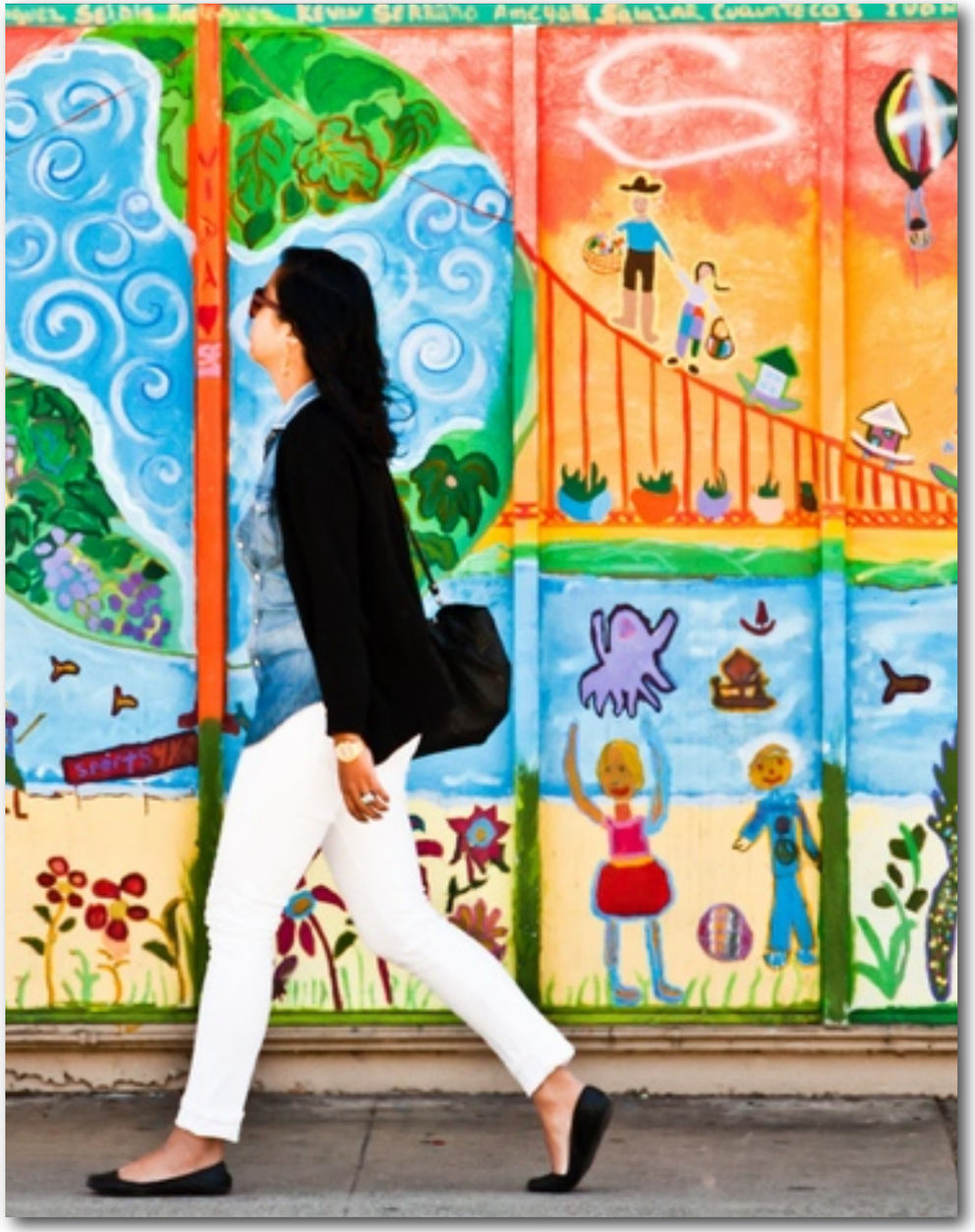
Feature-Based Locomotion Controllers

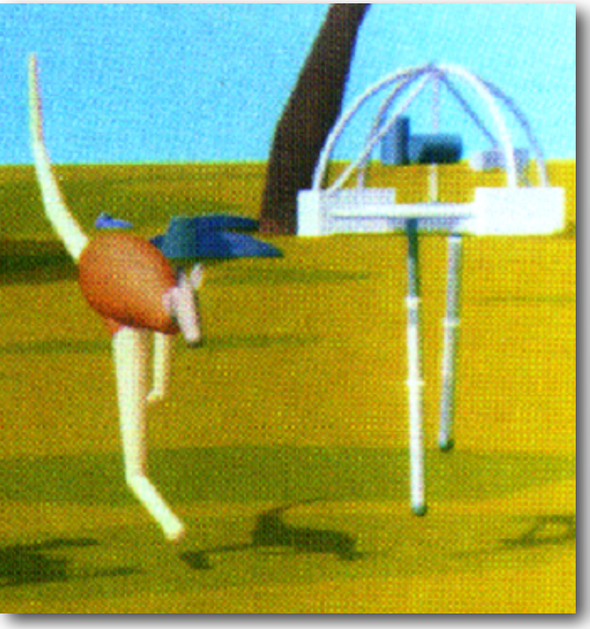
Martin de Lasa
Igor Mordatch
Aaron Hertzmann

University of Toronto

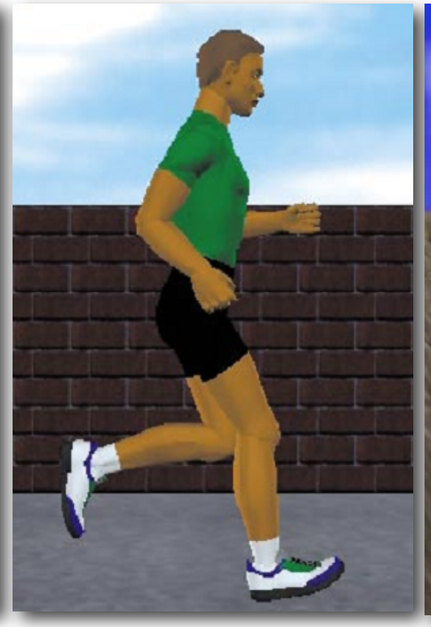

88



Related Work: Linear Control

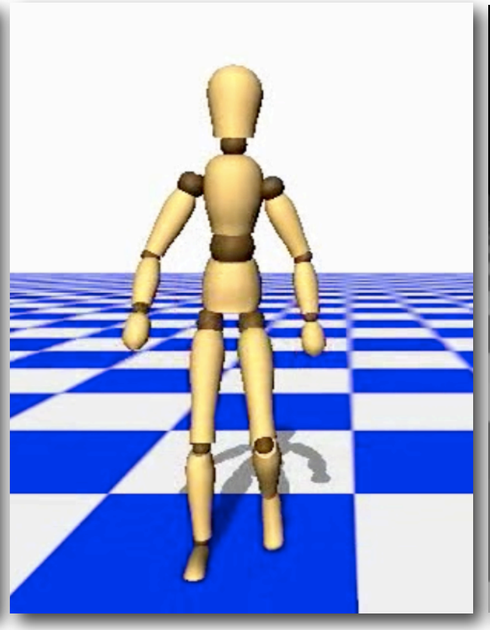


Raibert91

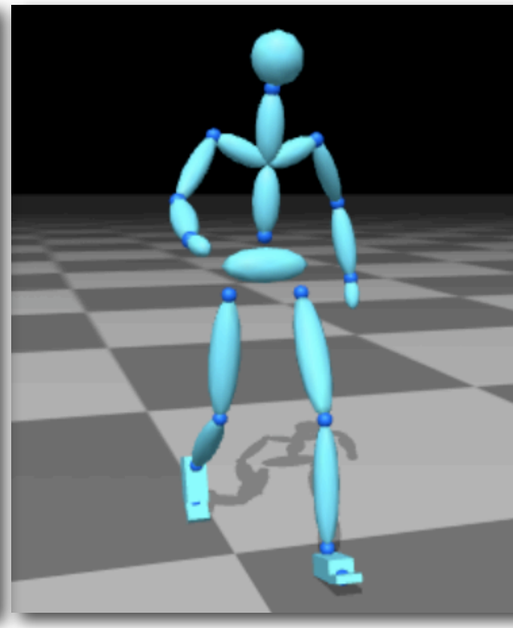


Hodgins9X

Faloutsos01

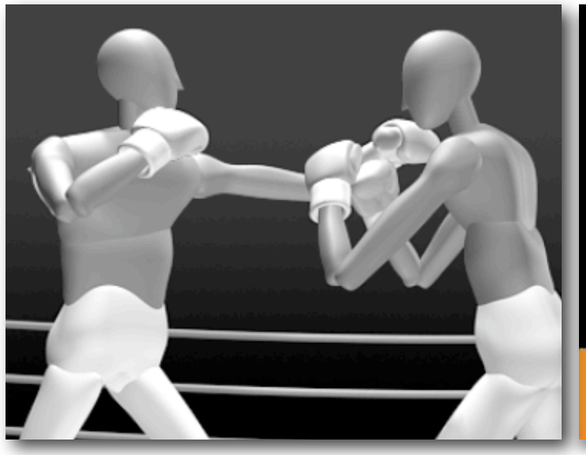


Yin07,08

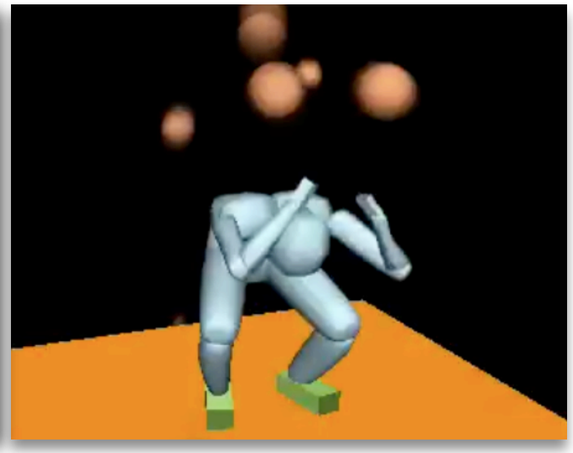


Wang09,10

Related Work: MOCAP Tracking



Zordan02



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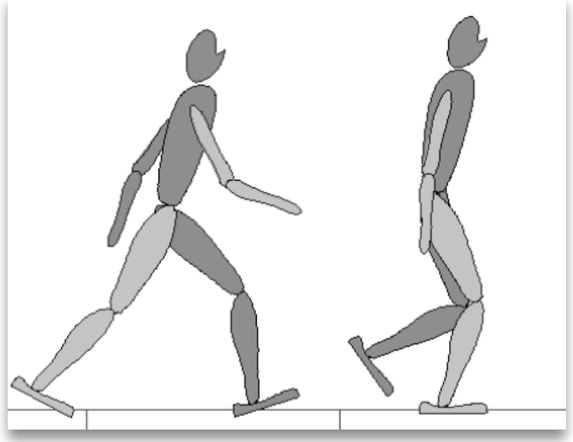
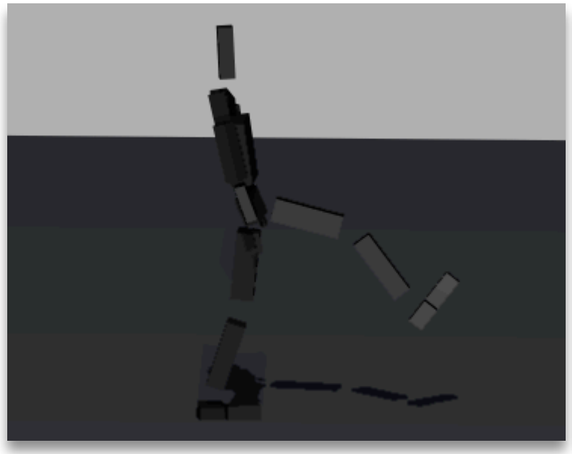
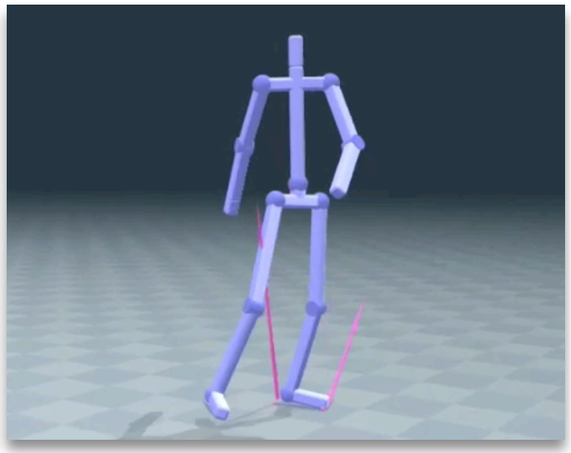


Sok07

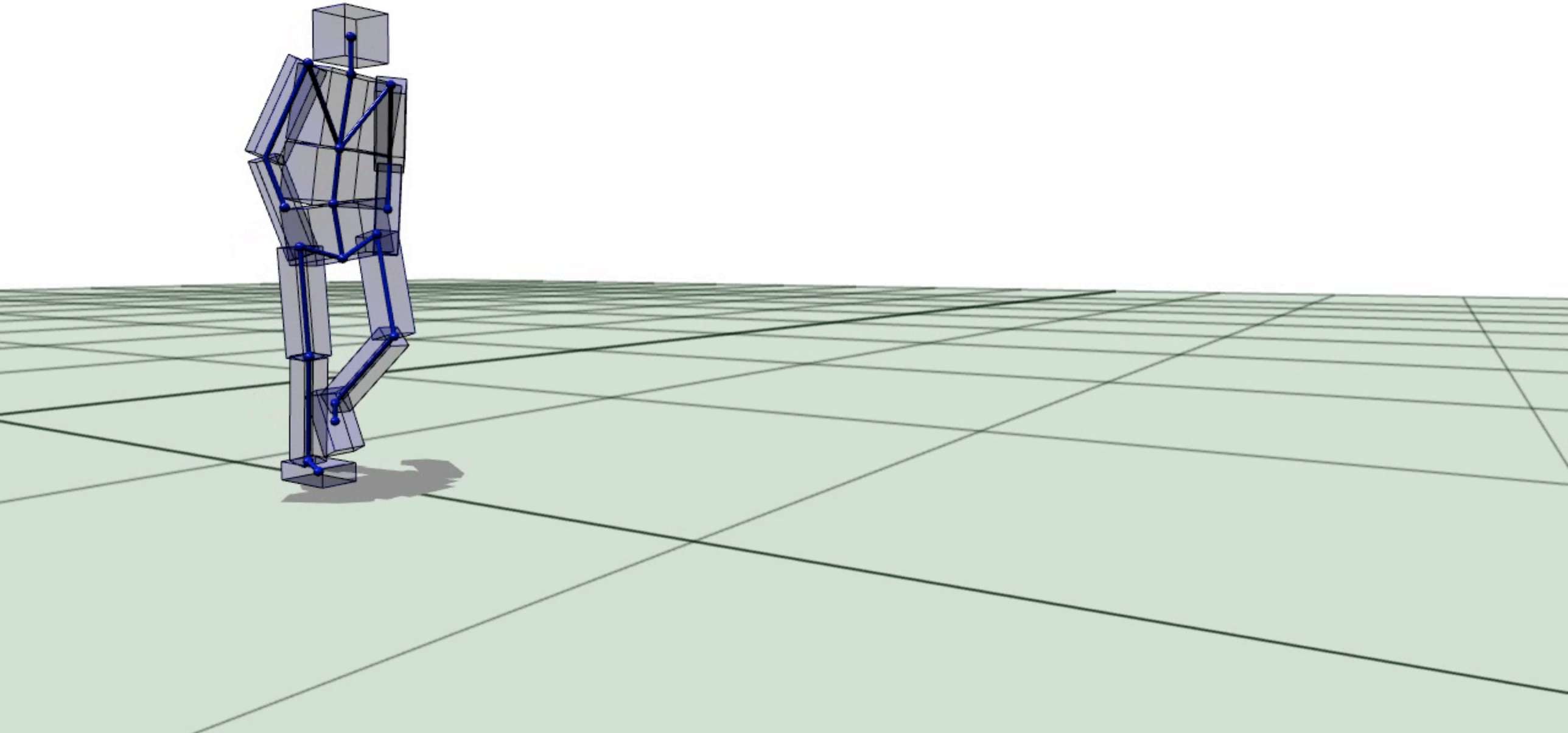


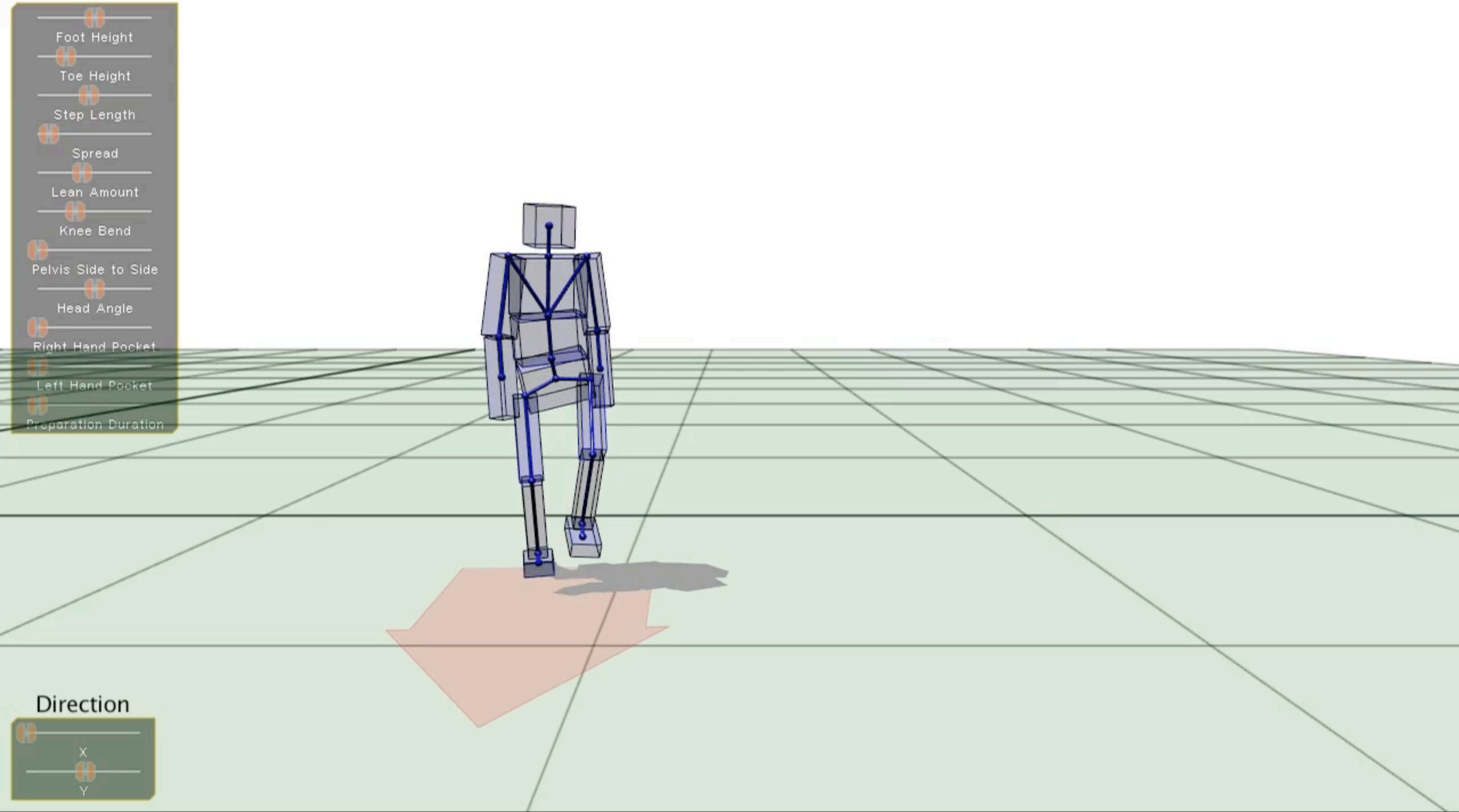
daSilva08

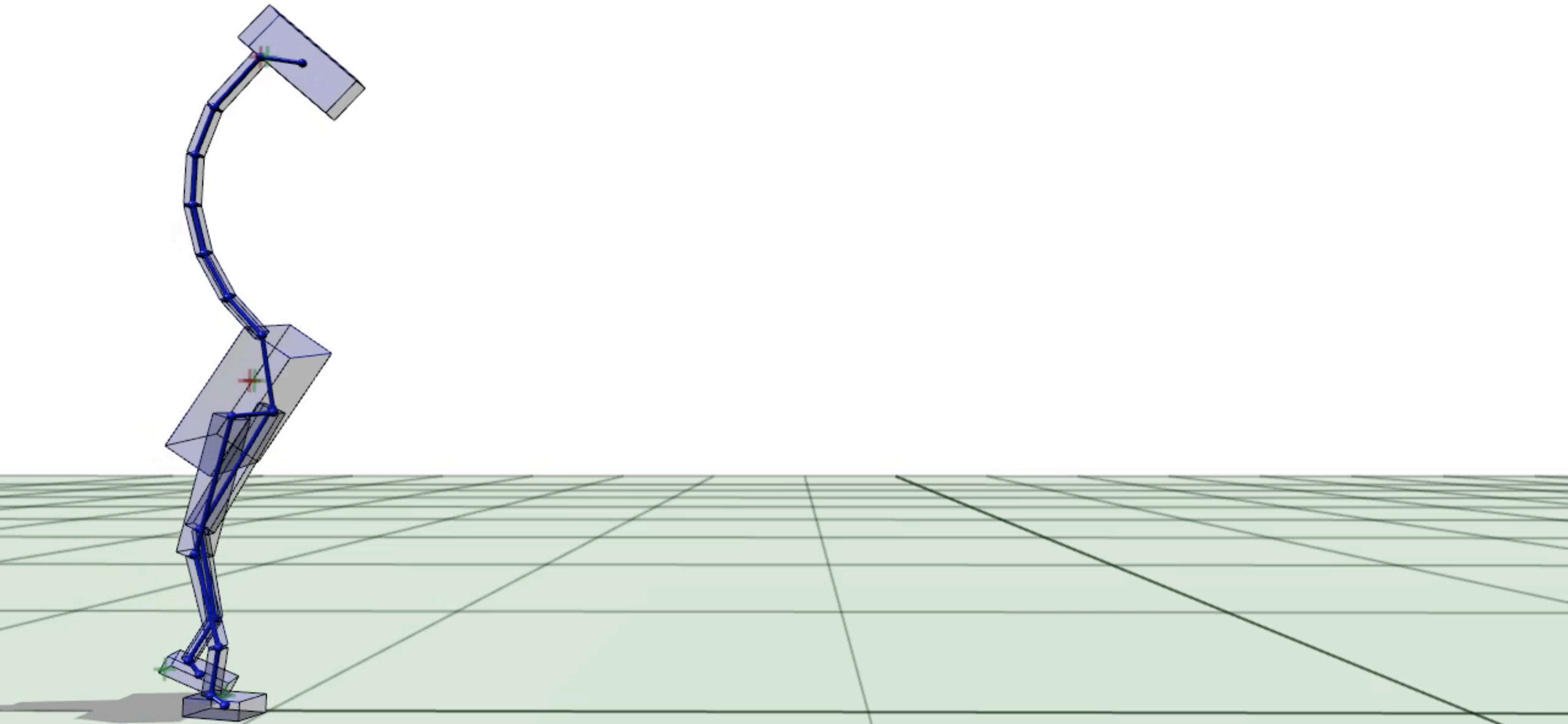


Muico09

Tsai10




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



Feature-Based Control

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Describe control using a small set of goals

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Goals describe high-level aspects of motion

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Directly map biomechanical observations

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Simplifies reasoning about control

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Describe control using a small set of goals

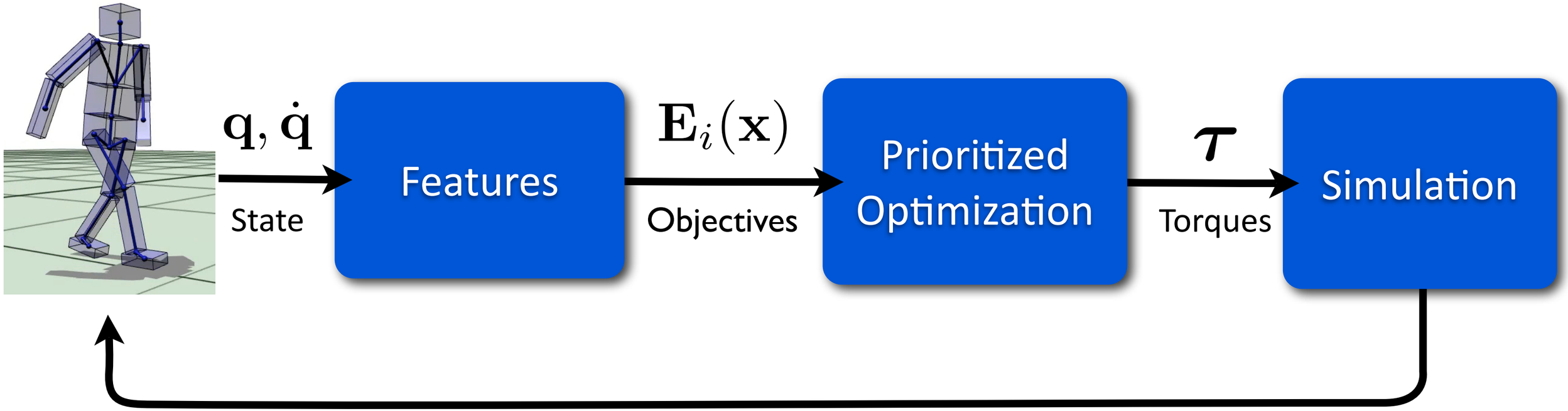
Goals describe high-level aspects of motion

