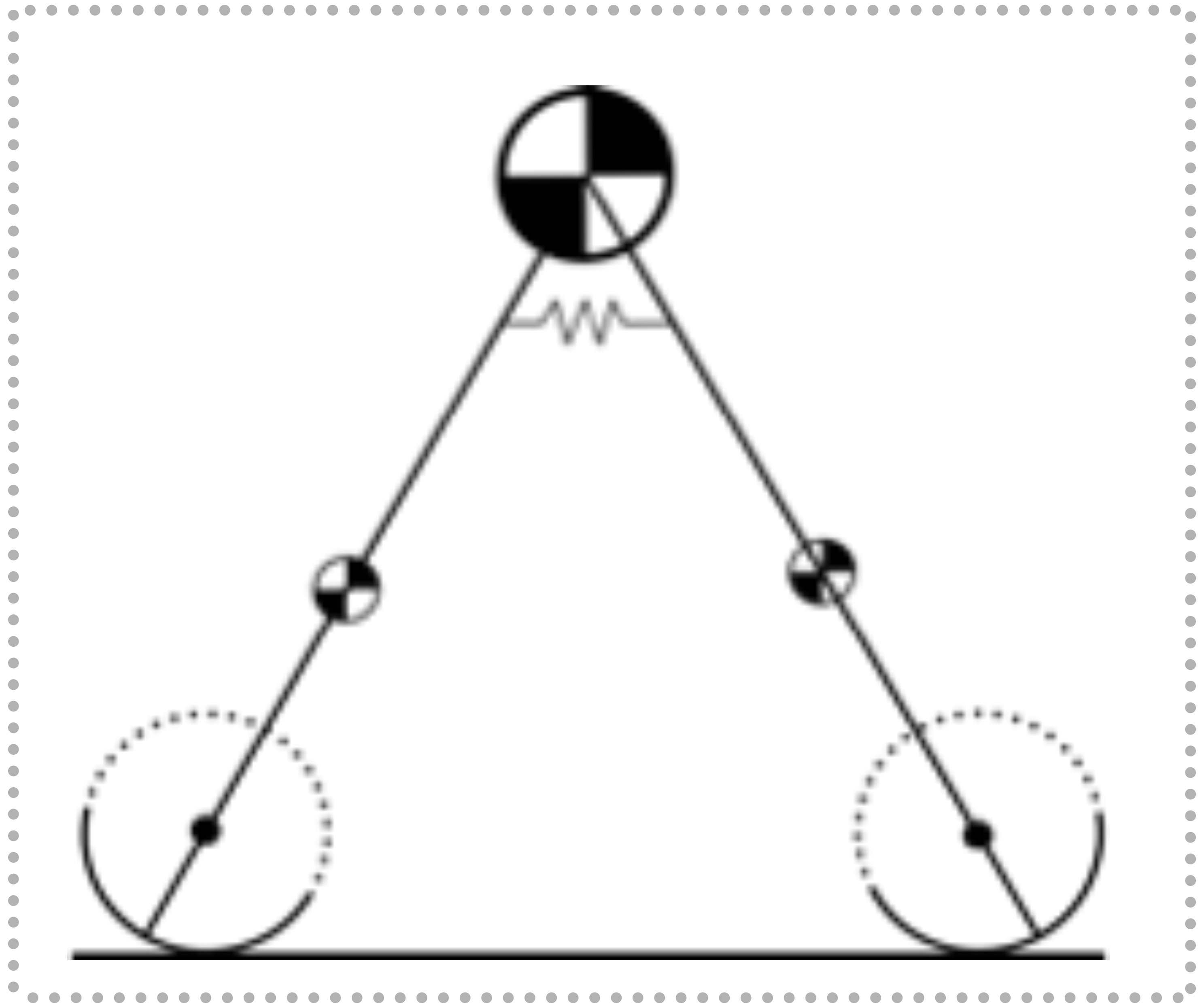
da Silva et al. SIGGRAPH 2008



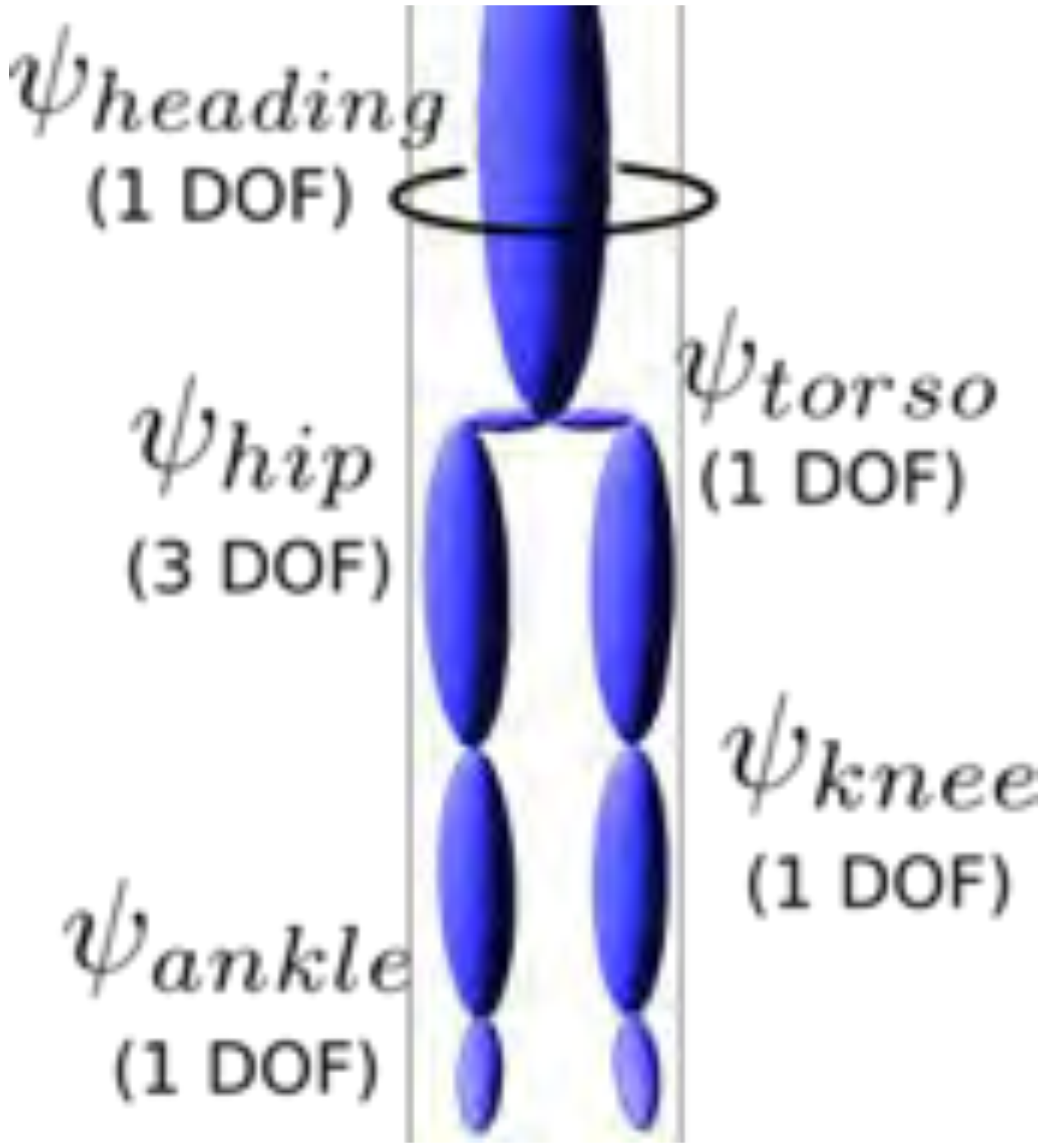
Kwon and Hodgins. TOG 2017

Physics-based person tracking

Brubaker, Hertzmann, Fleet. IJCV 2010



Anthropomorphic walker



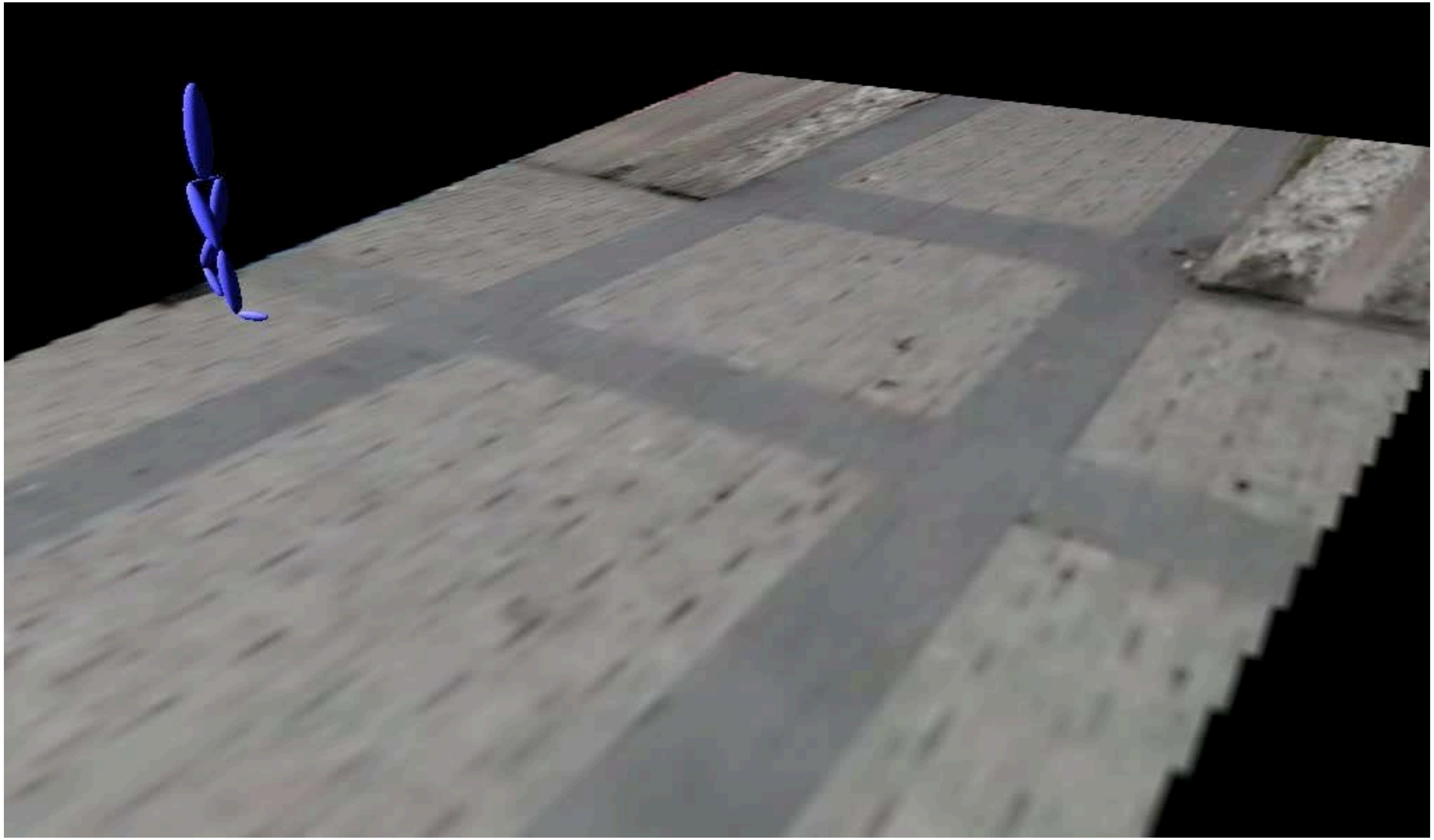
Kinematic model

Observations

Input data with occlusions

Tracking result

Side view



Displaying results

For 3D tracking and animation, you must:

- Show a different viewpoint
- With a textured ground plane
- Cast shadows

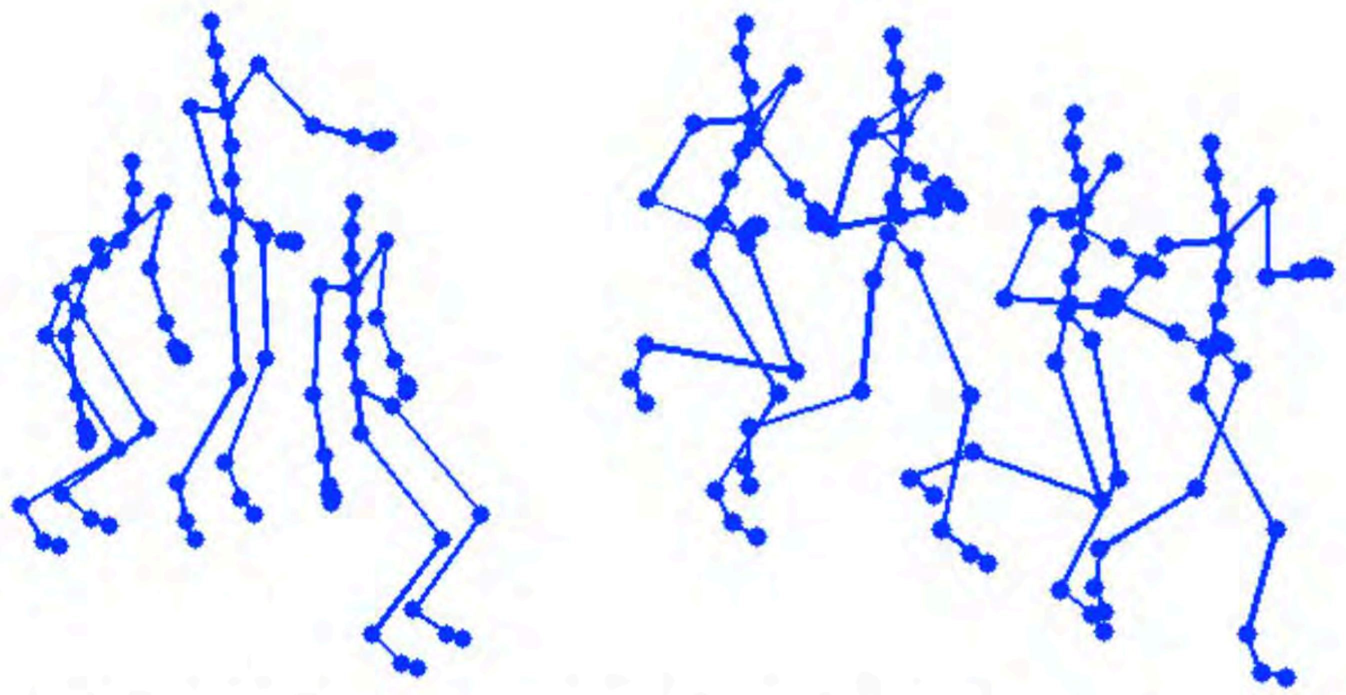
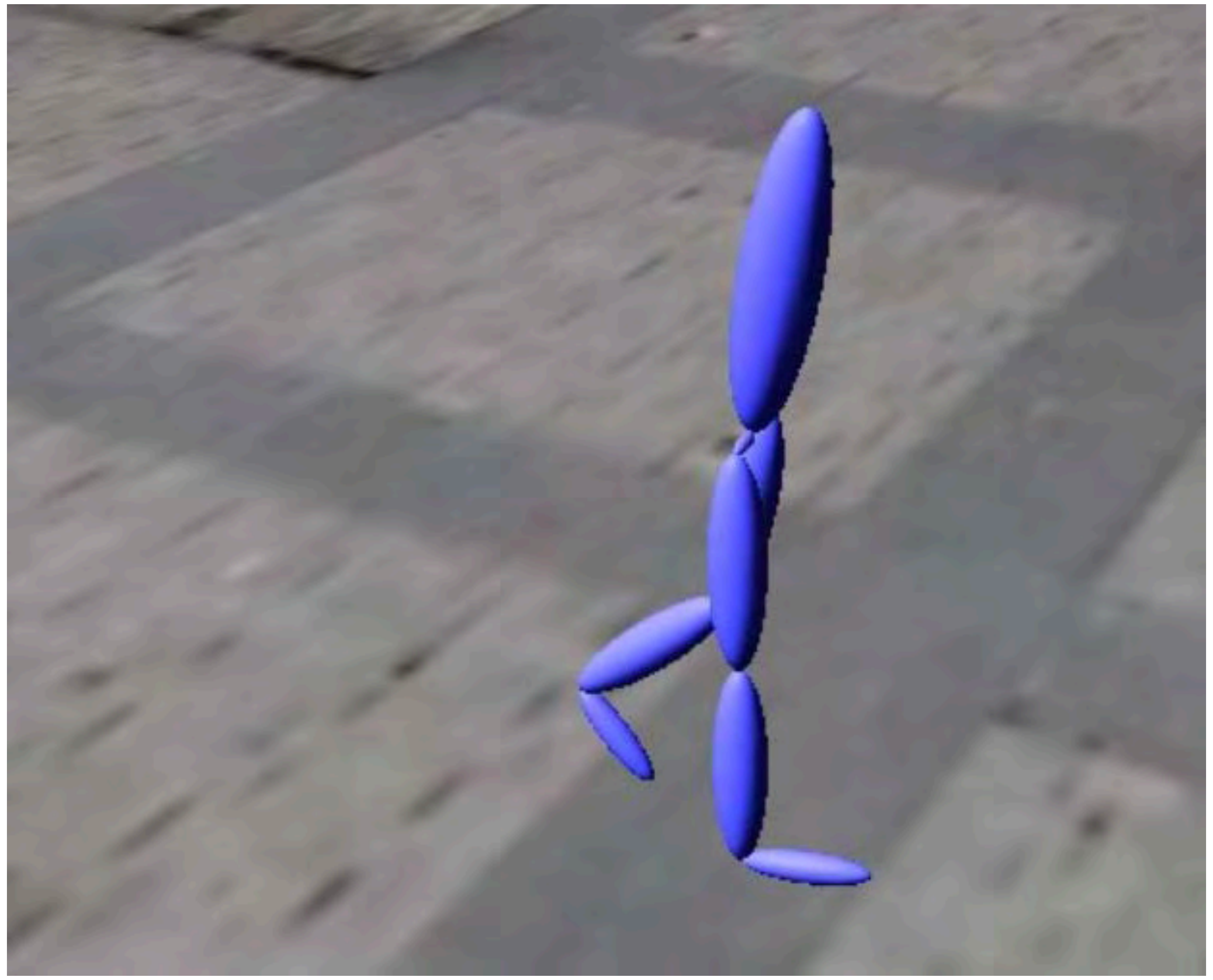


Figure 11. **Tracking human motion.** Reconstructions of a jumping and a jogging sequence with an image noise of variance 4.

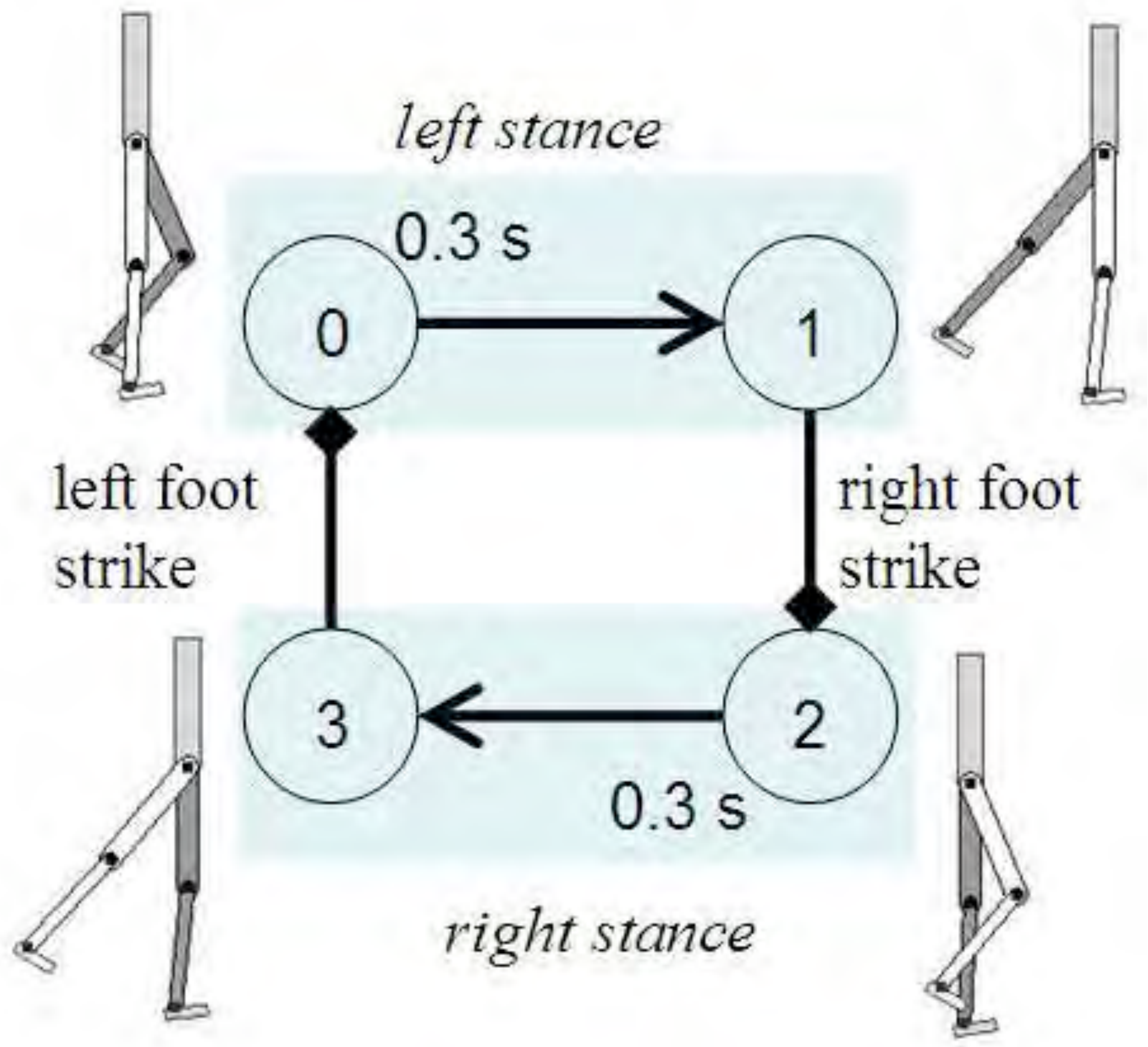
Bad



Better

Best

Controllers

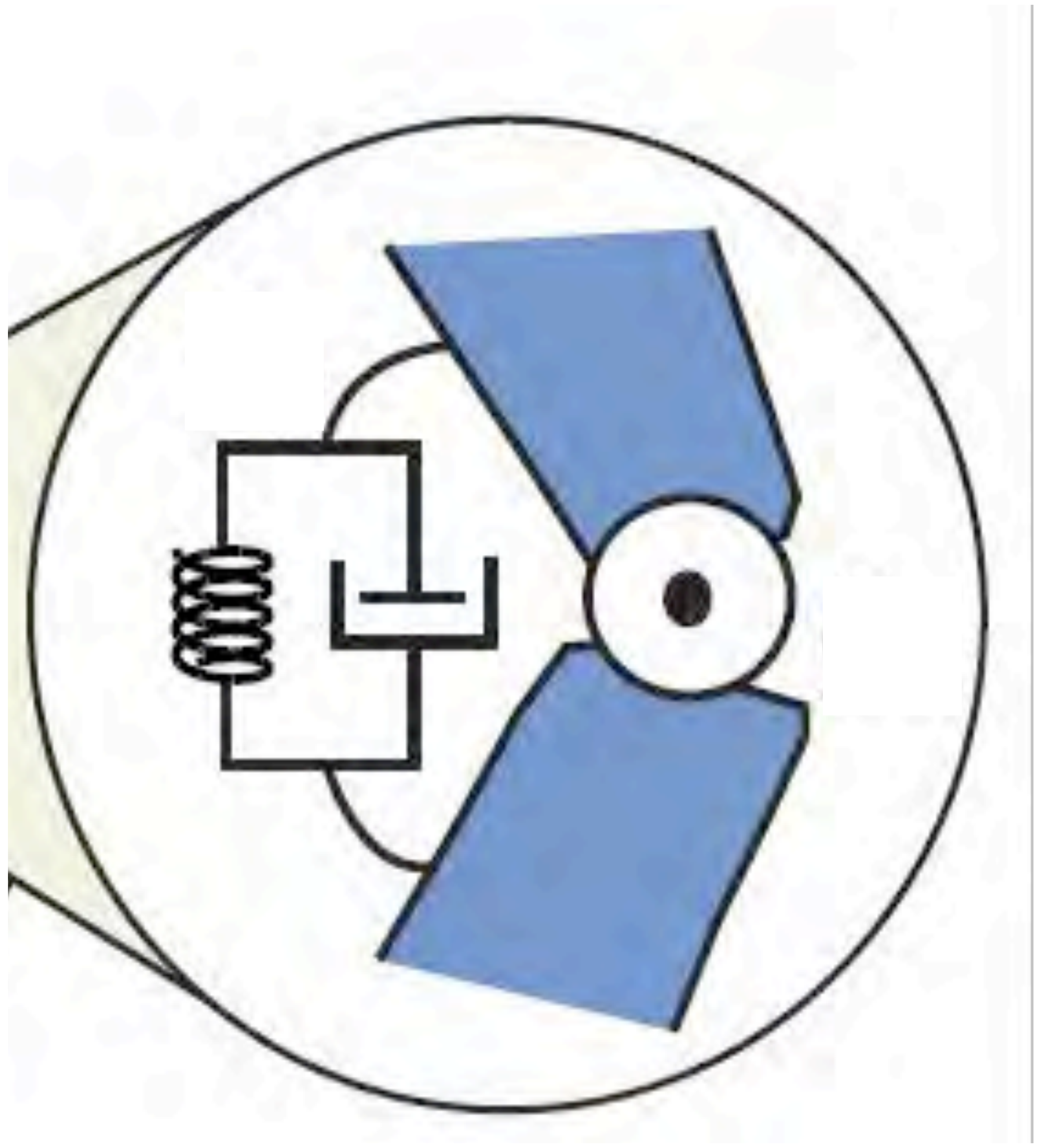


Controller:

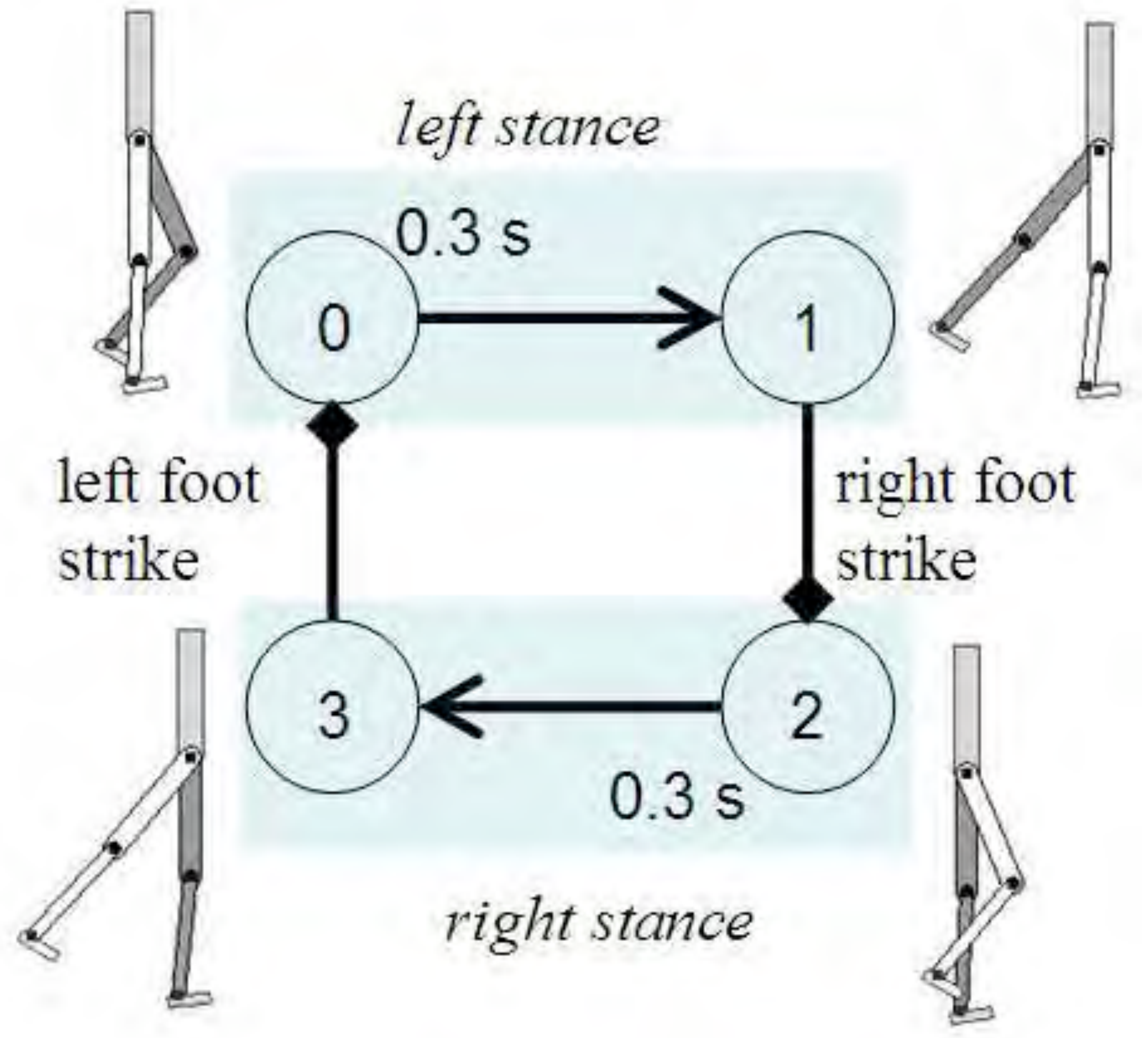
Mapping from state to joint torques:

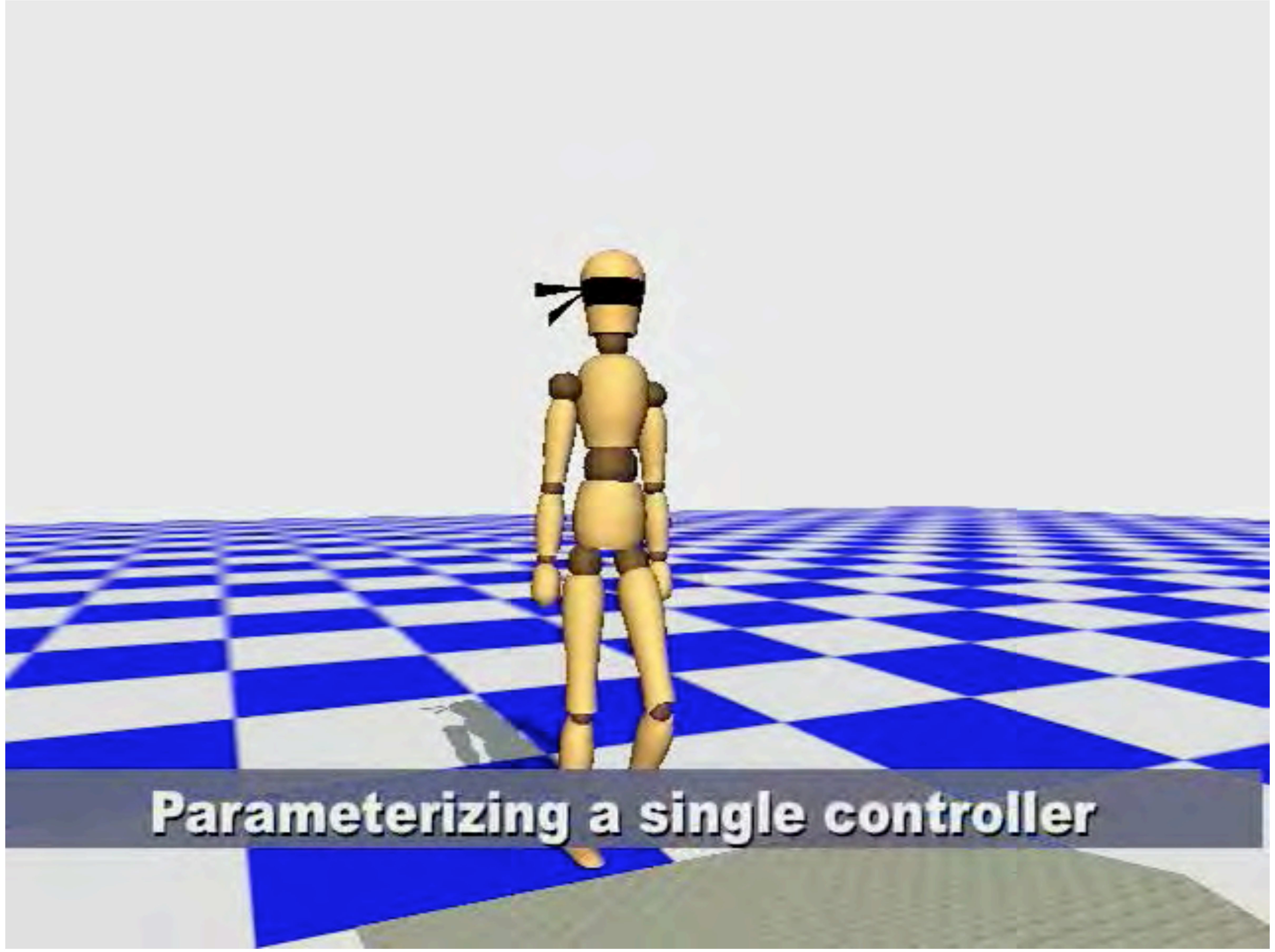
$$\boldsymbol{\tau} = f(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{S})$$

Proportional-Derivative (PD) control: $\tau = k_s(q - \bar{q}) + k_d\dot{q}$

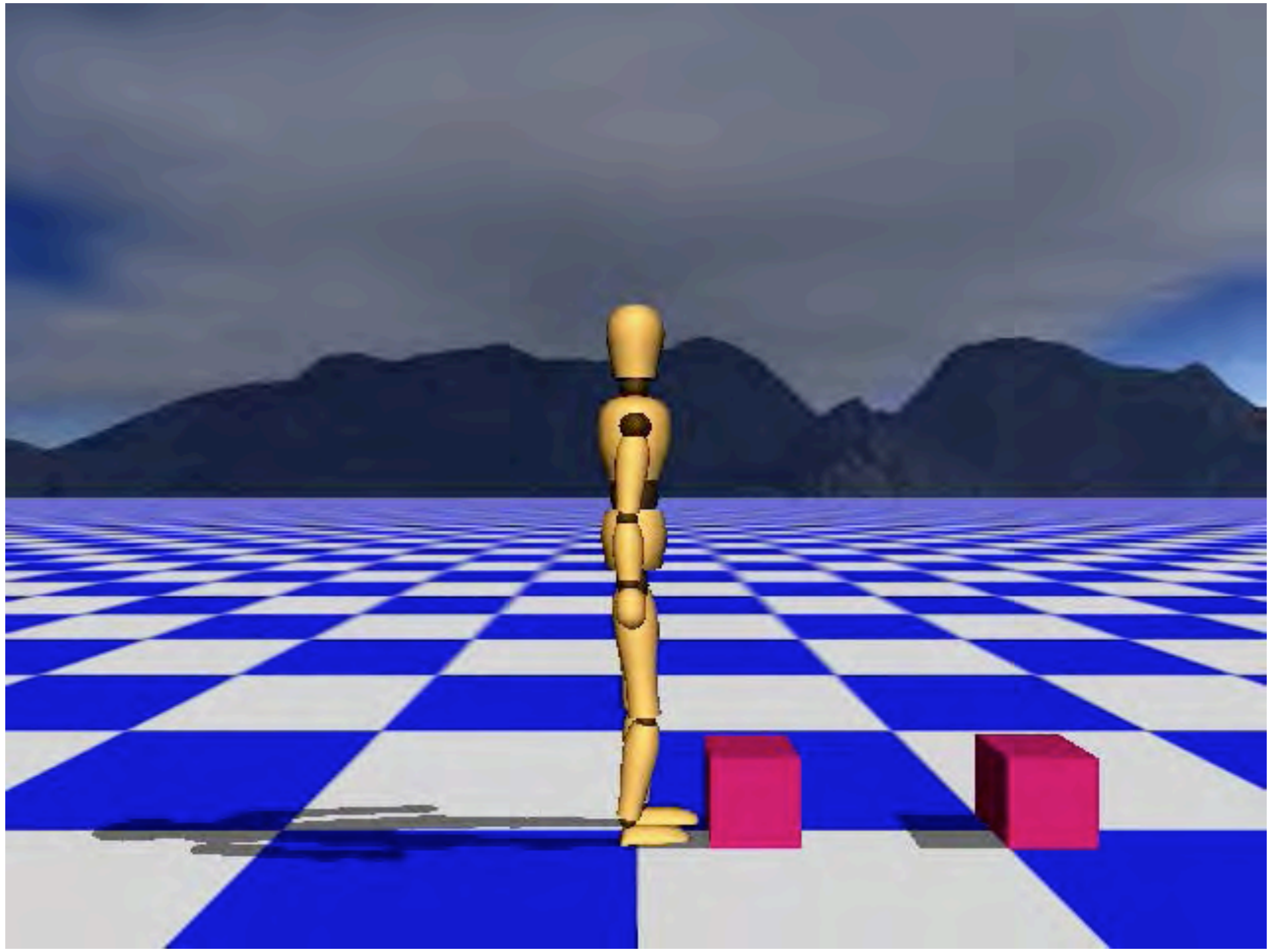


K. Yin et al. SIMBICON: Simple Biped Locomotion Control. SIGGRAPH 2007





K. Yin et al. SIMBICON: Simple Biped Locomotion Control. SIGGRAPH 2007



K. Yin et al. SIMBICON: Simple Biped Locomotion Control. SIGGRAPH 2007

Optimizing walking controllers

with:

Jack Wang

David Fleet

SIGGRAPH 2009, SIGGRAPH Asia 2010

Optimization overview

Control parameters
& Start state

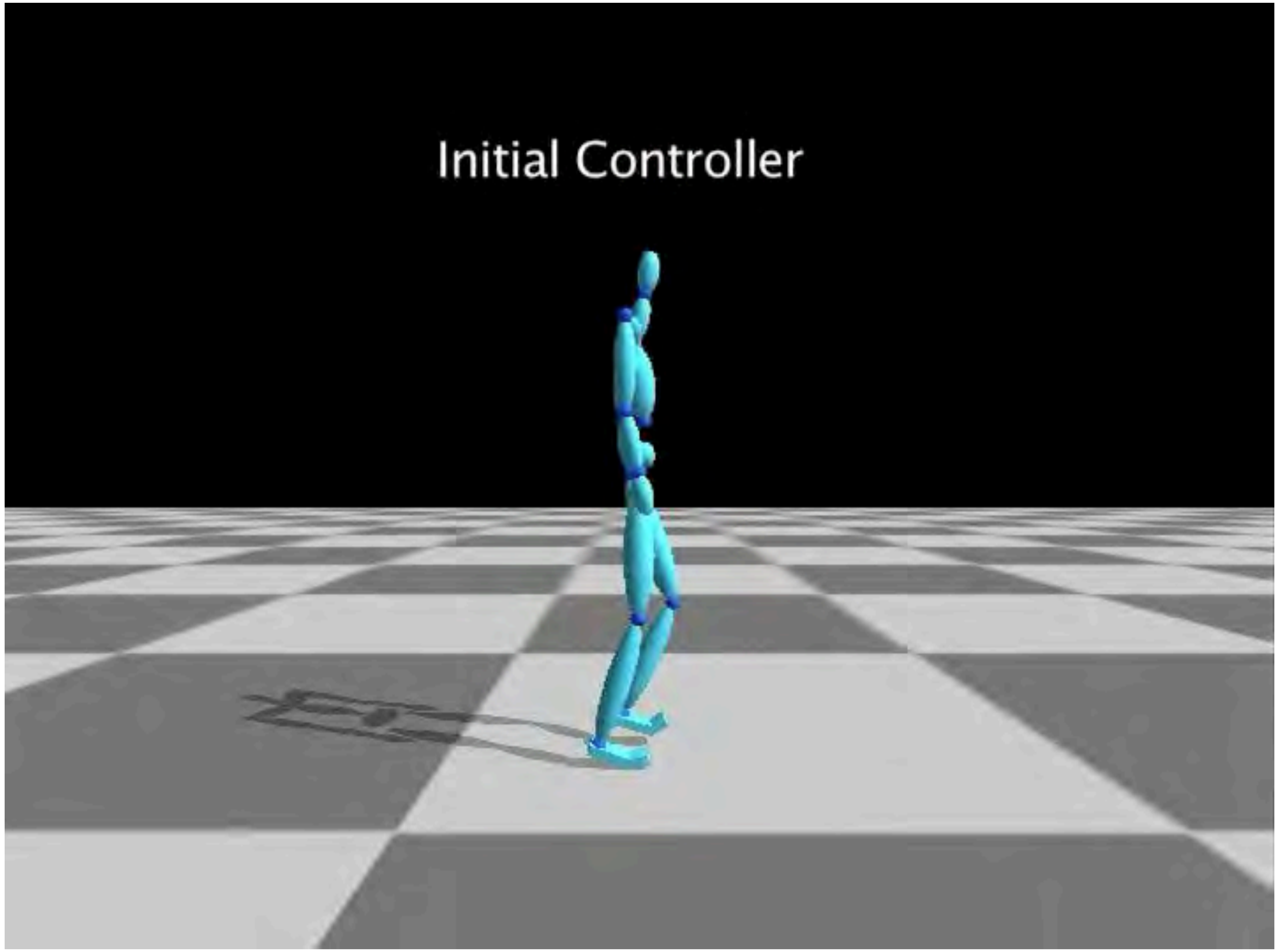
Simulation

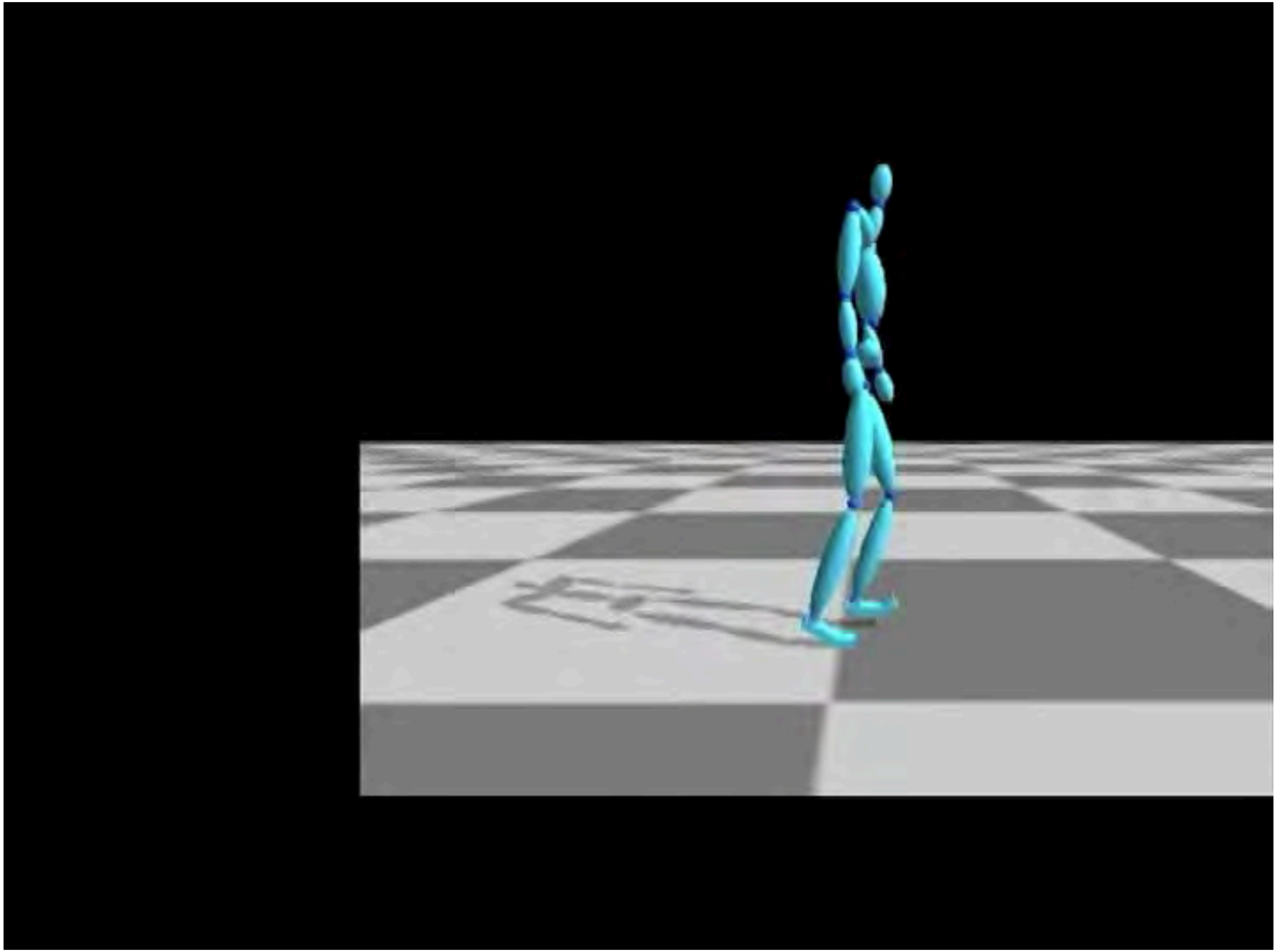
Walking motion (**x**)

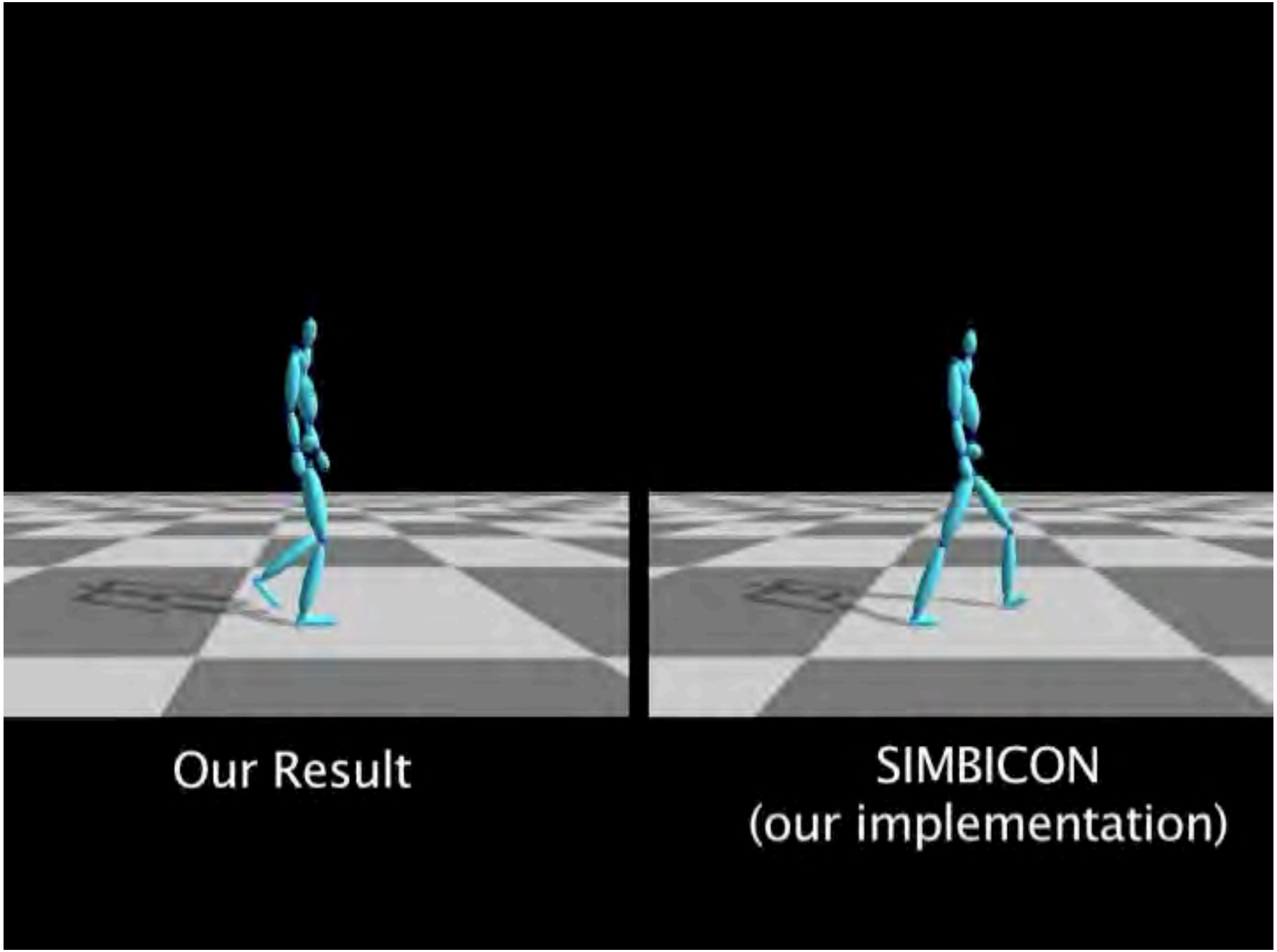
Objective
function

$$R(\mathbf{s}_{1:T}) = \sum_i w_i E(\mathbf{s}_{1:T})$$

Optimization

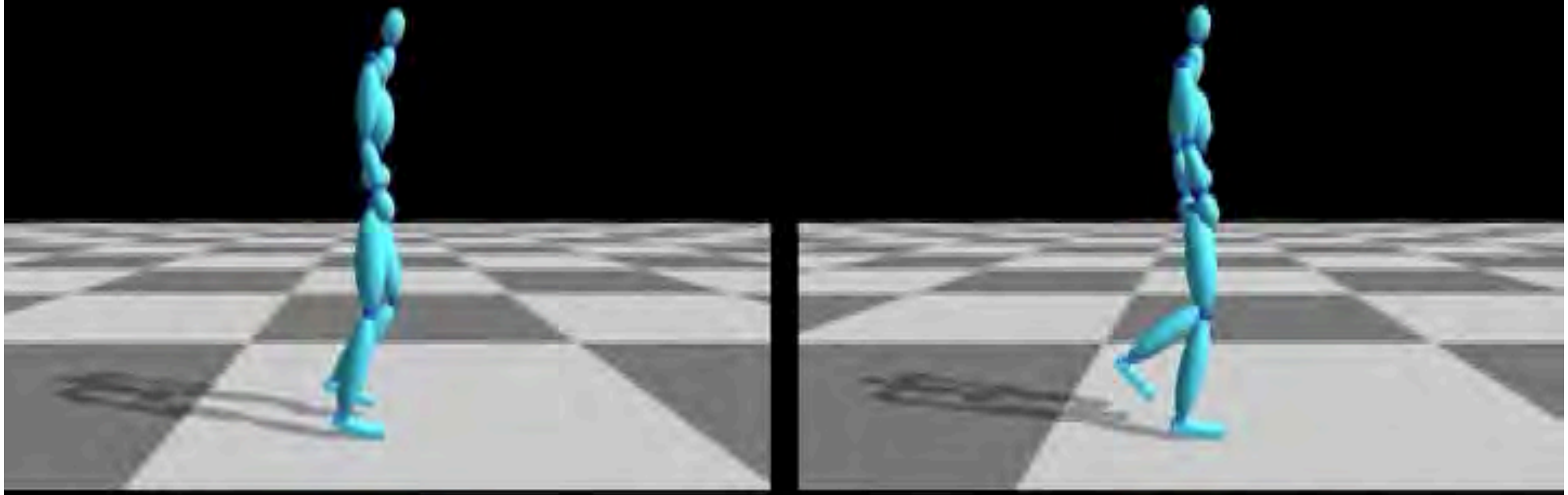




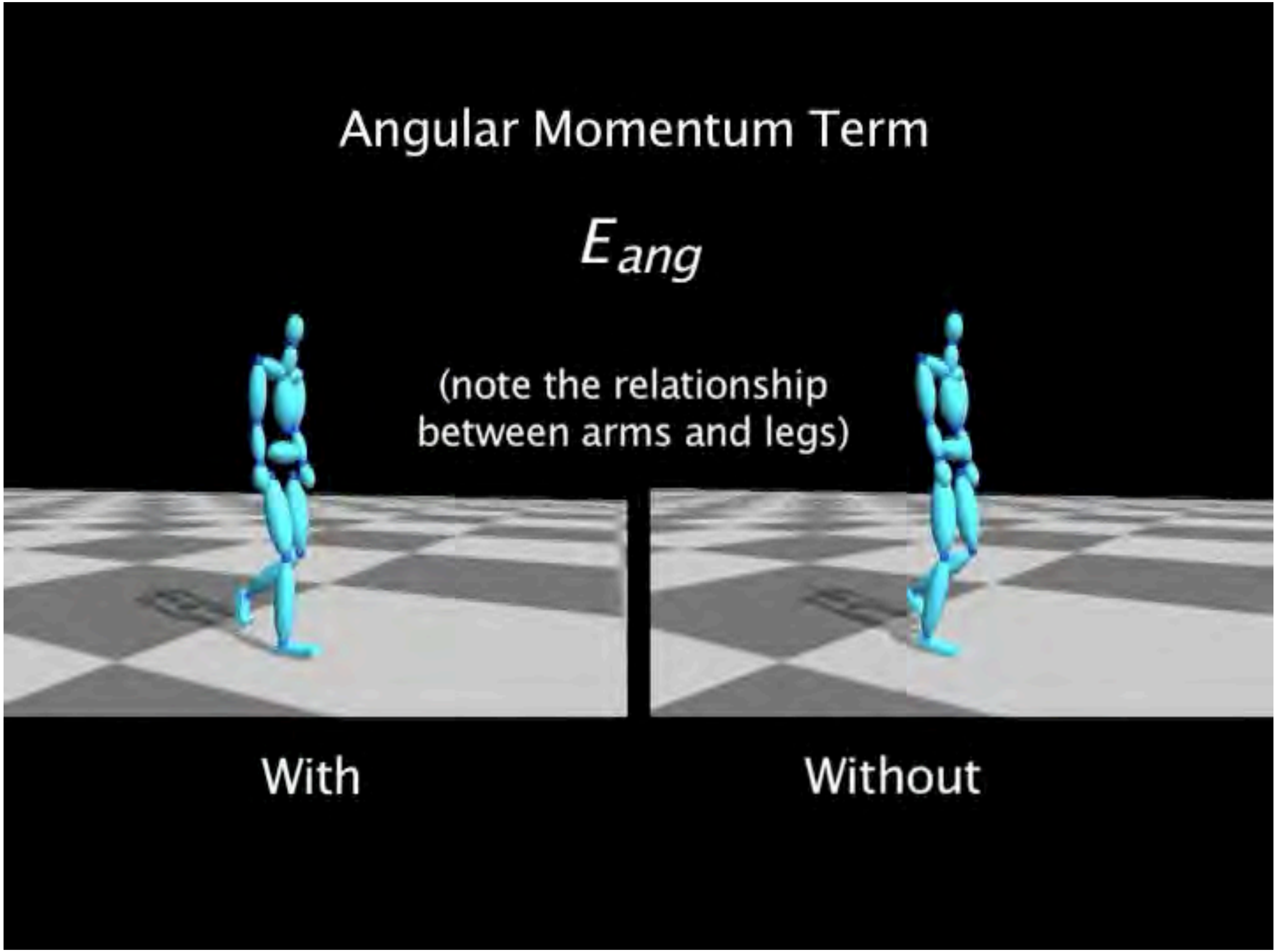

Our Result
SIMBICON
(our implementation)

Head Stabilization Term

E_{head}

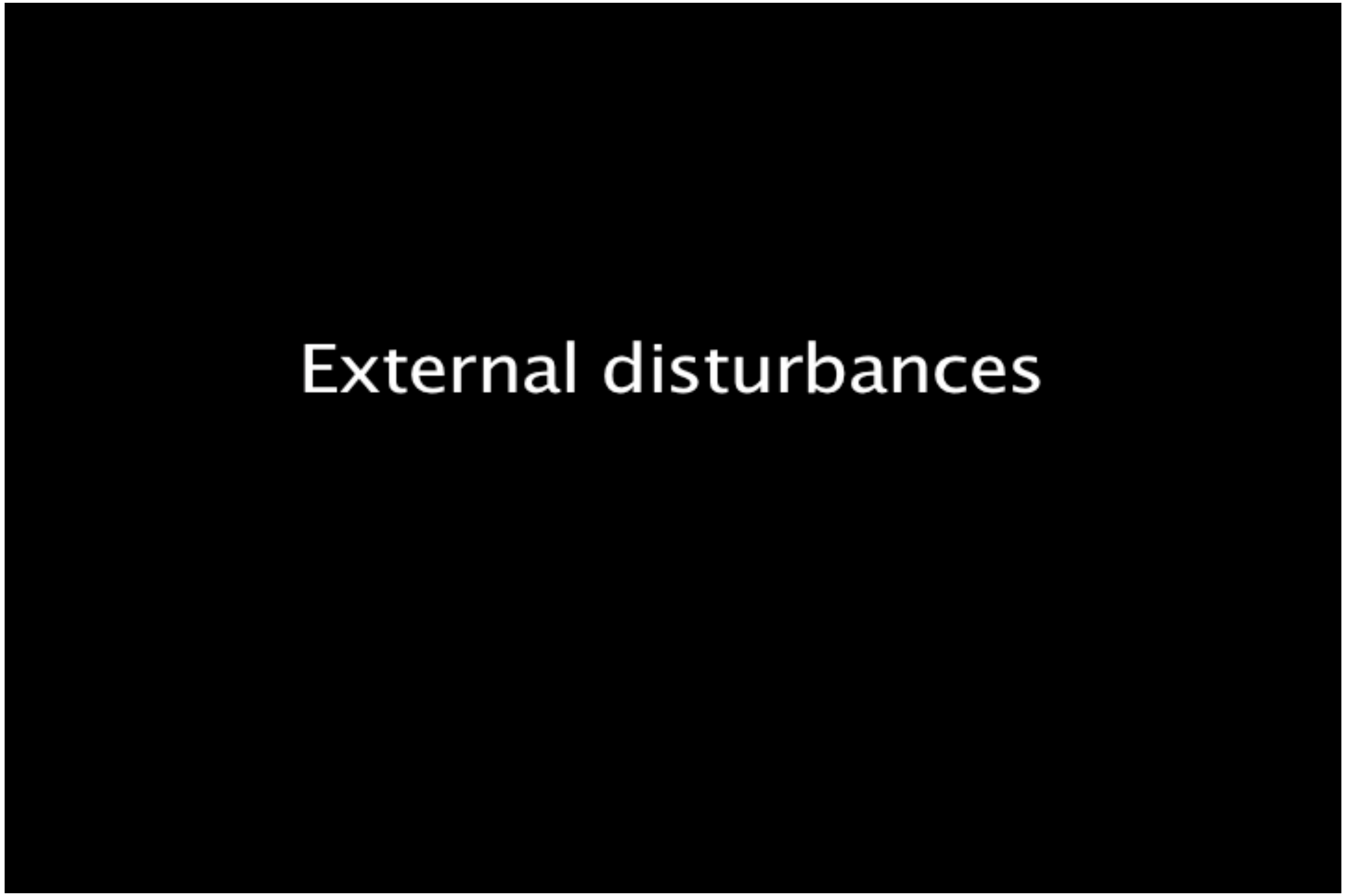


With | Without


Angular Momentum Term
E_{ang}
(note the relationship between arms and legs)
With
Without

The role of uncertainty

Many elements of natural environments are unpredictable



The role of uncertainty

Many sources of uncertainty:

- Environment
- External forces
- User control
- Motor noise [Harris and Wolpert *Nature* 1998]

Approach

Define a probability distribution:

$$p(\mathbf{s}_{1:T})$$

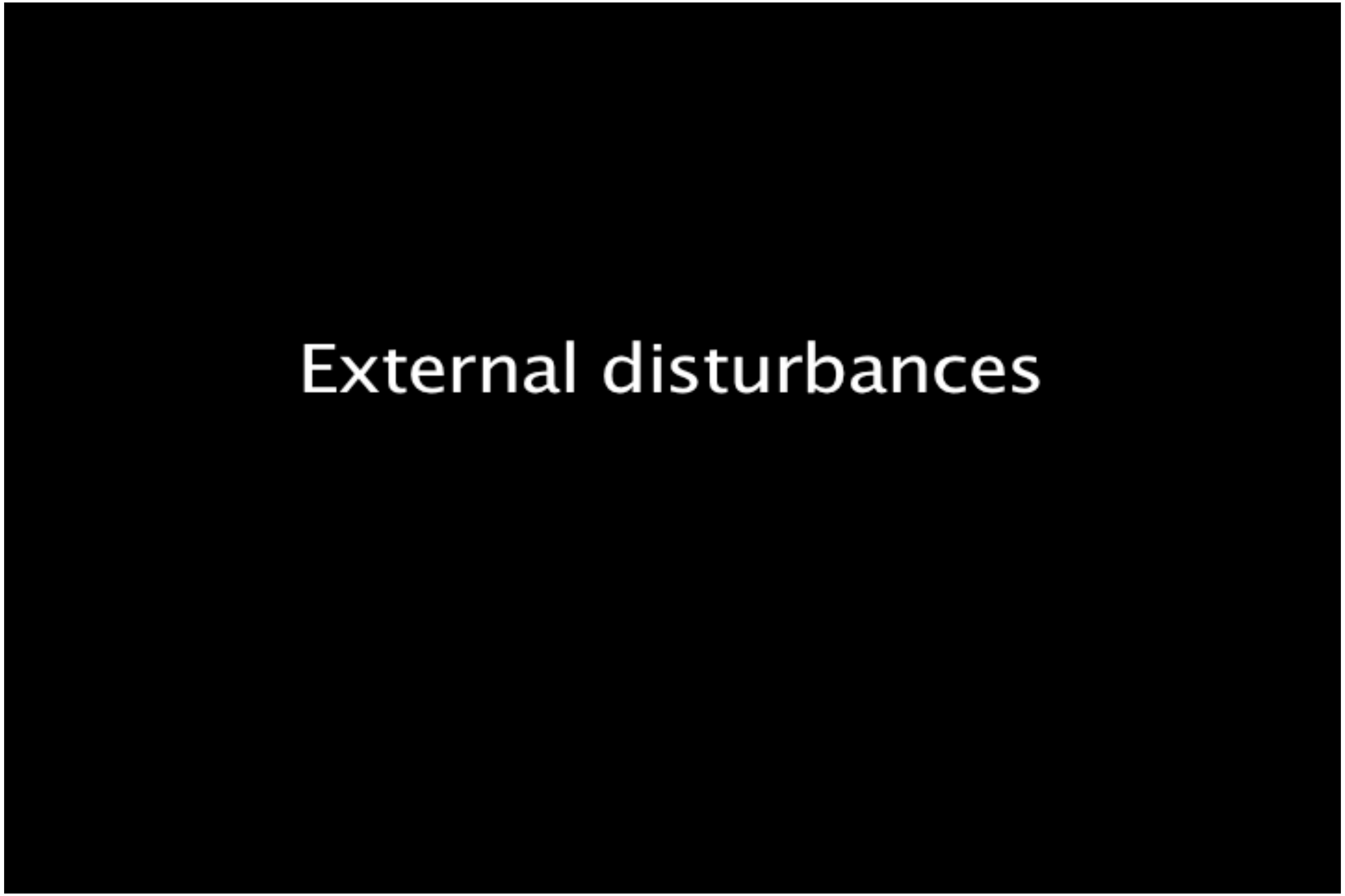
Want to optimize:

$$E_{p(\mathbf{s}_{1:T})}[R(\mathbf{s}_{1:T})]$$

Monte Carlo approximation:

$$\frac{1}{N}\sum_j R(\mathbf{s}_{1:T}^{(j)}) \qquad \mathbf{s}_{1:T}^{(j)} \sim p(\mathbf{s}_{1:T})$$