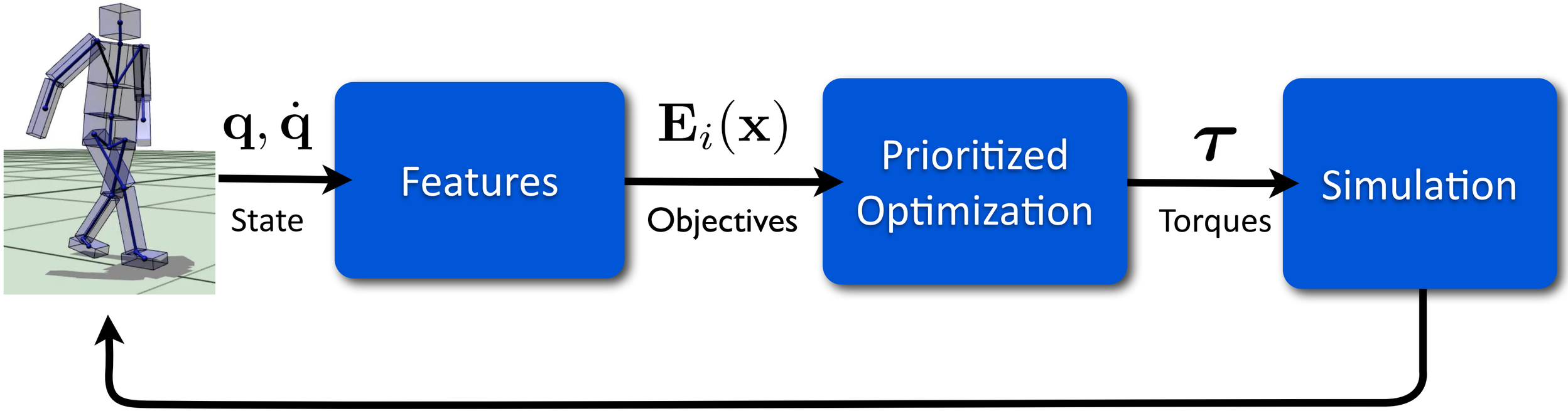
Directly map biomechanical observations

Simplifies reasoning about control

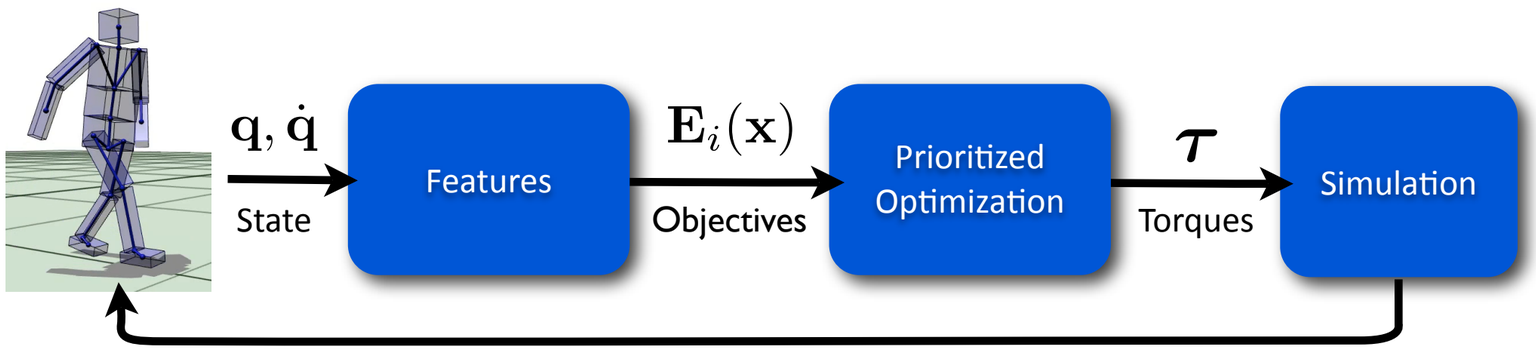
Speeds up controller development


$\mathbf{q}, \dot{\mathbf{q}}$
State
Control
τ
Torques
Simulation


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



[Todorov and Jordan, 2002]


$\mathbf{q}, \dot{\mathbf{q}}$
State
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$\mathbf{E}_i(\mathbf{x})$
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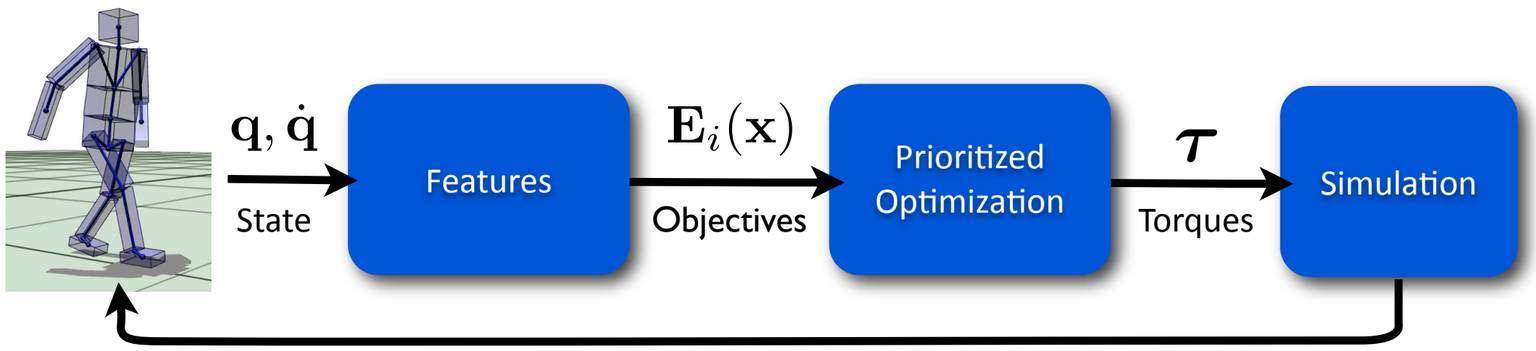
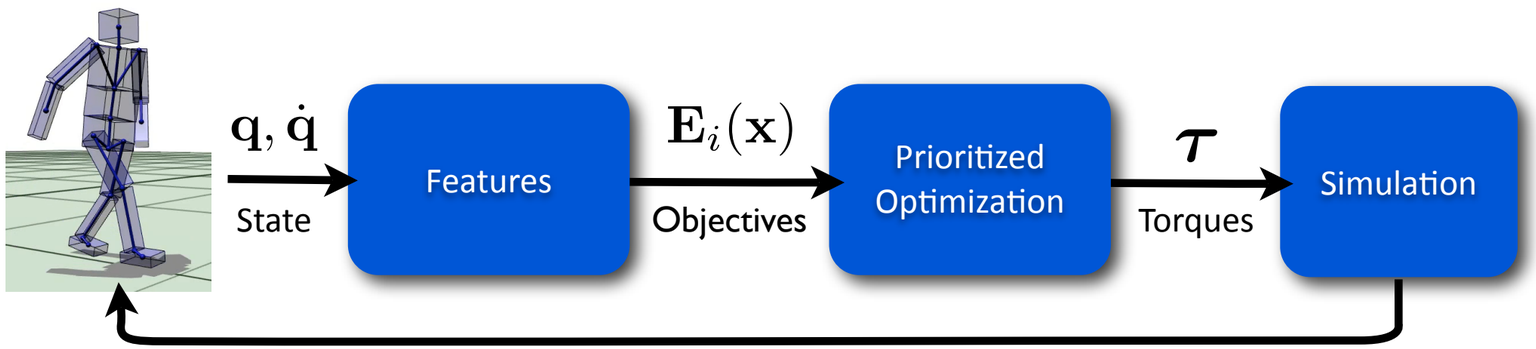
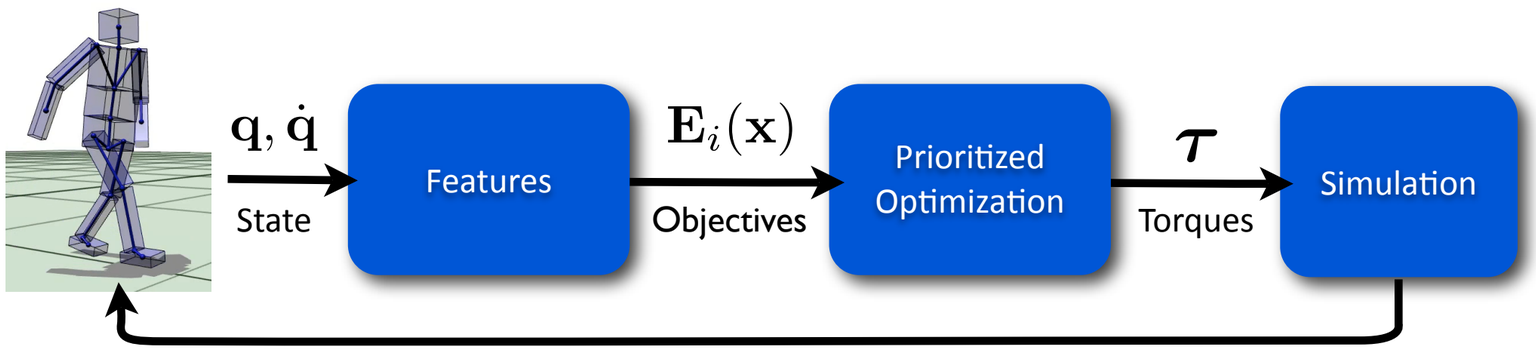


$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\tau}^T & \ddot{\mathbf{q}}^T & \boldsymbol{\lambda}^T \end{bmatrix}^T$$



$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\tau}^T & \ddot{\mathbf{q}}^T & \boldsymbol{\lambda}^T \end{bmatrix}^T$$

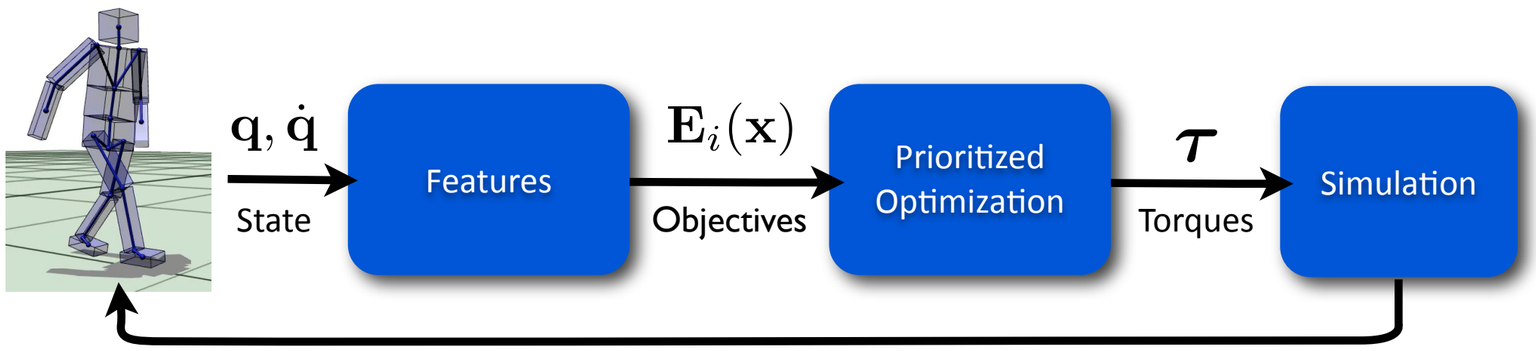
Joint Torques



Joint Accelerations

$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\tau}^T & \ddot{\mathbf{q}}^T & \boldsymbol{\lambda}^T \end{bmatrix}^T$$

Joint Torques

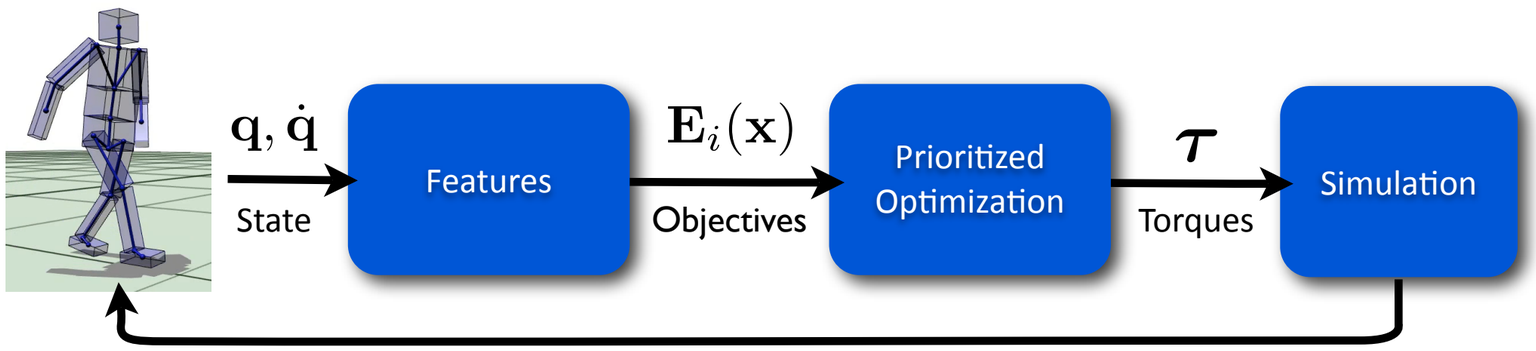


Joint Accelerations

$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\tau}^T & \ddot{\mathbf{q}}^T & \boldsymbol{\lambda}^T \end{bmatrix}^T$$

Joint Torques

Contact Forces



Joint Accelerations

$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\tau}^T & \ddot{\mathbf{q}}^T & \boldsymbol{\lambda}^T \end{bmatrix}^T$$

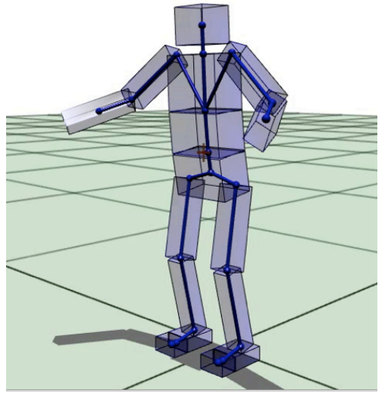
Joint Torques

Contact Forces

Optimize $\mathbf{x}$ subject to

$$\mathbf{C}(\mathbf{x}) = 0, \mathbf{D}(\mathbf{x}) + \mathbf{f} \geq 0$$

Balancing



Features

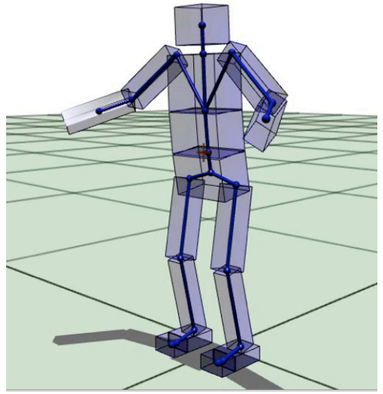
Contact

COM

AM

Posture

Balancing



Features

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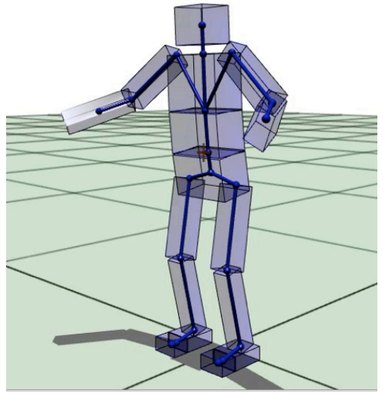

Features

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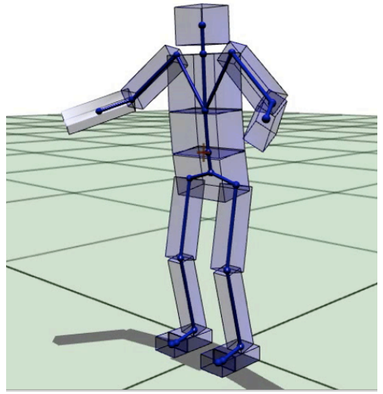

Features

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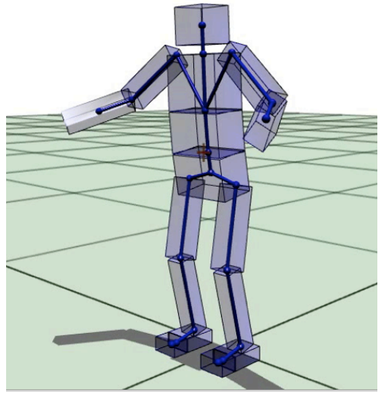

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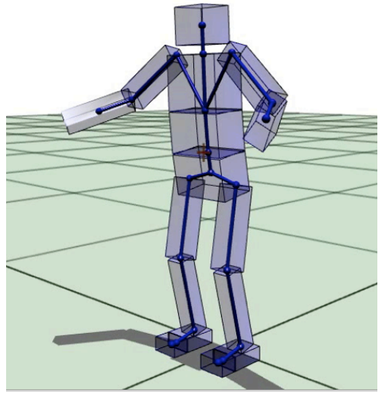

Features

Contact

COM

AM

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Features

Features

- Contact
- COM
- AM
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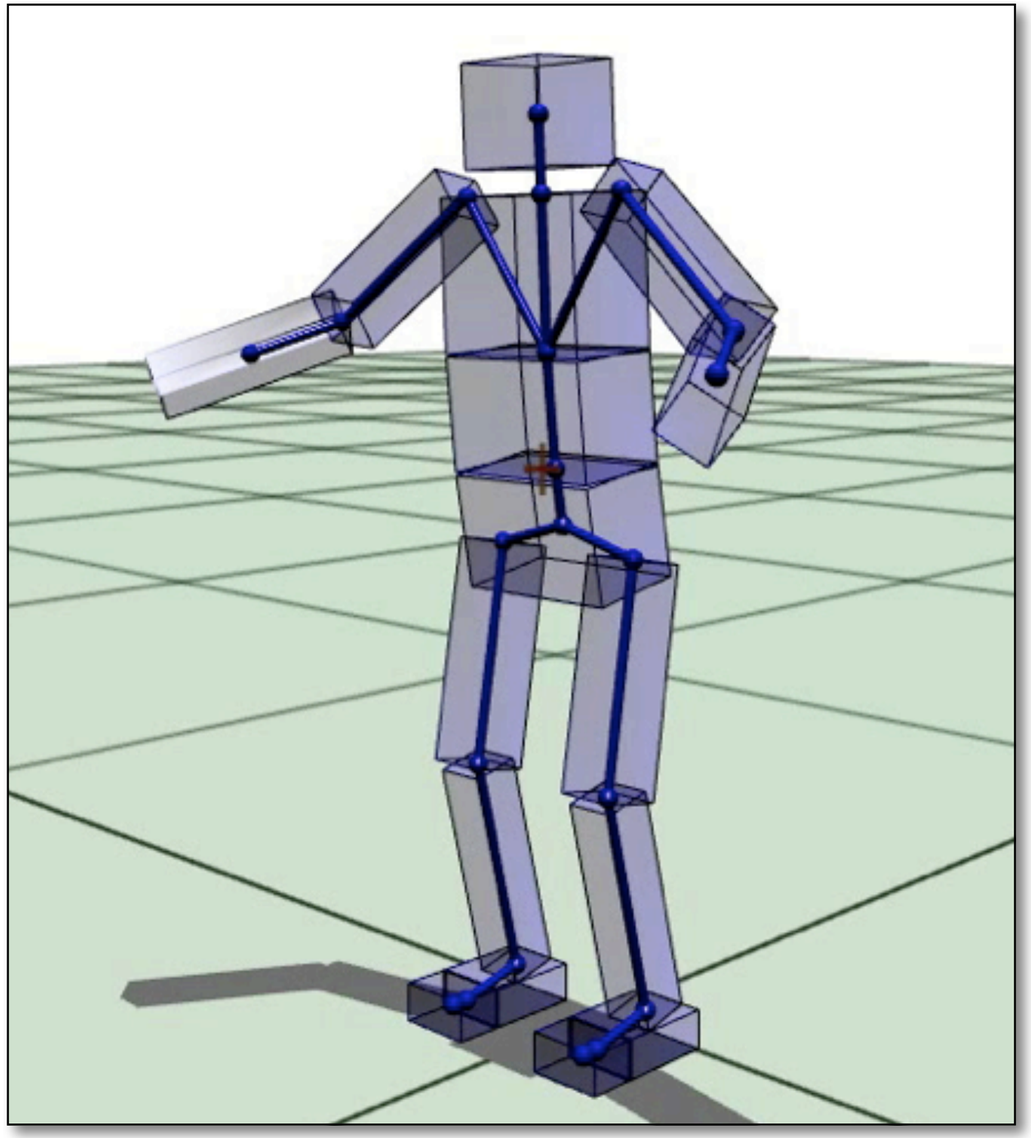

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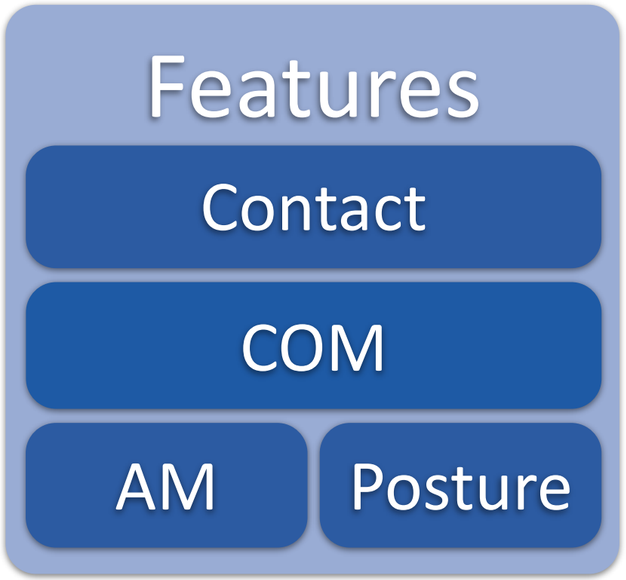
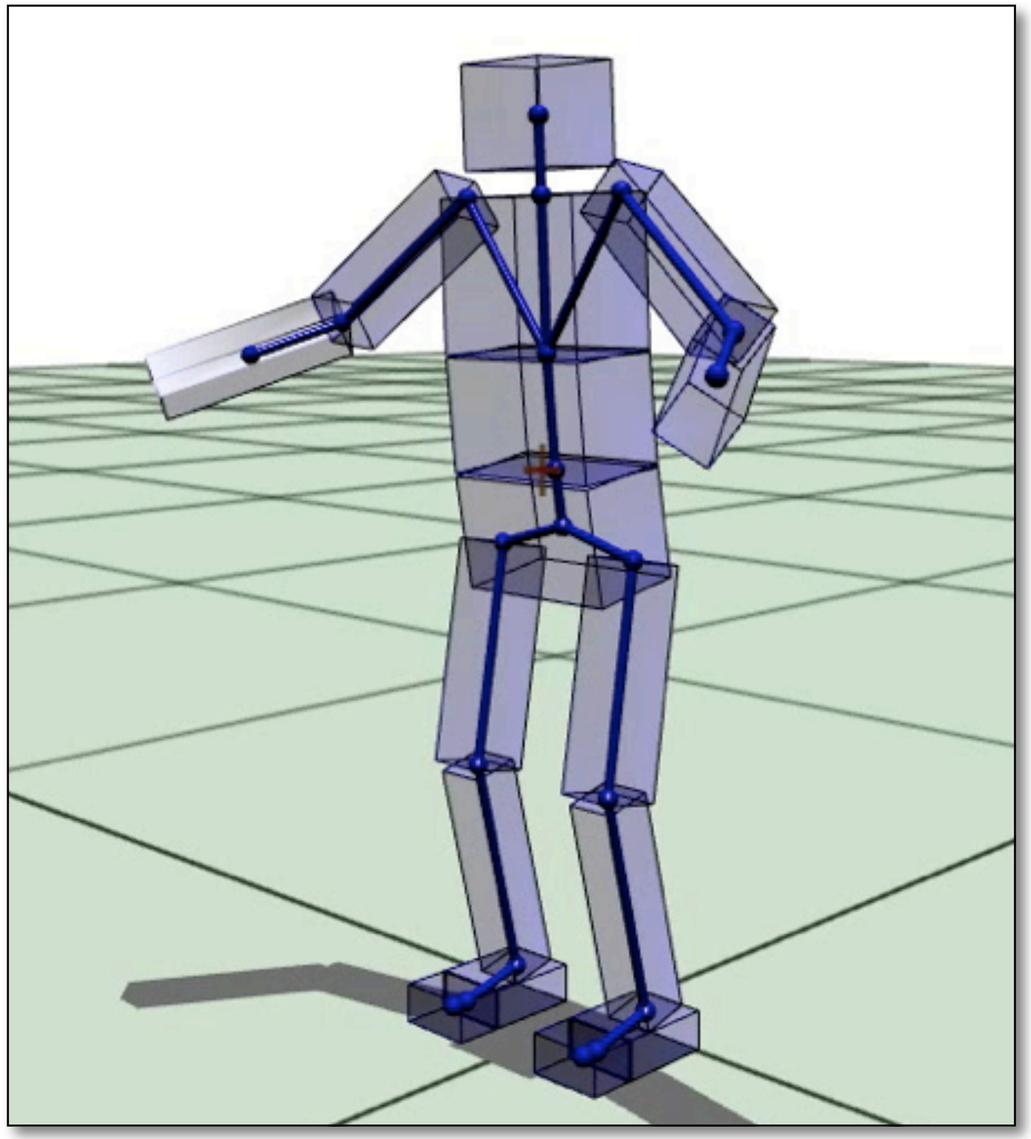
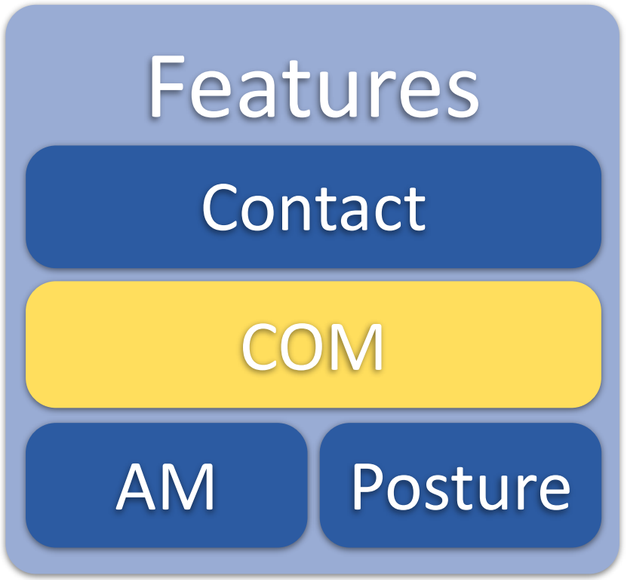


Feature Pose

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



Features



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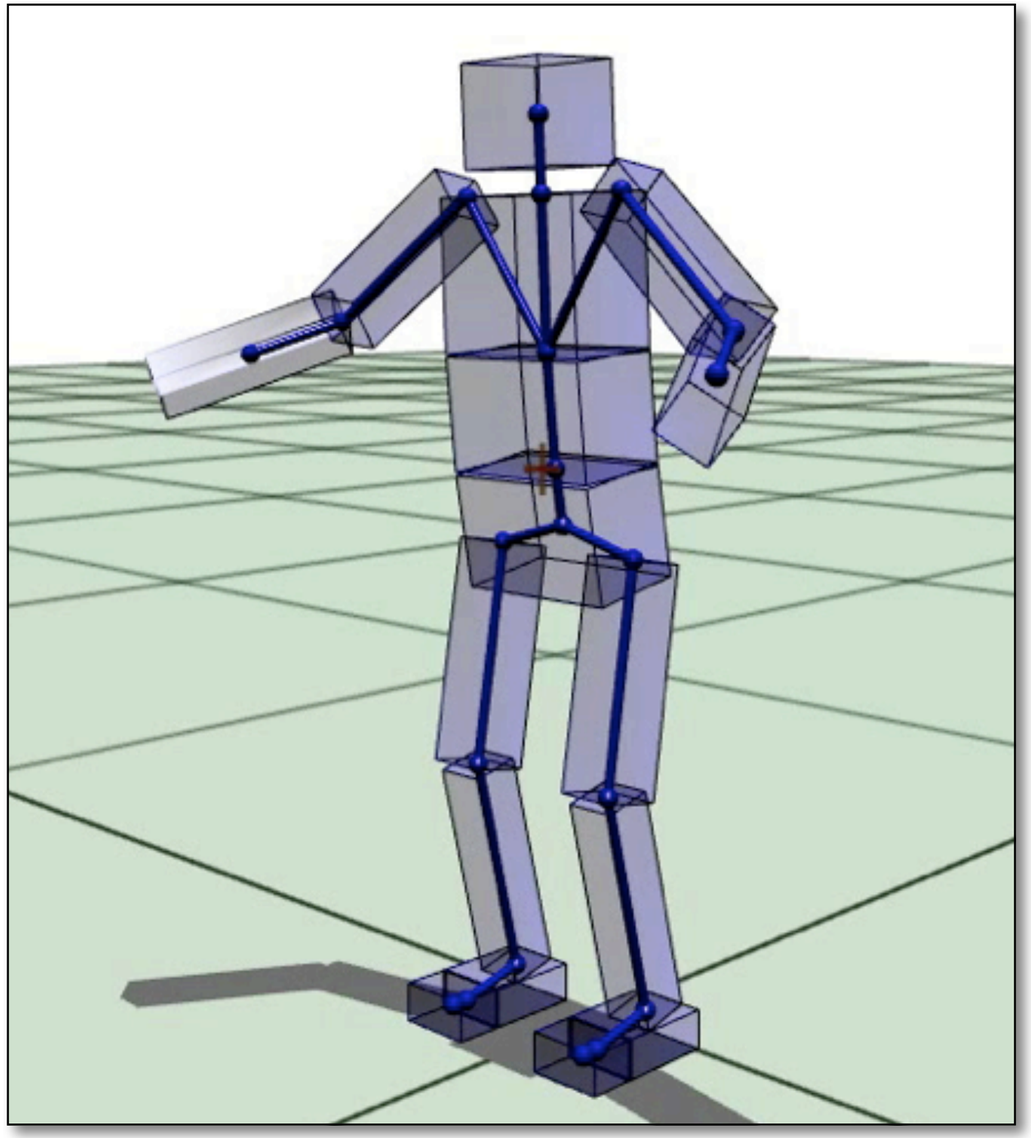
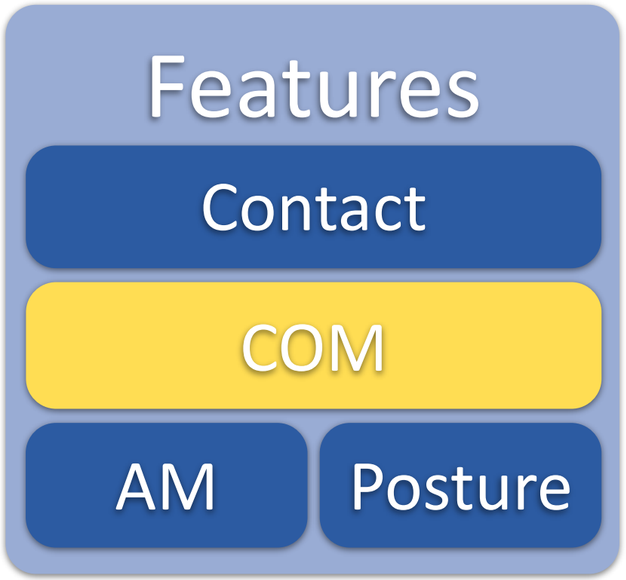


Features



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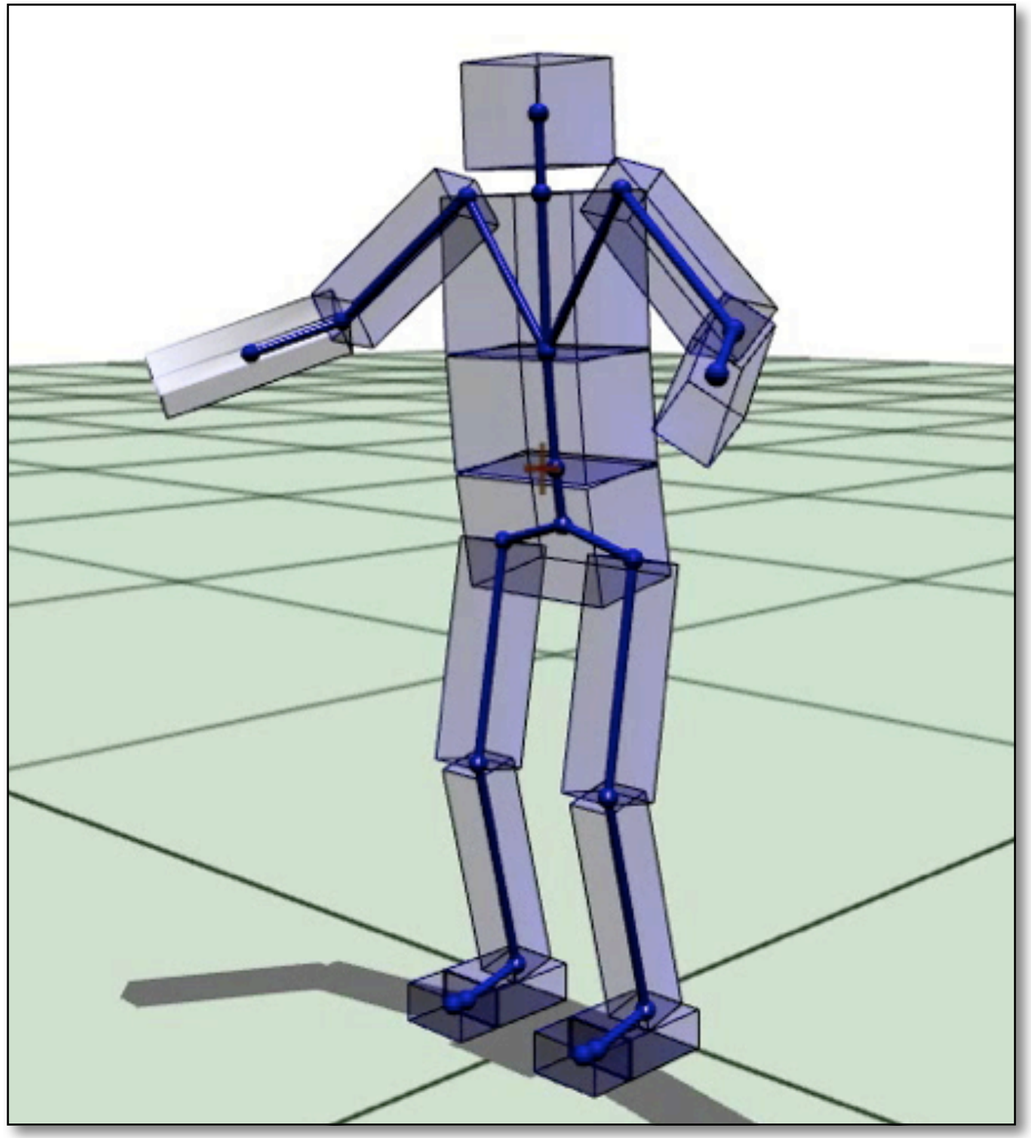

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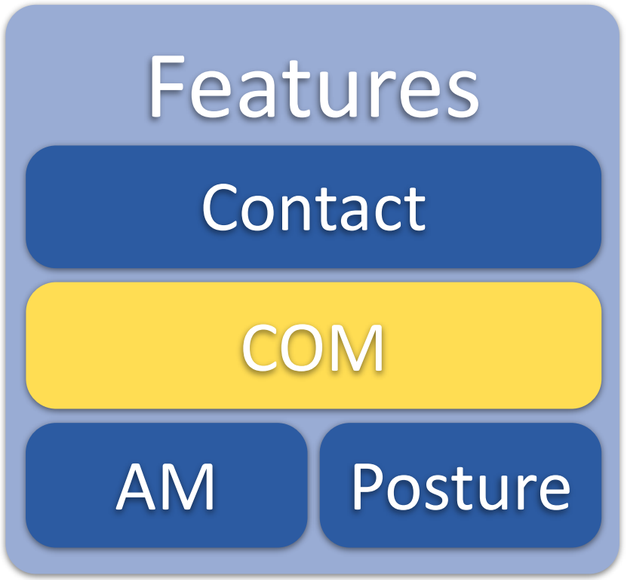

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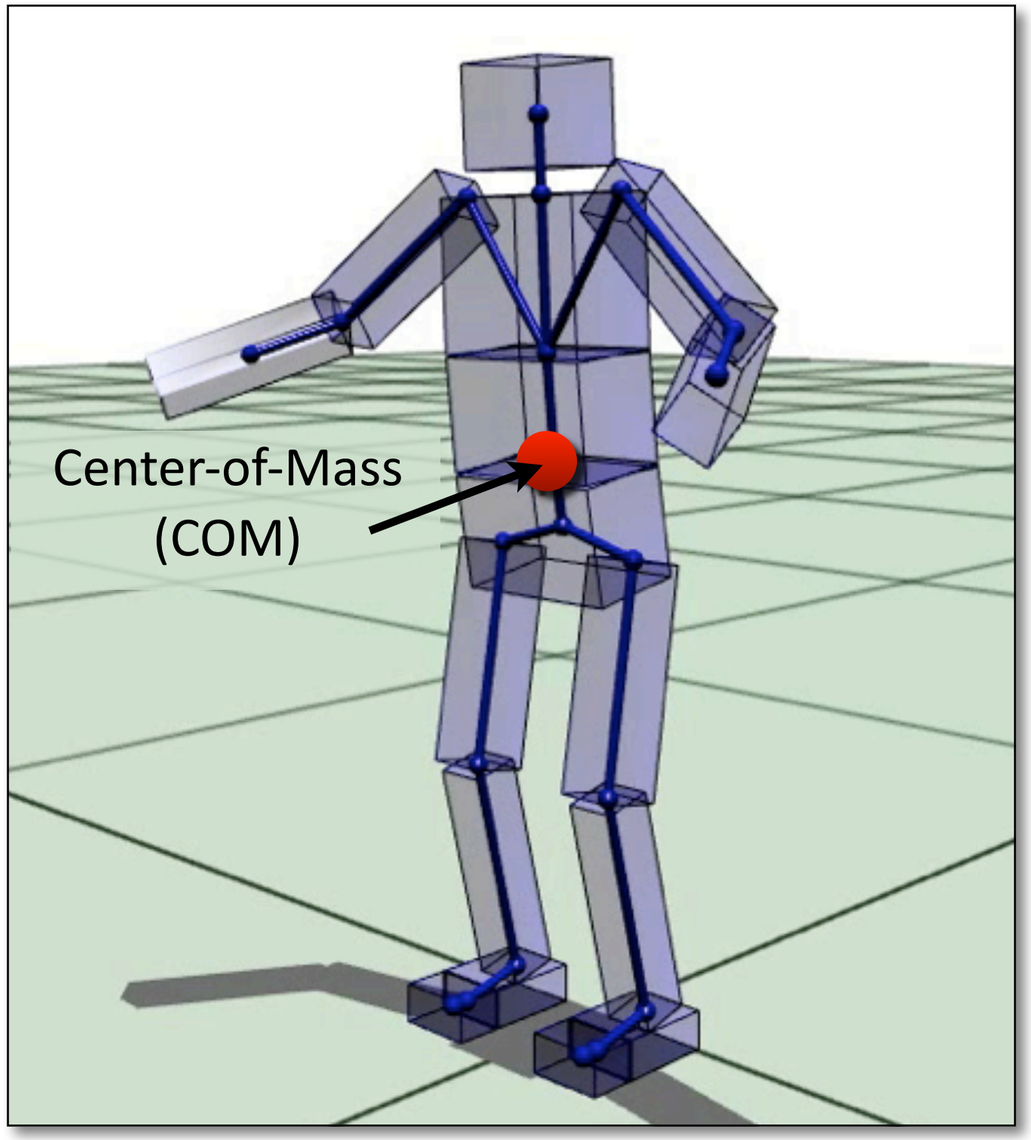

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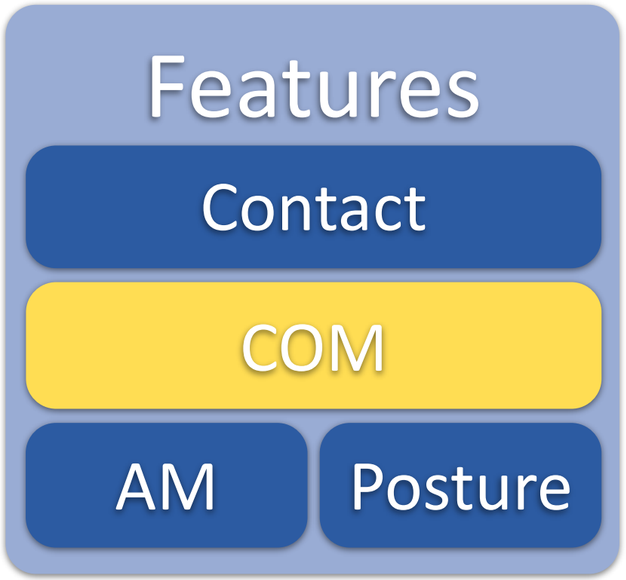

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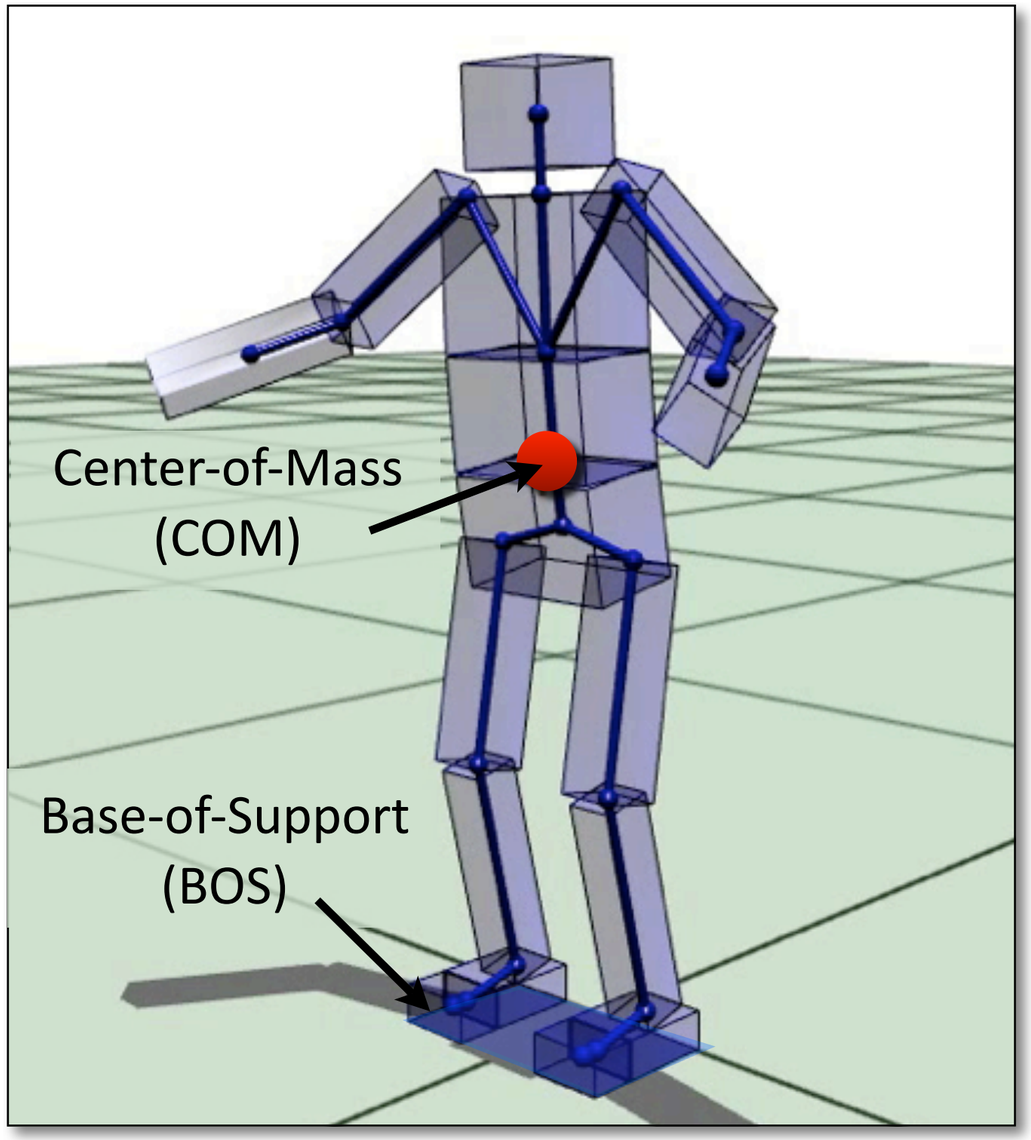

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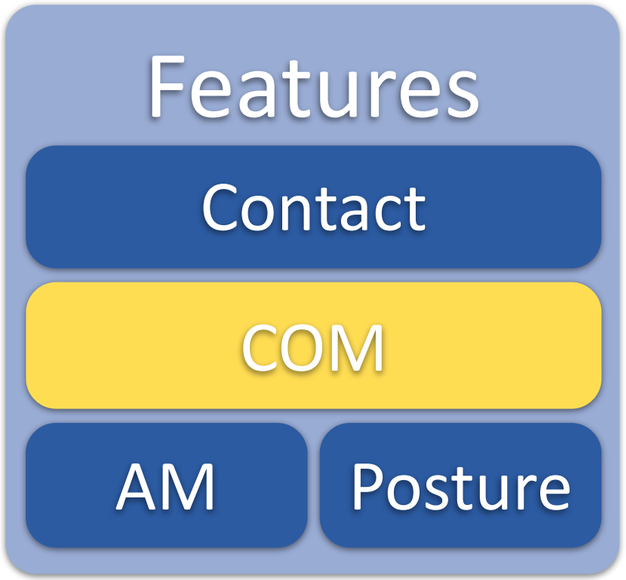

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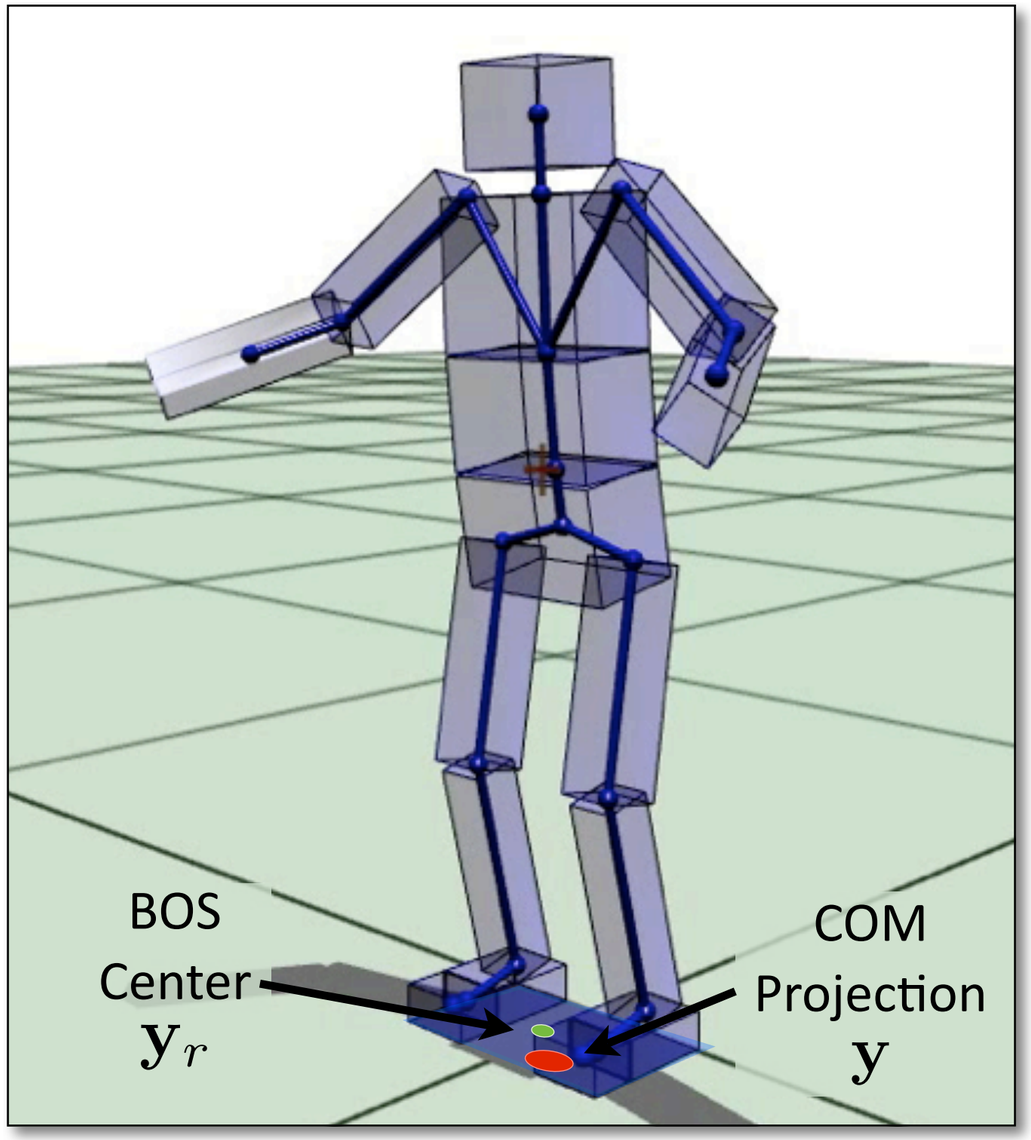