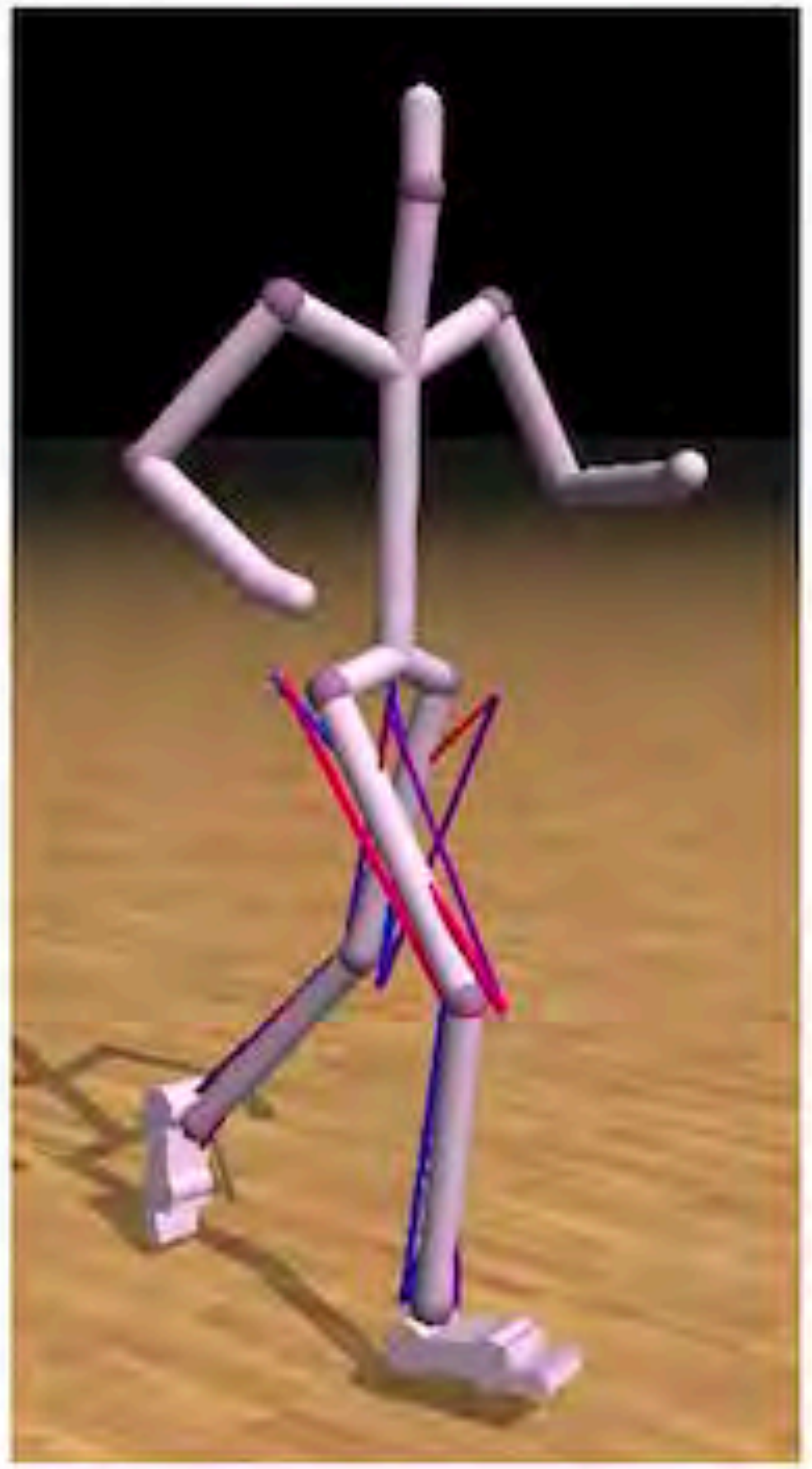
Optimizing controllers with uncertainty

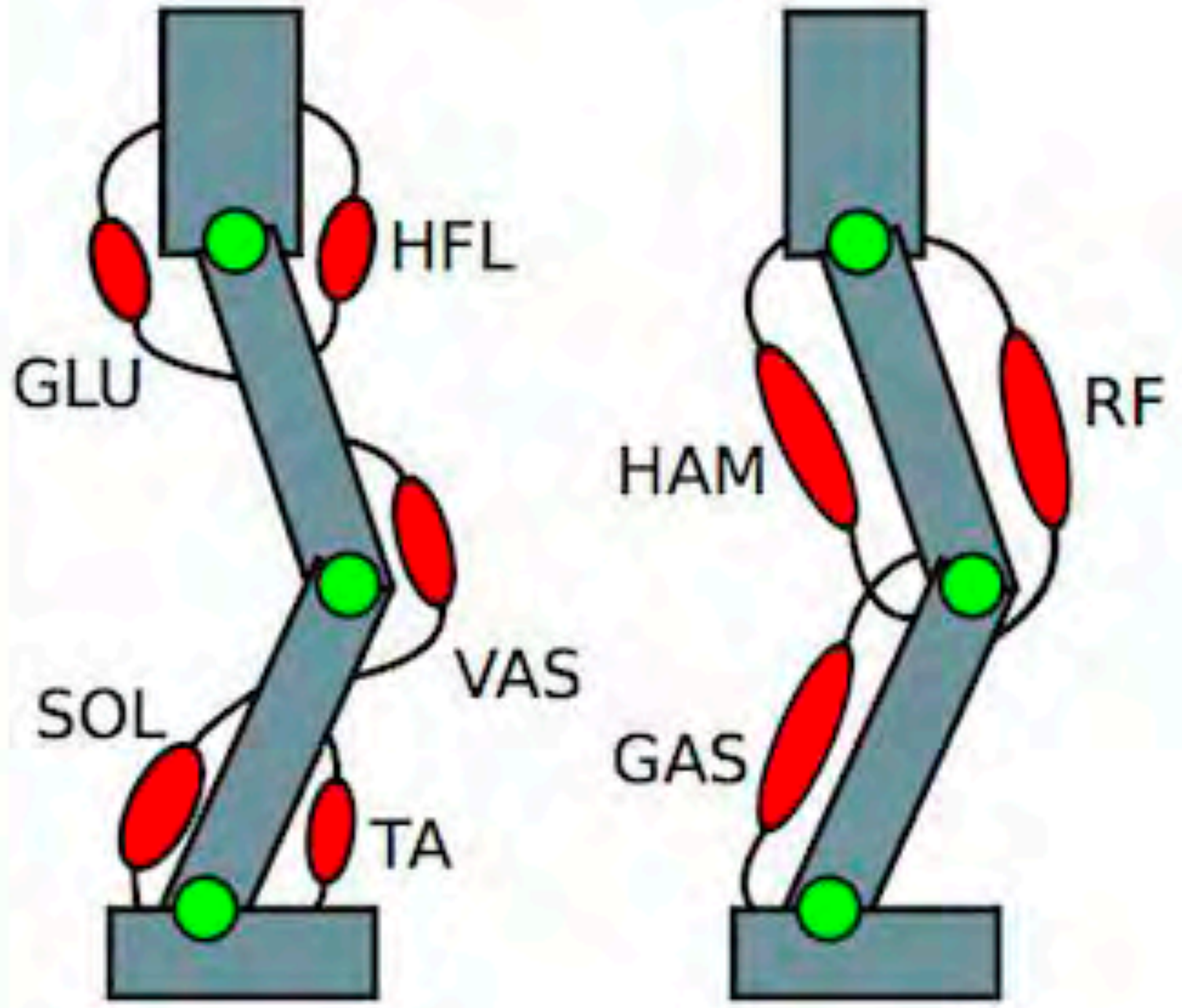


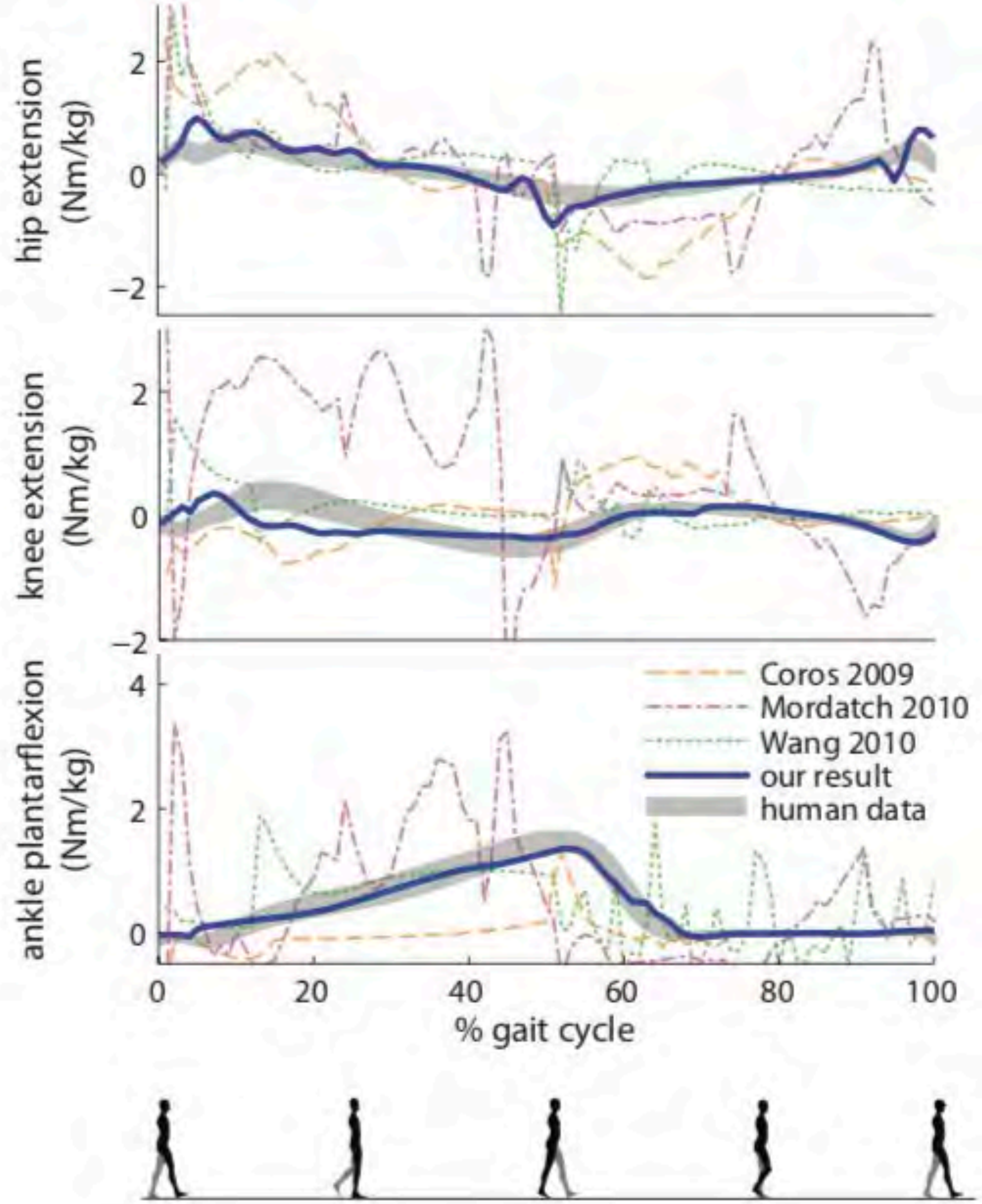
Optimizing controllers with uncertainty

Optimizing controllers with uncertainty

Biology-based actuators and objectives

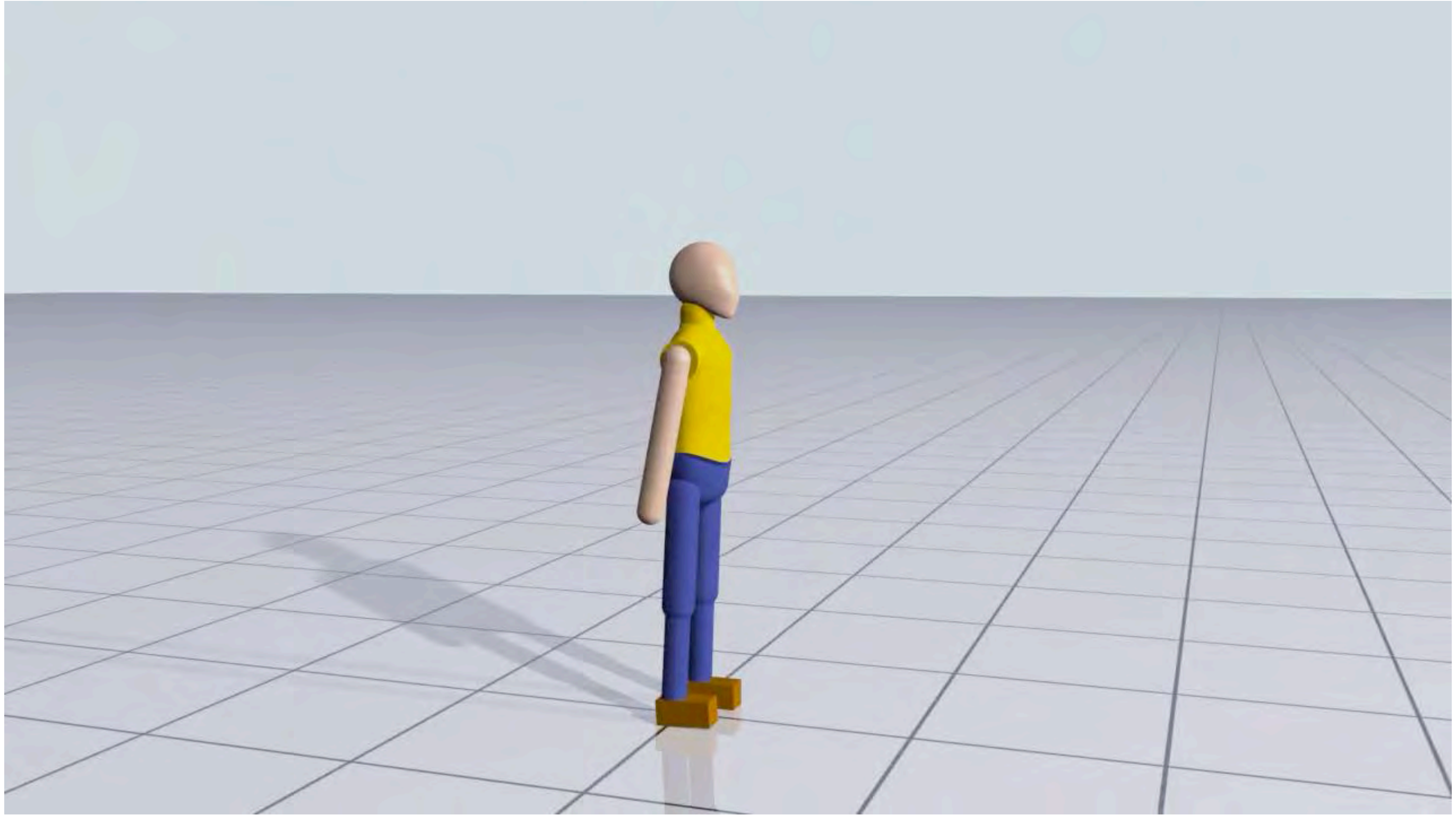






J.M.Wang et al. SIGGRAPH 2012

Deep controllers with symmetry



Yu, Turk, Liu. SIGGRAPH 2018

Optimization-based control

At each time step, optimize torques:

$$\boldsymbol{\tau}^* = \arg\min E(\boldsymbol{\tau})$$

Typical objective terms:

1. Follow specified trajectory (mocap or MPC)
2. Maintain balance

Reference-based control

Motion capture

da Silva et al. SIGGRAPH 2008

Controller

da Silva et al. SIGGRAPH 2008

New environment

da Silva et al. SIGGRAPH 2008

Feature-based control

with:

Martin de Lasa

Igor Mordatch

Feature-Based Control

Author control using a small set of *features*

- Goals describe high-level aspects of motion
- Directly apply biomechanical observations

Control is much easier/faster to design

Controllers have many new skills and abilities

Note: everything is hand-tuned for now

Key features

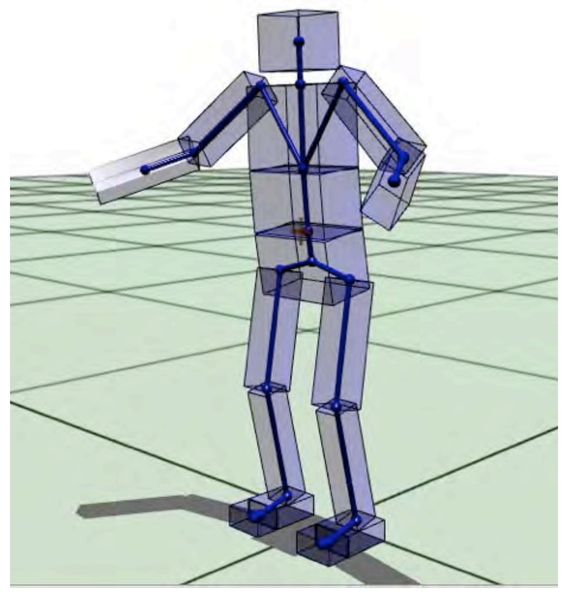
1. Center-of-mass (COM)
2. Angular momentum (AM)
3. End-effectors (feet)

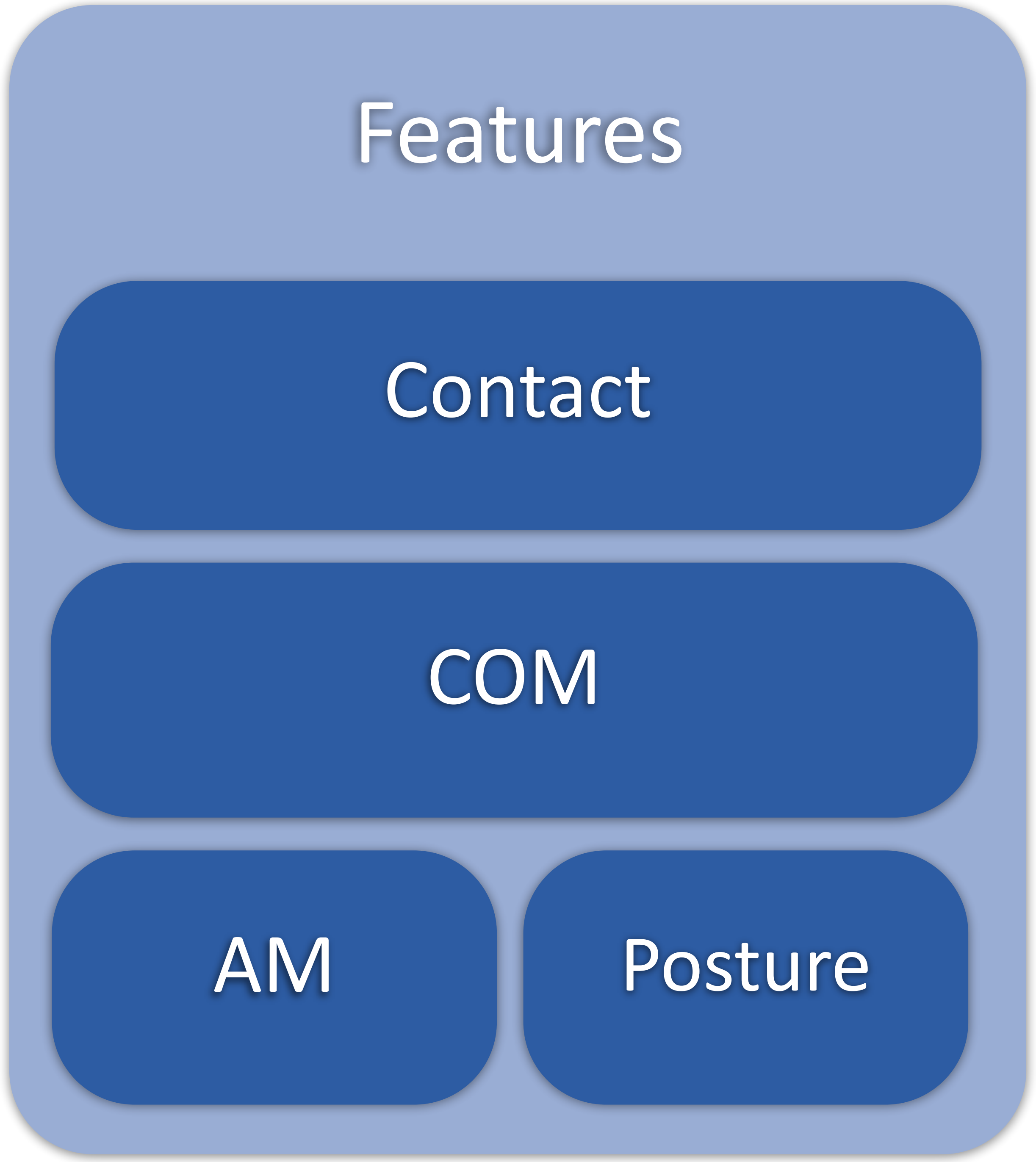
Feature ↓   Pose ↓

$$\mathbf{y} = f(\mathbf{q})$$

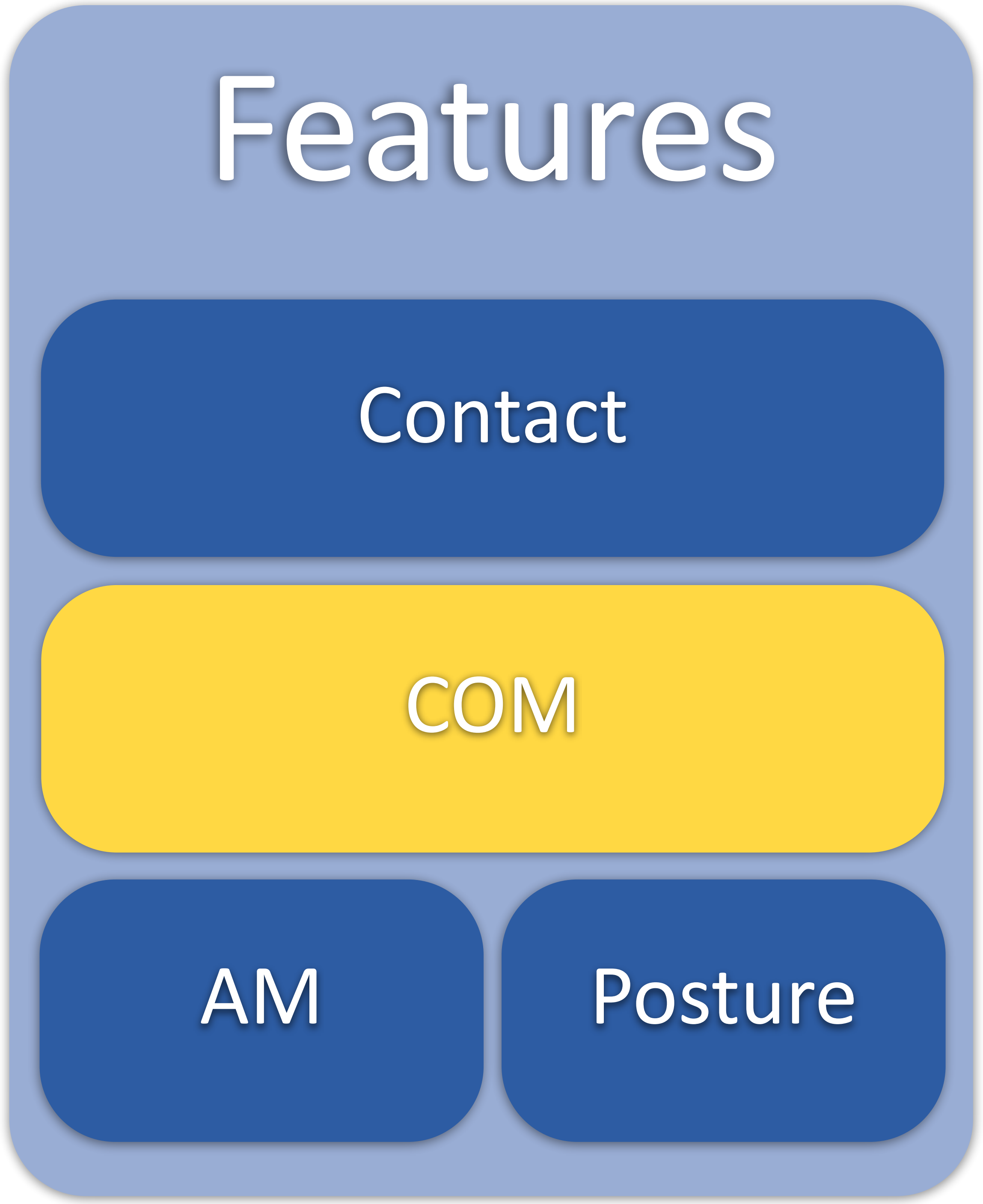
$$\mathbf{L} = g(\mathbf{q}, \dot{\mathbf{q}})$$