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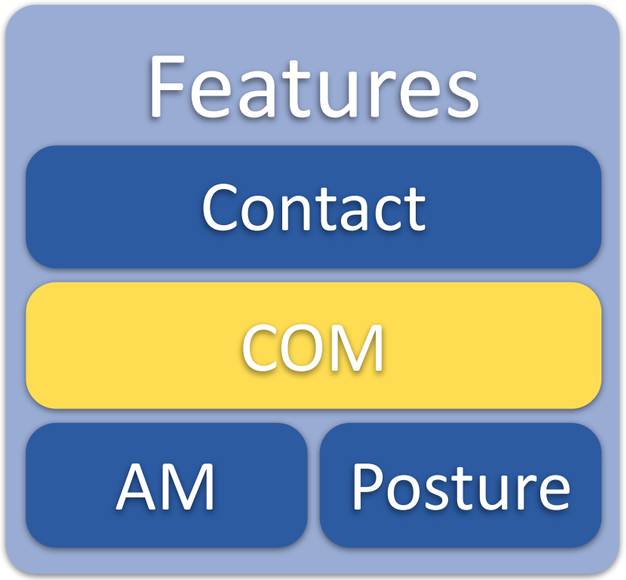
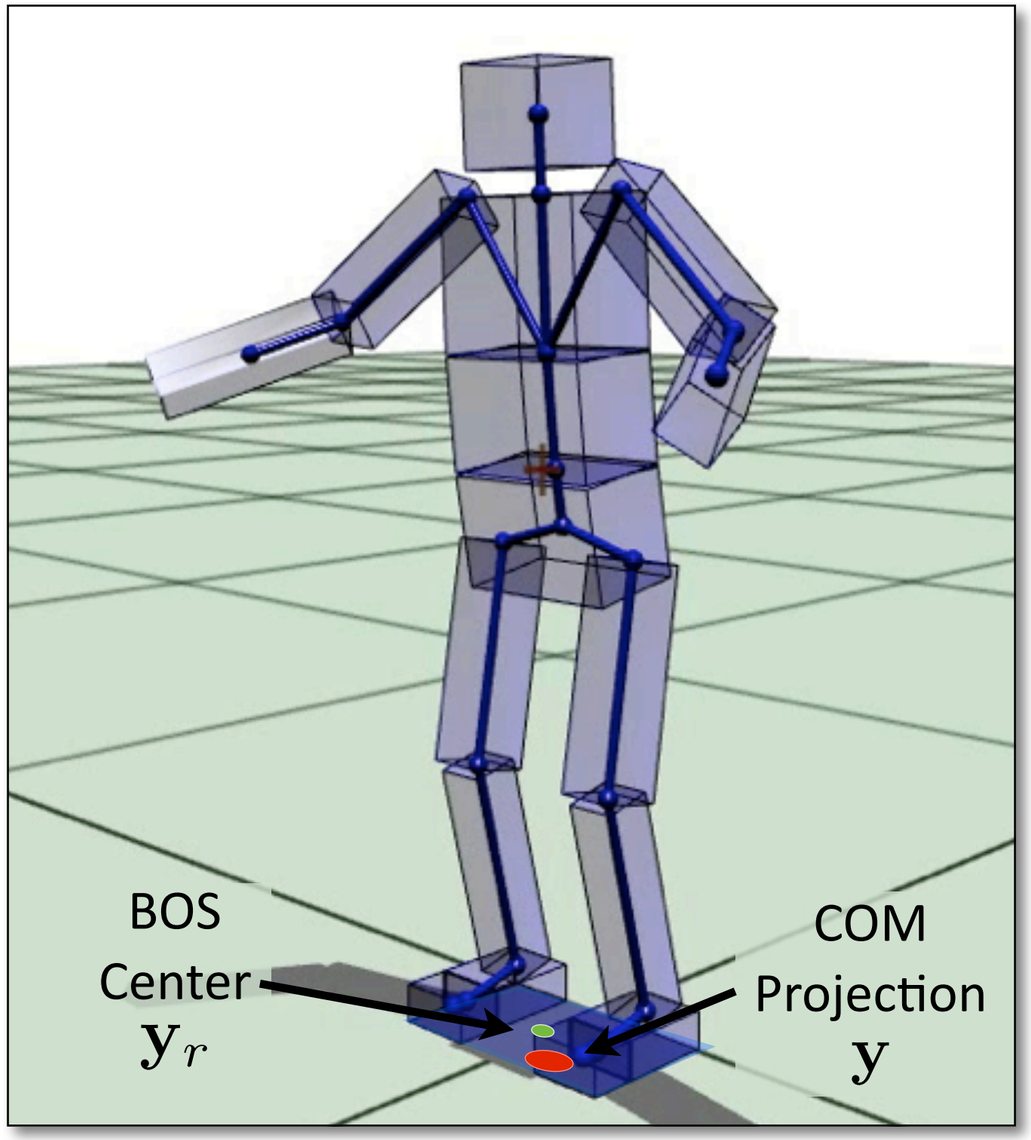
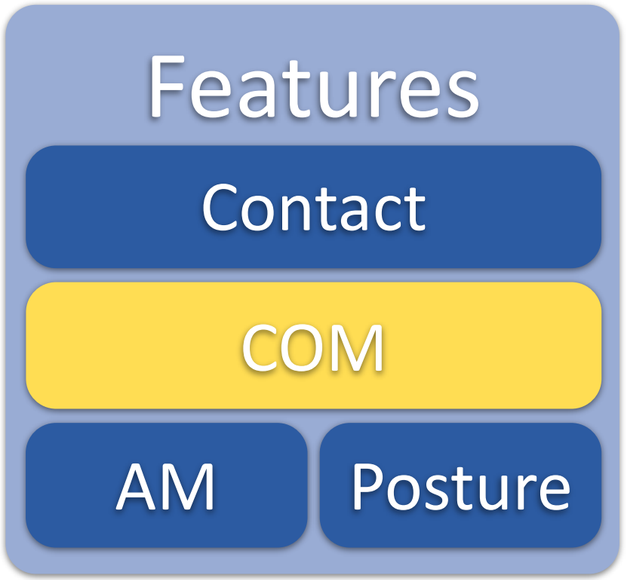


$$\mathbf{y} = f(\mathbf{q})$$

$$\ddot{\mathbf{y}}_d = k_p(\mathbf{y}_r - \mathbf{y}) - k_v\dot{\mathbf{y}}$$



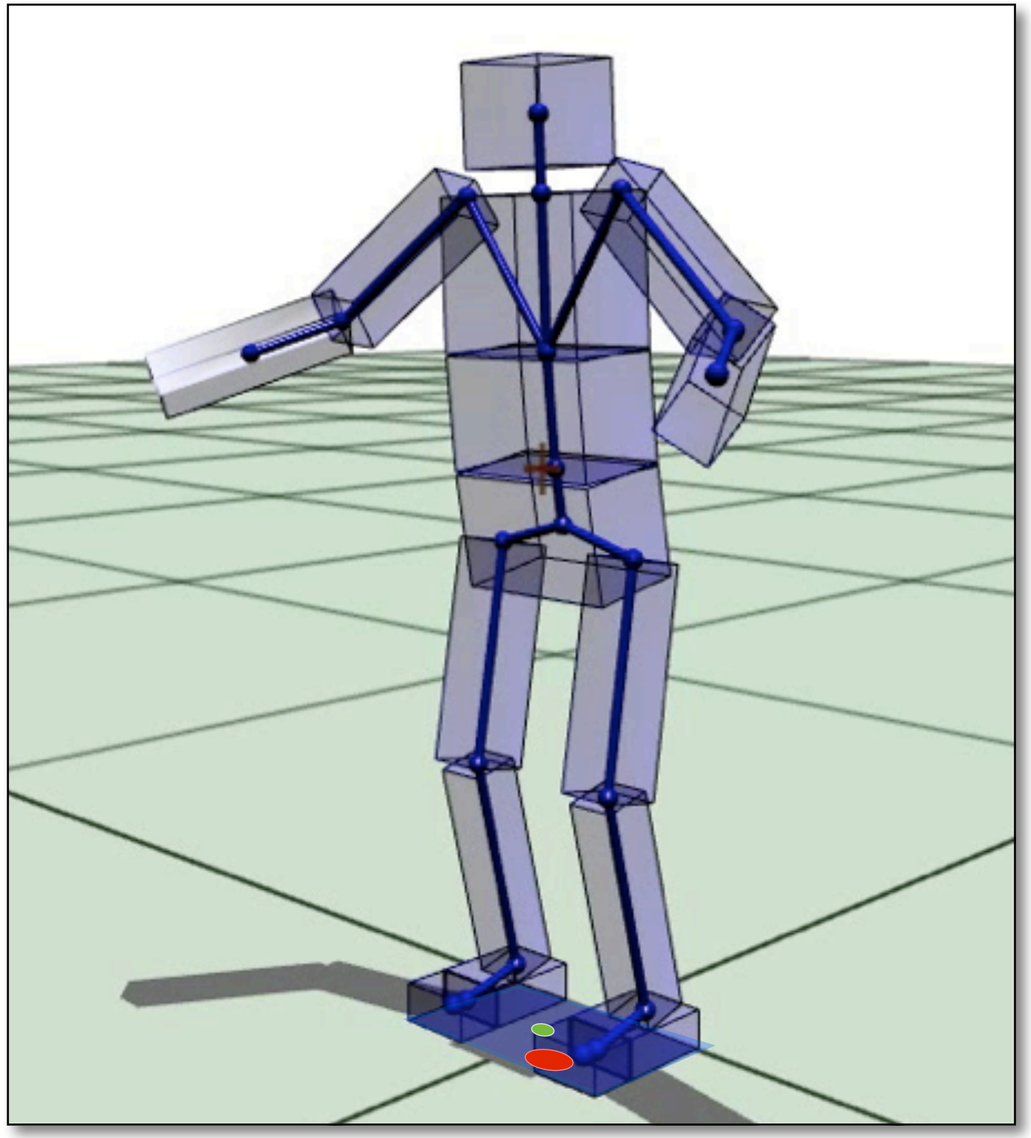
Features



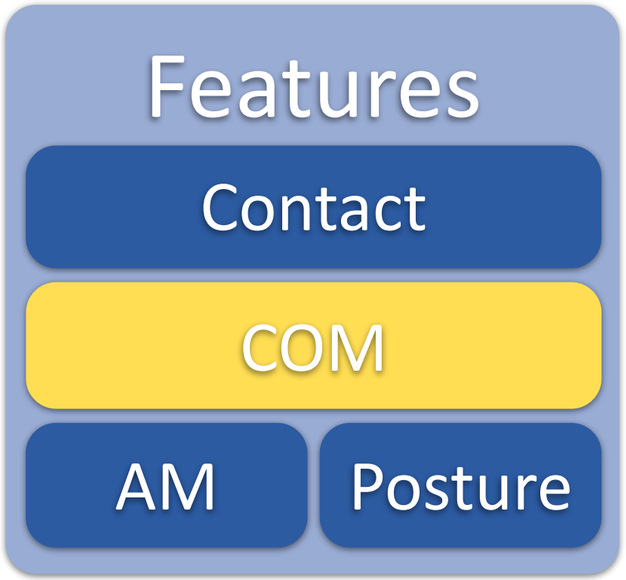
$$\mathbf{y} = f(\mathbf{q})$$

$$\ddot{\mathbf{y}}_d = k_p(\mathbf{y}_r - \mathbf{y}) - k_v\dot{\mathbf{y}}$$

$$\mathbf{E}(\mathbf{x}) = ||\ddot{\mathbf{y}}_d - \ddot{\mathbf{y}}||^2$$



Setpoint Objective



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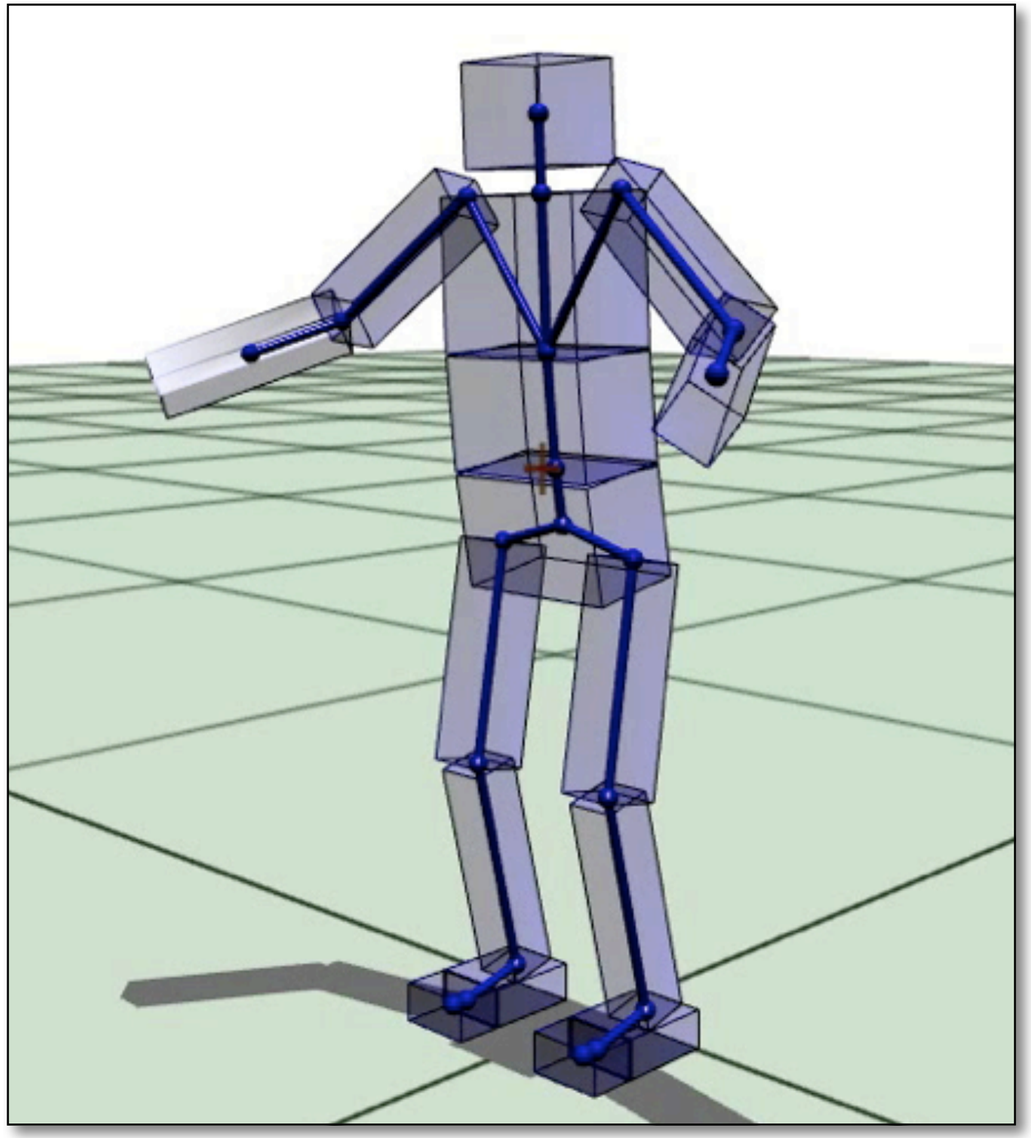

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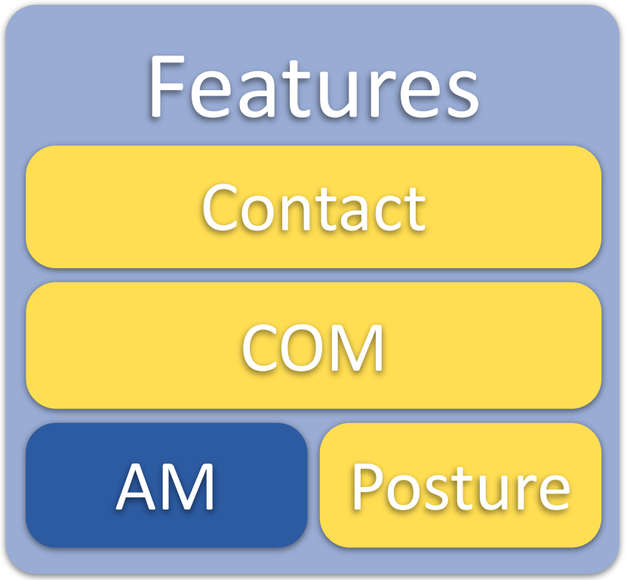

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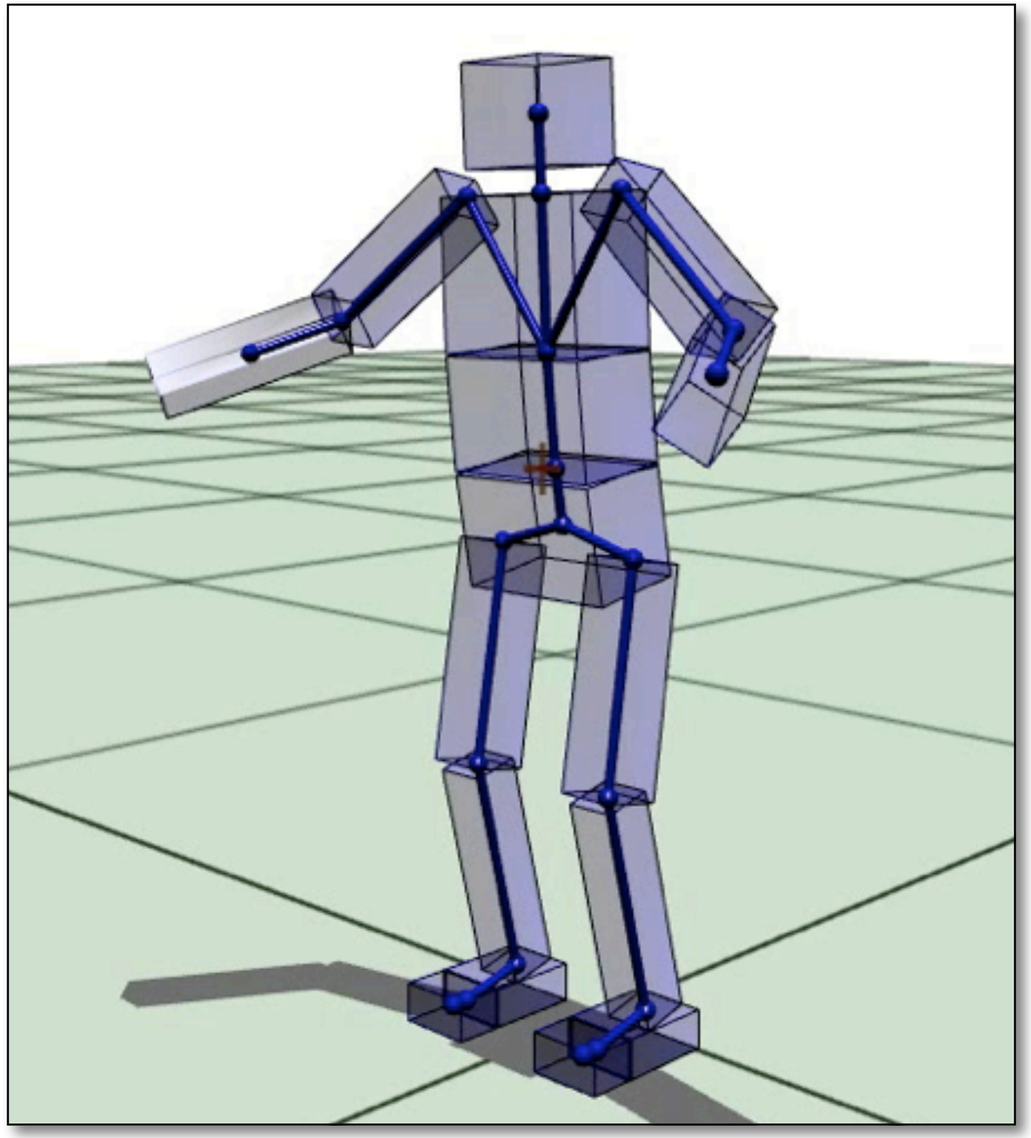

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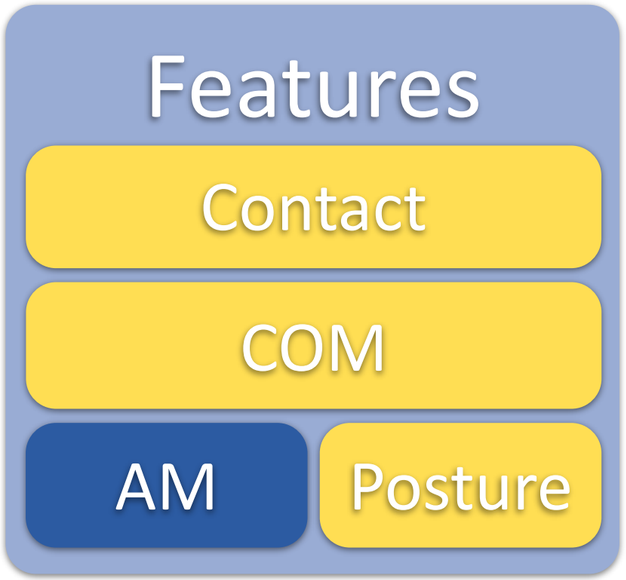

$$\mathbf{y} = f(\mathbf{q})$$

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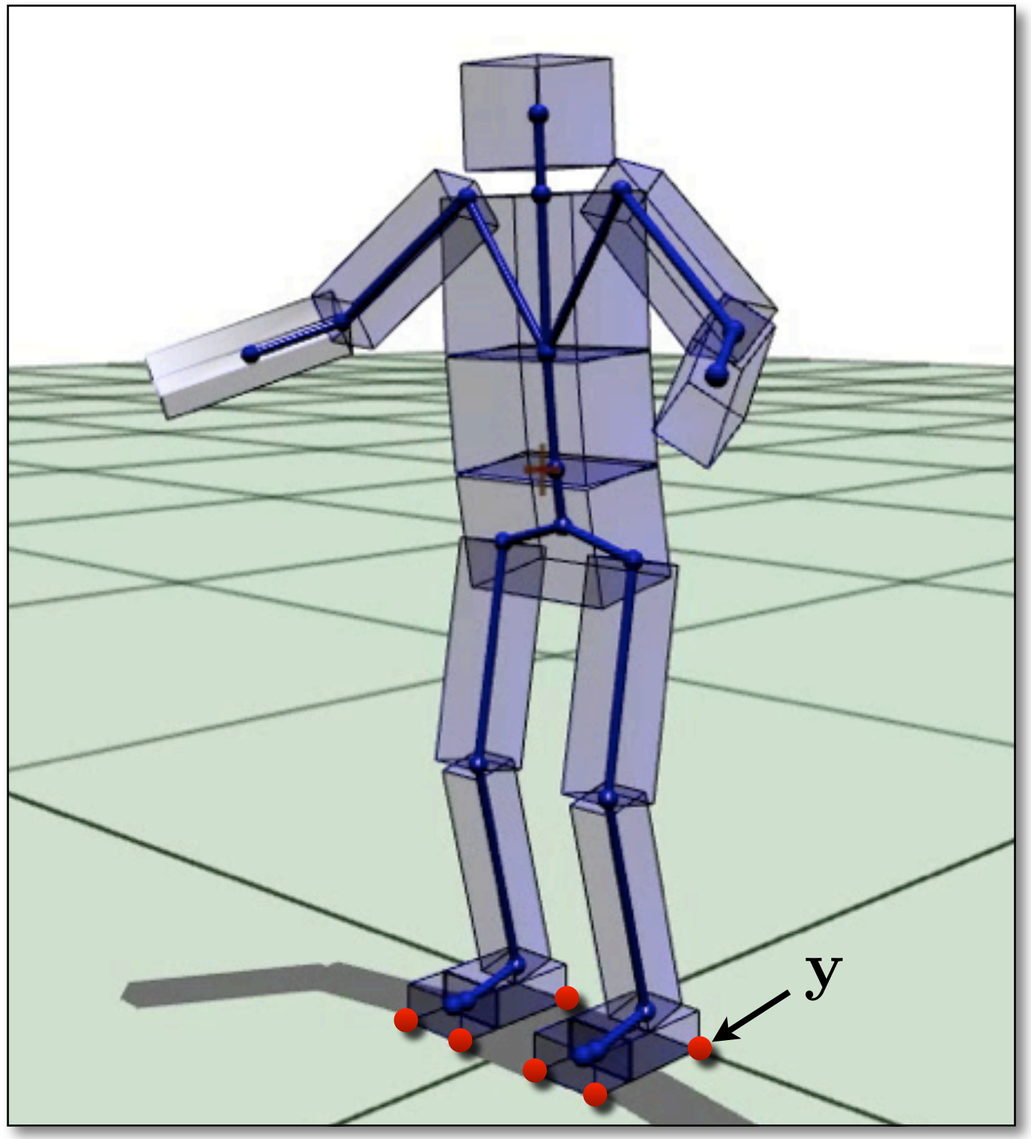
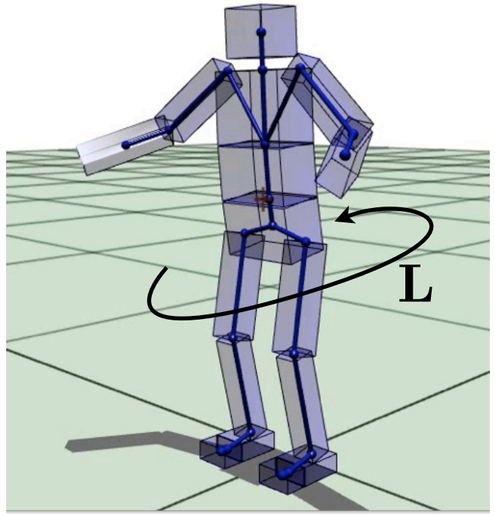
$$\mathbf{E}(\mathbf{x}) = ||\ddot{\mathbf{y}}_d - \ddot{\mathbf{y}}||^2$$



AM Objective



Features

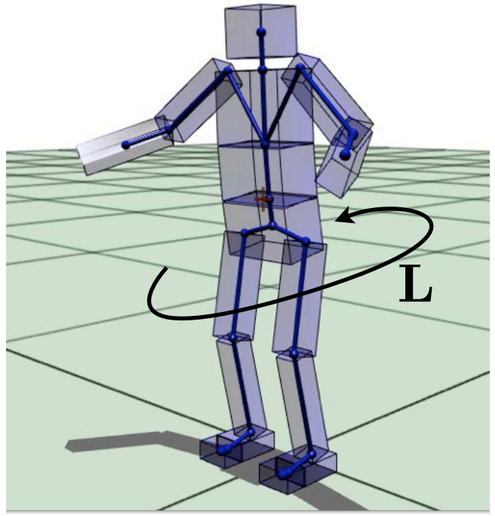
Contact

COM

AM

Posture

AM Objective



Features

- Contact
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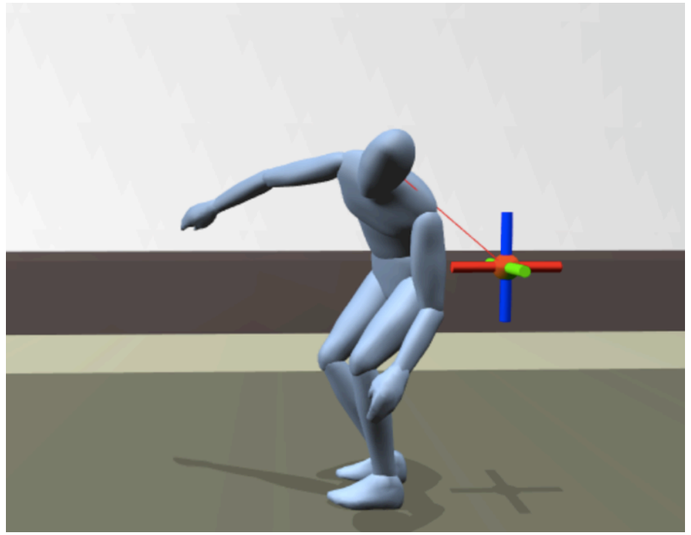
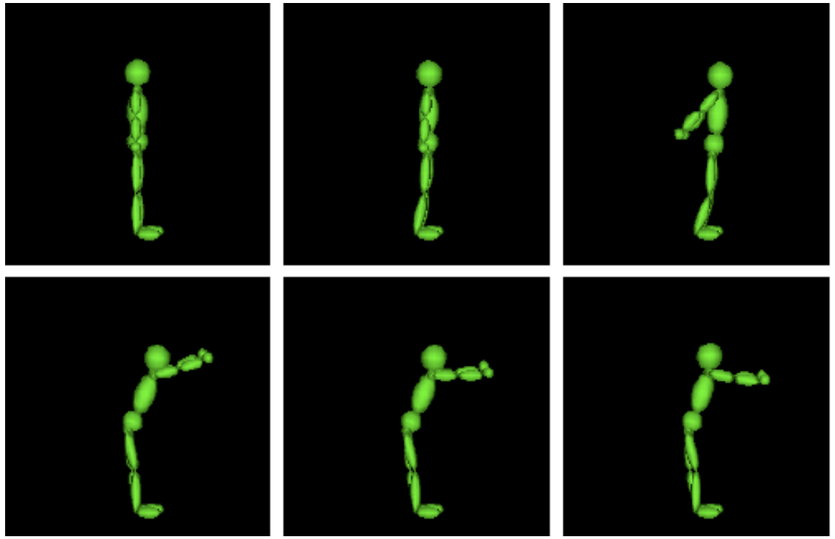
- AM
- Posture