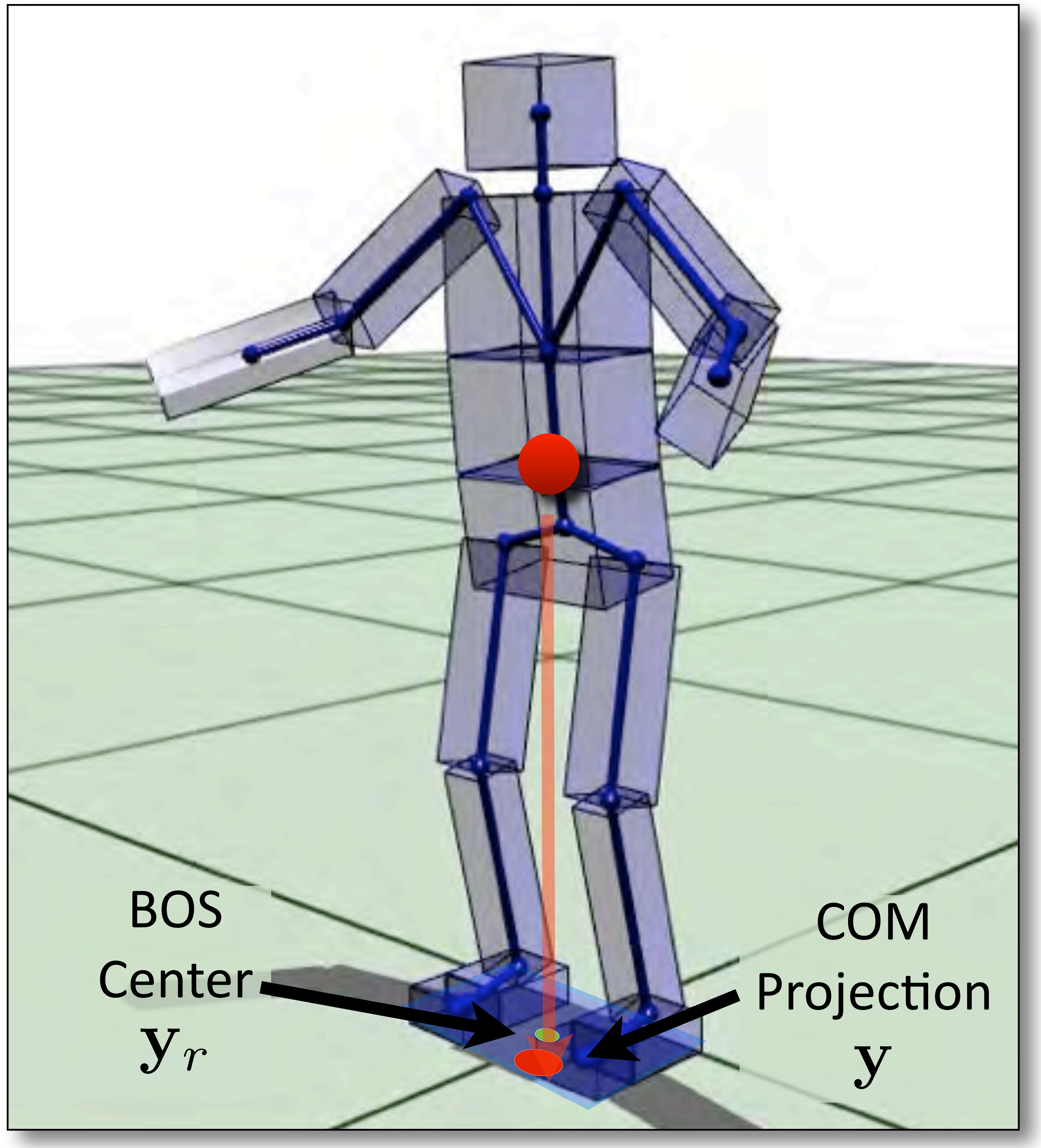
Balancing



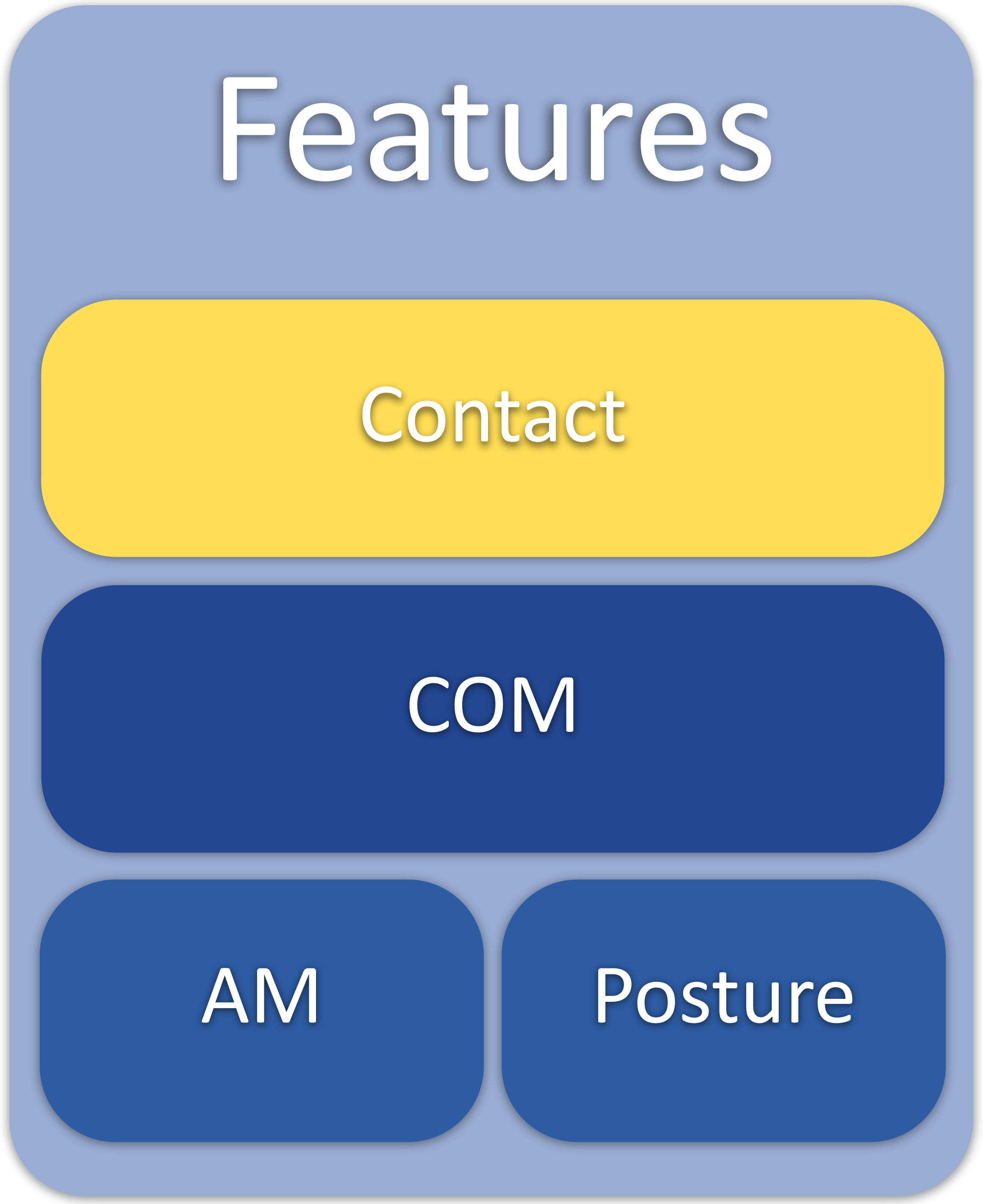


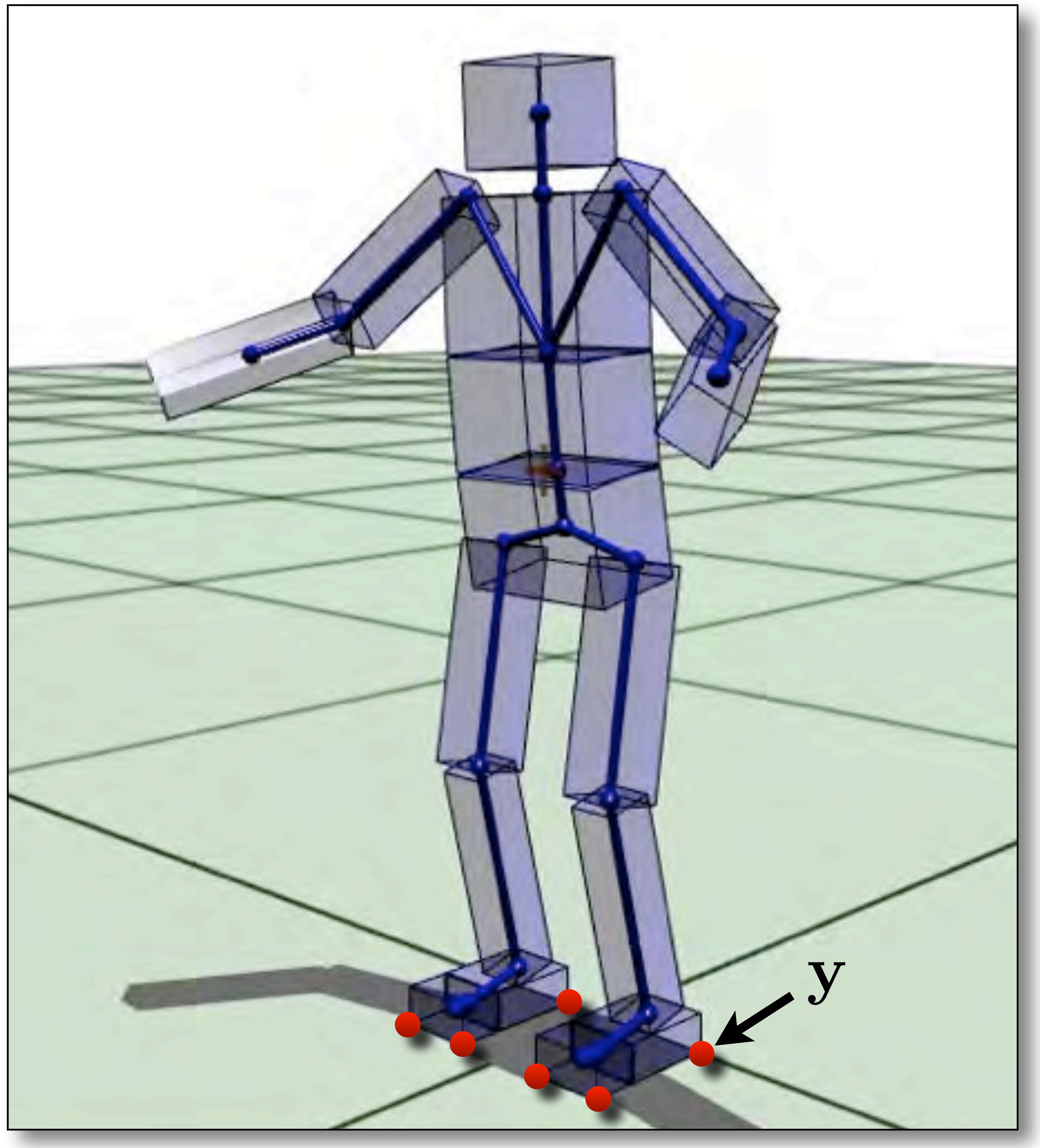
COM Control


Features
Contact
COM
AM
Posture


BOS
Center
$\mathbf{y}_r$
COM
Projection
$\mathbf{y}$

Contact Control

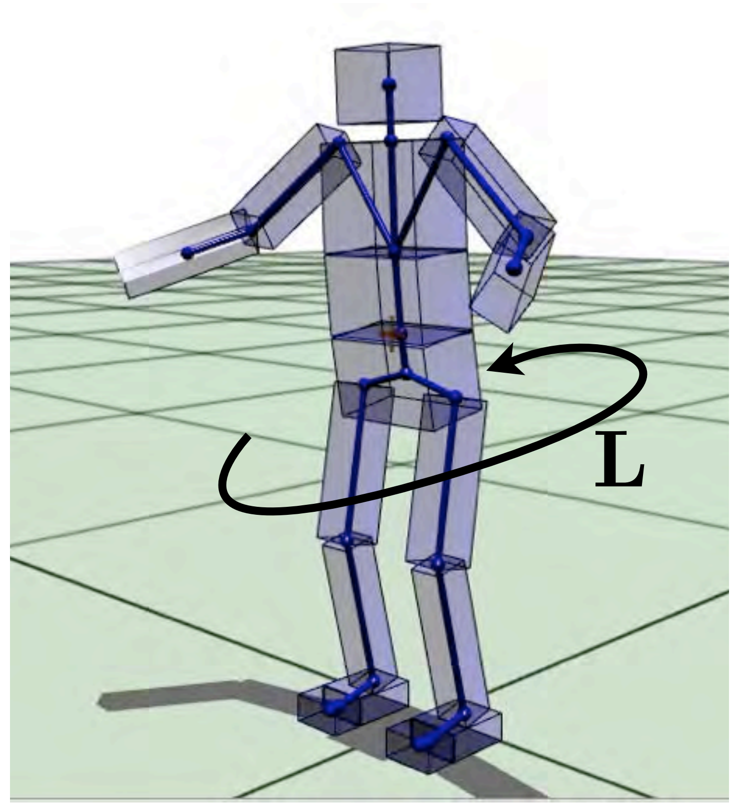


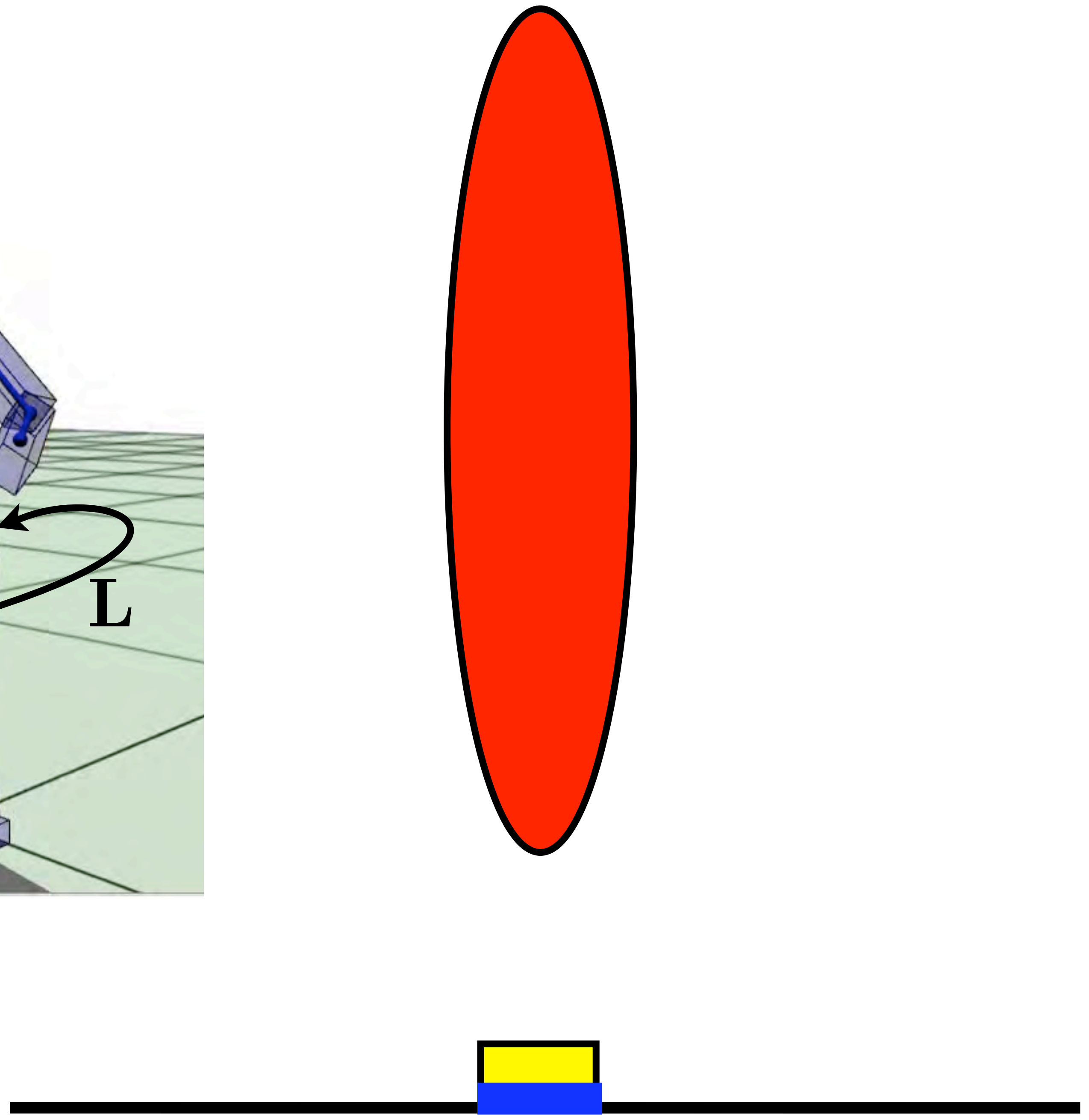


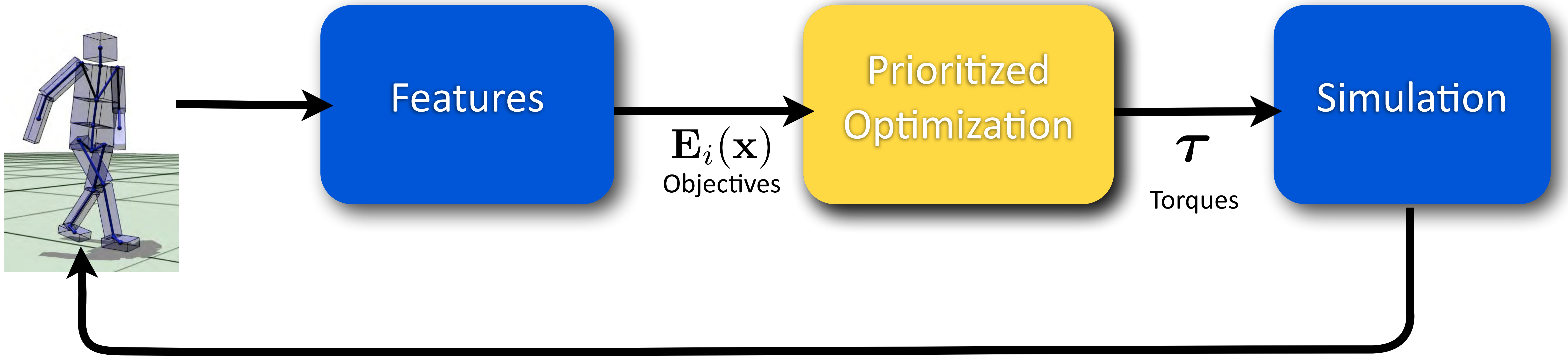
AM Control

Features

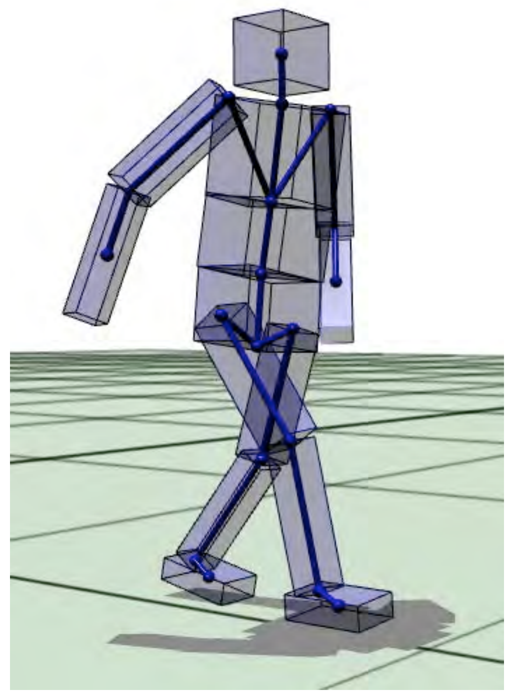
- Contact
- COM
- AM
- Posture

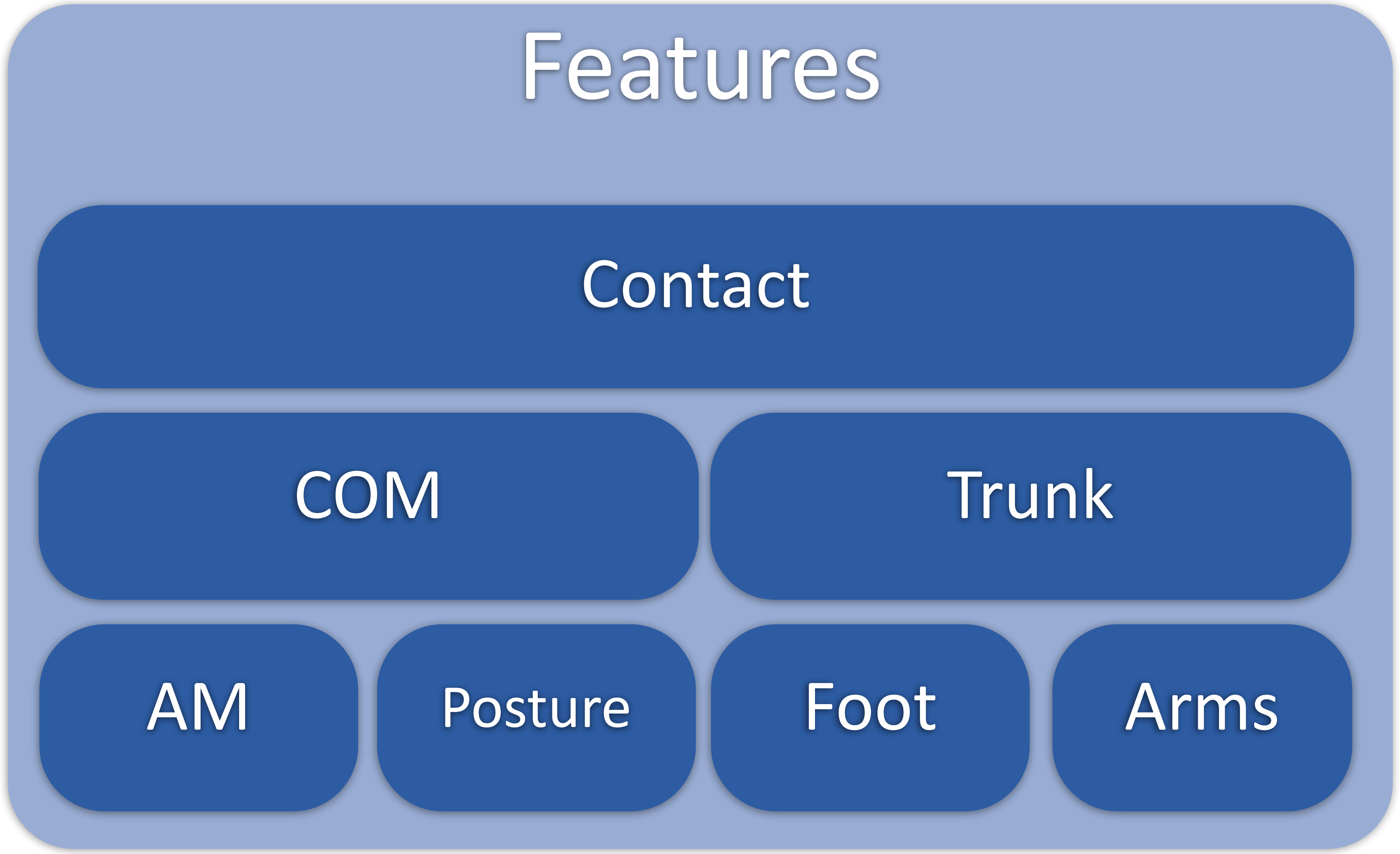




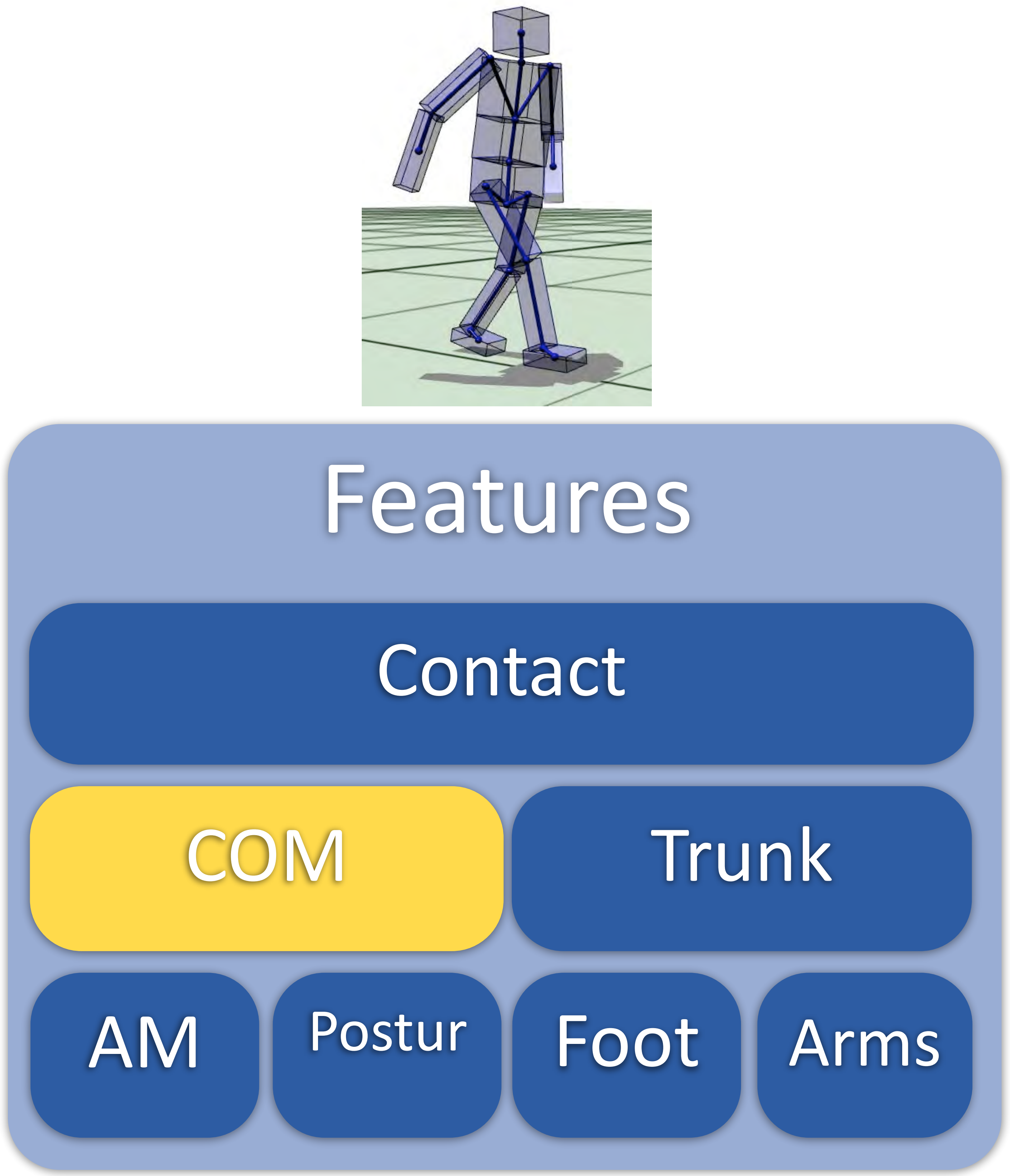

Features
$\mathbf{E}_i(\mathbf{x})$
Objectives
Prioritized
Optimization
$\boldsymbol{\tau}$
Torques
Simulation