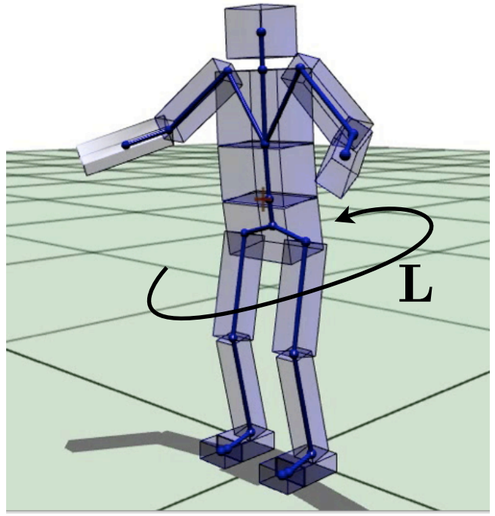


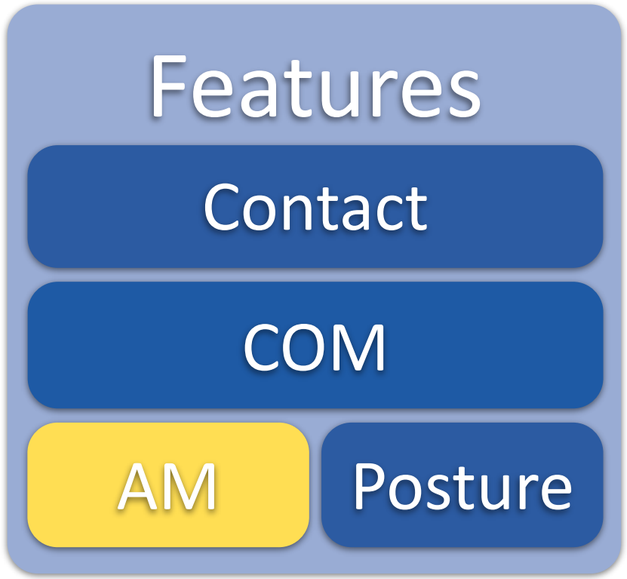
Macchietto09



Kudoh02,06

AM Objective

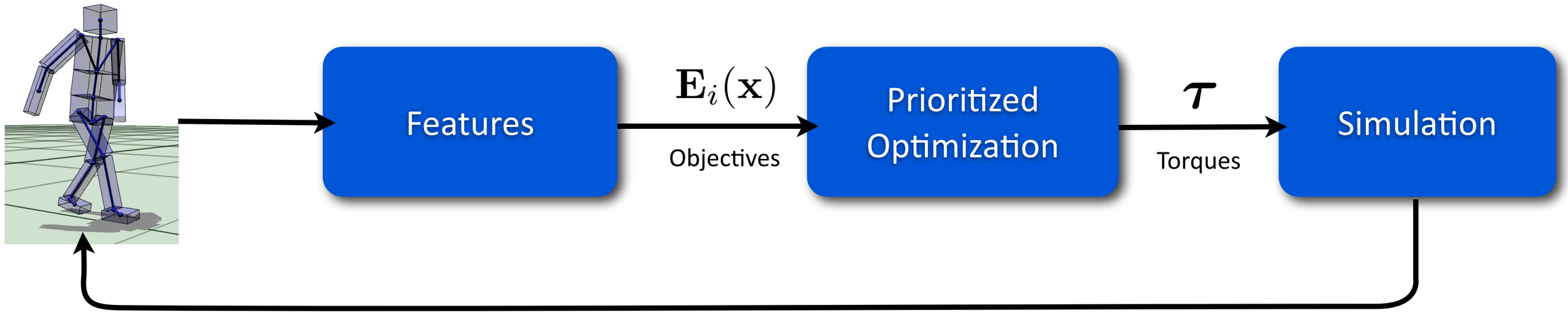


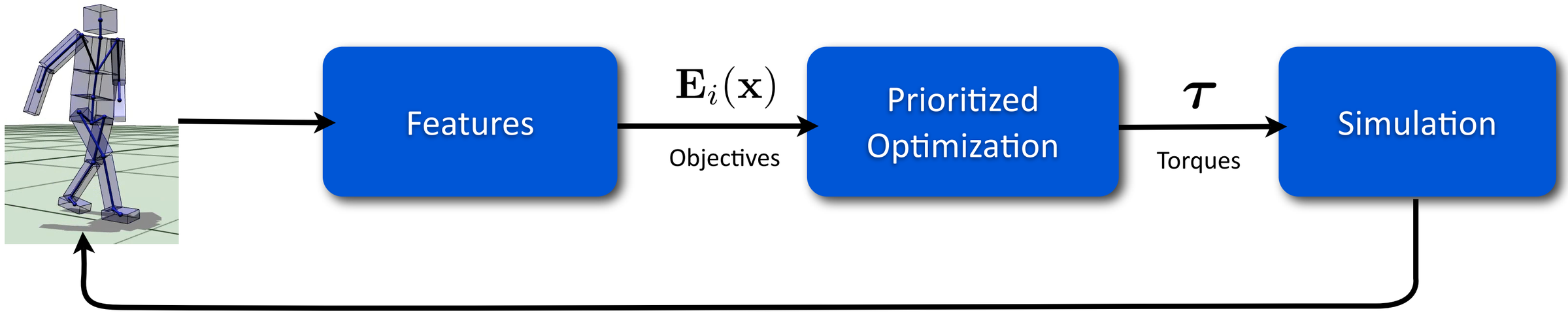


$$\mathbf{E}_{AM}(\mathbf{x}) = ||\dot{\mathbf{L}}_d - \dot{\mathbf{L}}||^2$$

$$\dot{\mathbf{L}}_d = k_p(\mathbf{L}_r - \mathbf{L})$$

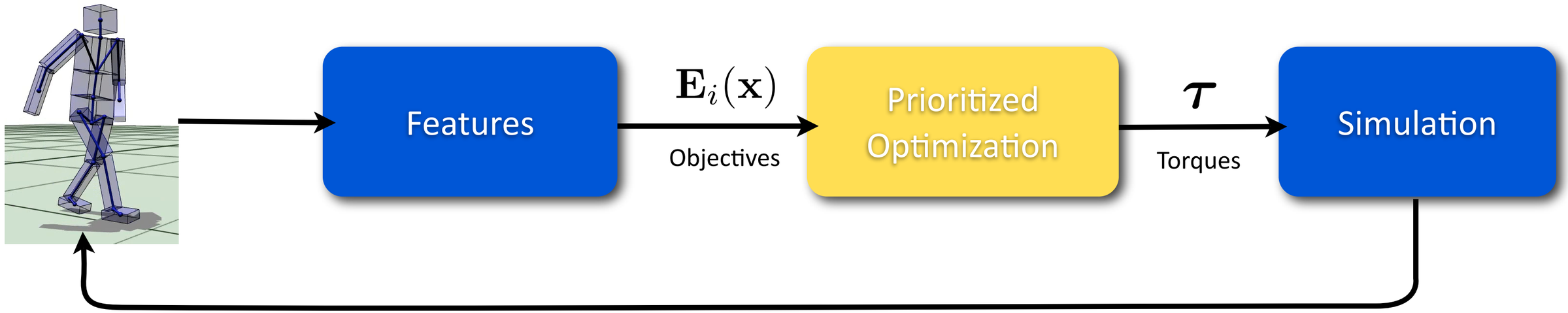
$$\dot{\mathbf{L}} = \mathbf{A}_L \ddot{\mathbf{q}} + \mathbf{b}_L$$


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



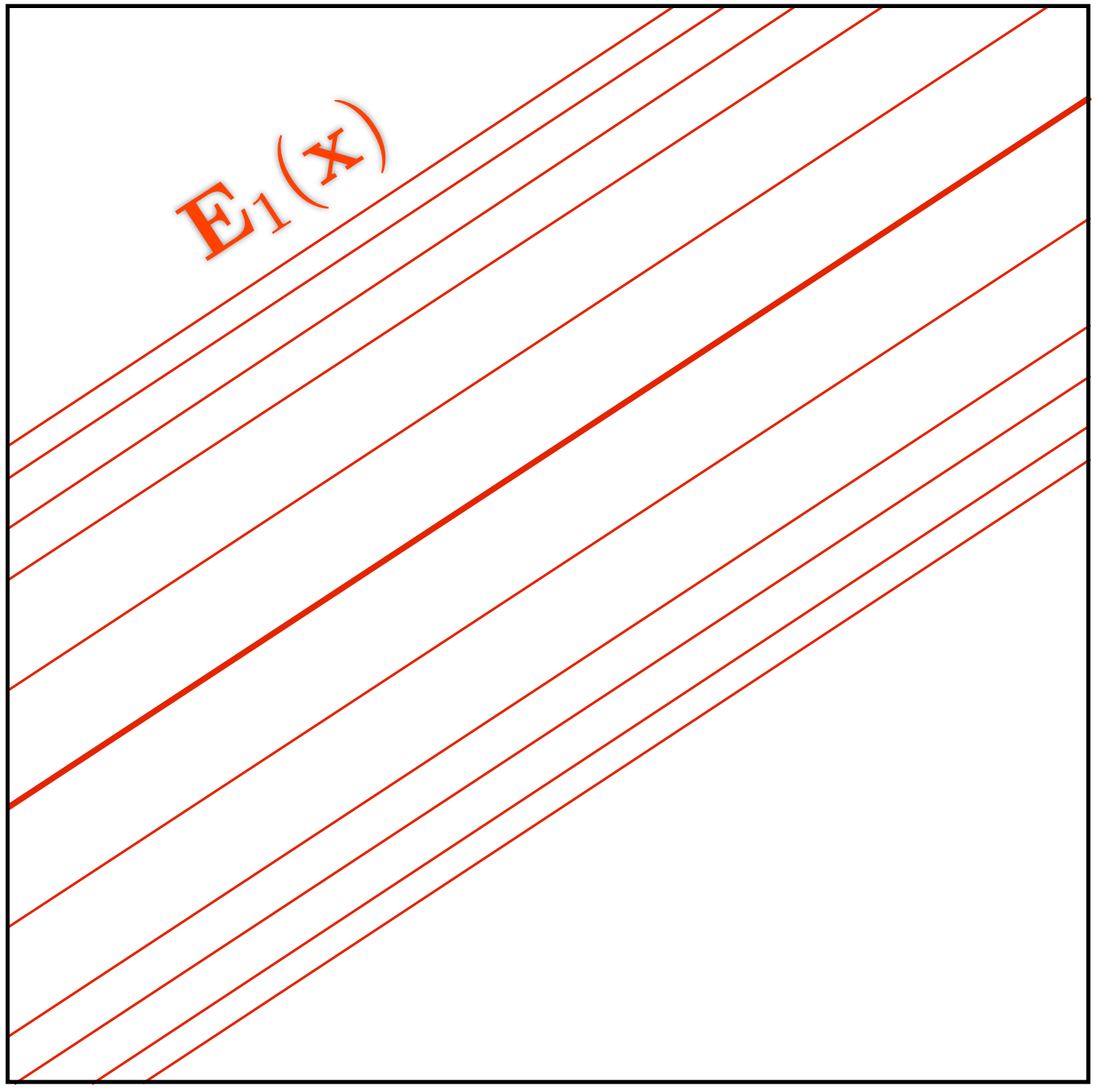
Weighted QP

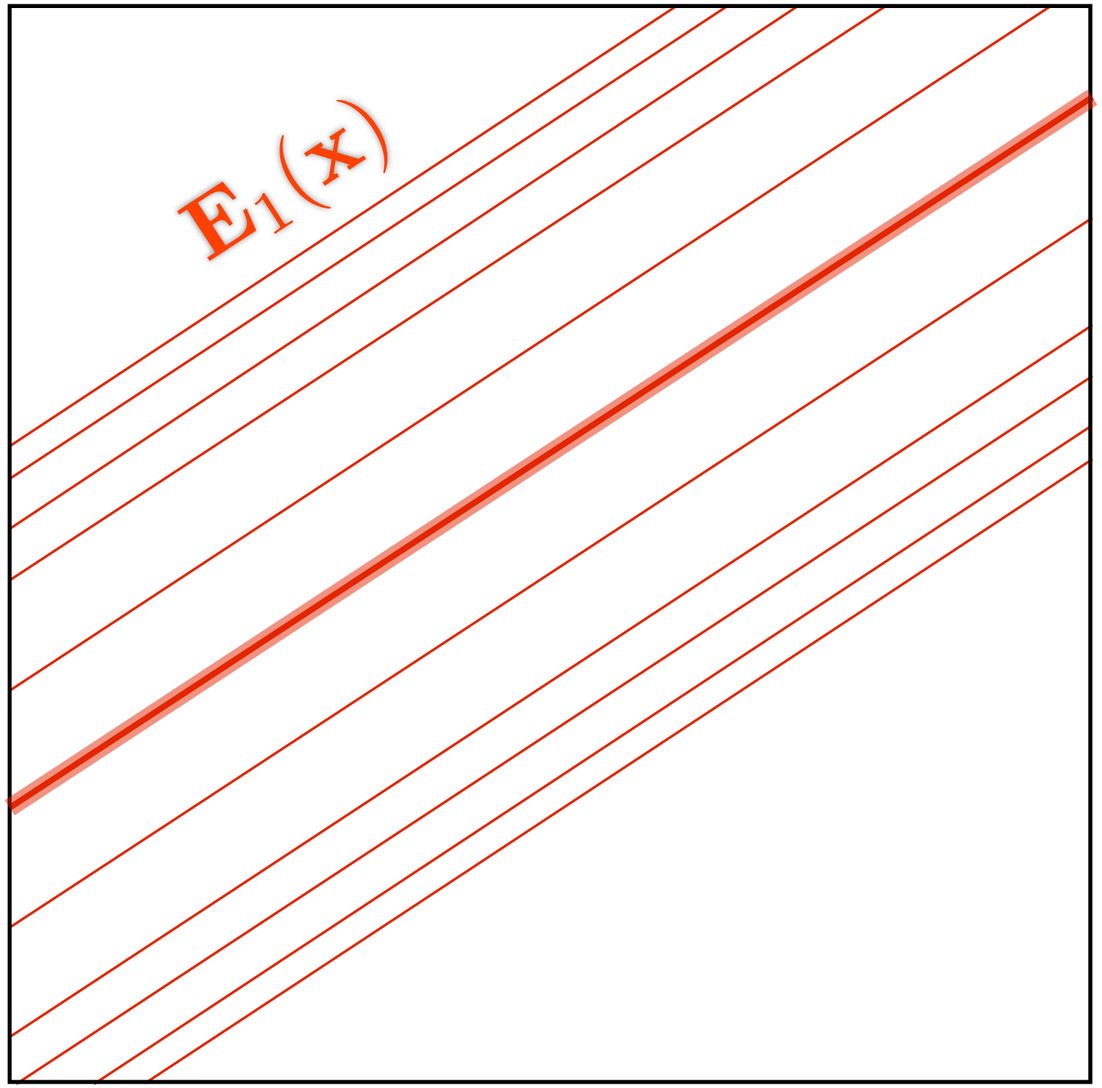
$$\mathbf{E}(\mathbf{x}) = \sum_i \alpha_i \mathbf{E}_i(\mathbf{x})$$

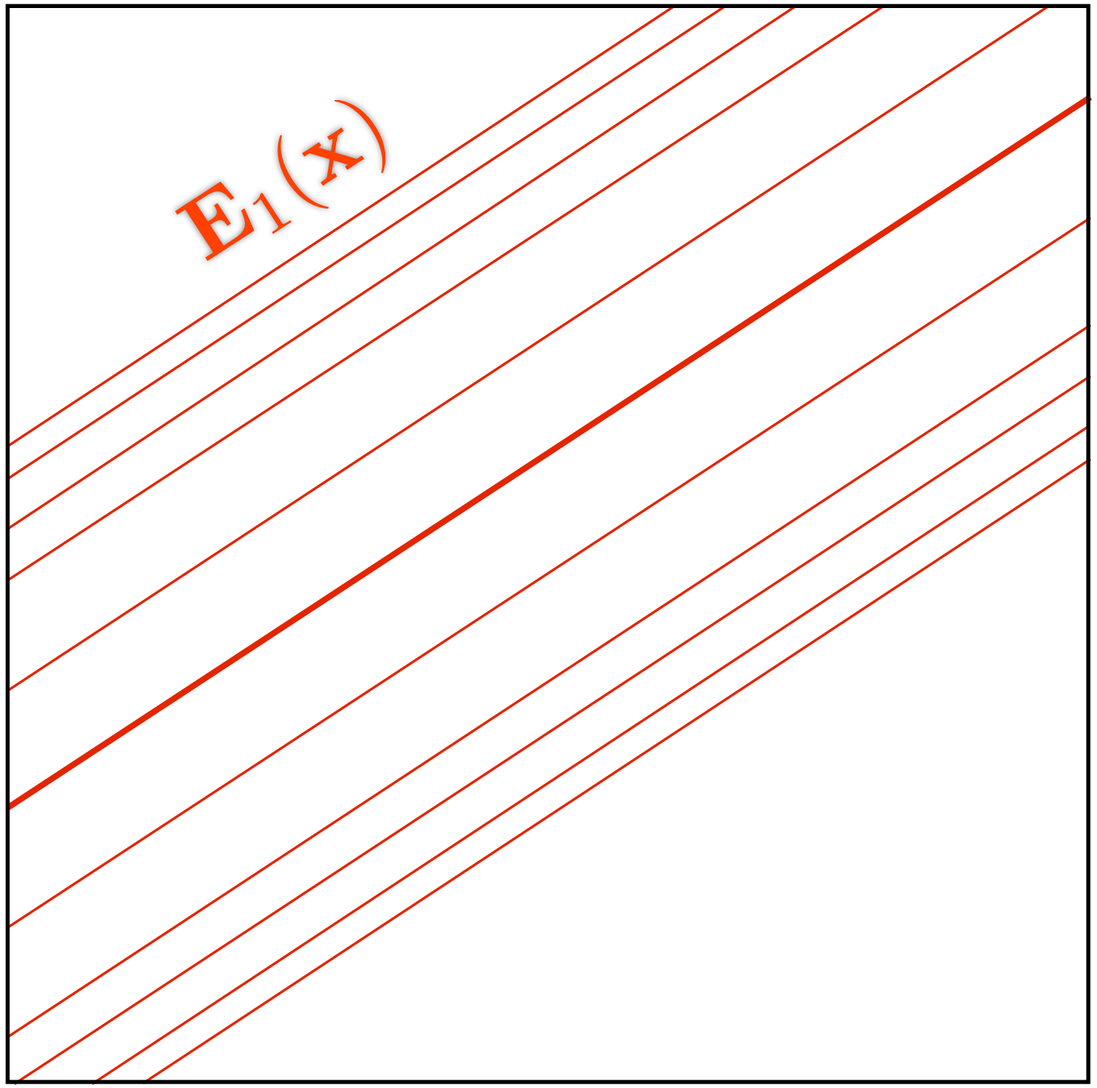


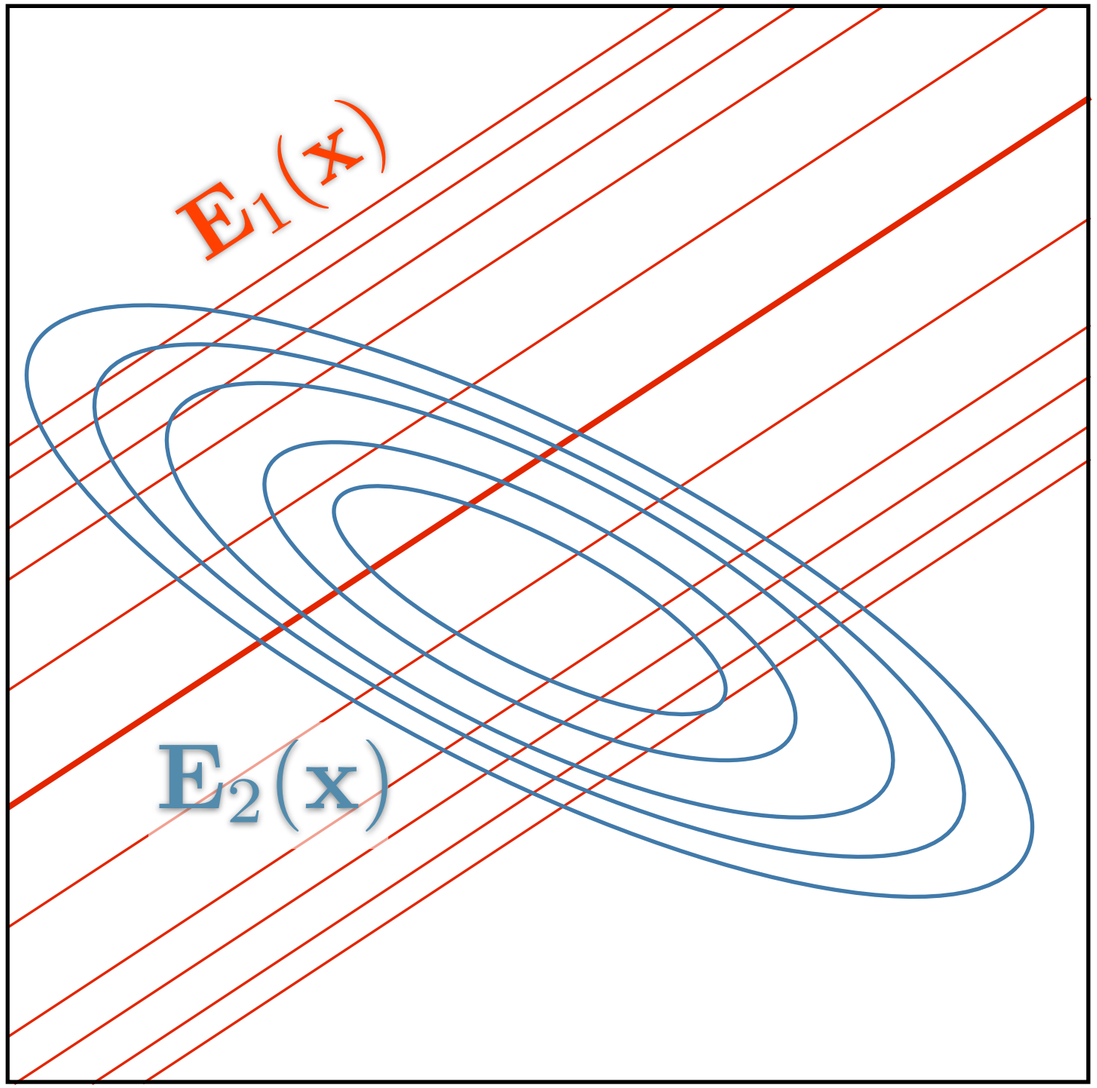
Weighted QP

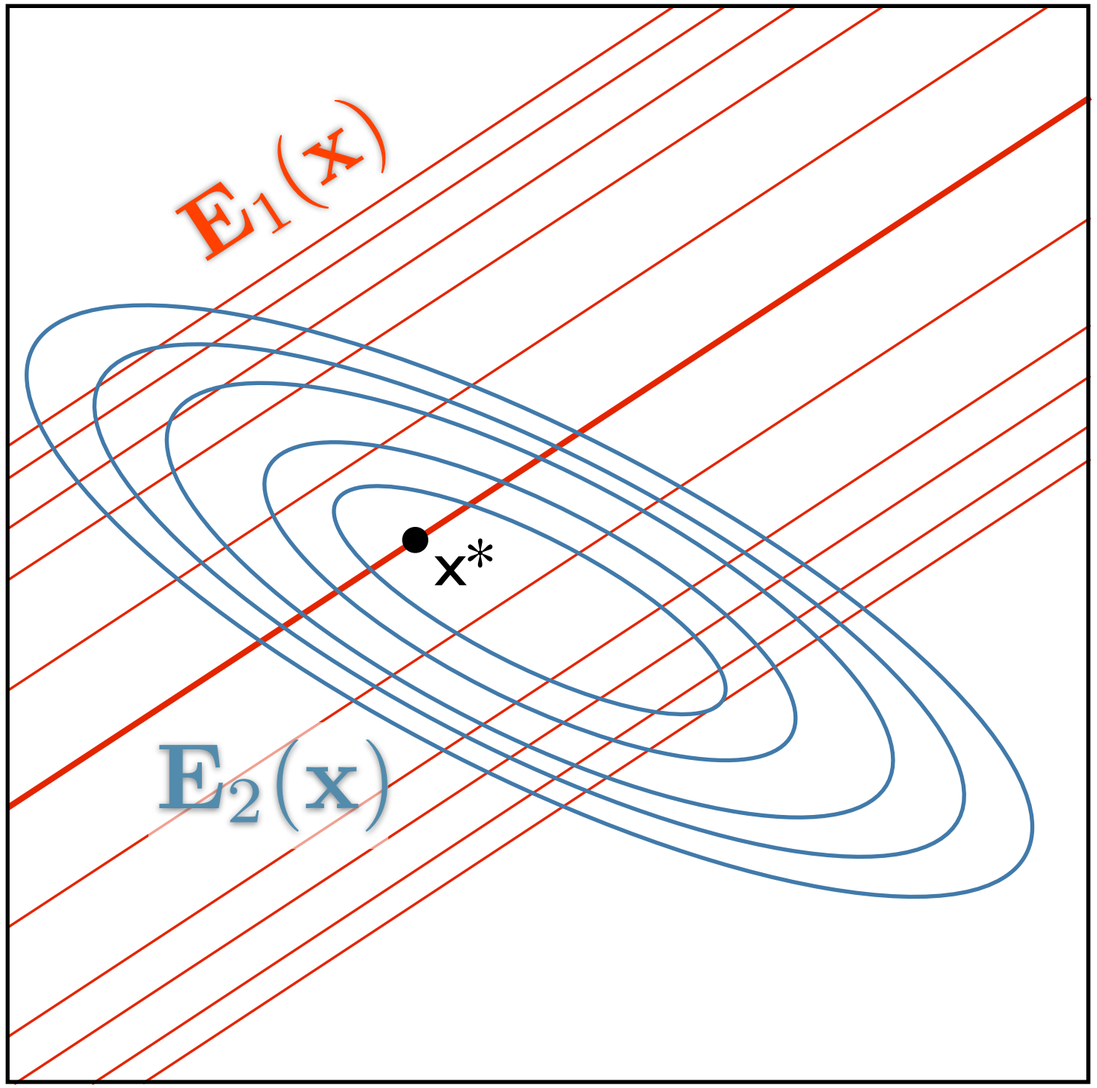
$$\mathbf{E}(\mathbf{x}) = \sum_i \alpha_i \mathbf{E}_i(\mathbf{x})$$