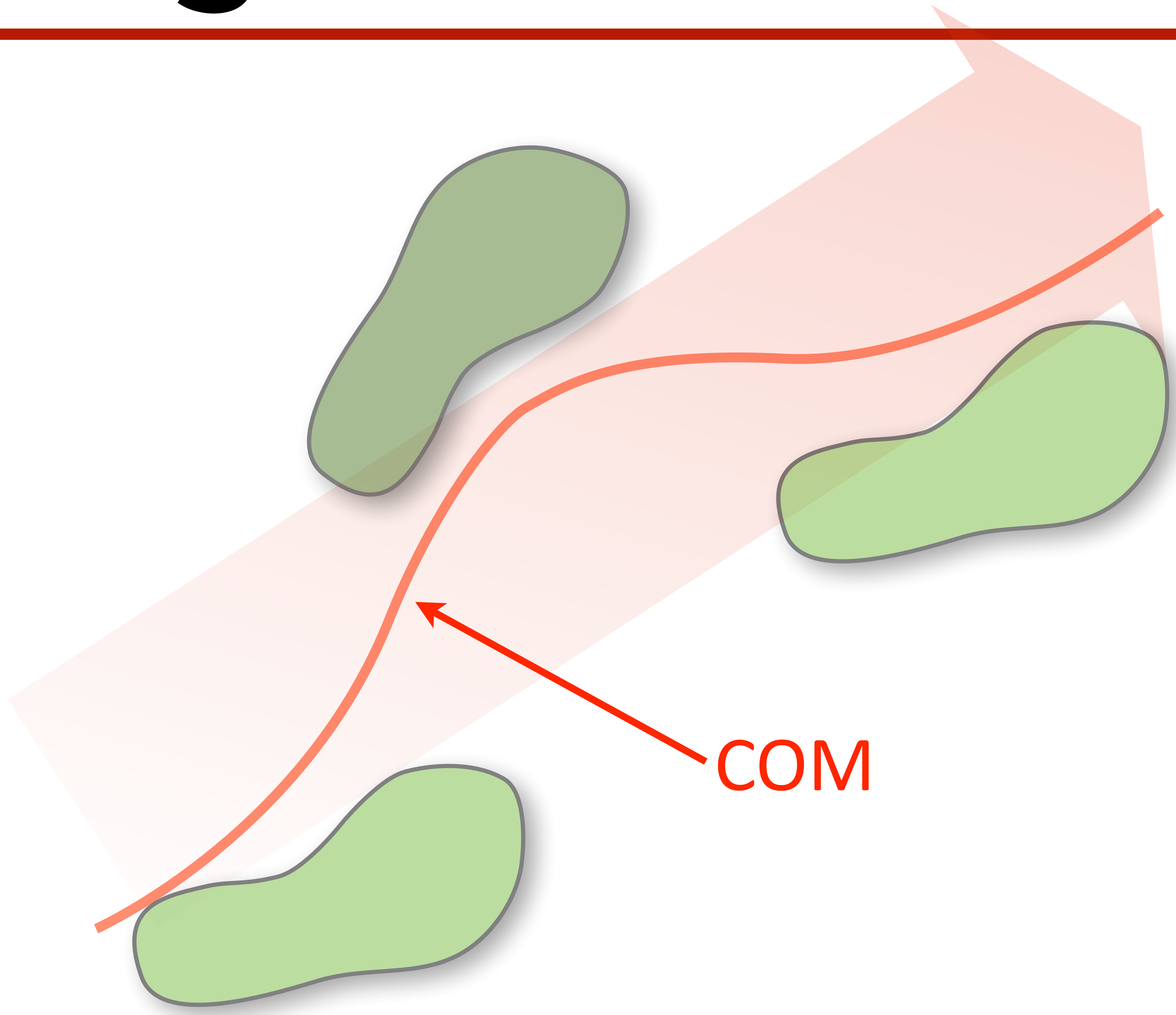
Walking



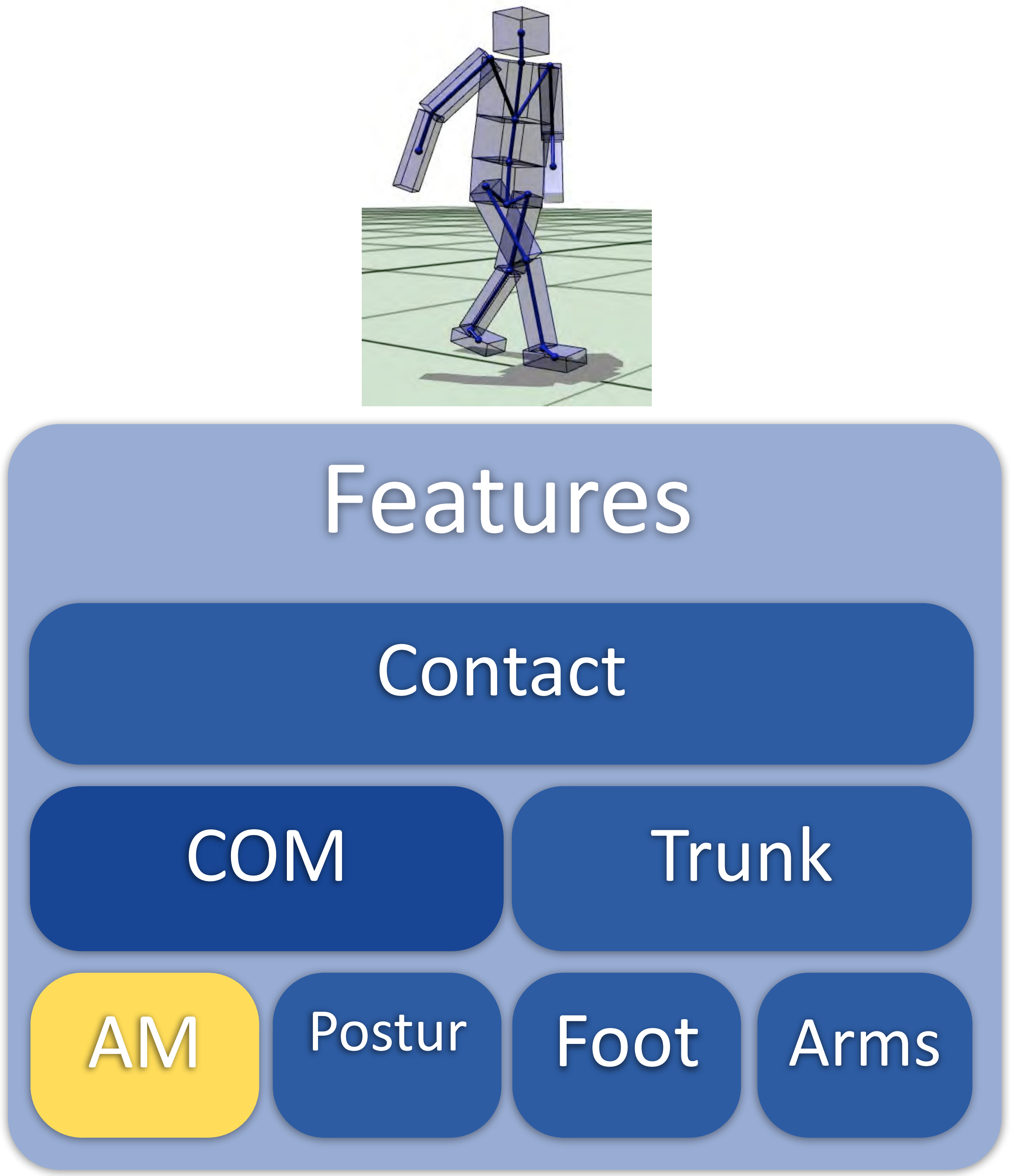


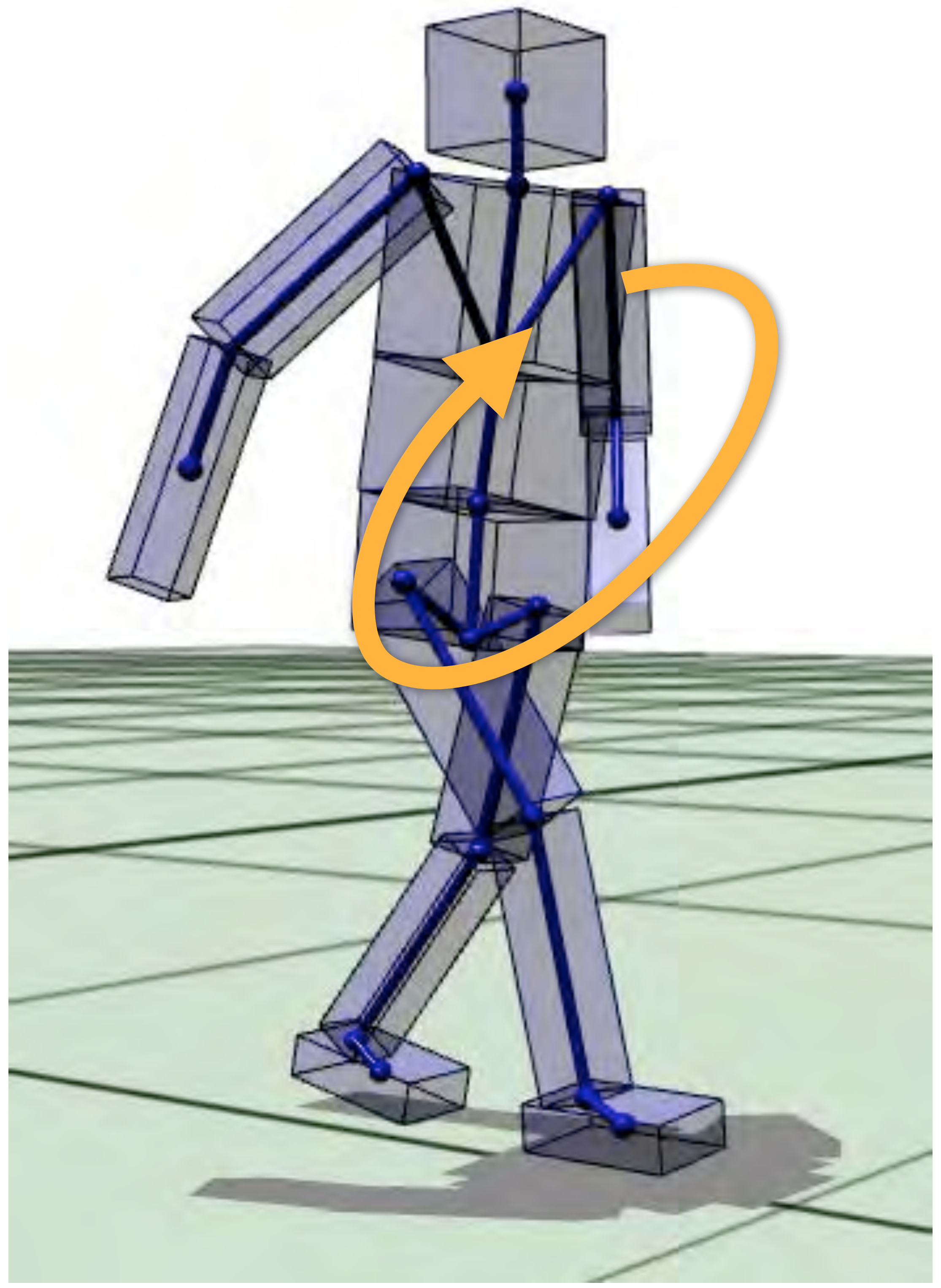
Walking: COM



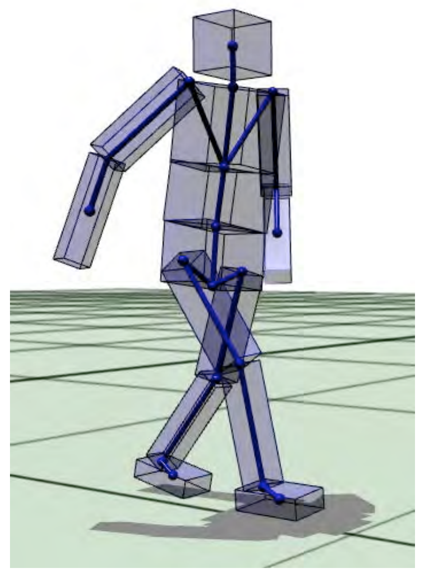


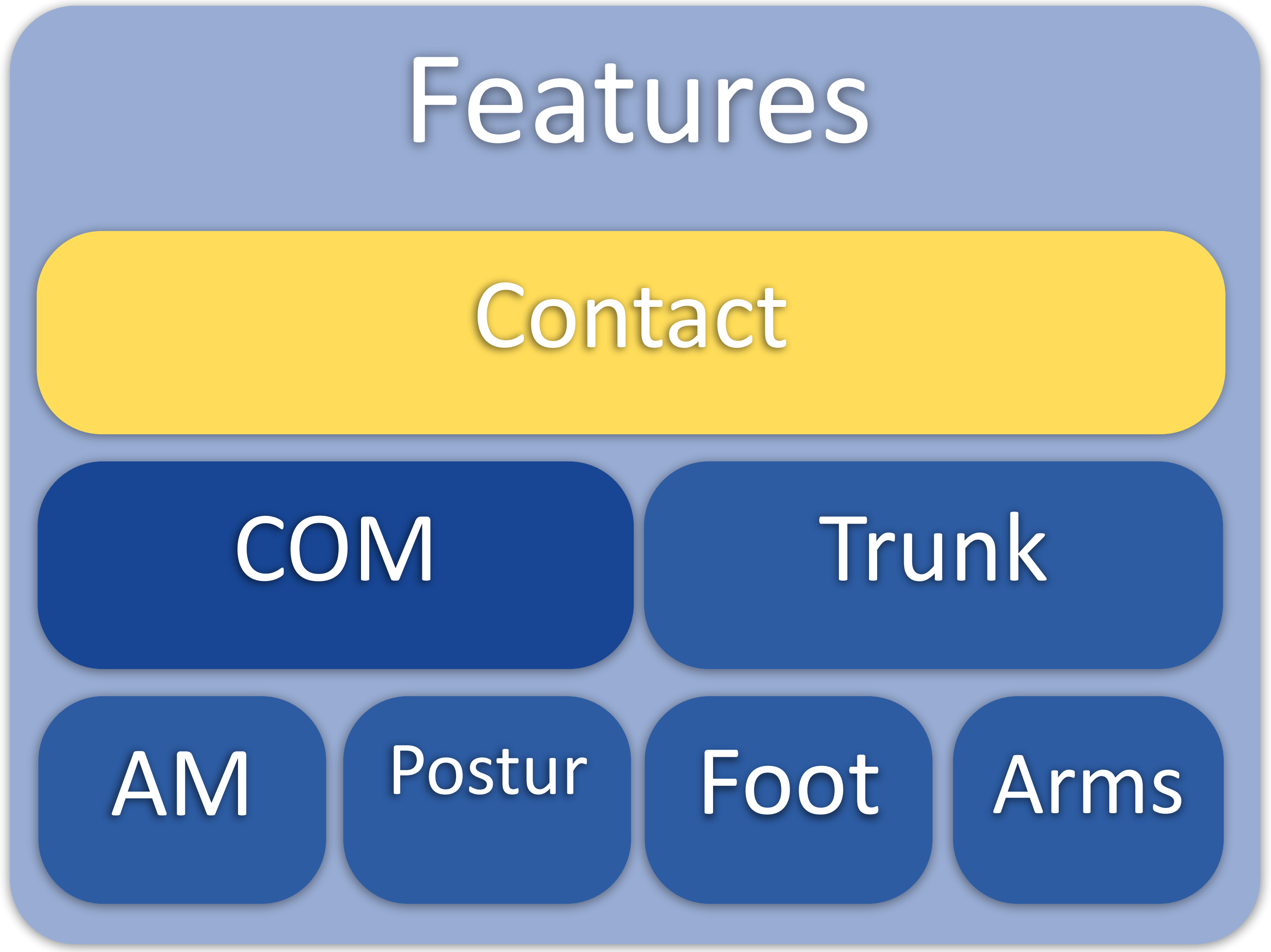
Walking: AM Control

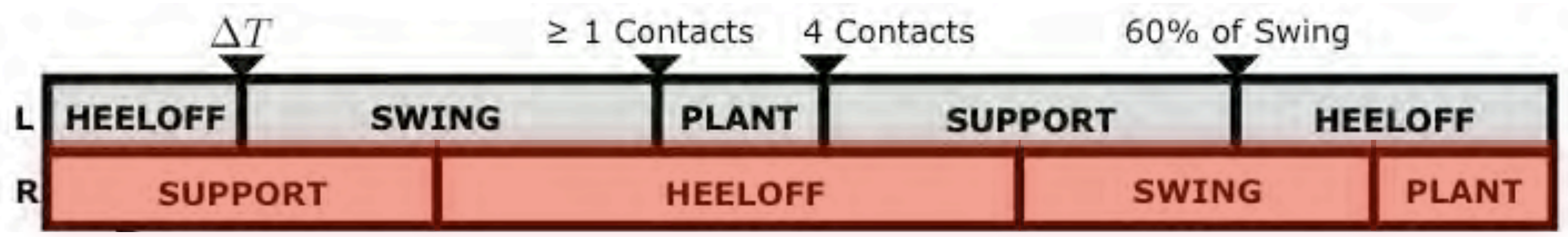


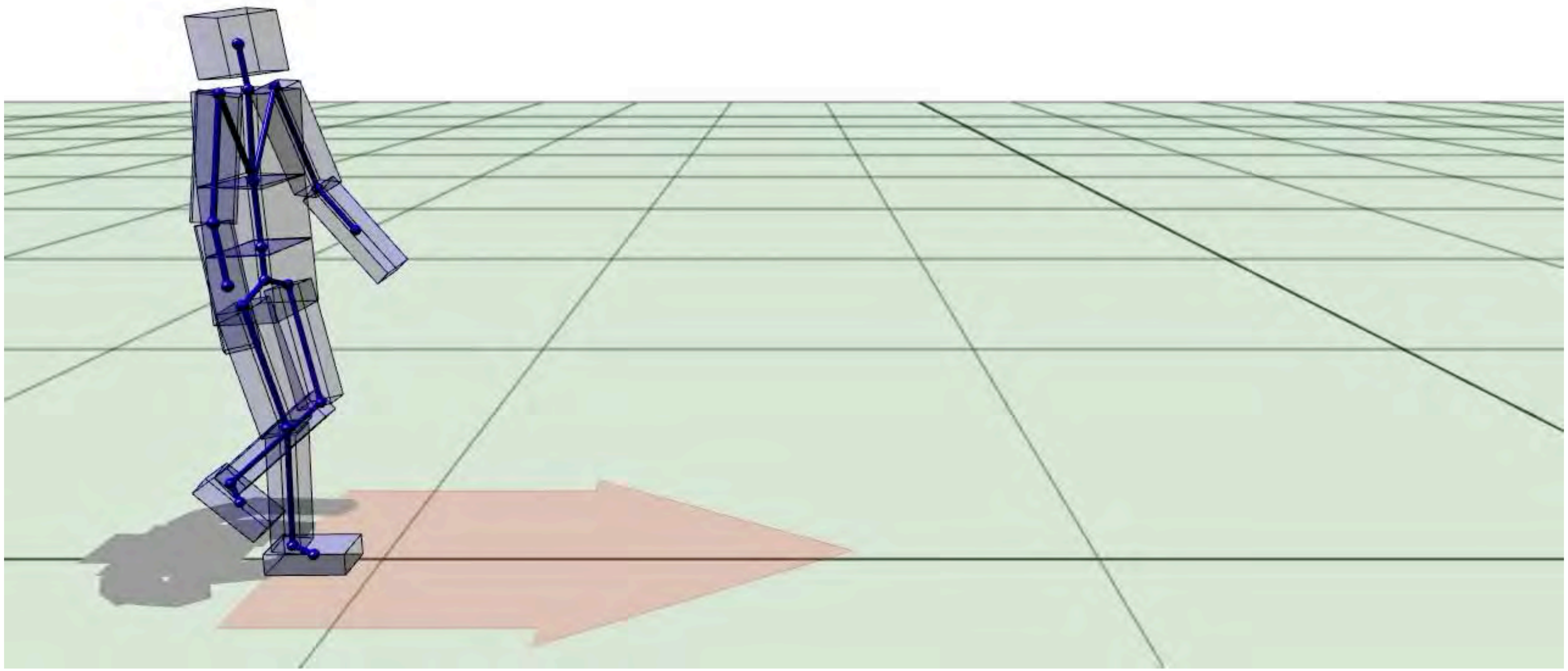


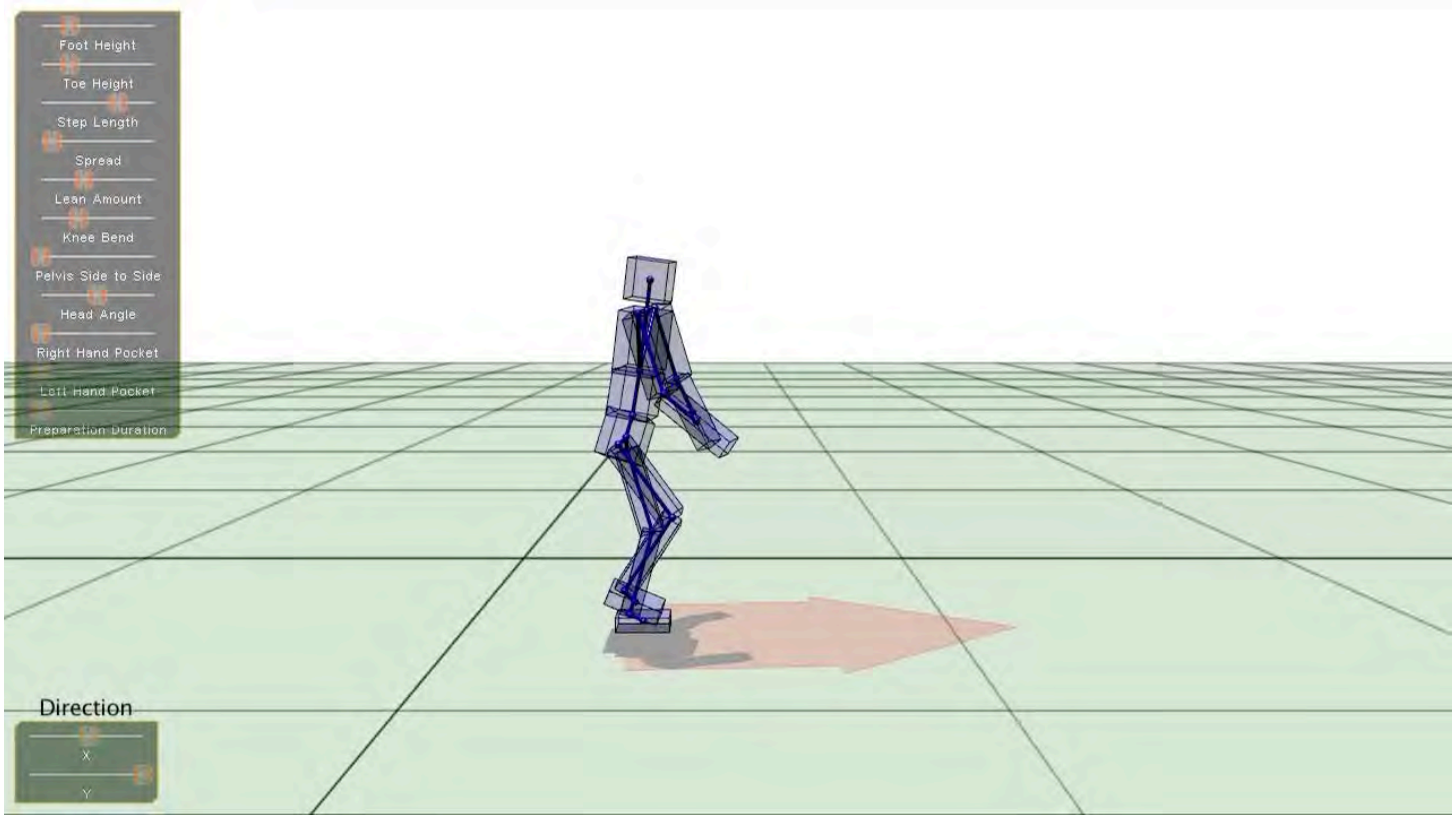
Walking: State-Machine



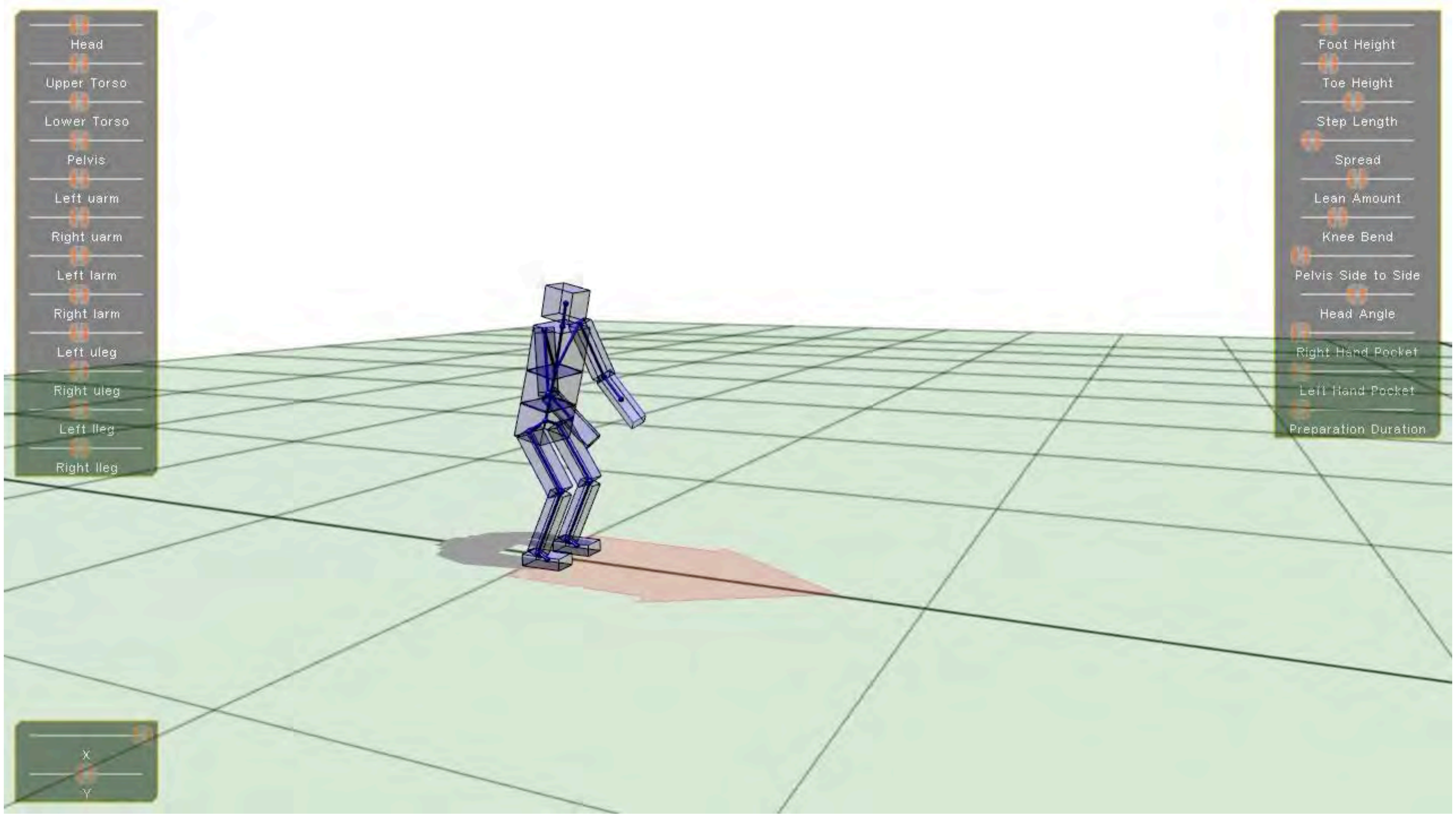


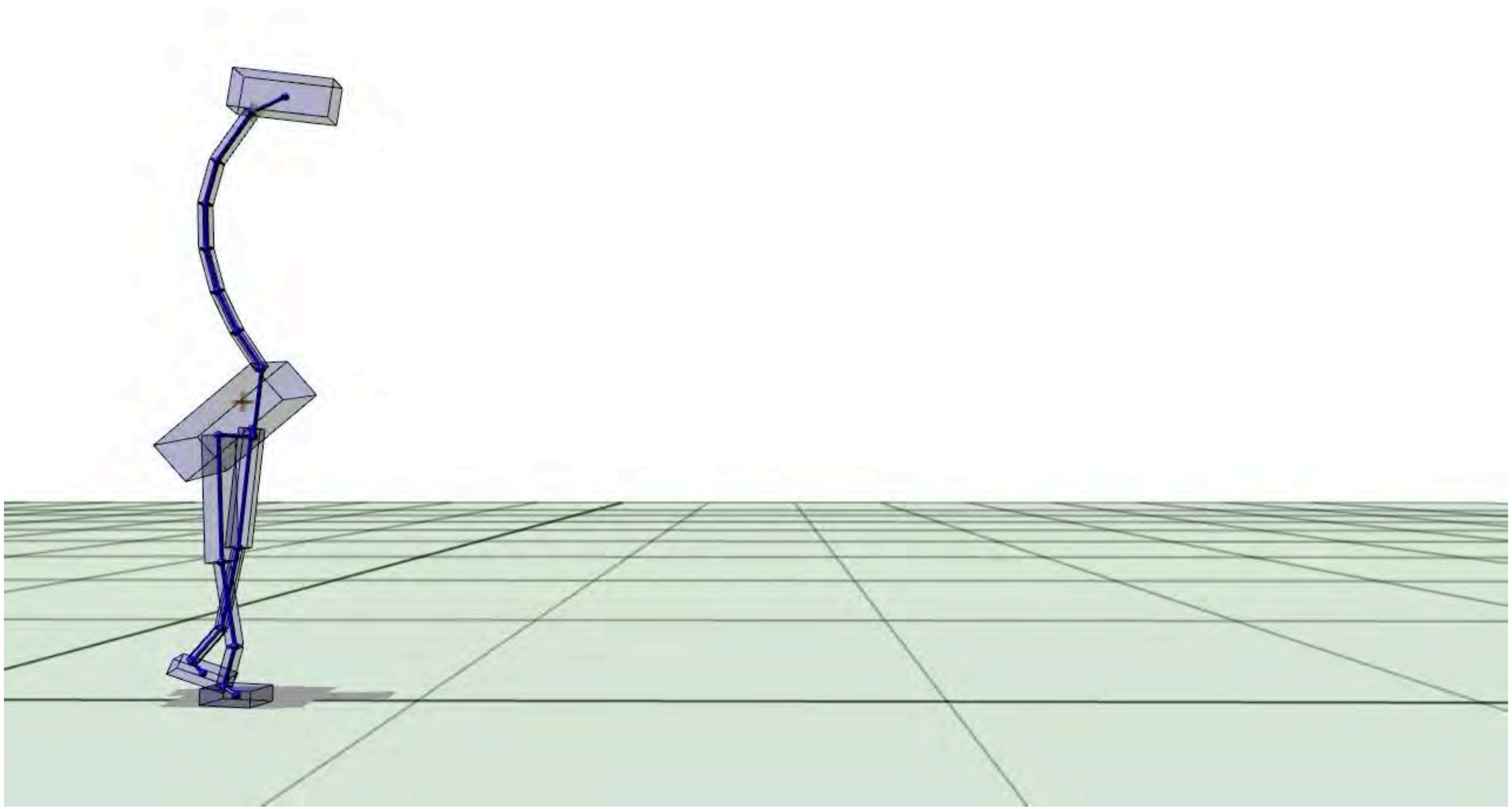






Foot Height
Toe Height
Step Length
Spread
Lean Amount
Knee Bend
Pelvis Side to Side
Head Angle
Right Hand Pocket
Left Hand Pocket
Preparation Duration
Direction
X
Y


Head
Upper Torso
Lower Torso
Pelvis
Left uarm
Right uarm
Left larm
Right larm
Left uleg
Right uleg
Left lleg
Right lleg
X
Y
Foot Height
Toe Height
Step Length
Spread
Lean Amount
Knee Bend
Pelvis Side to Side
Head Angle
Right Hand Pocket
Left Hand Pocket
Preparation Duration



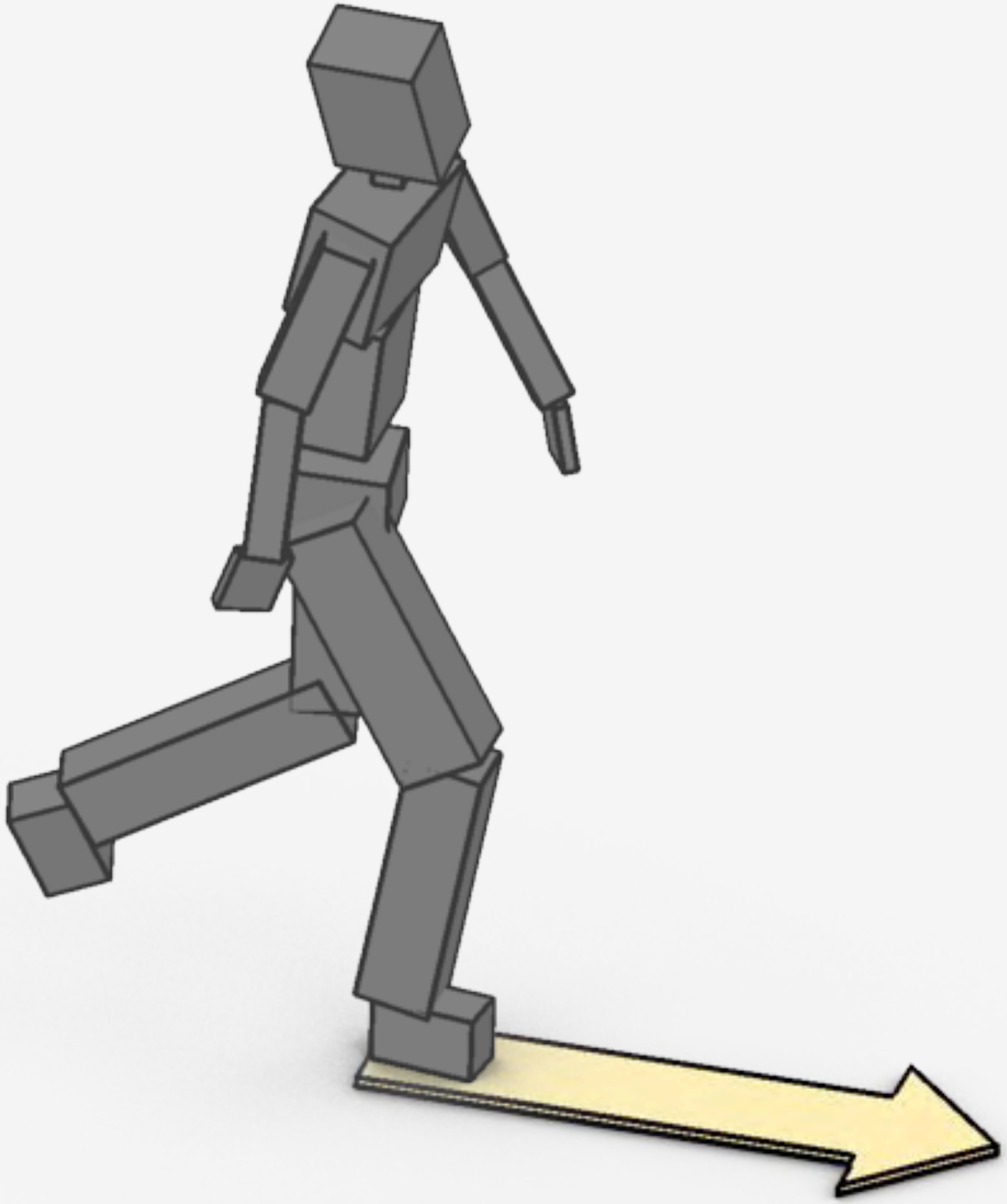
Low-dimensional planning

with:

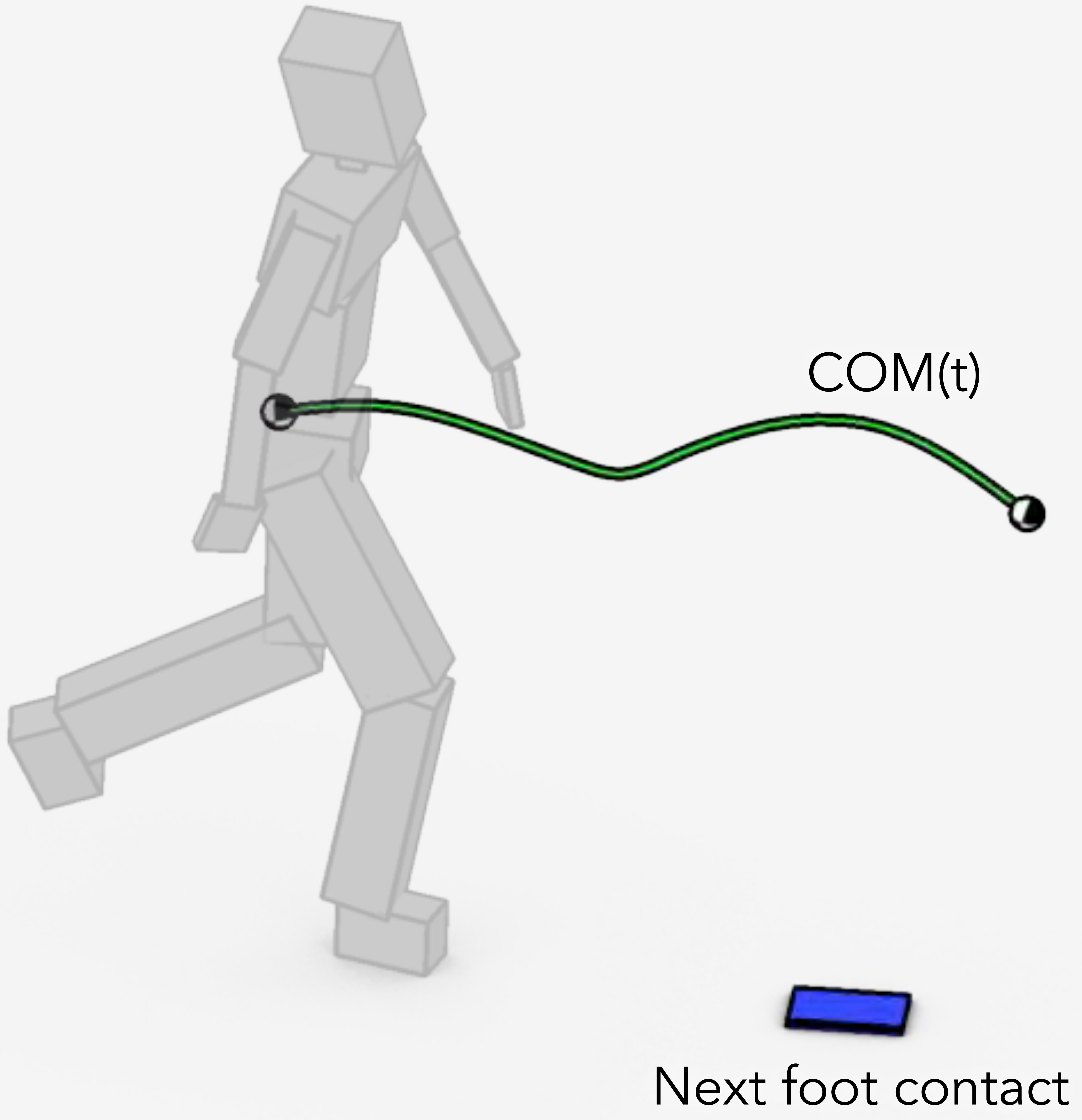
Igor Mordatch

Martin de Lasa

Feature trajectories depend on future goals

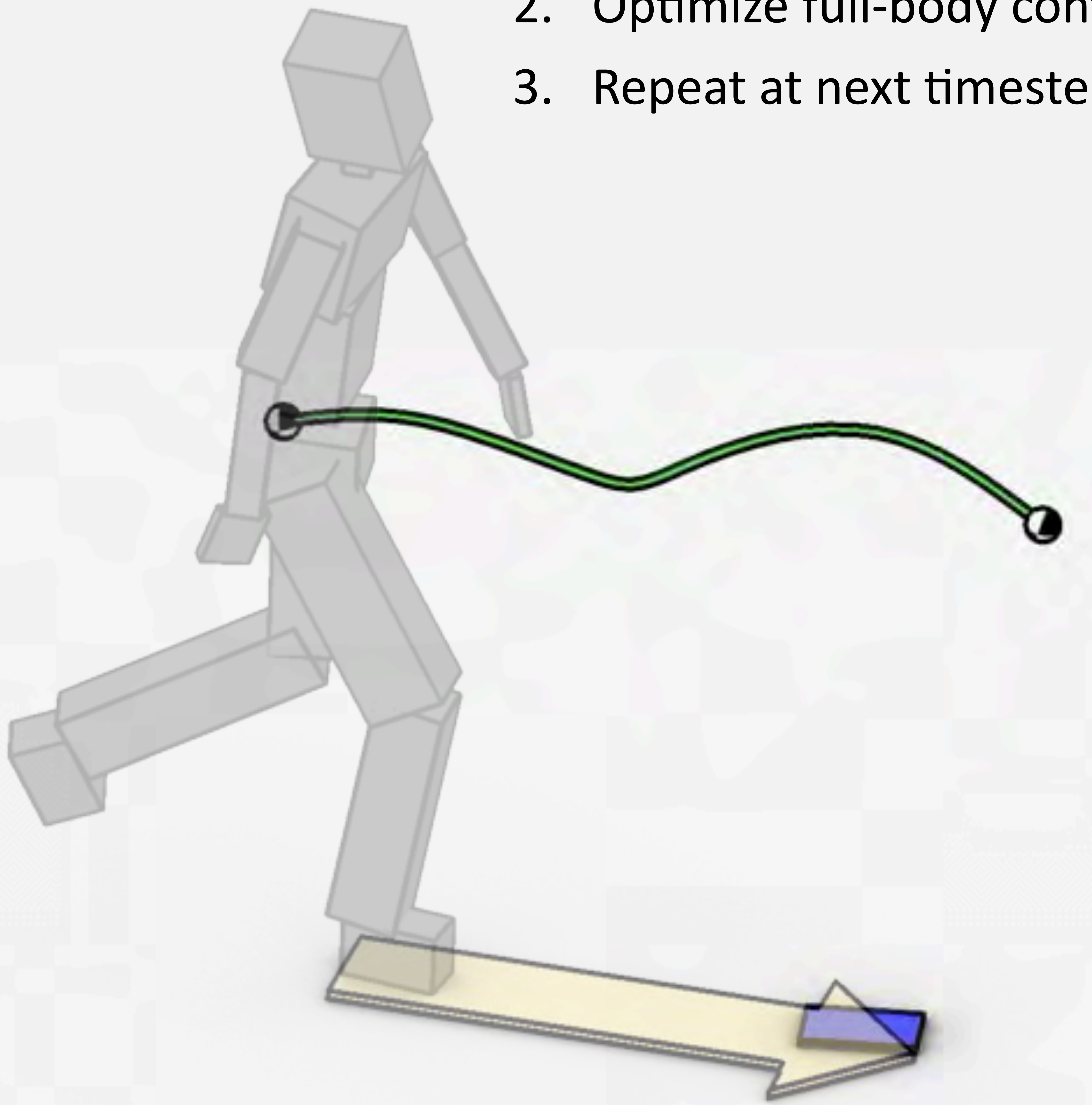


Optimize with a low-dimensional motion model



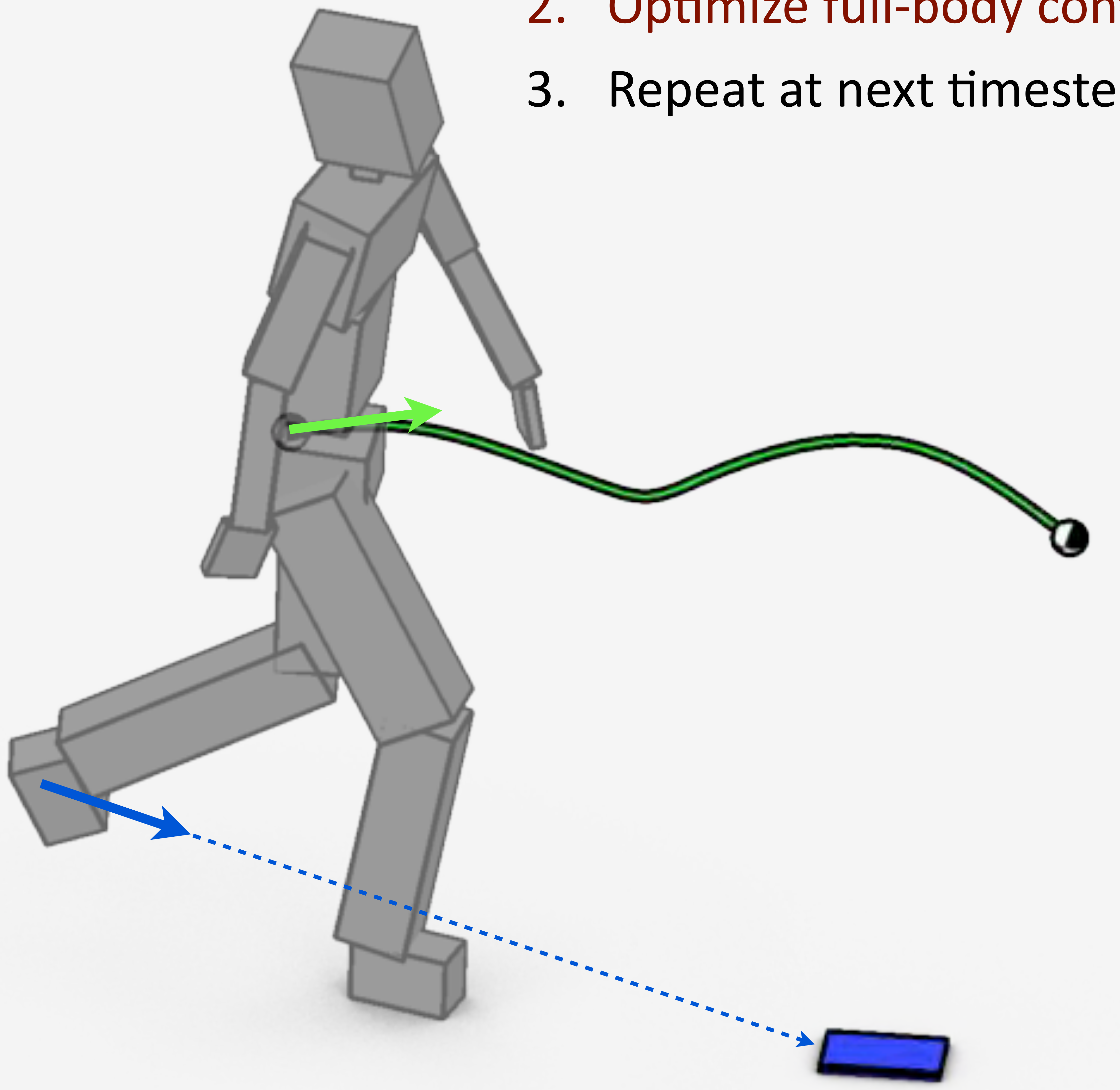
Algorithm

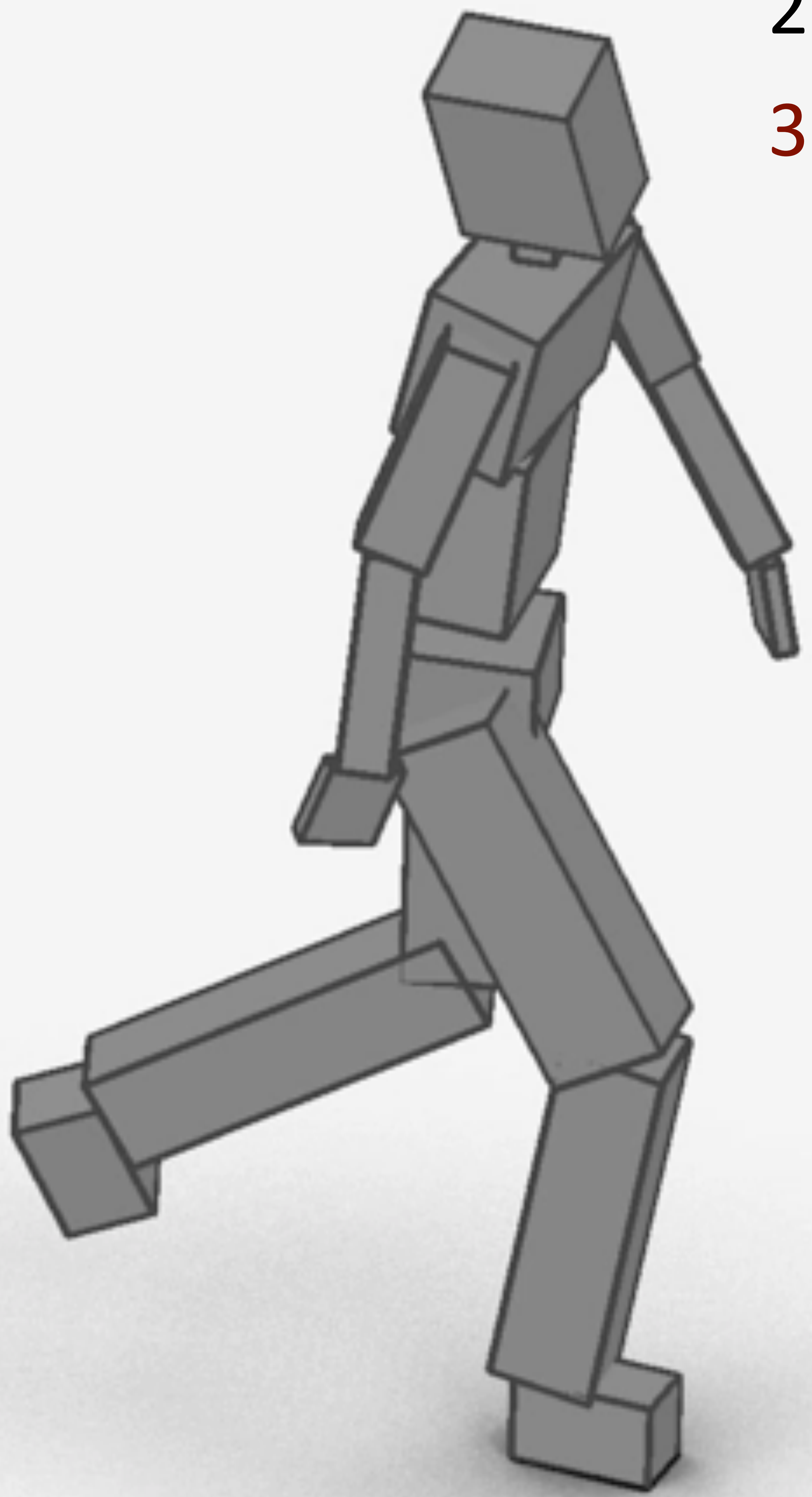
1. Optimize feature trajectory
2. Optimize full-body control and simulate
3. Repeat at next timestep



Algorithm

1. Optimize feature trajectory
2. Optimize full-body control and simulate
3. Repeat at next timestep



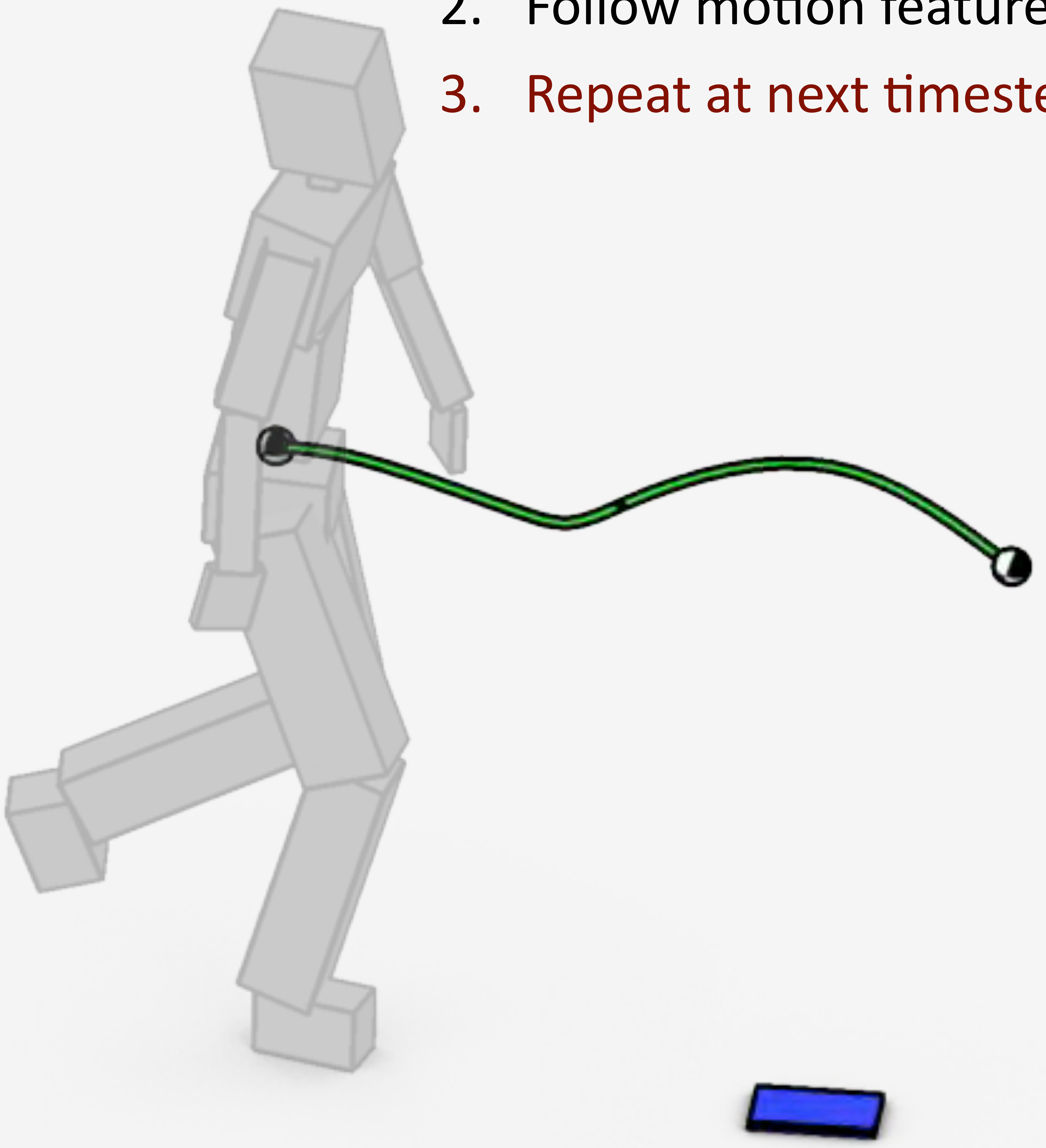


Algorithm

1. Optimize feature trajectory
2. Optimize full-body control and simulate
3. Repeat at next timestep

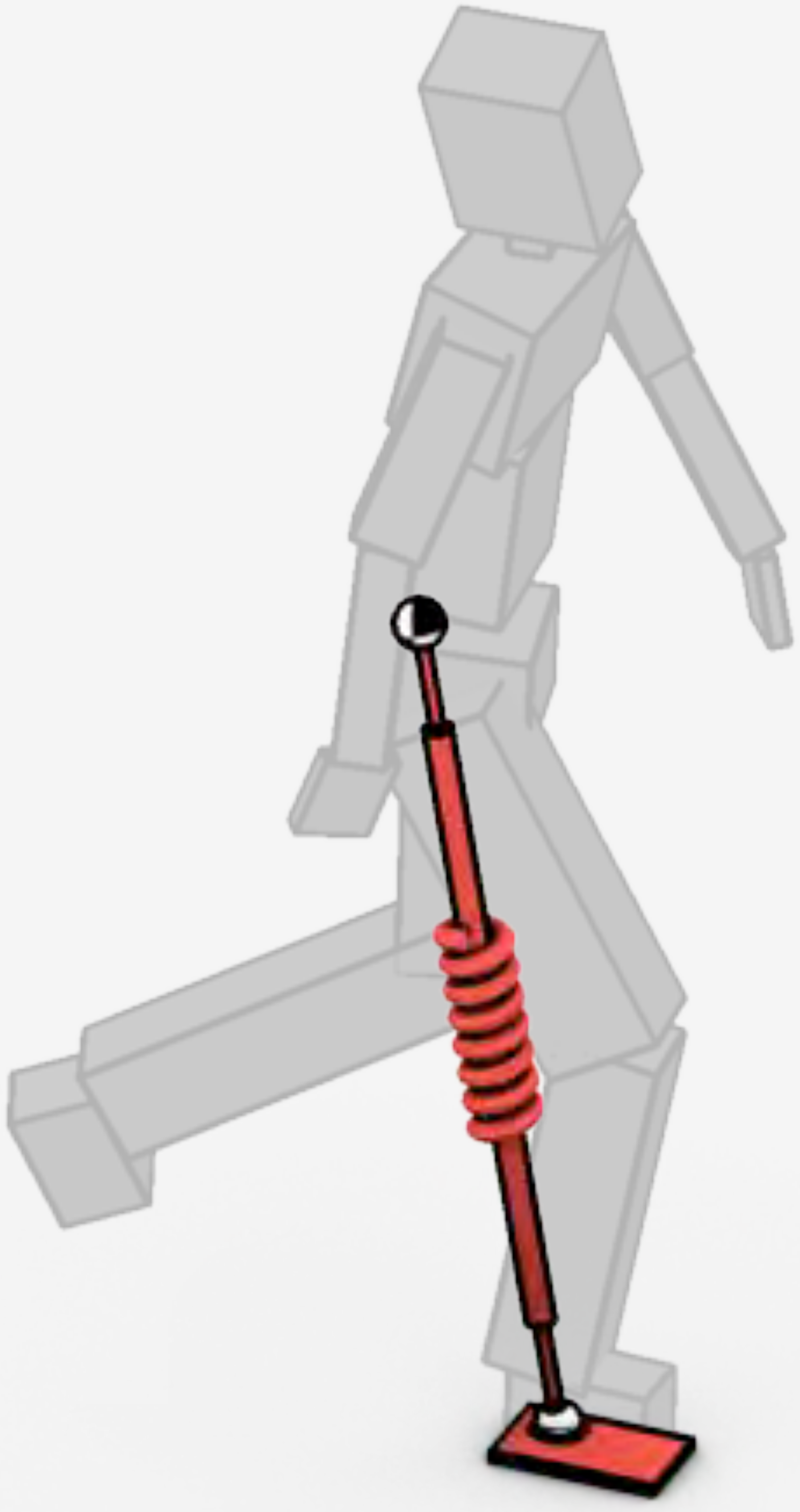
Algorithm

1. Optimize motion trajectory
2. Follow motion features with full character
3. Repeat at next timestep

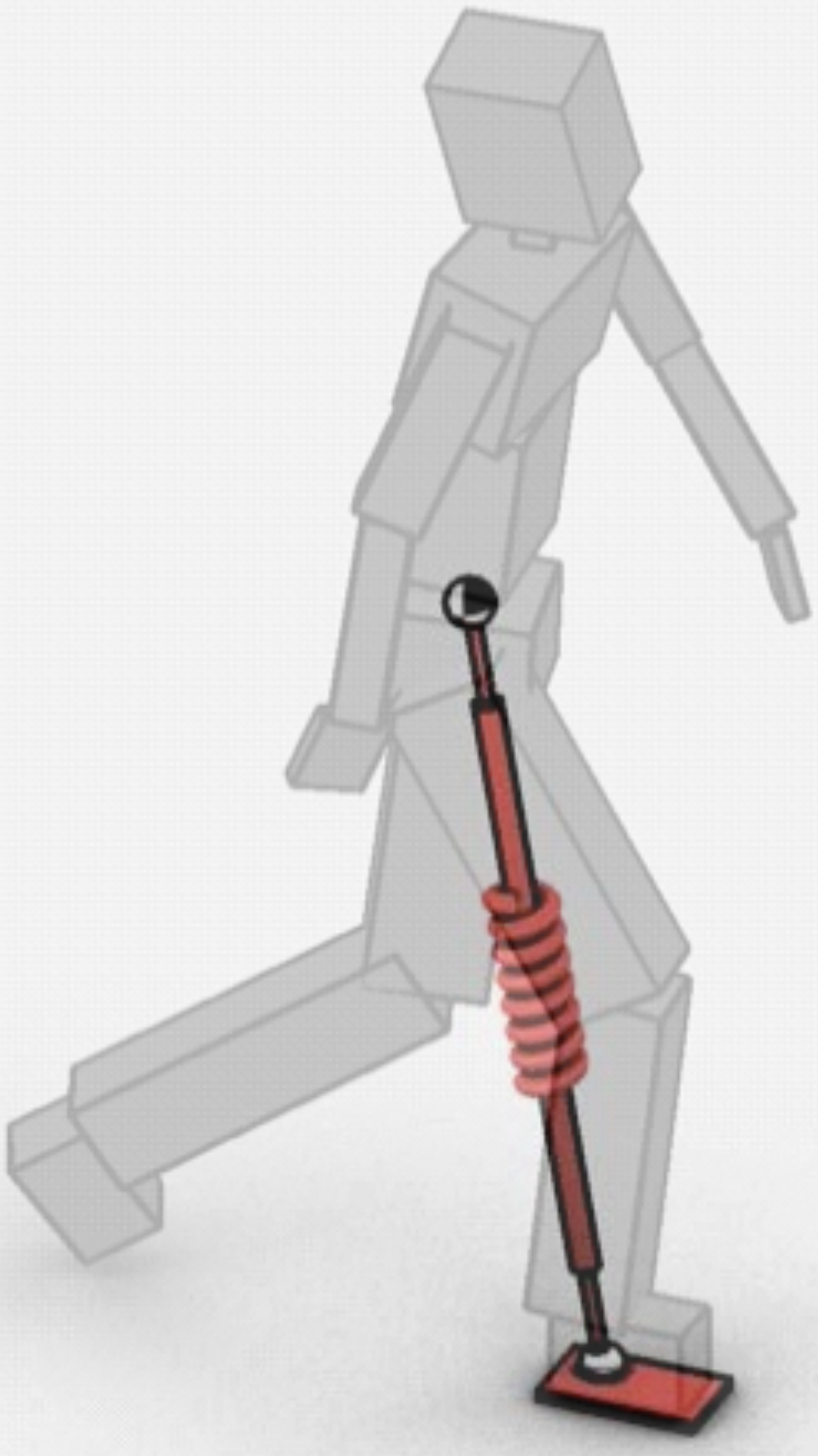


Spring-Loaded Inverted Pendulum

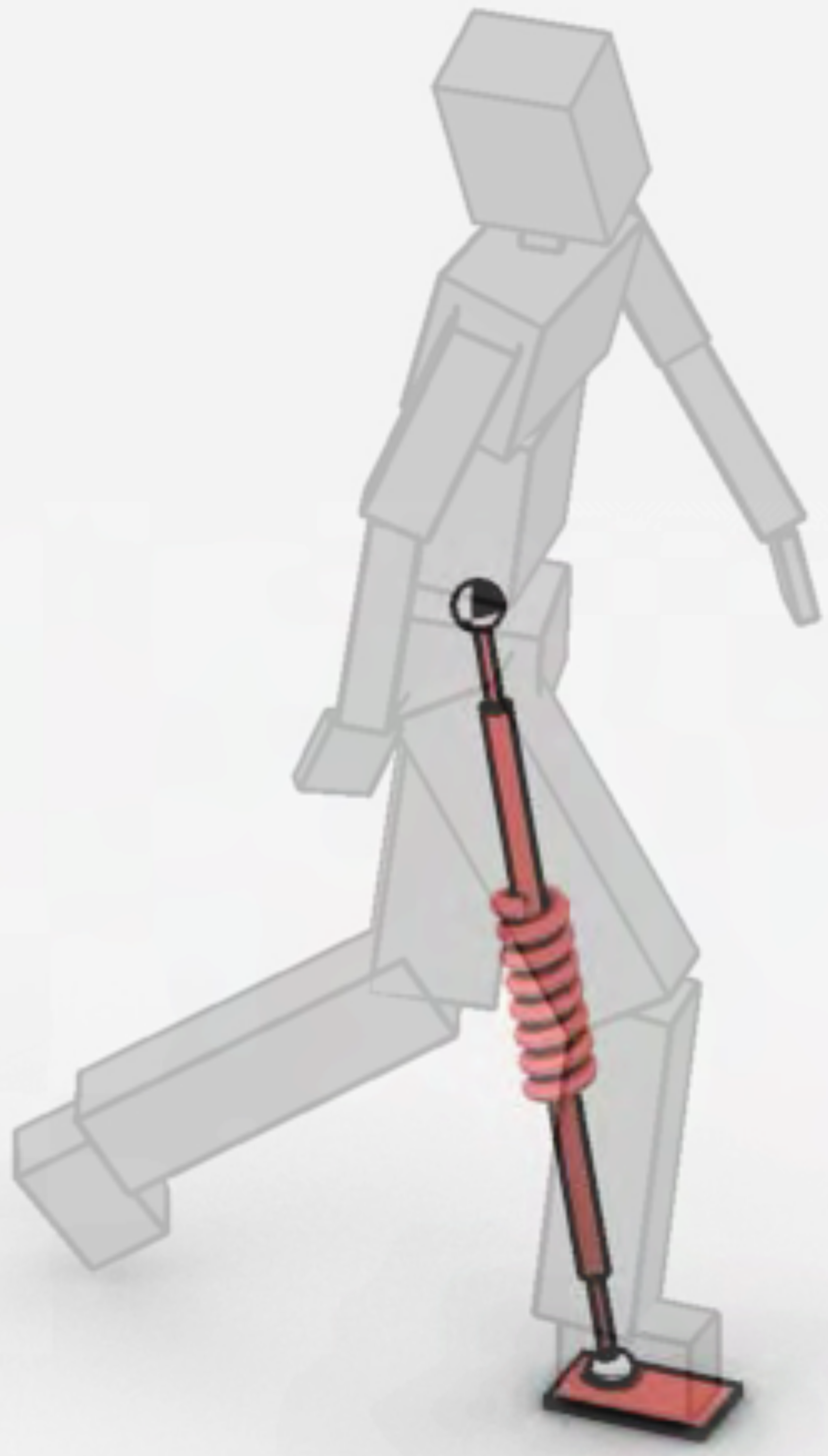
(SLIP)



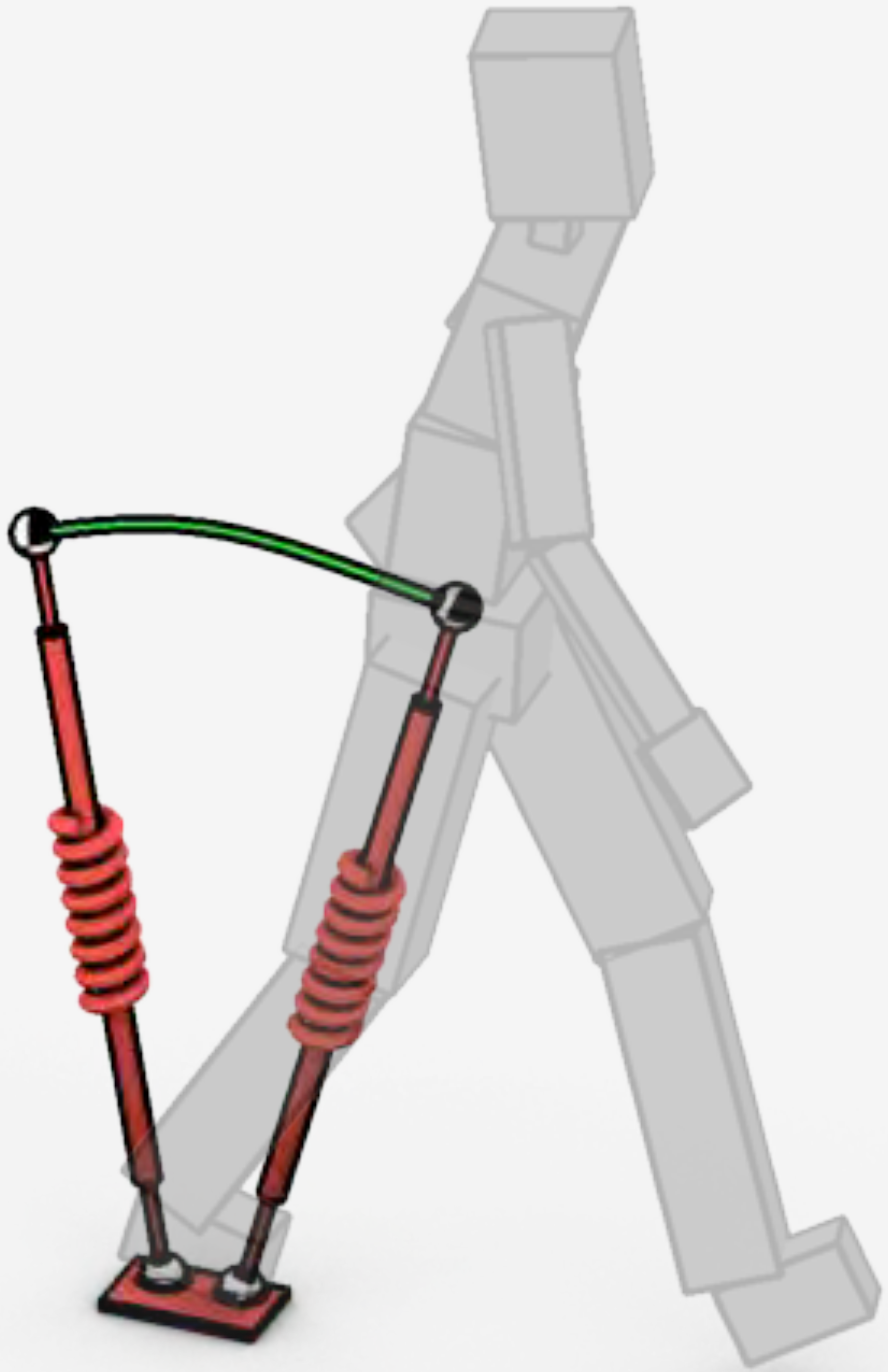
Walking



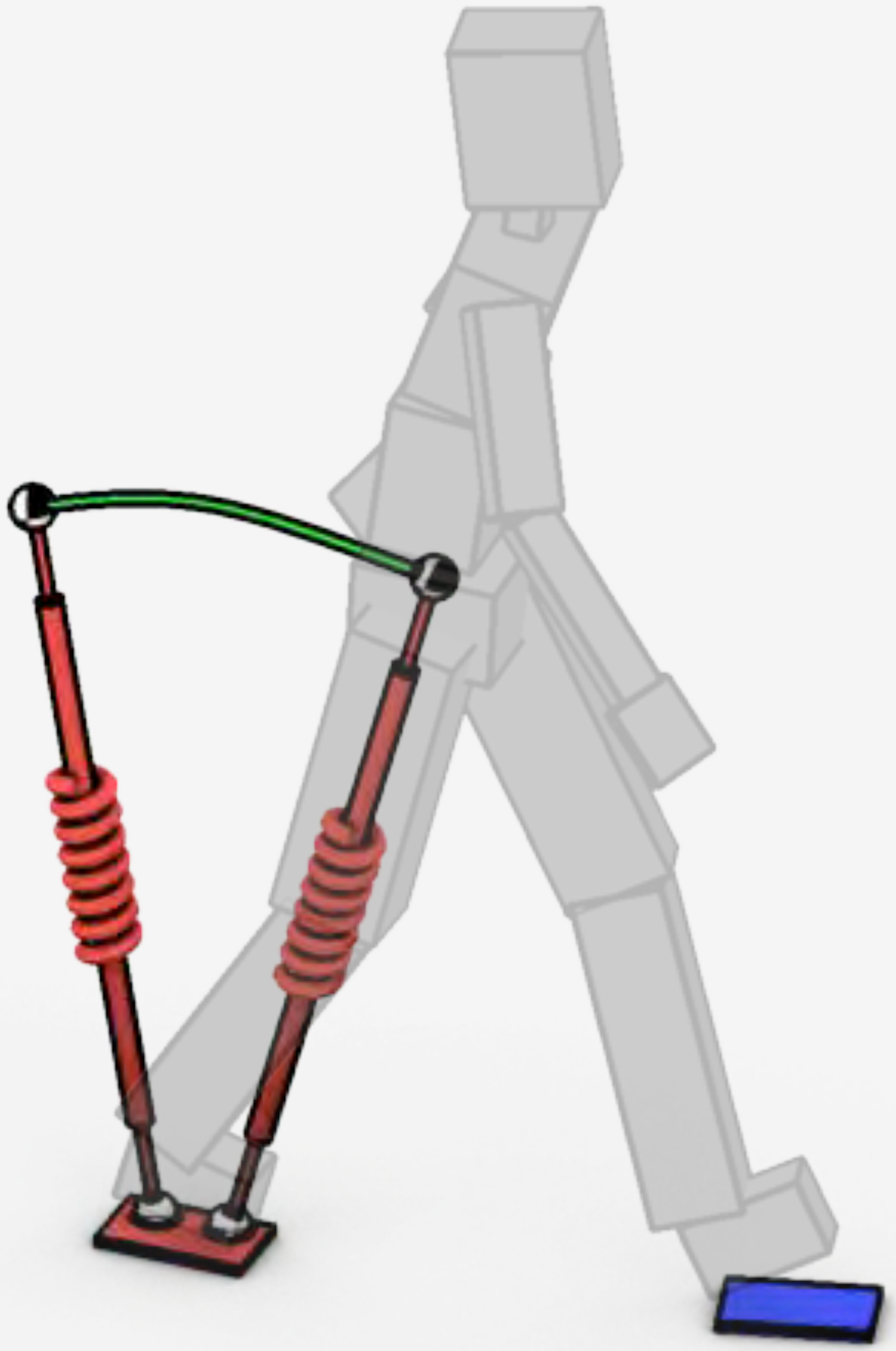
Walking



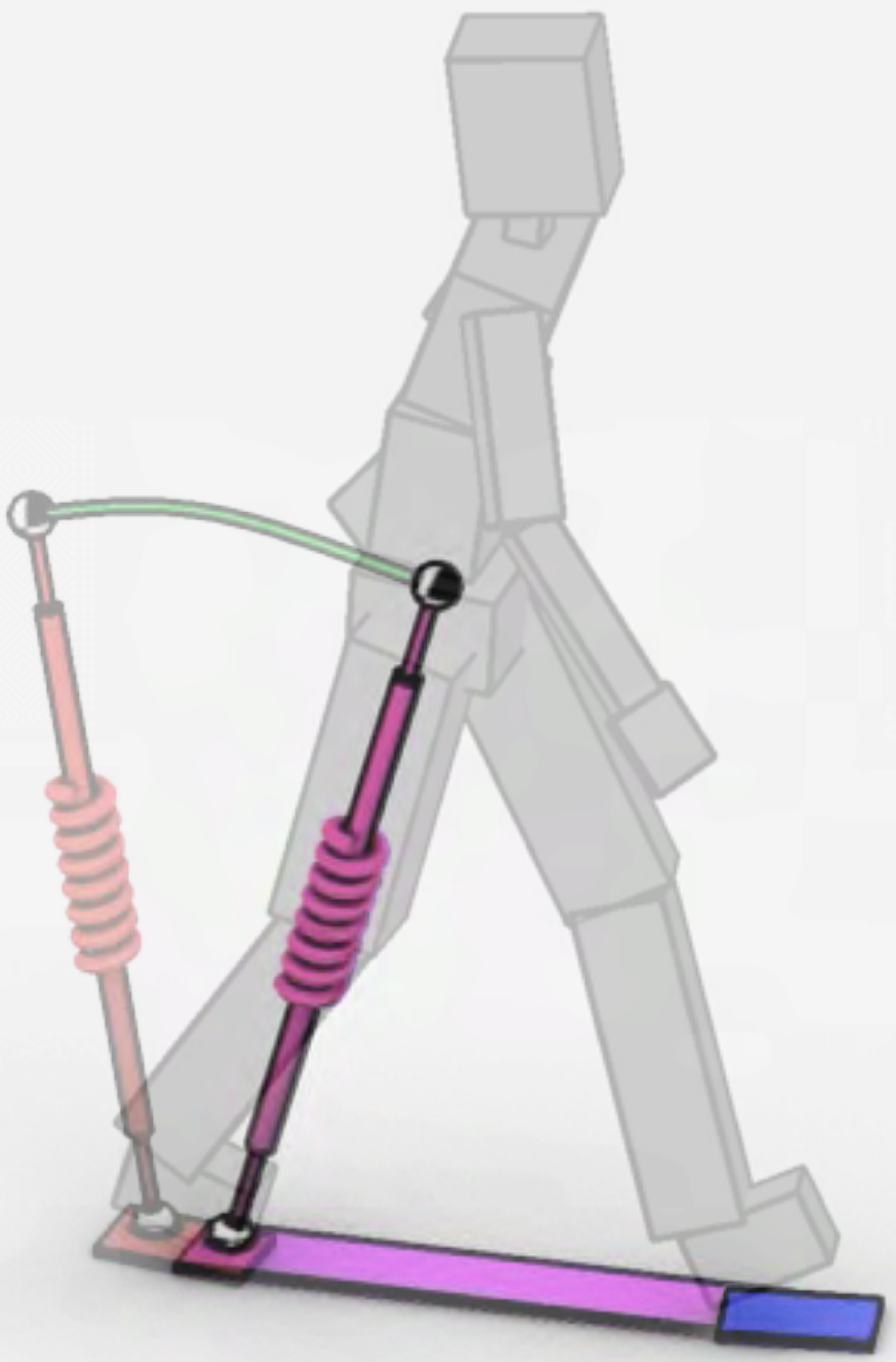
Walking



Walking

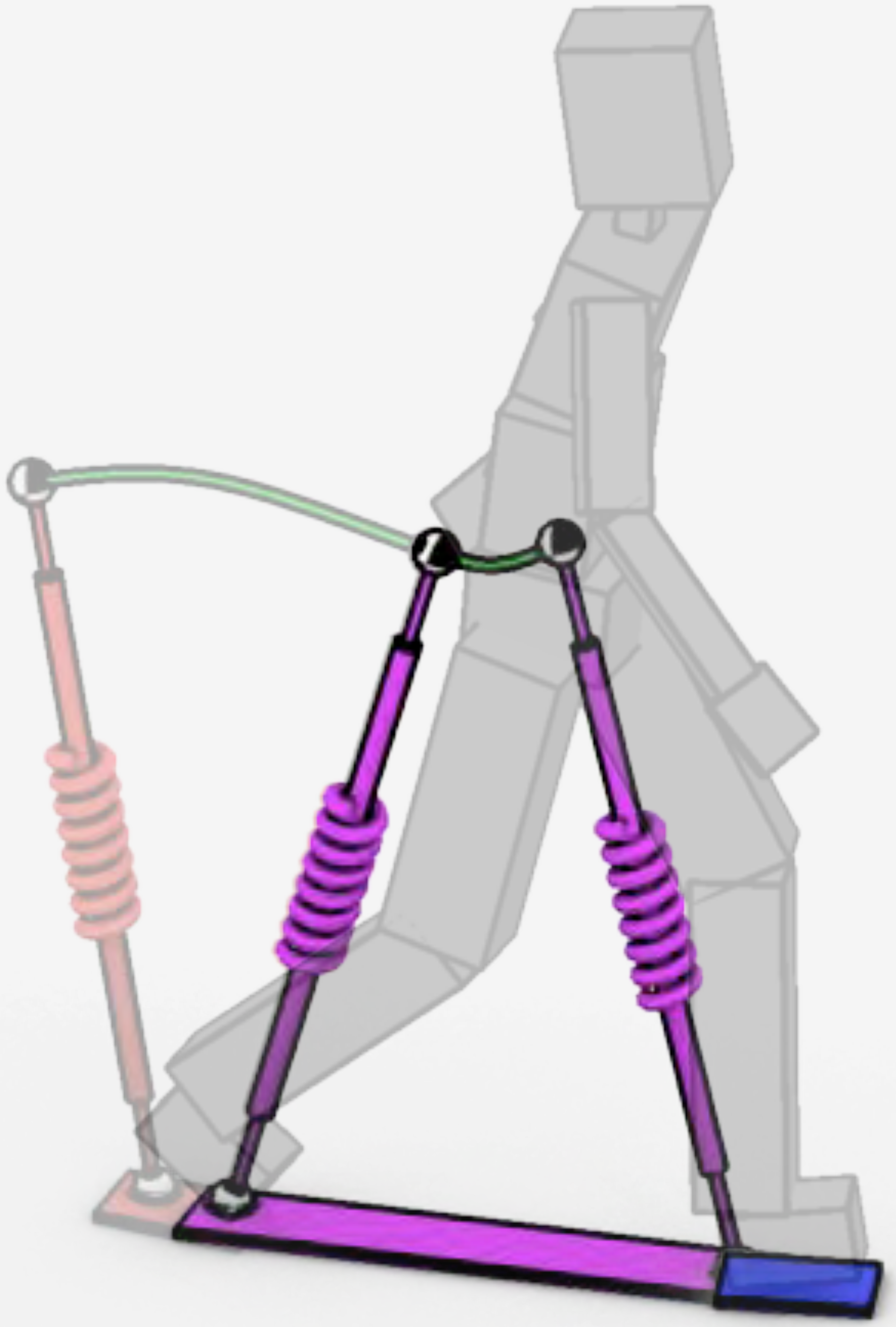


Walking



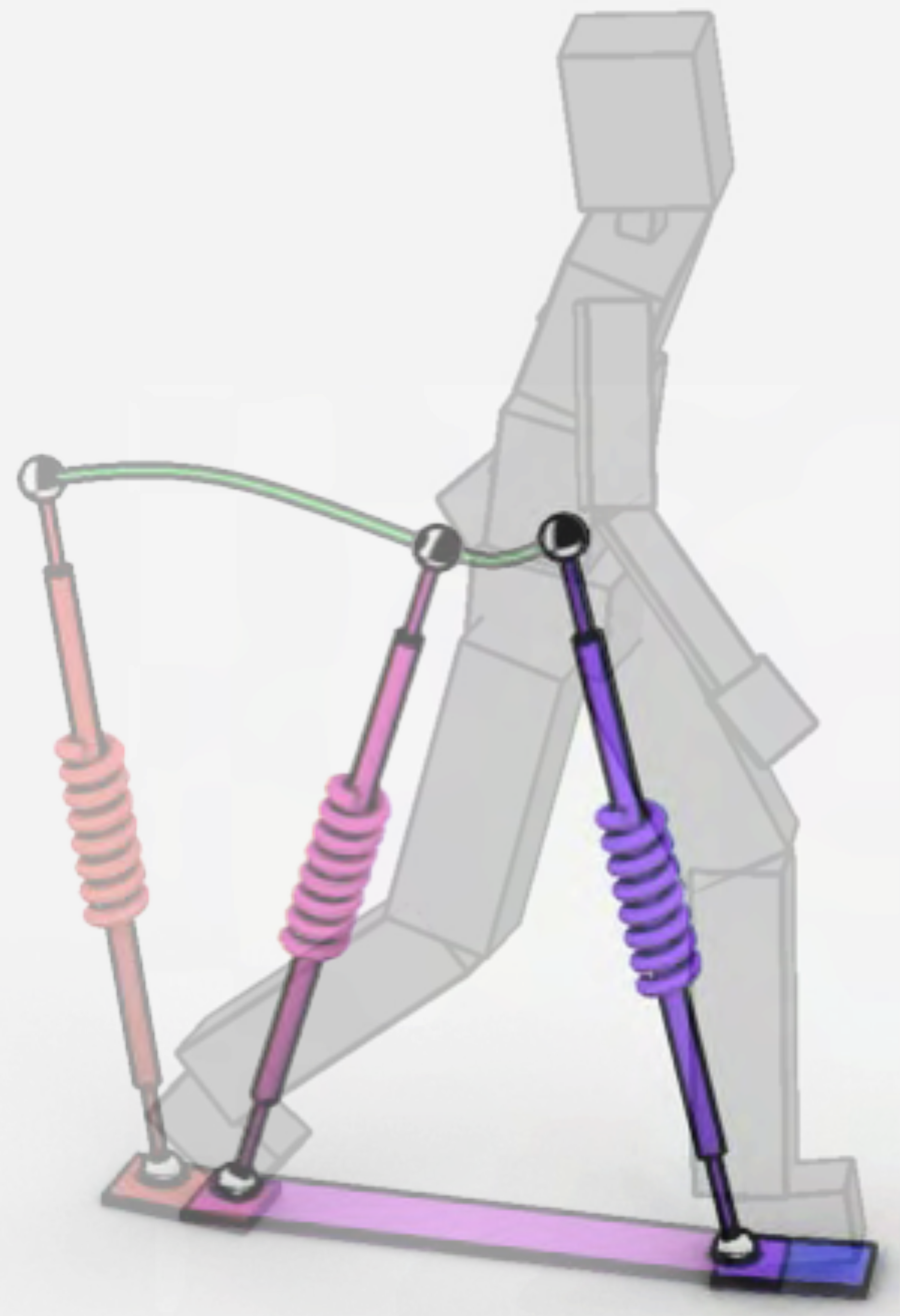
Next Foot Contact

Walking

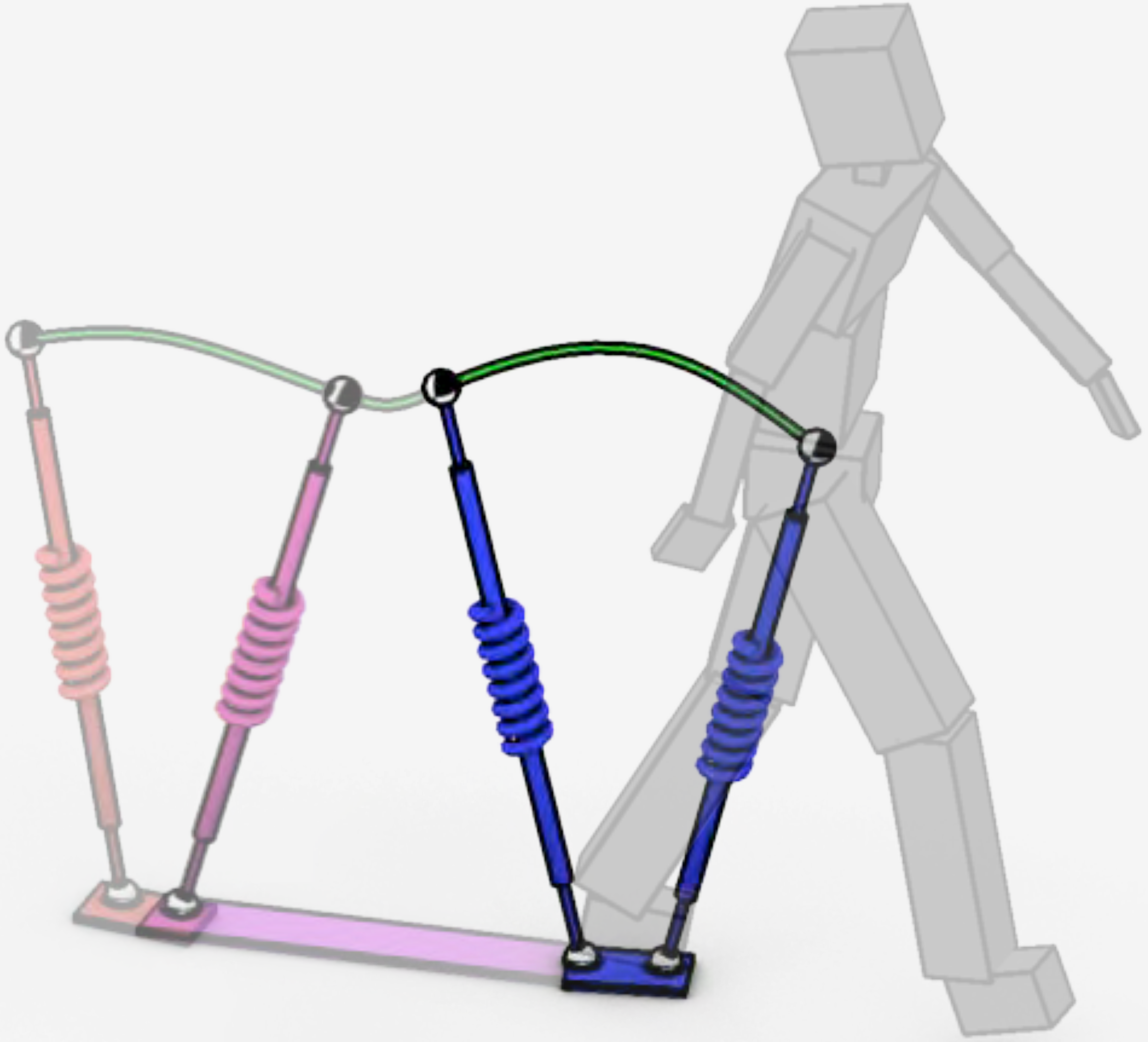


Next Foot Contact

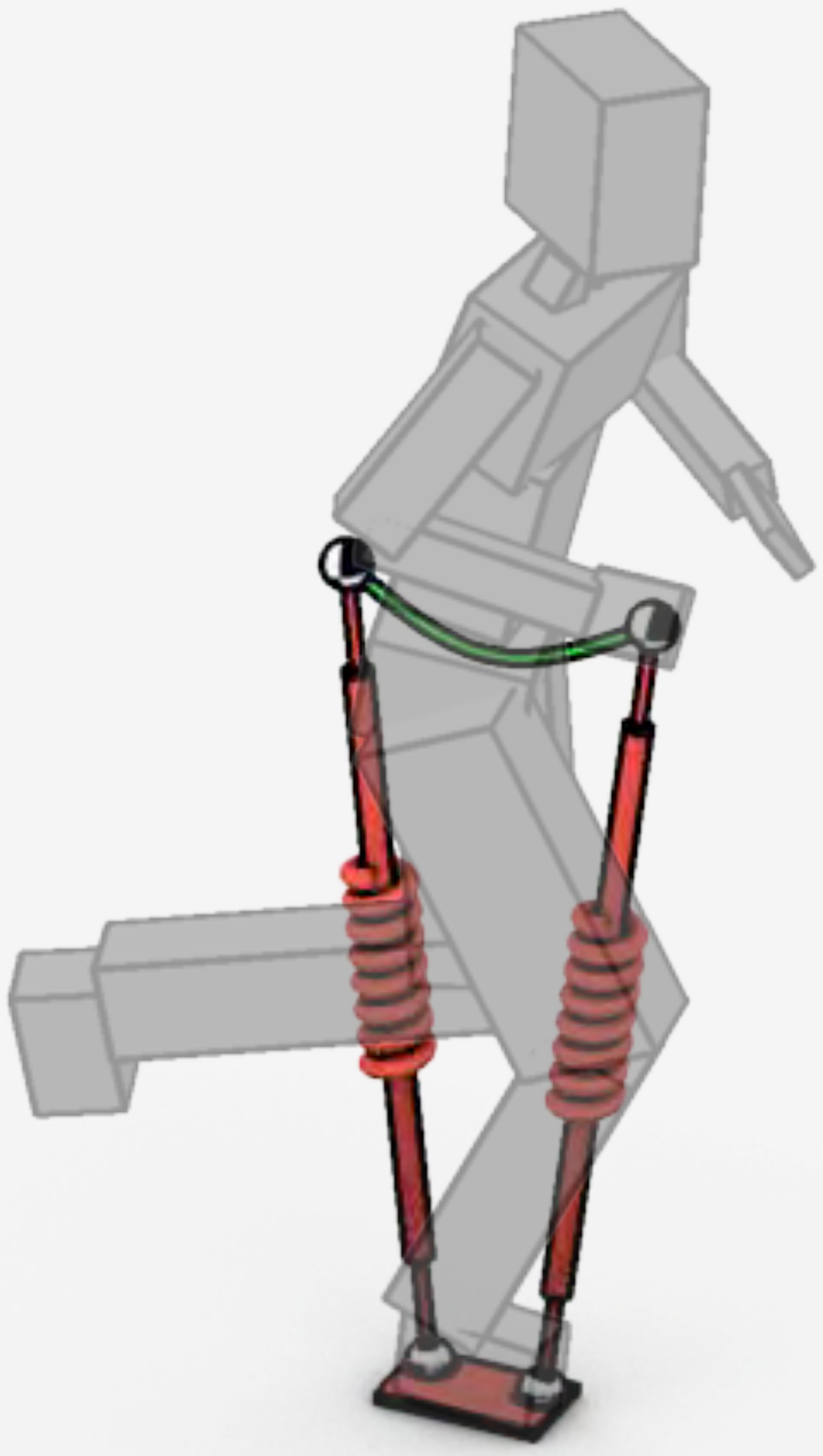
Walking



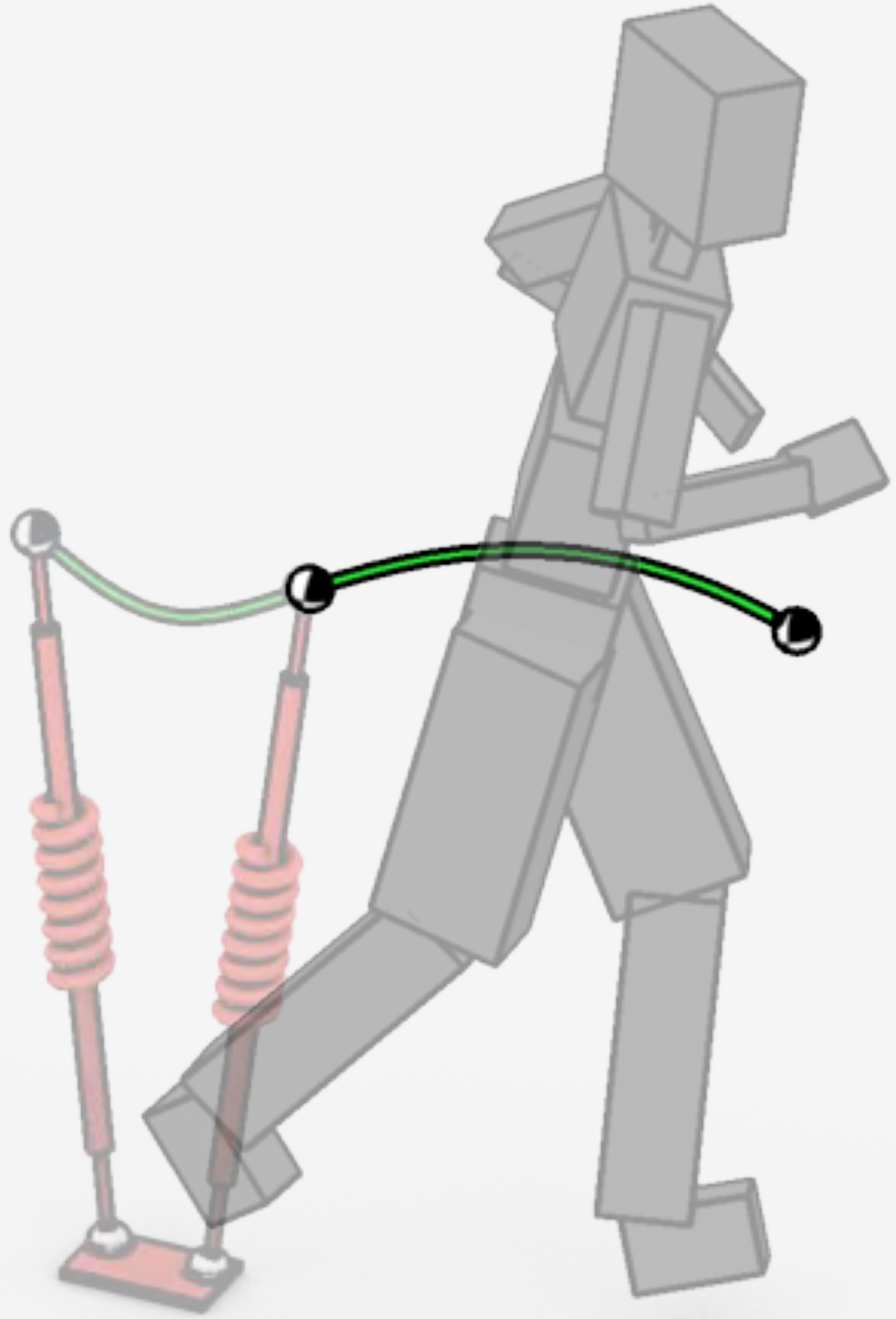
Walking



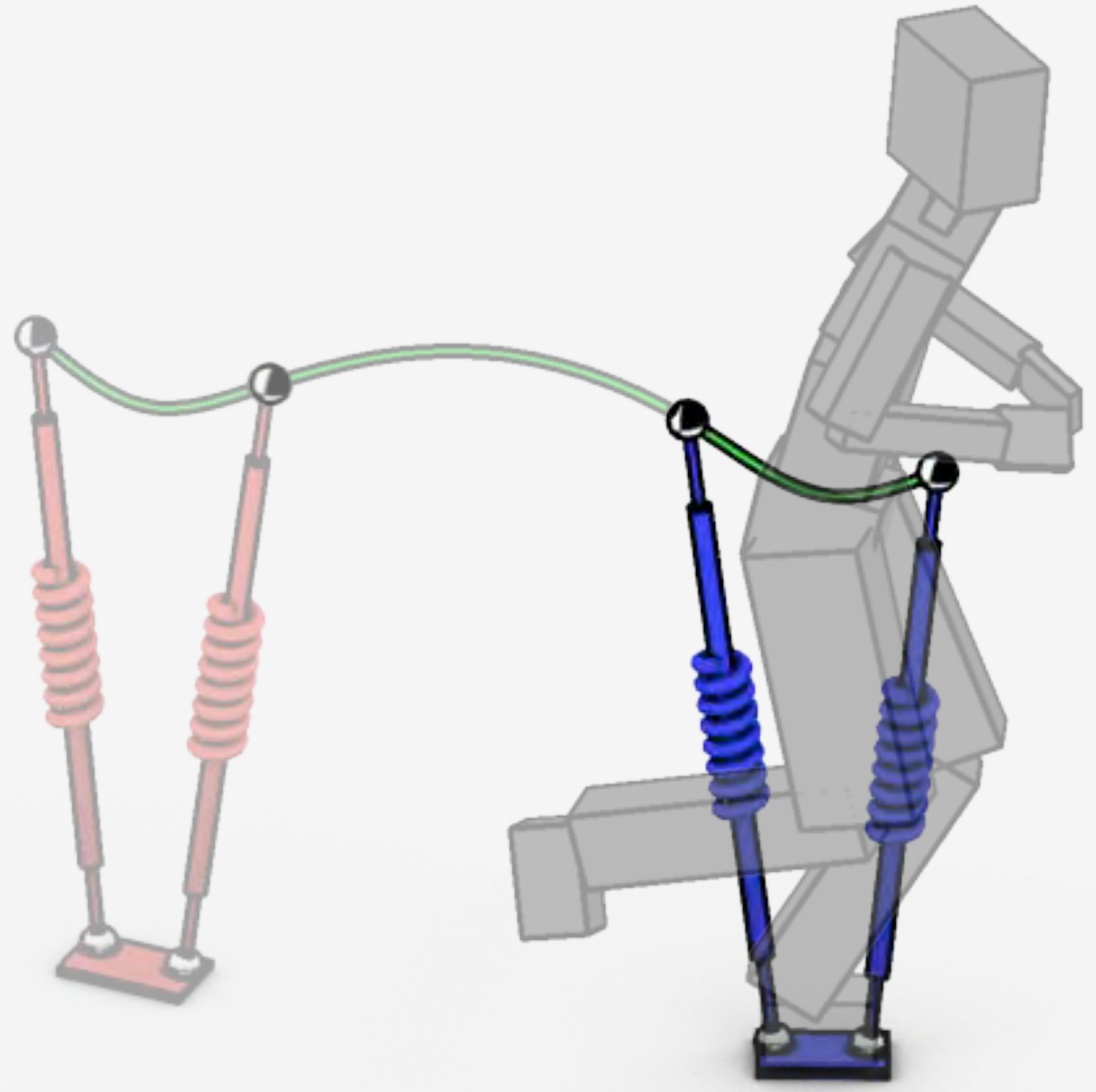
Running



Running

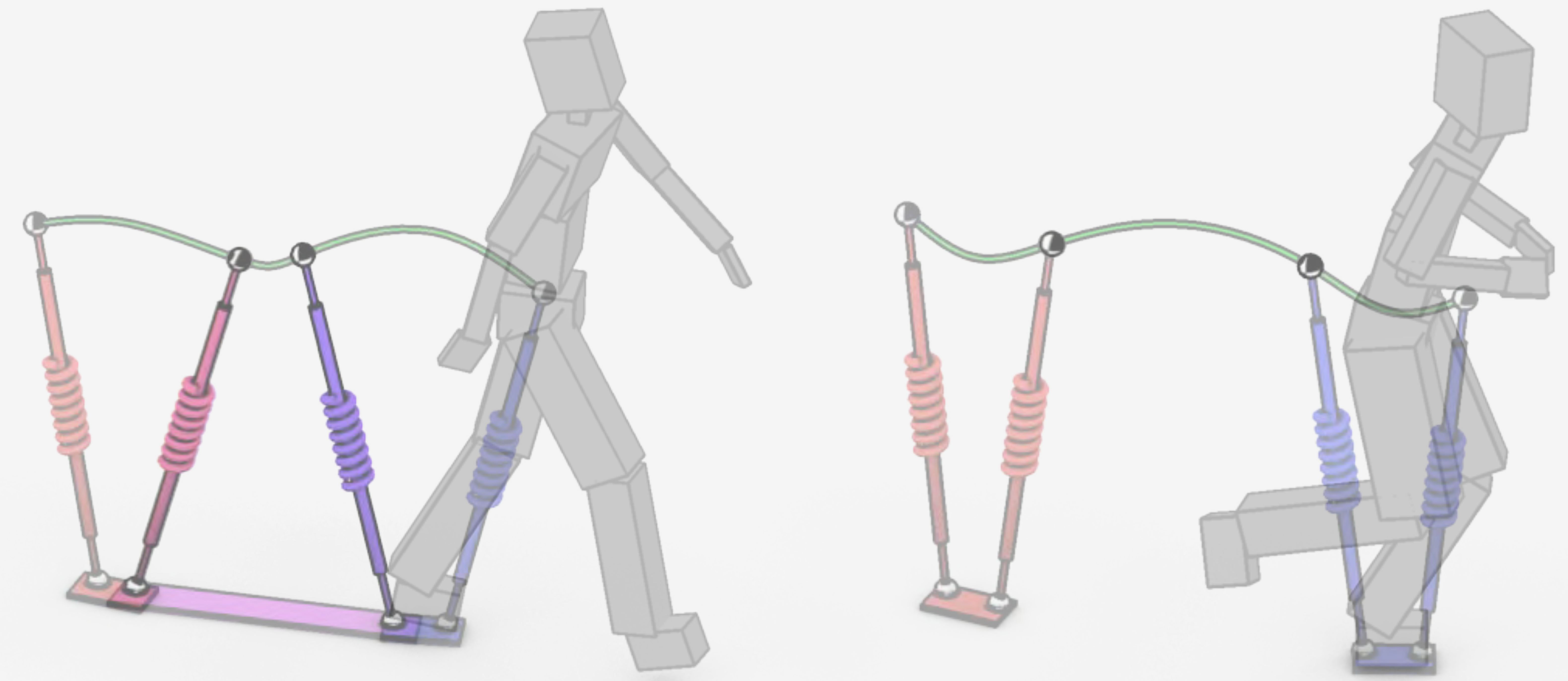


Running



General Gaits:

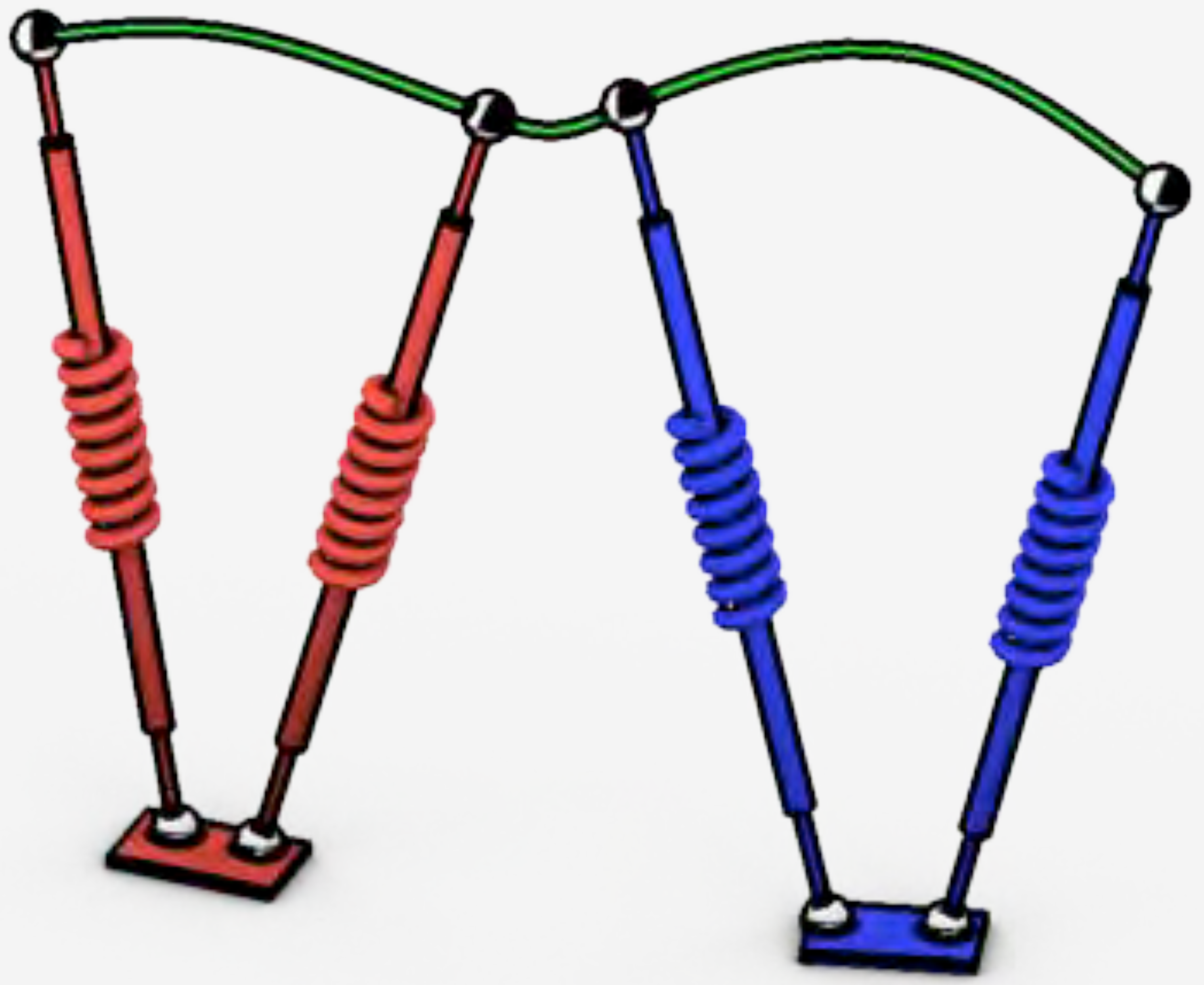
sequence of single/double SLIP and flight phases



Optimization

Optimize U* to satisfy goals:

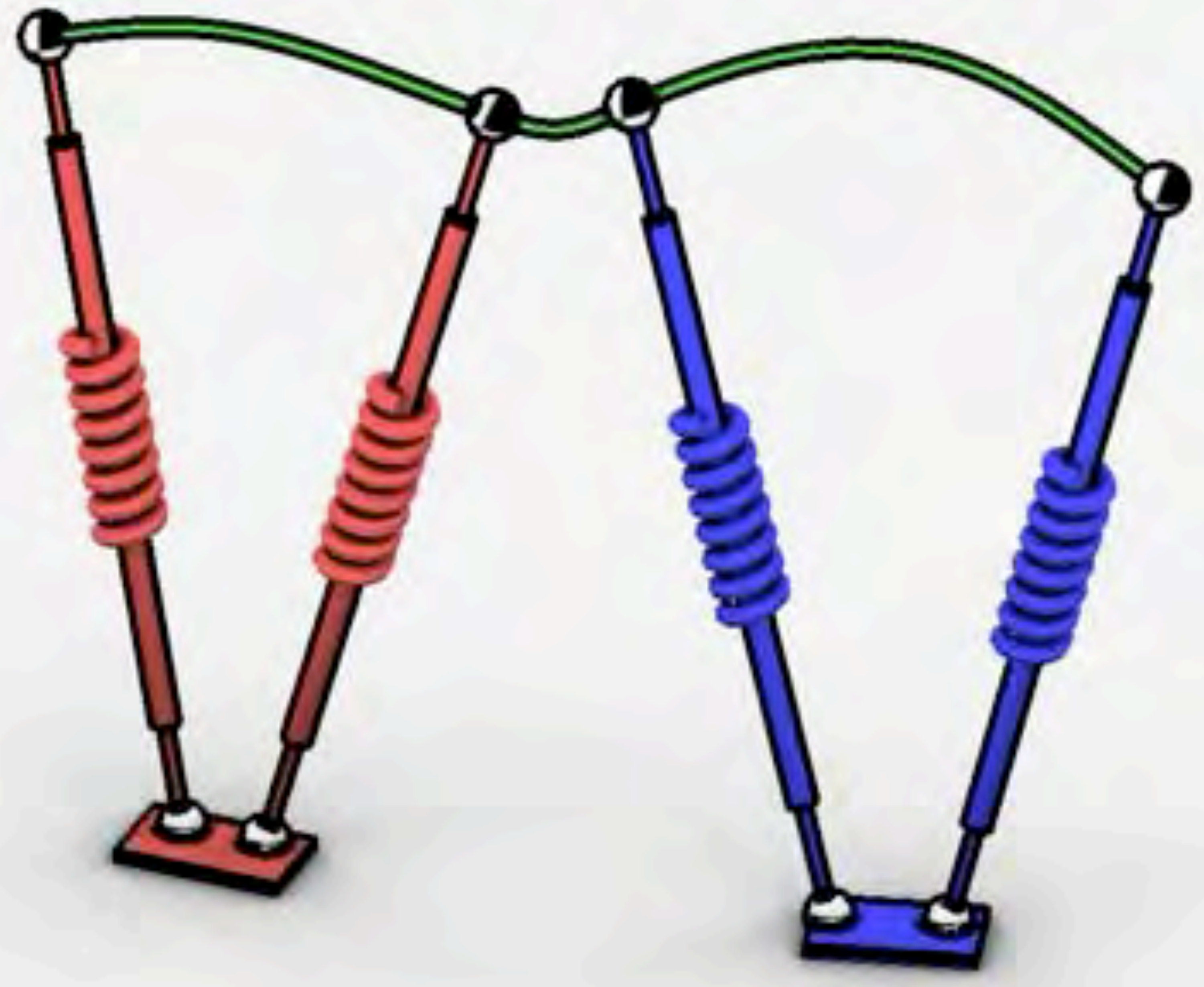
$$U^* = \text{argmin} \sum_i w_i g_i(S(t))$$

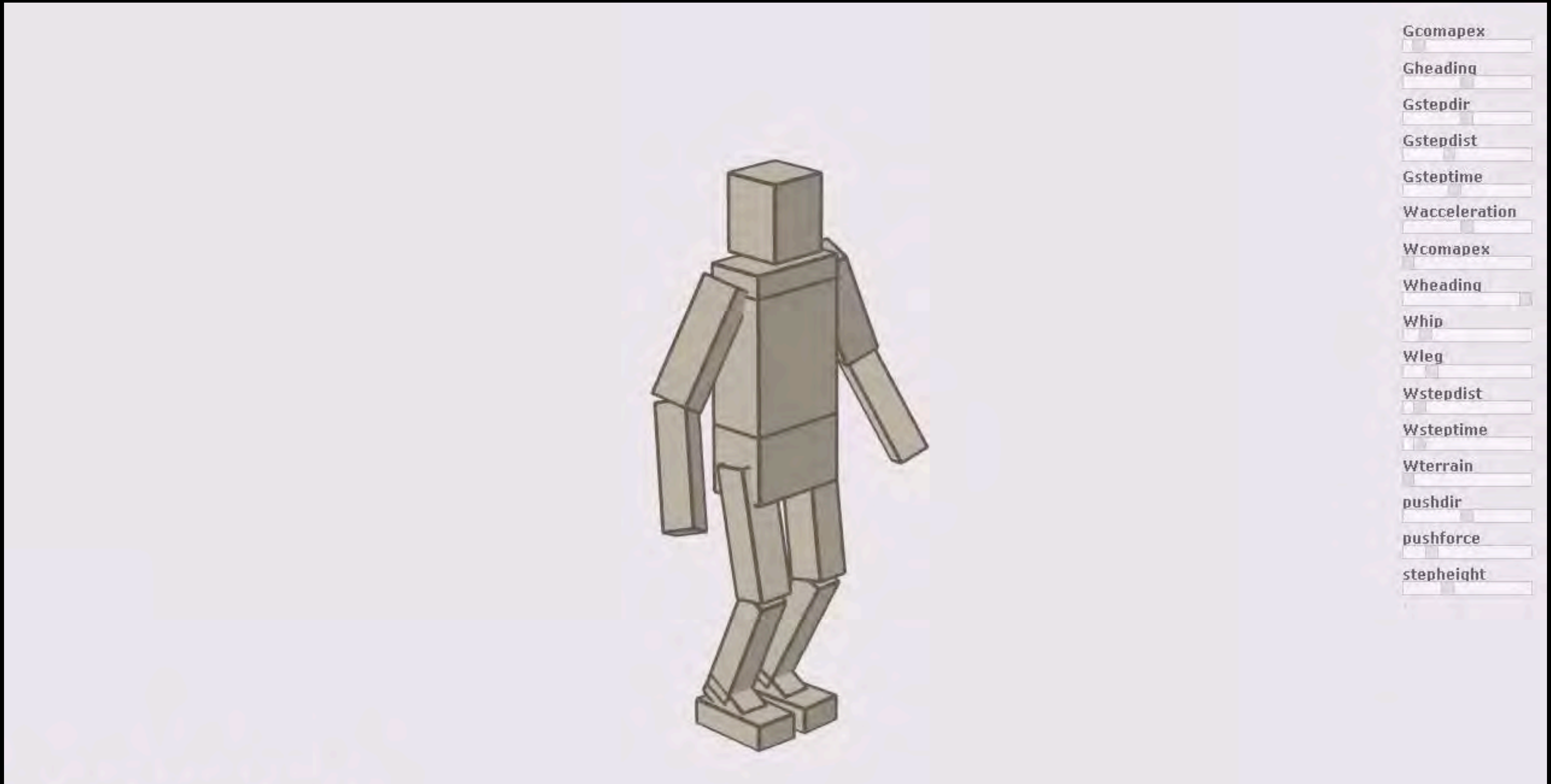


Optimize U* to satisfy goals:

$$U^* = \underset{U}{\operatorname{argmin}} \sum_i w_i g_i(S(t))$$

General nonlinear optimization
23-dimensional
Solved using CMA [Hansen 2006]

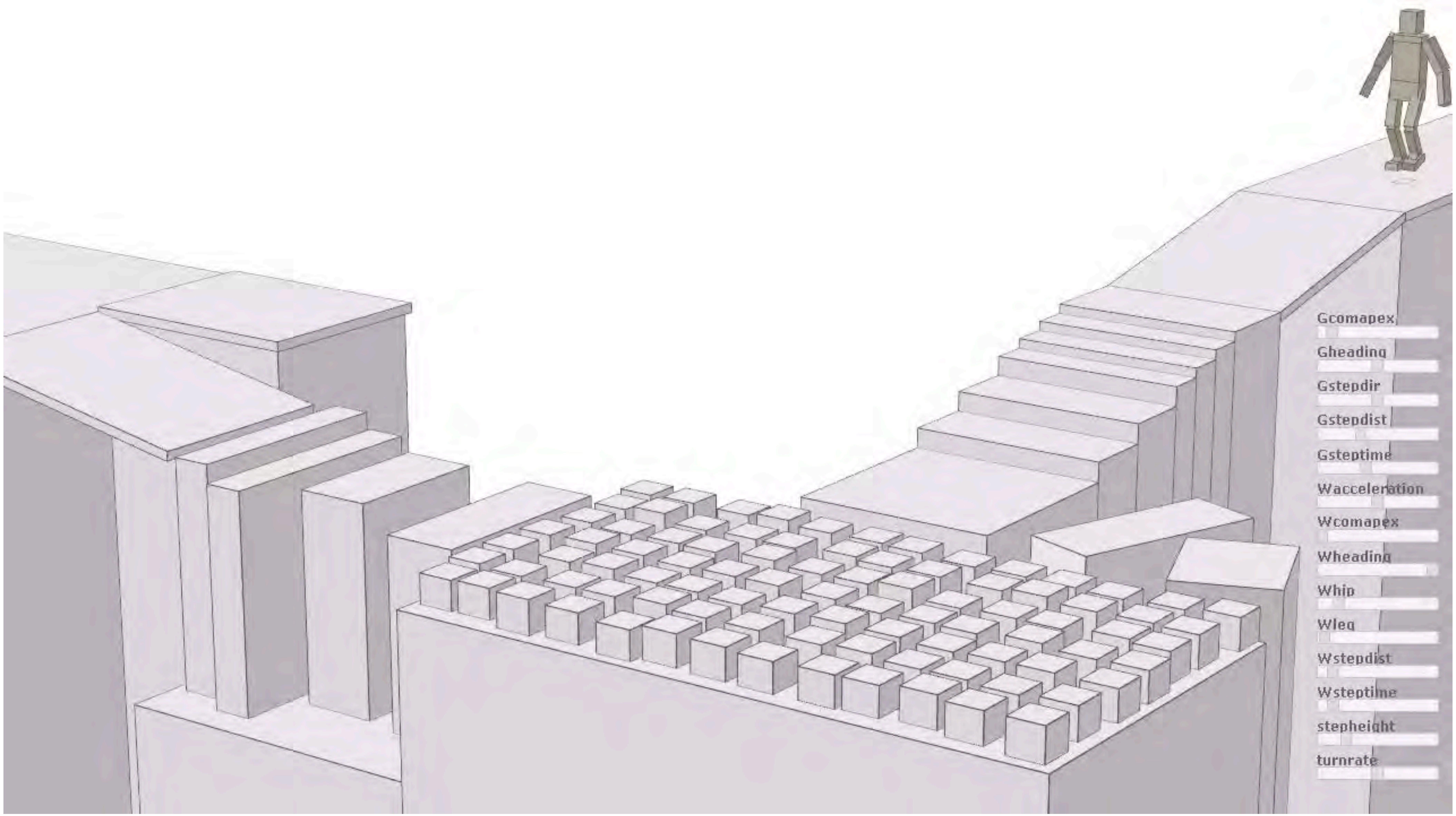




Step Distance

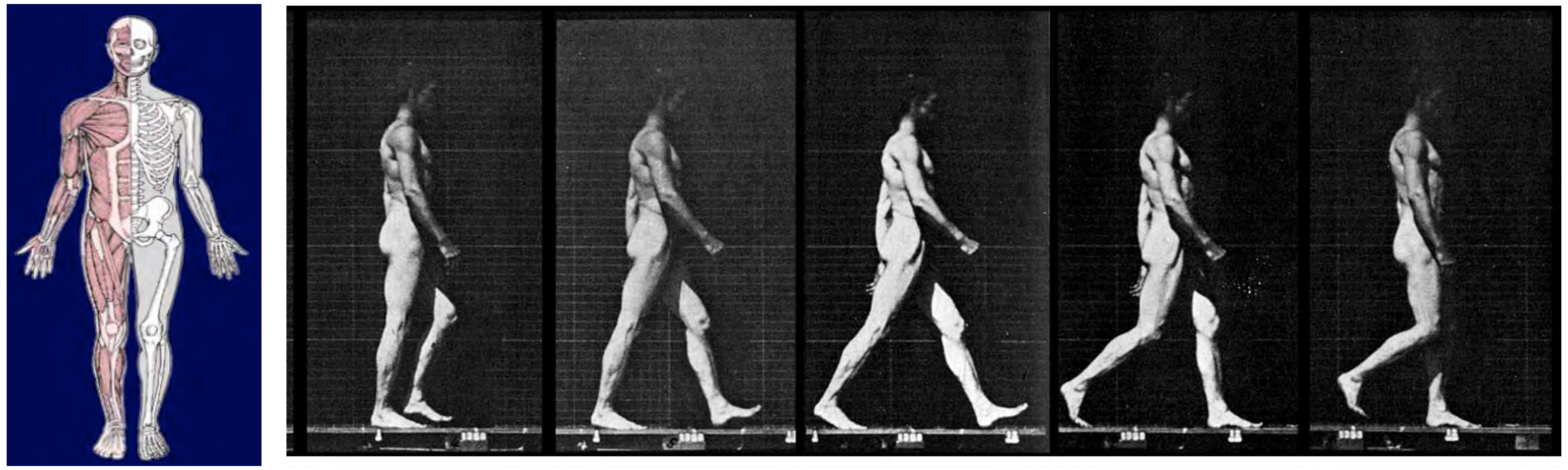
Pushes

Projectile Avoidance

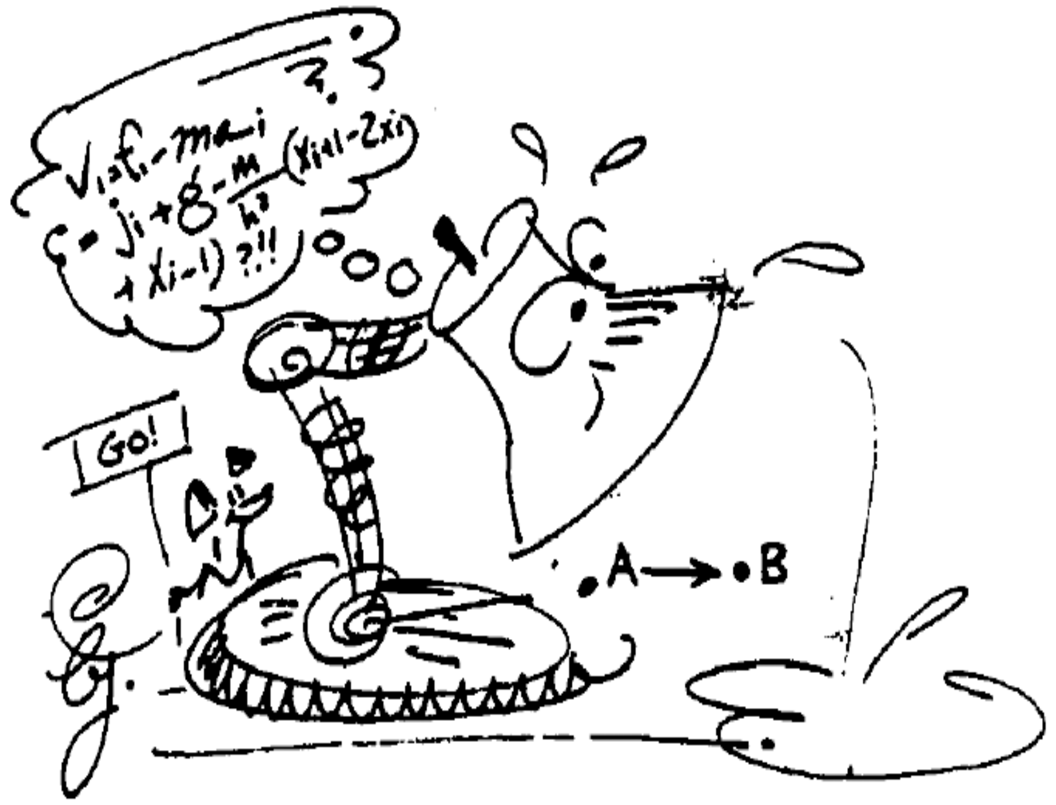


Gcomapex
Gheading
Gstepdir
Gstepdist
Gsteptime
Wacceleration
Wcomapex
Wheading
Whip
Wleg
Wstepdist
Wsteptime
stepheight
turnrate

Summary



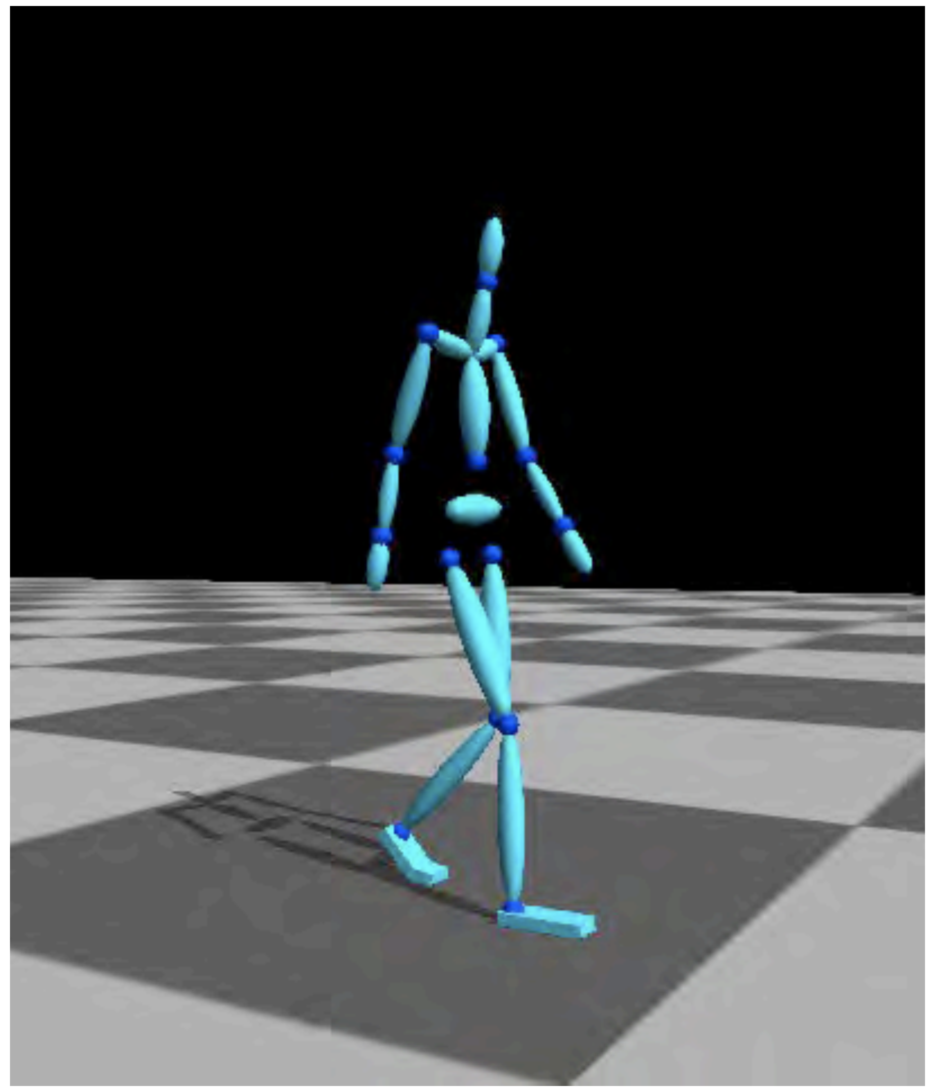
Basics of body and gait



Optimality

Ballistic motion
and balance

Simplified
models



Controllers

Key *features* of motion

Contact

Center-of-mass

(simplified models)

Angular momentum

Symmetry

Task constraints

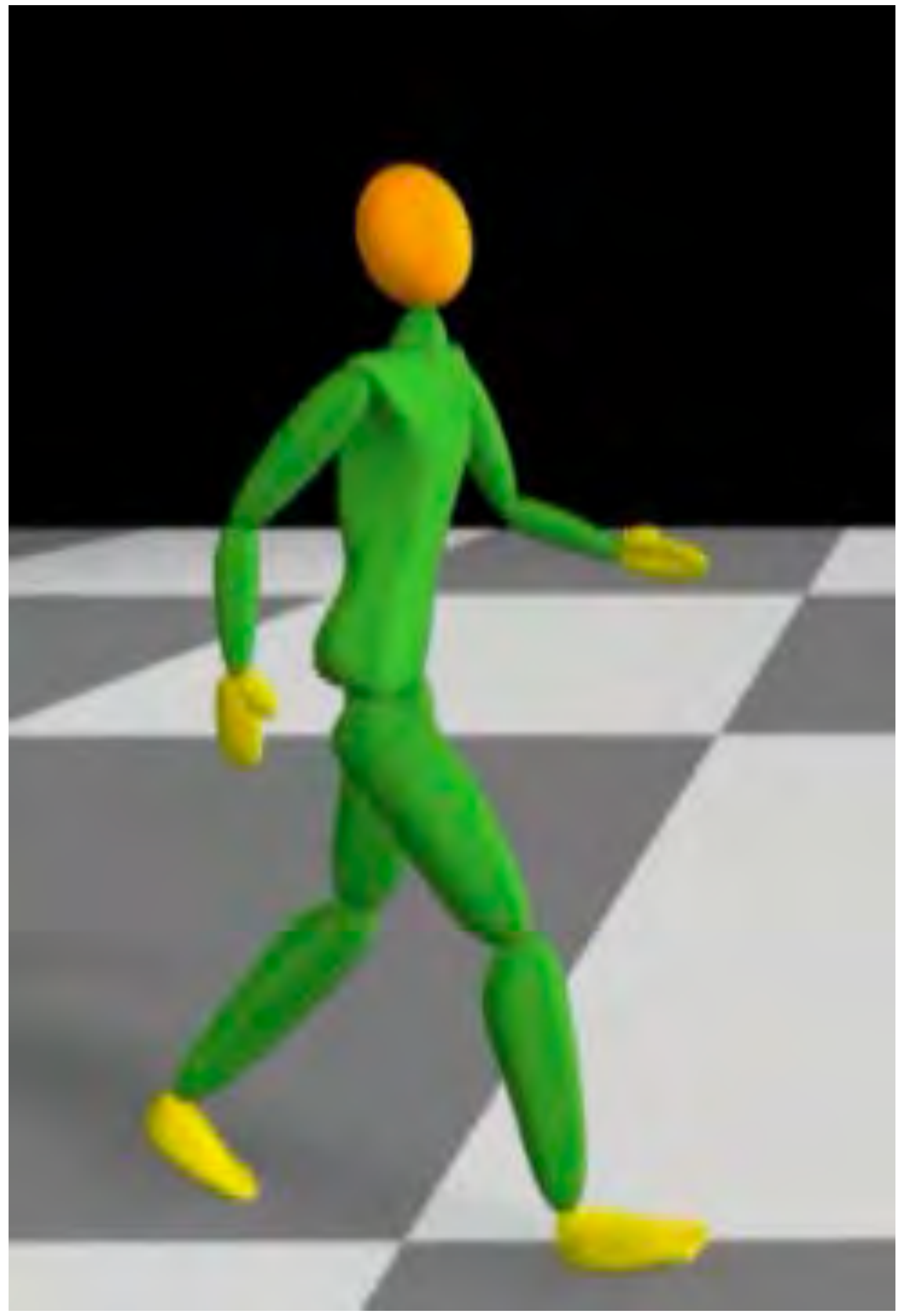
Head stability

Stability/Robustness

Energy use

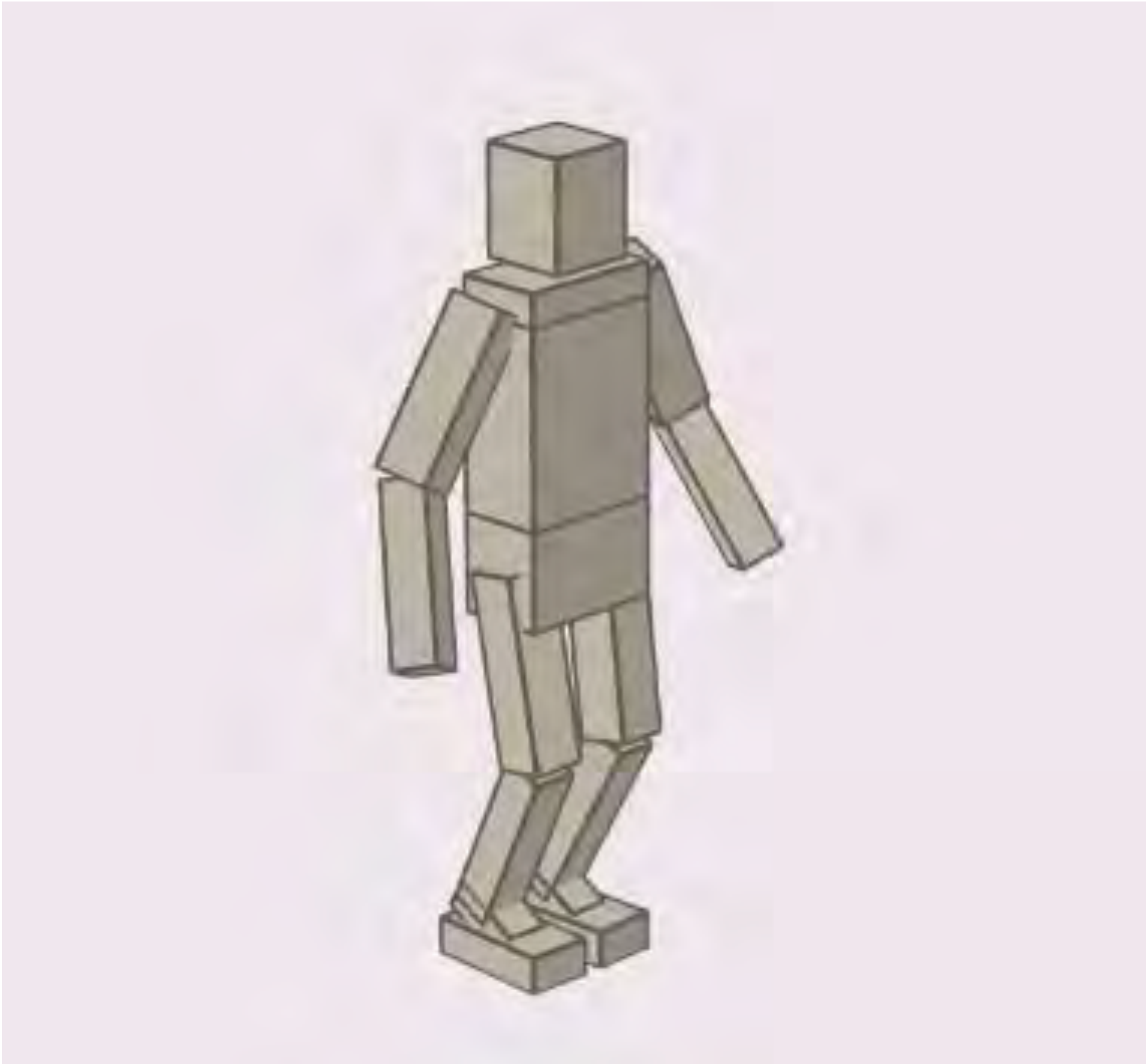
Stiffness/Tension

Types of controllers



Trajectory Optimization
(no runtime control)

Feed-forward mappings
(including deep control)
Optimized beforehand



Run-time optimization (MPC)
(possibly low-dimensional)

Some topics not covered today

Fundamentals	*Applications*
Physics simulation	Other animals
Contact and foot models	Clothing
Perceptual uncertainty	Climbing
Eye movements/sensing	Bicycle stunts
Planning	Soft creatures
Evolution of Morphology	Crowds

Some grand challenges

How do we infer models from data?

Intuitions for deep controllers

Unify multiple controllers; high-level planning

Simplified models with rotations

User authoring and control