$\mathbf{E}_1(\mathbf{x})$

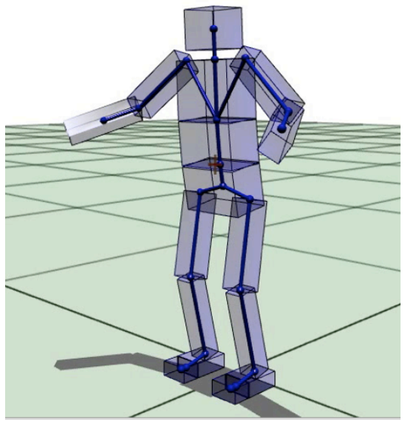

$\mathbf{E}_1(\mathbf{x})$

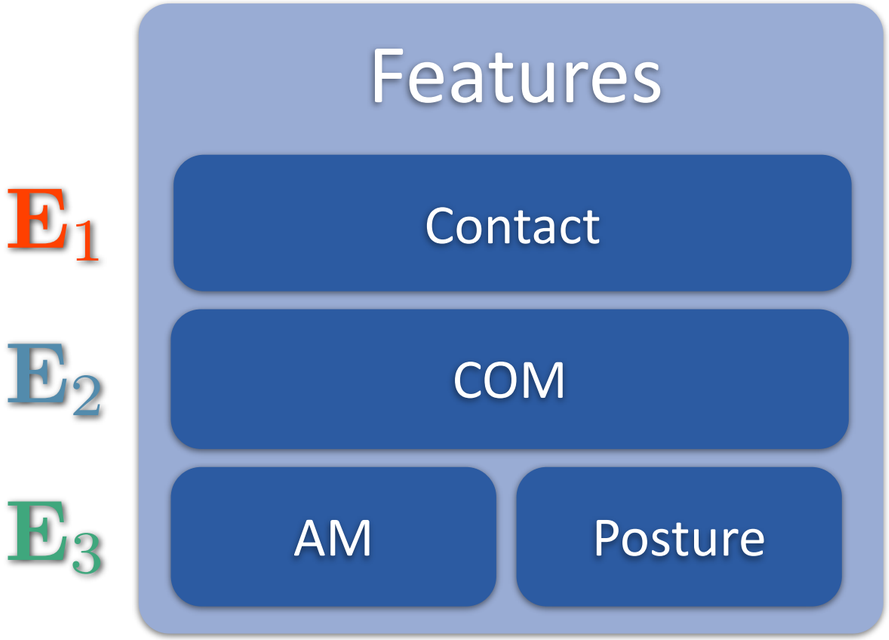

$\mathbf{E}_1(\mathbf{x})$


$\mathbf{E}_1(\mathbf{x})$
$\mathbf{E}_2(\mathbf{x})$


$\mathbf{E}_1(\mathbf{x})$
$\mathbf{x}^*$
$\mathbf{E}_2(\mathbf{x})$

Balancing

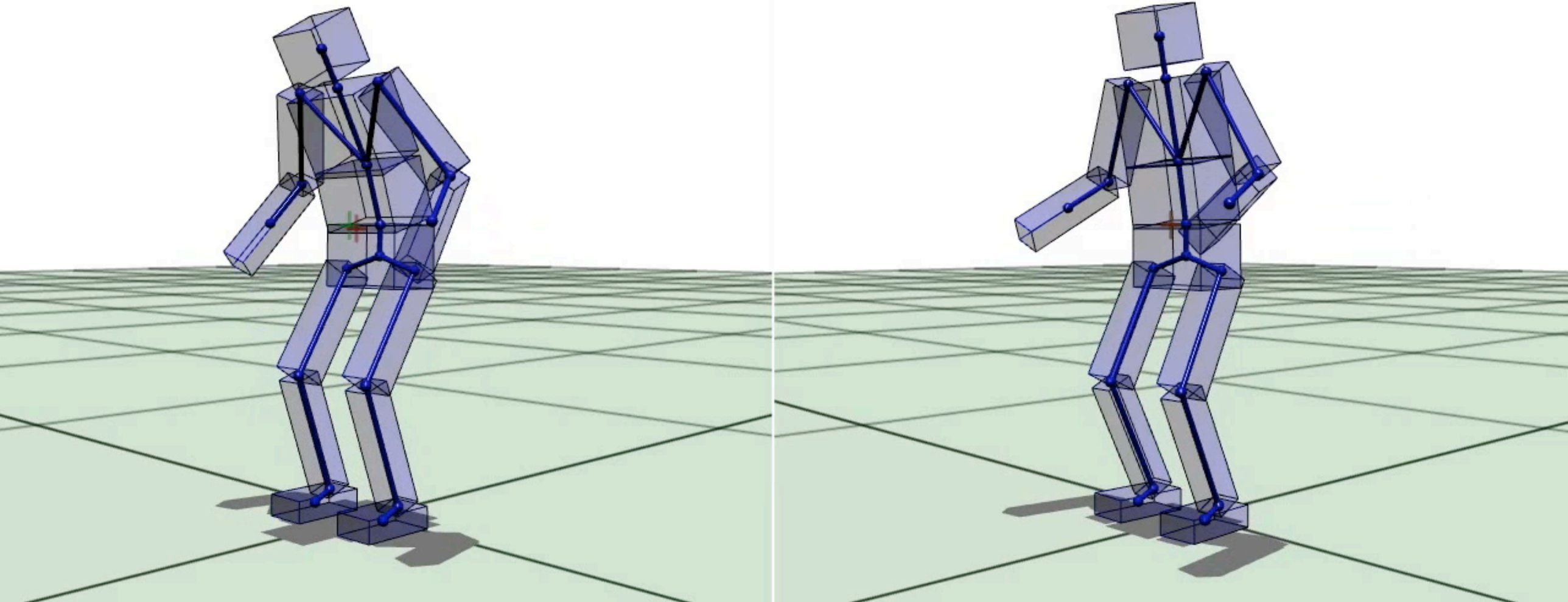




WEIGHTED QP

PRIORITIZED

Force: 200 N
Interval: 0.5 sec
Duration: 0.2 sec



Layering Control

Layering Control

Normally hard to achieve many goals due to interference

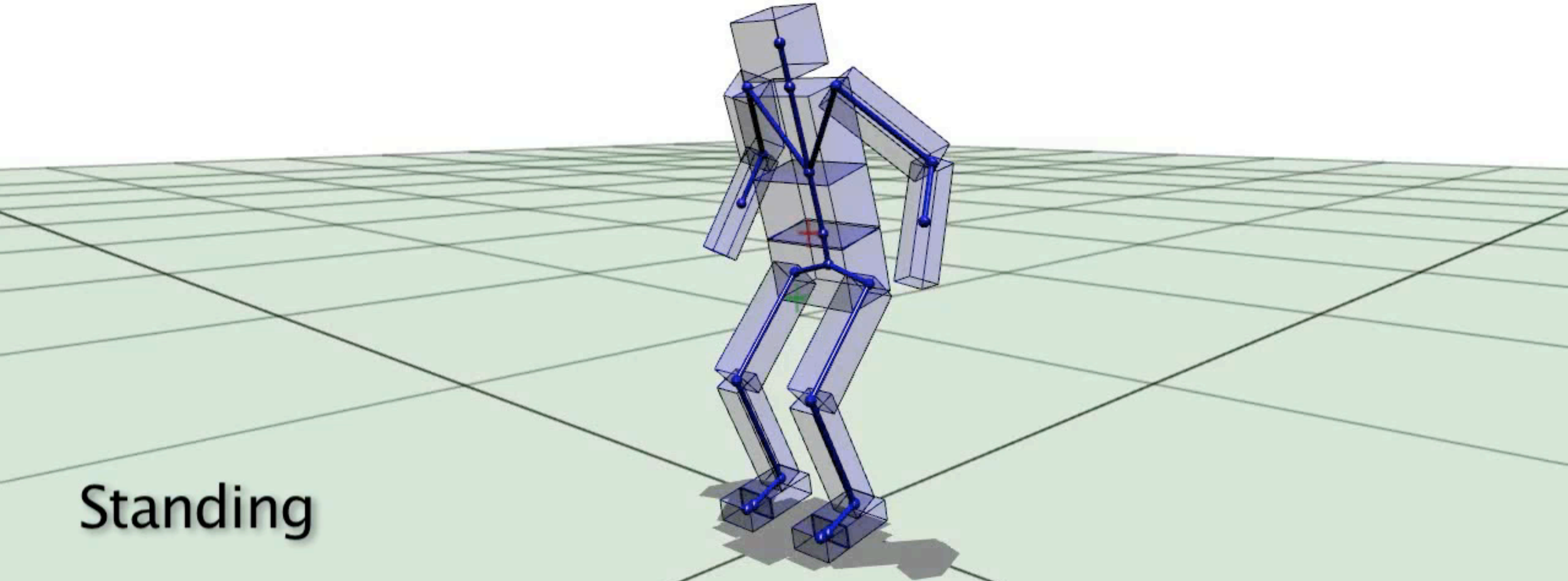
Layering Control

Normally hard to achieve many goals due to interference

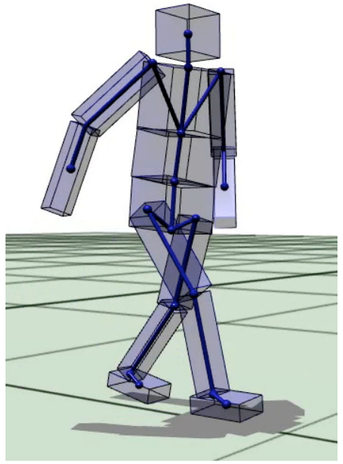
Prioritized Optimization allows control design and tuning in layers

Layering Control

Layering Control



Walking



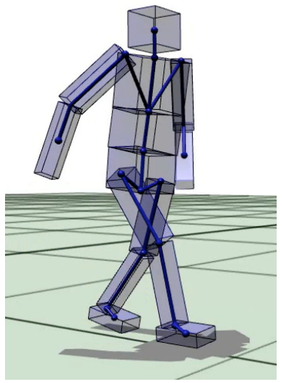
Features

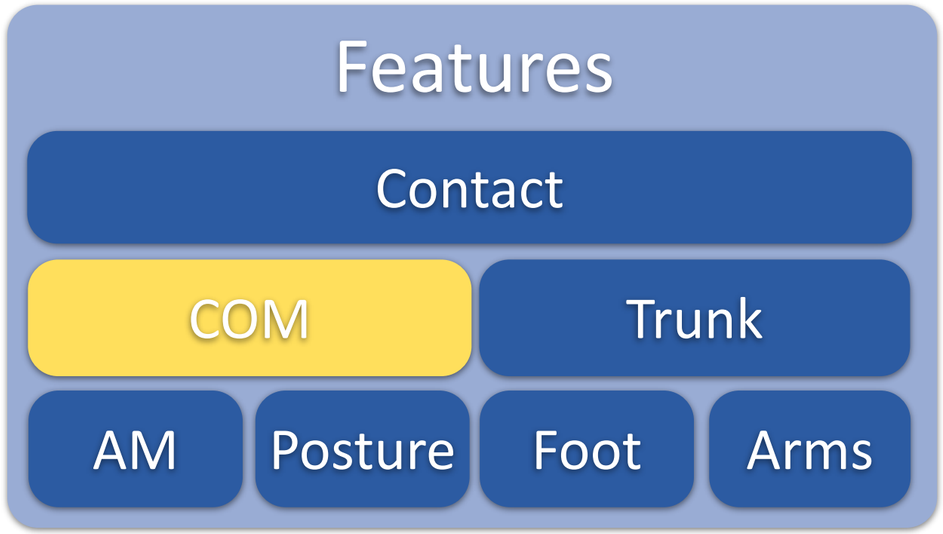
Contact

COM | Trunk

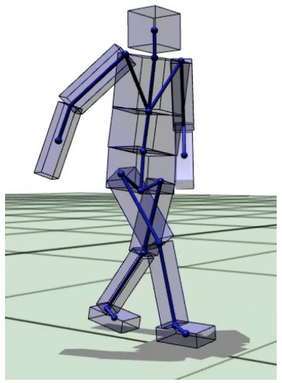
AM | Posture | Foot | Arms

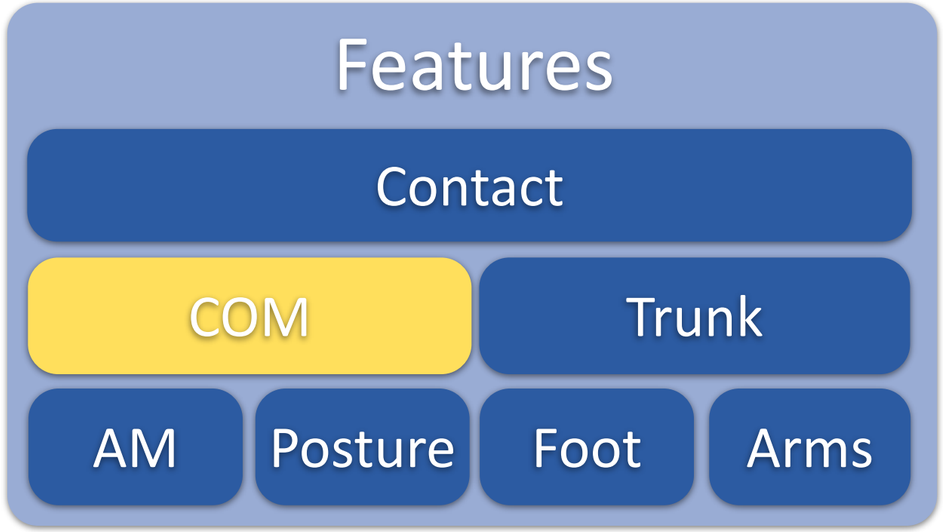
Walking: COM



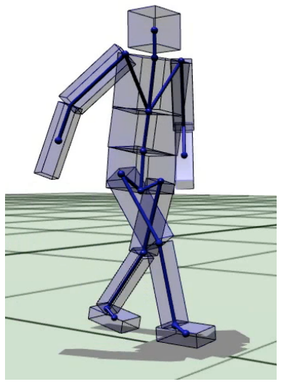


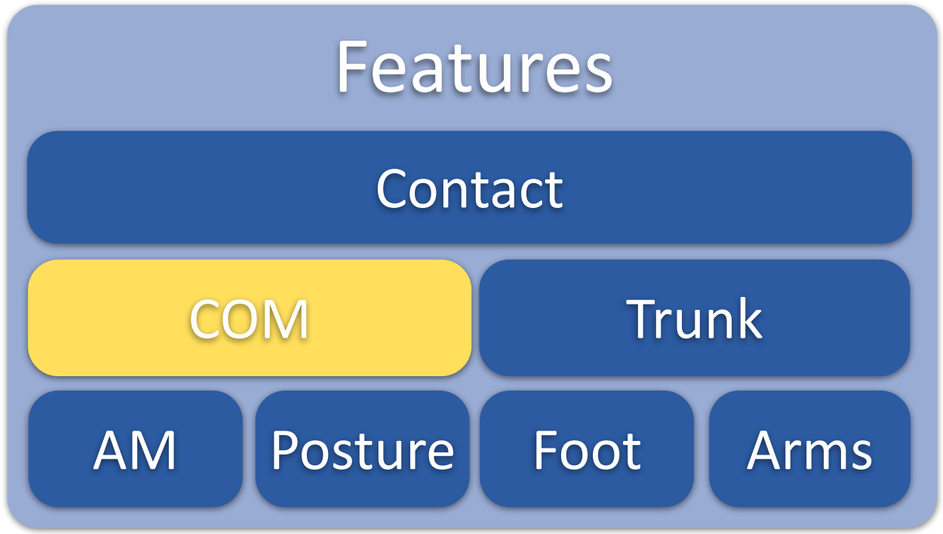
Walking: COM

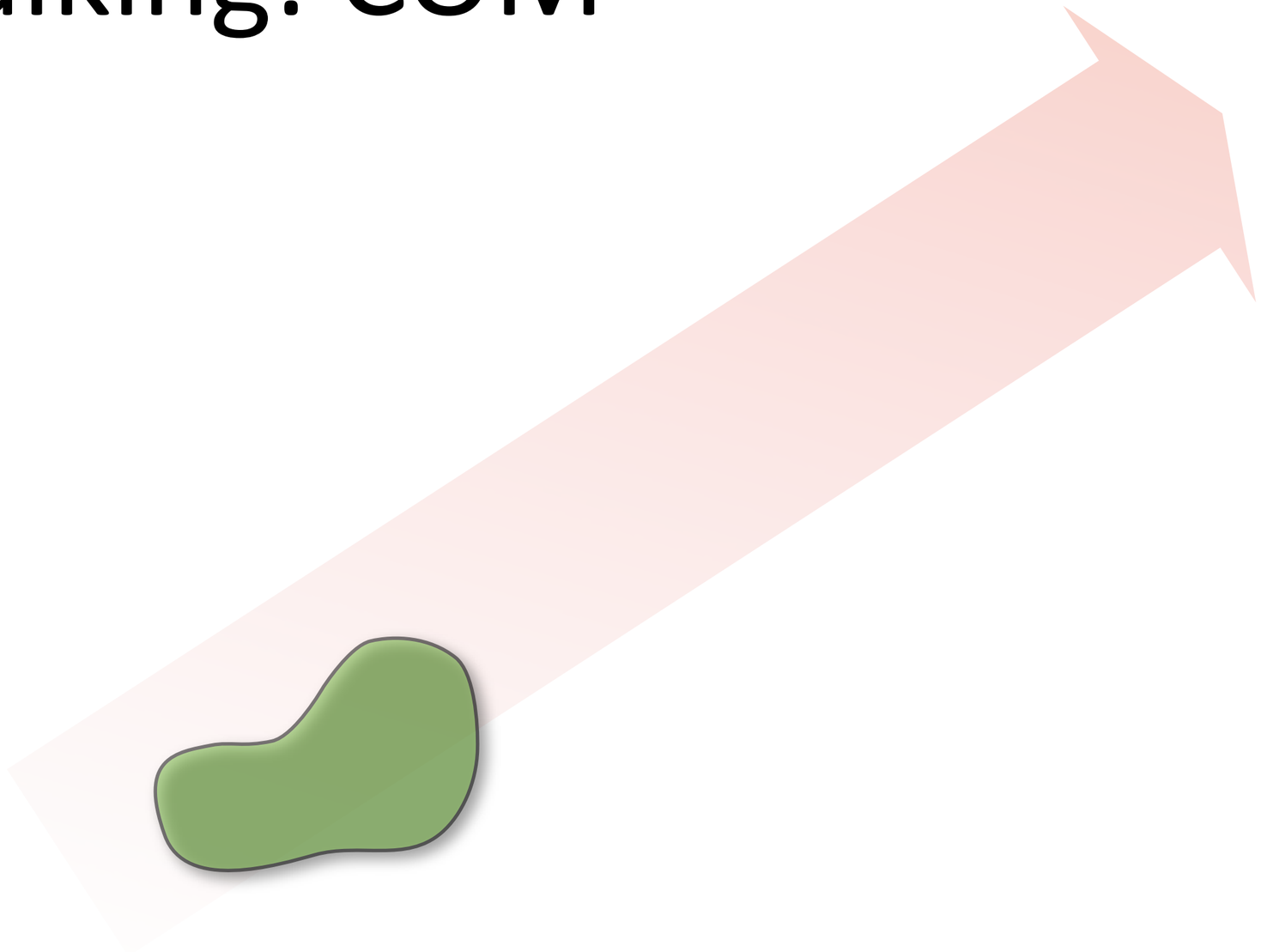




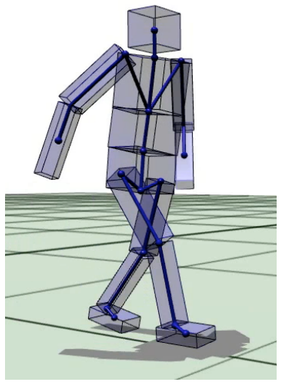
Walking: COM

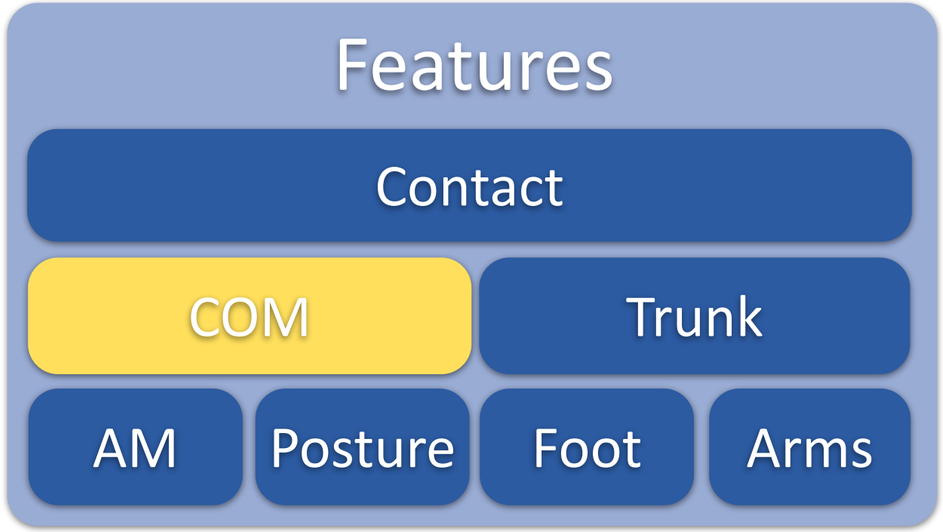


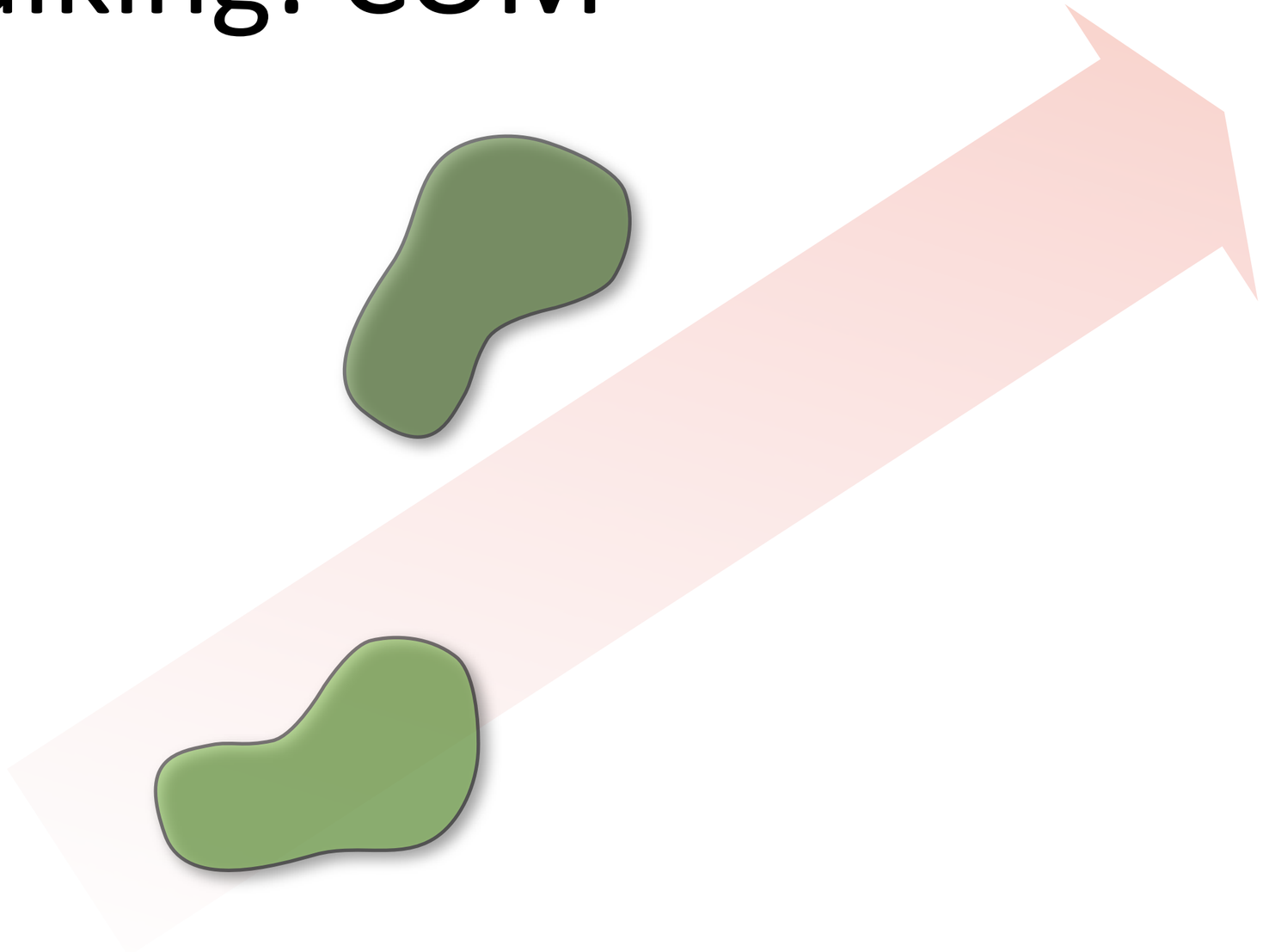




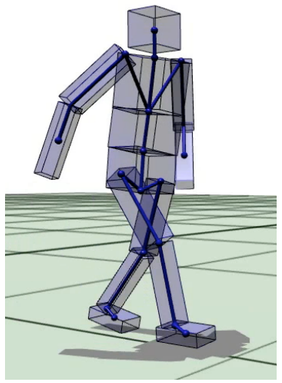
Walking: COM

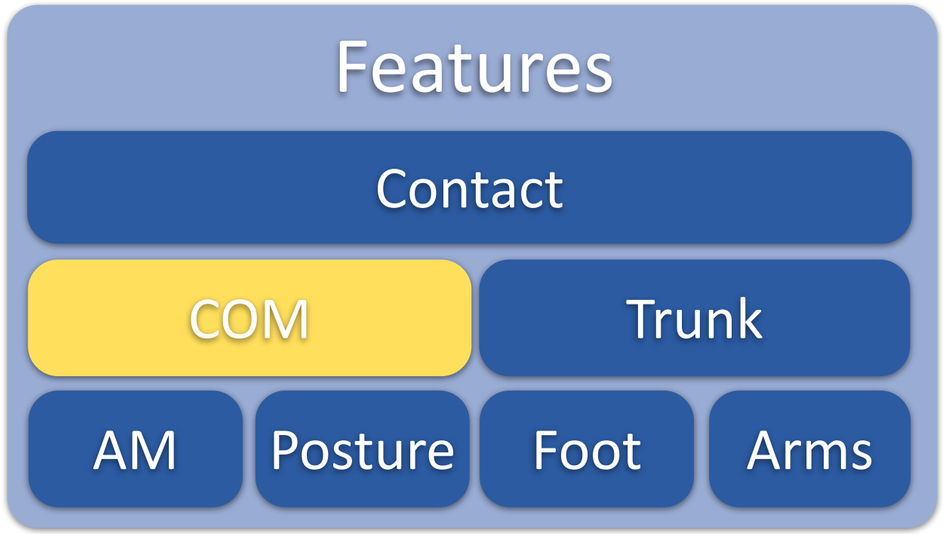


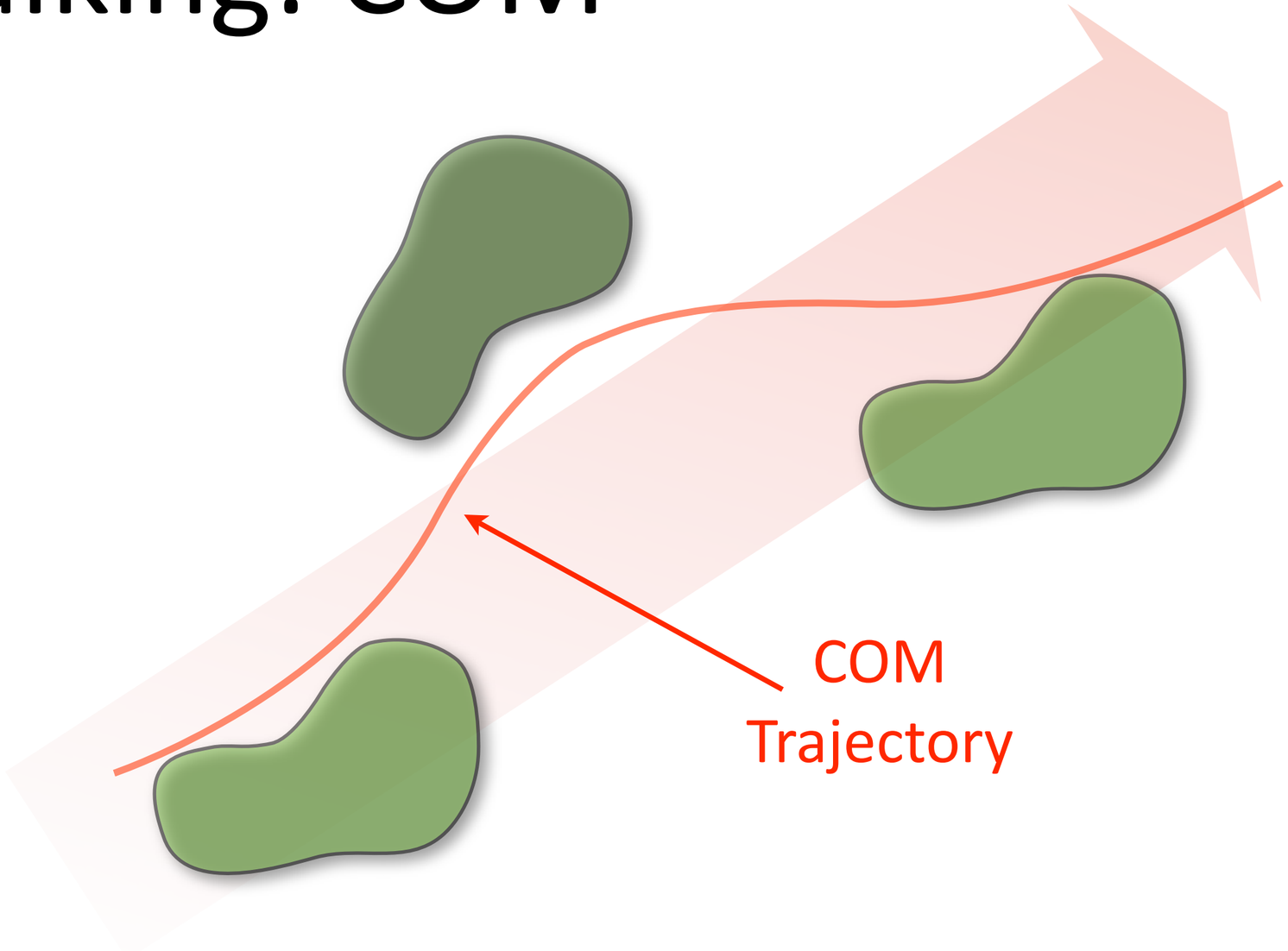




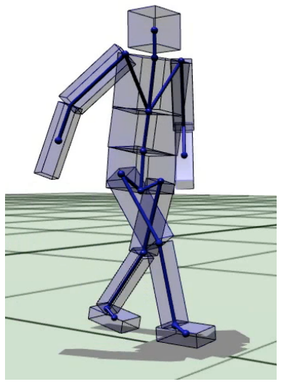
Walking: COM



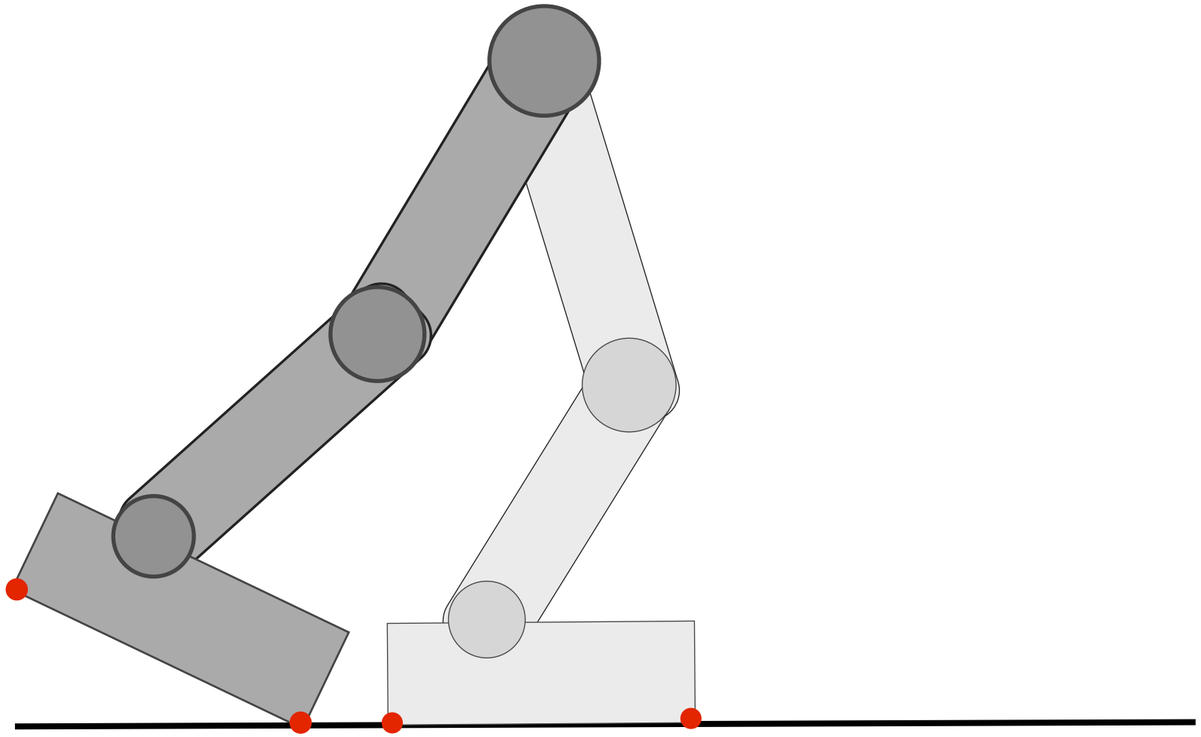

Features
Contact
COM
Trunk
AM
Posture
Foot
Arms

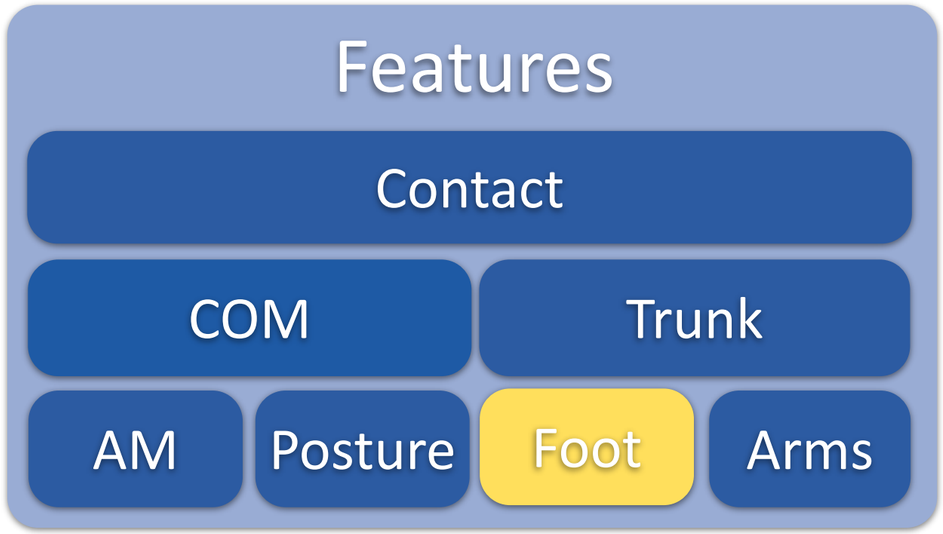

COM
Trajectory

Walking: Swing Foot

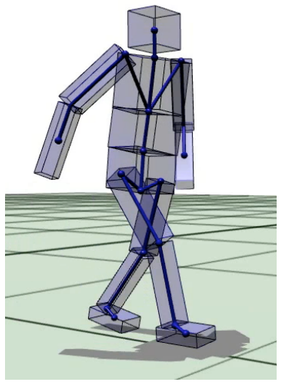


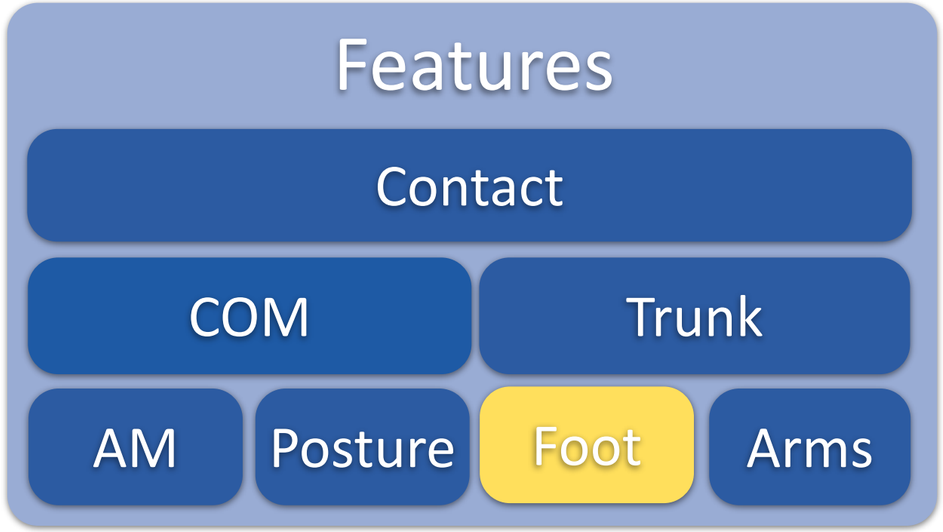
$$\mathbf{E}_{foot}(\mathbf{x}) = ||\ddot{y}_d - \ddot{y}||^2$$



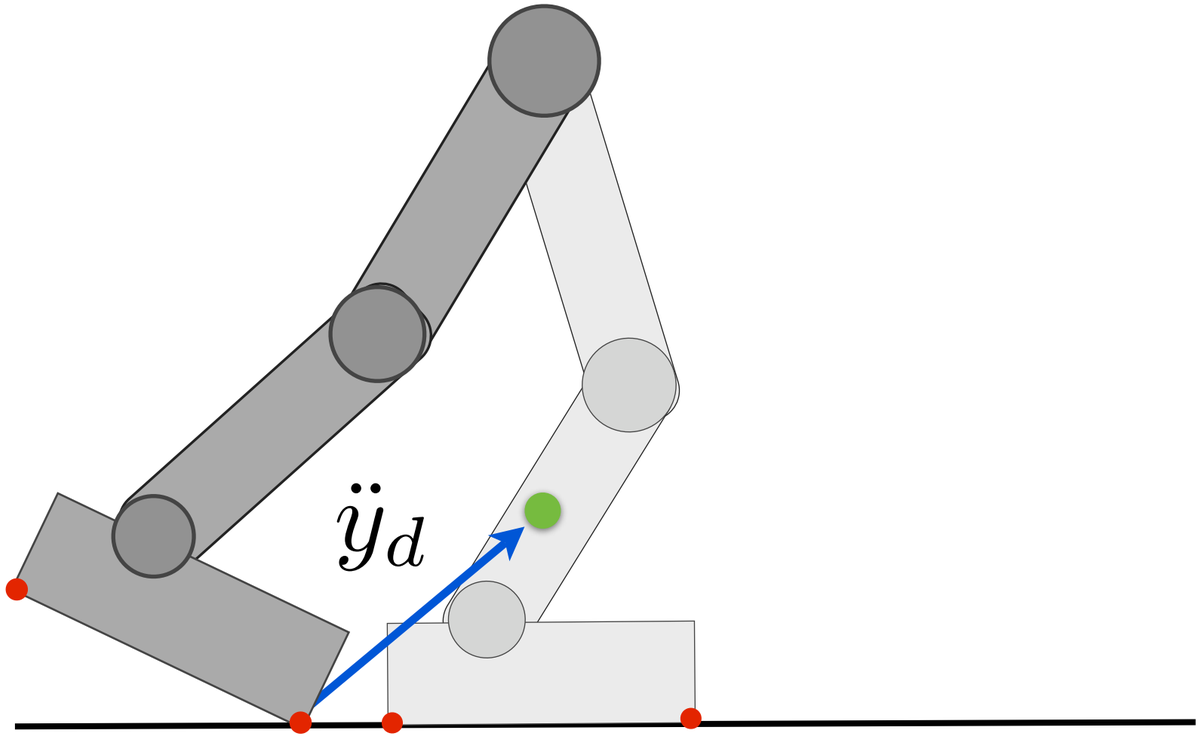


Walking: Swing Foot

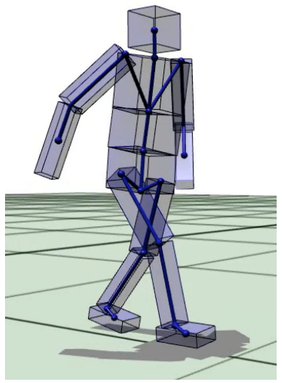


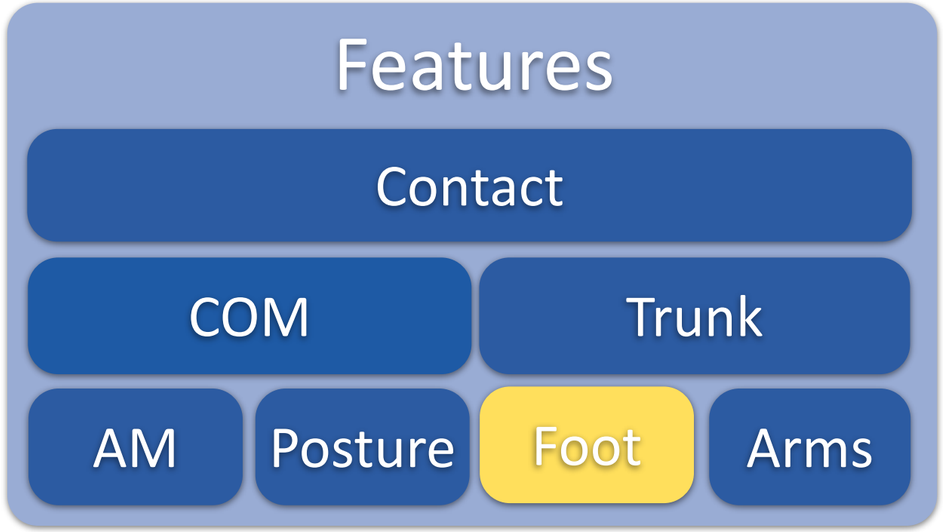


$$\mathbf{E}_{foot}(\mathbf{x}) = ||\ddot{y}_d - \ddot{y}||^2$$

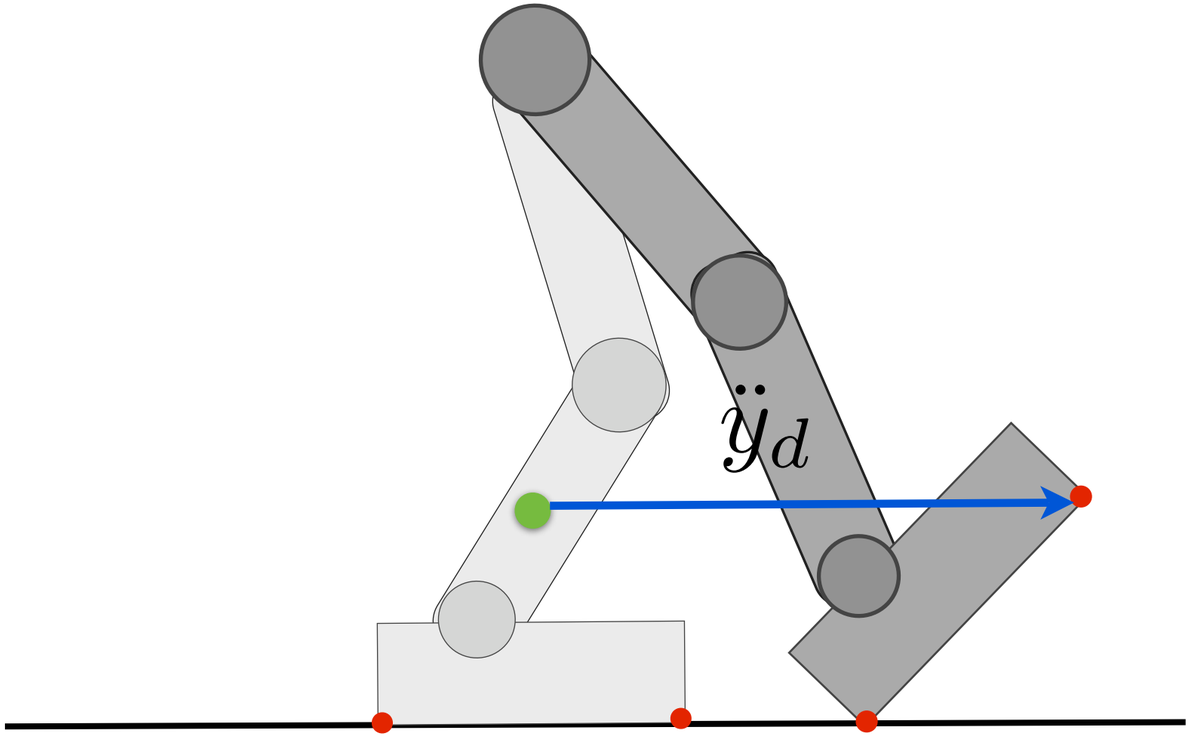


Walking: Swing Foot

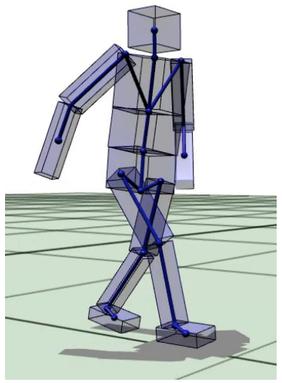


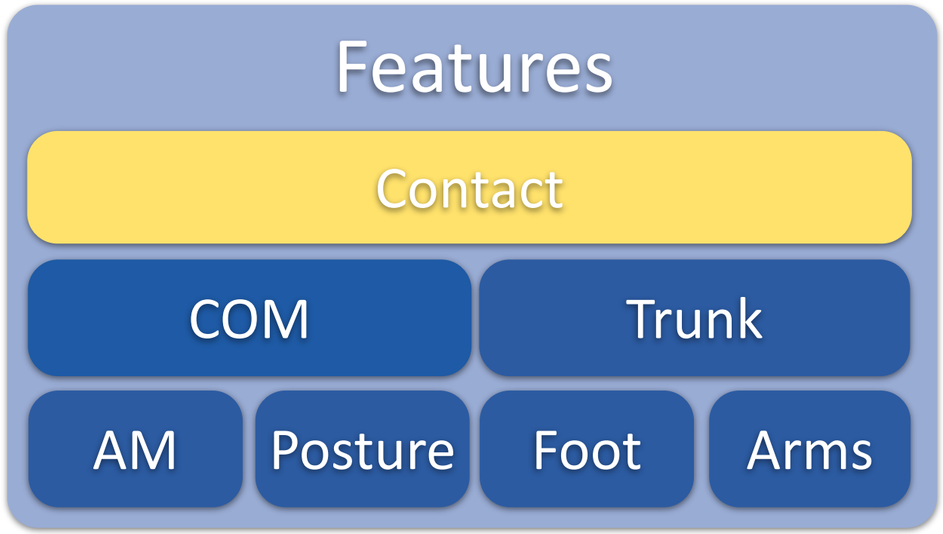


$$\mathbf{E}_{foot}(\mathbf{x}) = ||\ddot{y}_d - \ddot{y}||^2$$

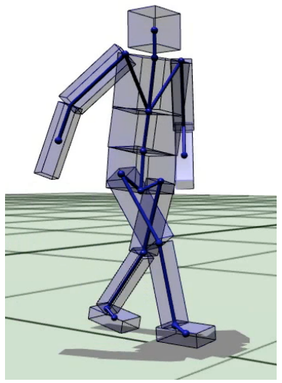


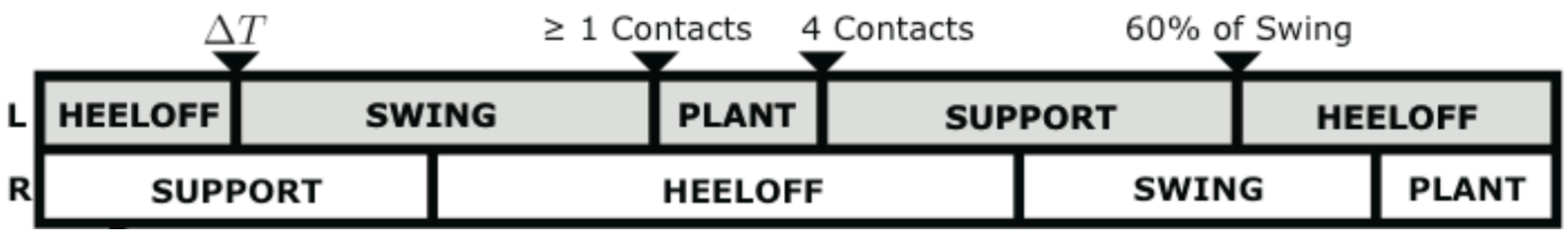
Walking: State-Machine

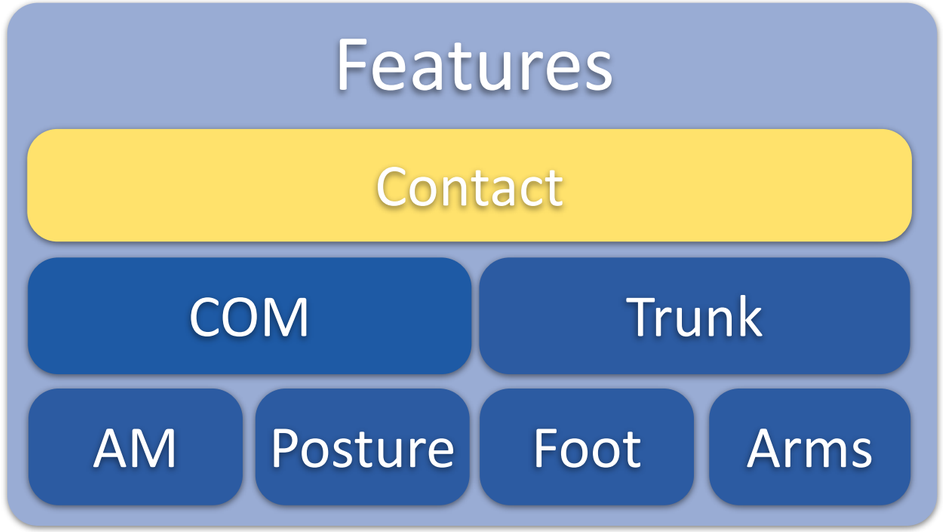




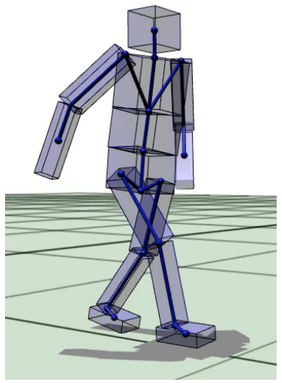
Walking: State-Machine

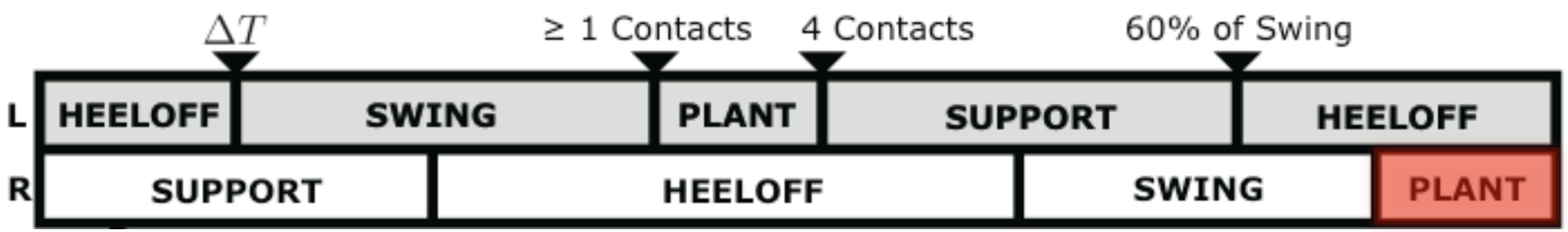


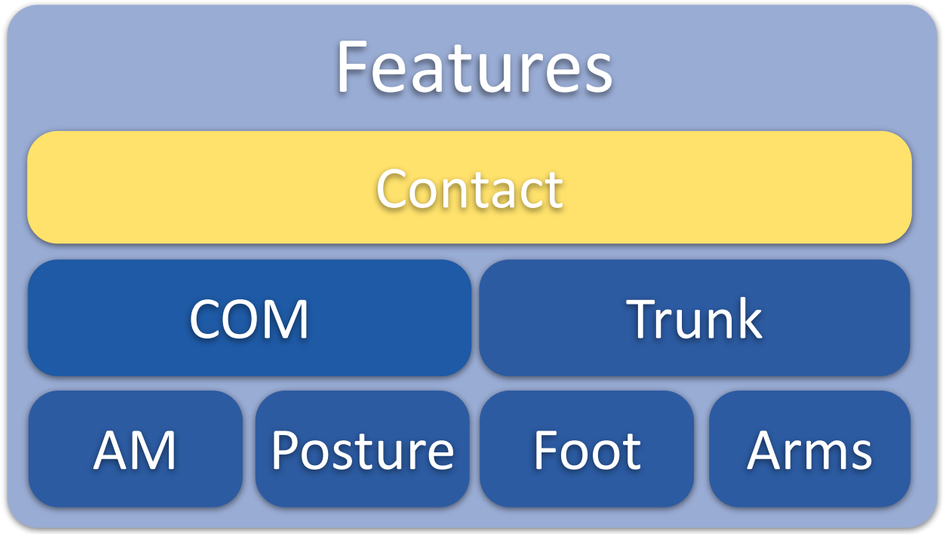




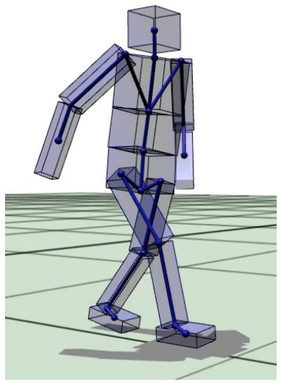
Walking: State-Machine





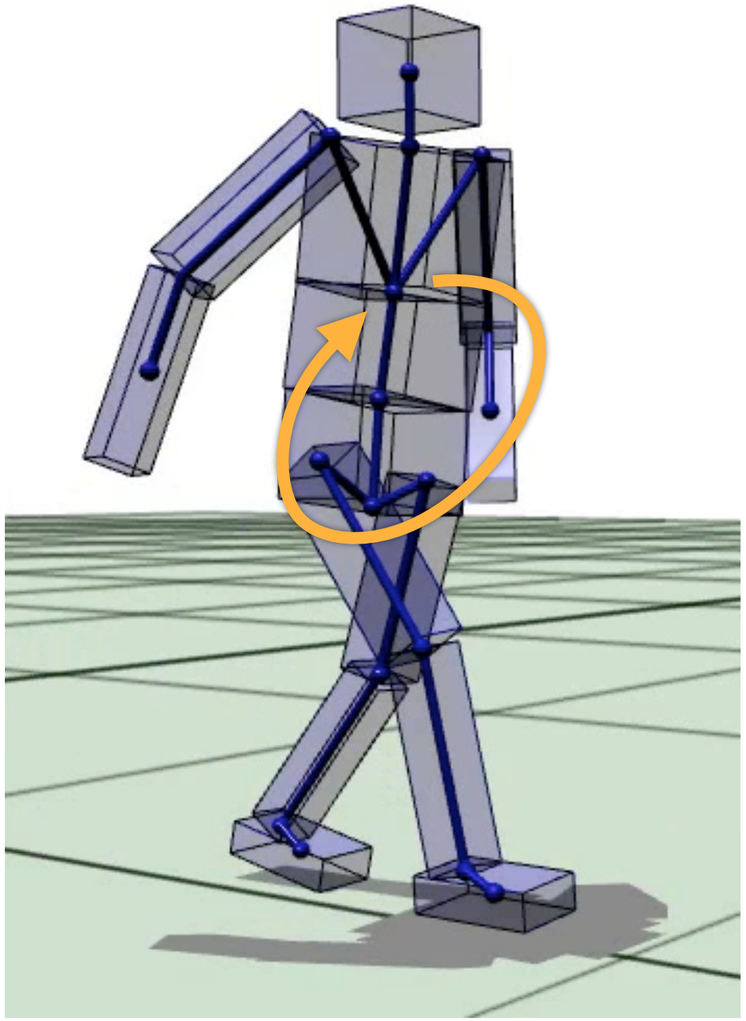


Walking: AM Control

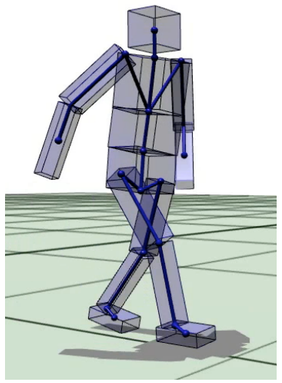


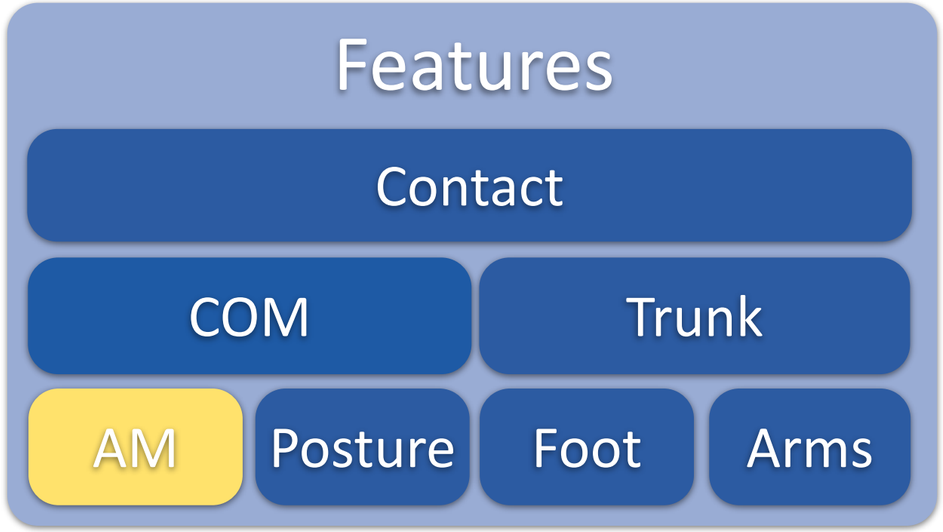
Features

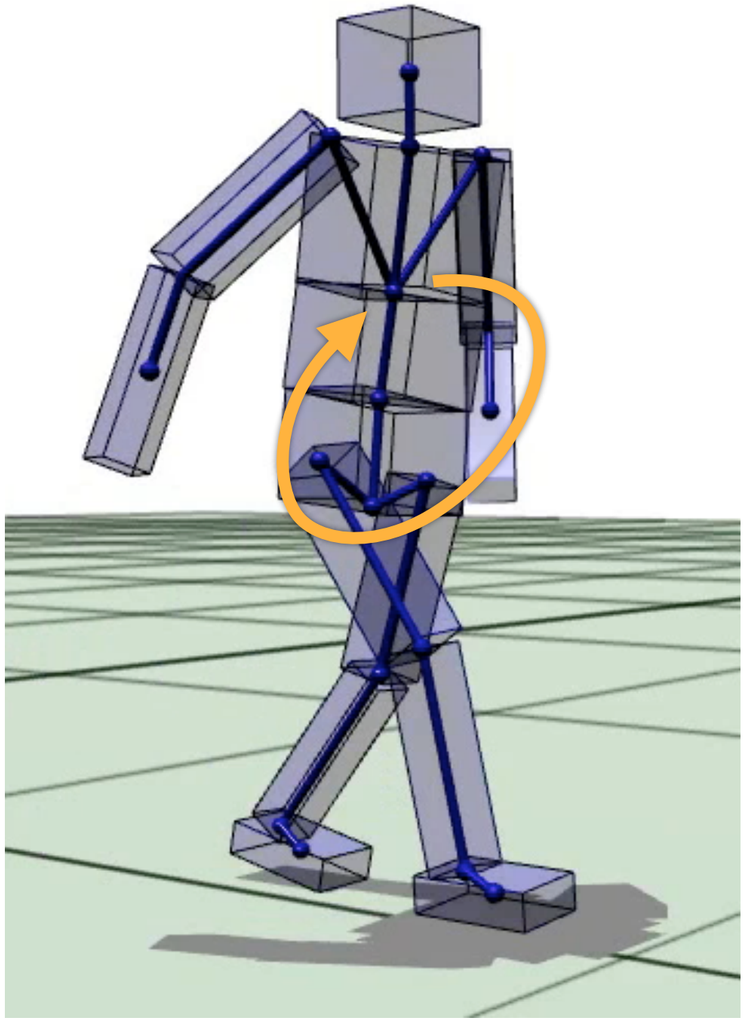
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms



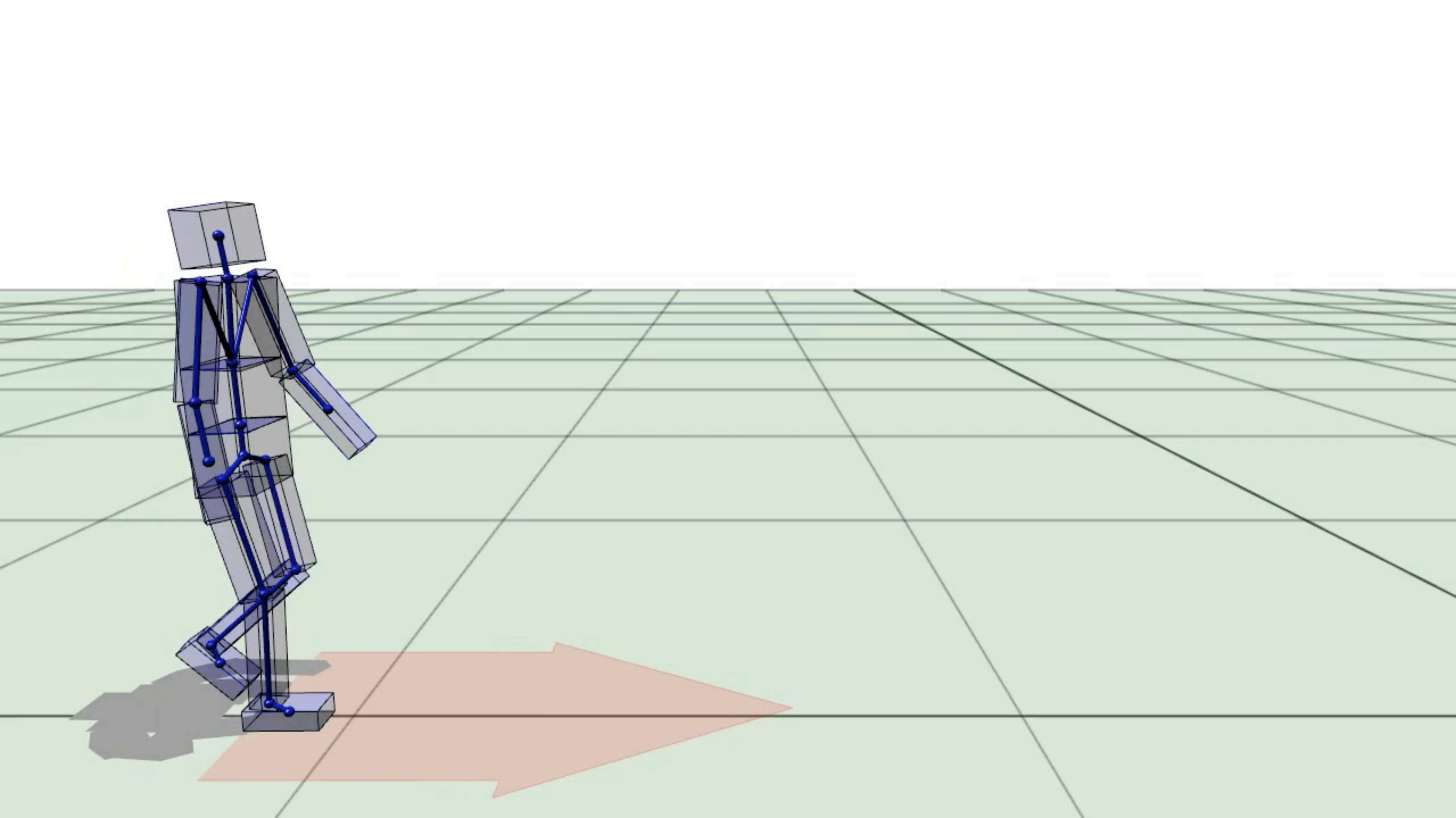
Walking: AM Control

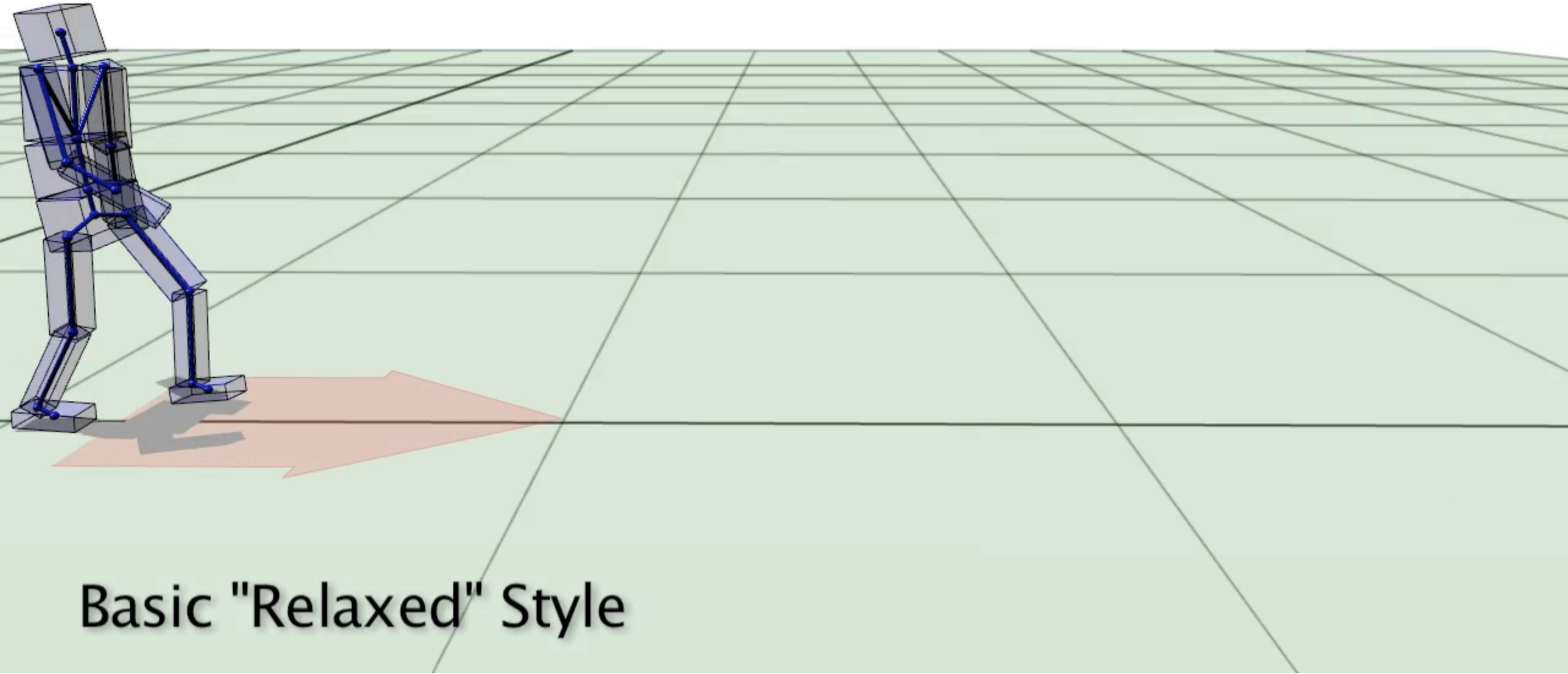


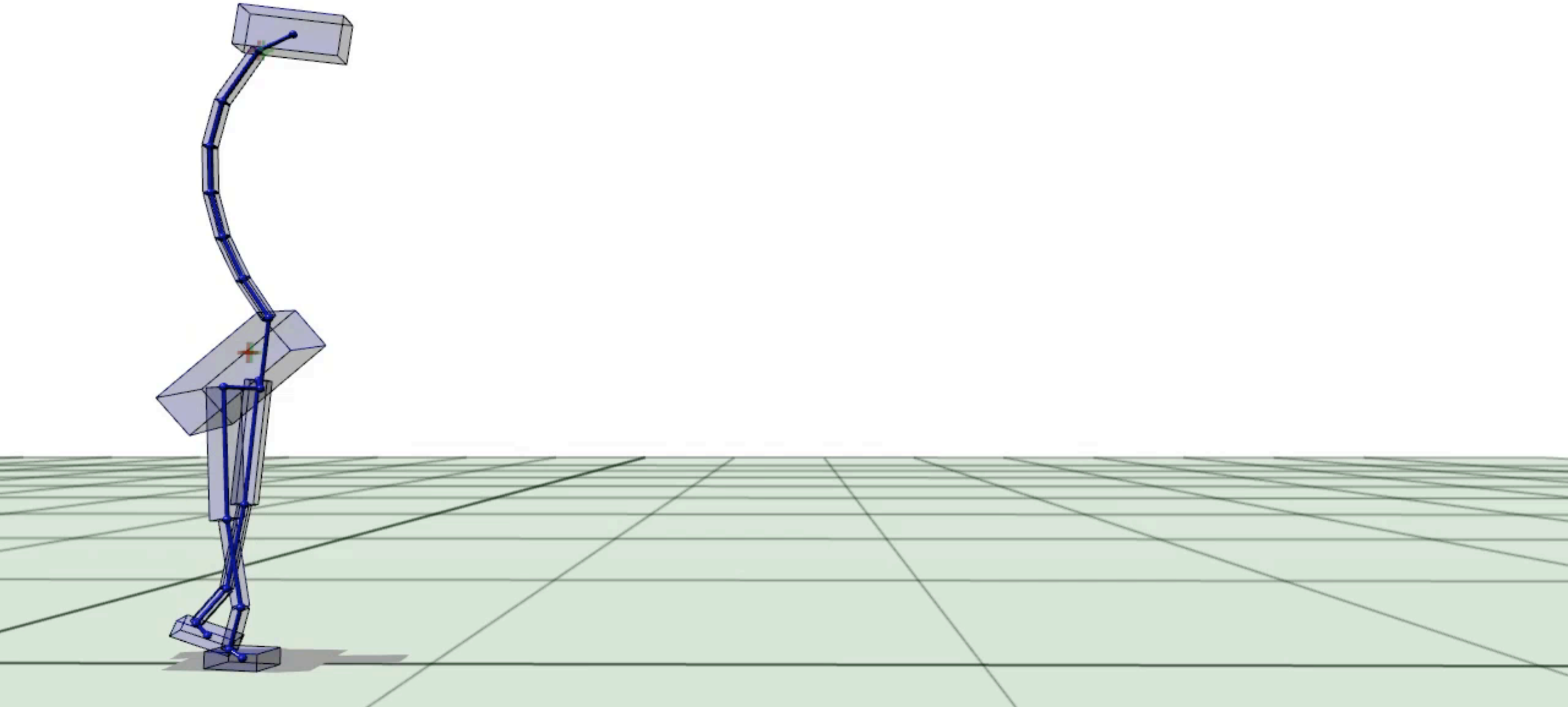


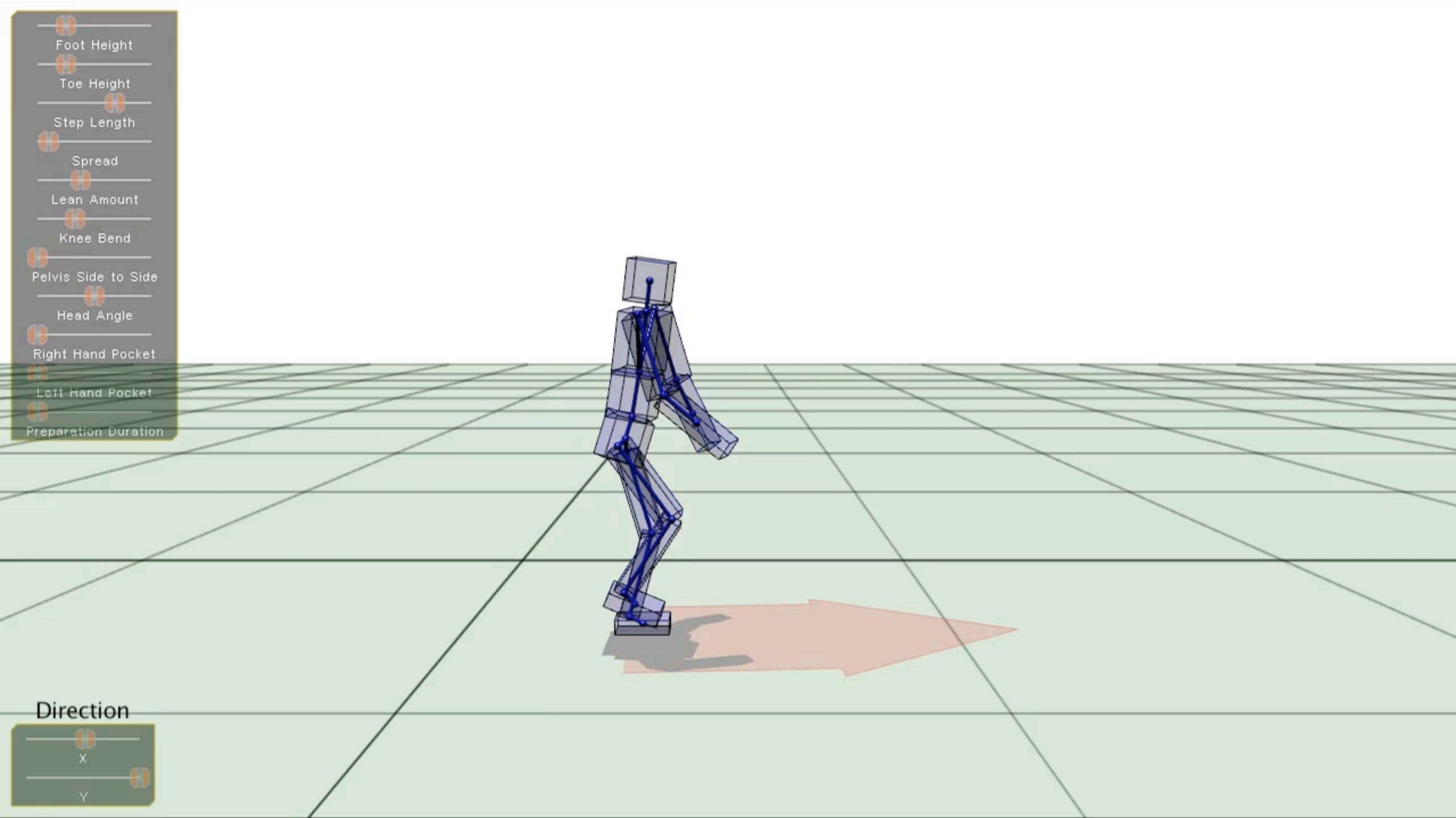


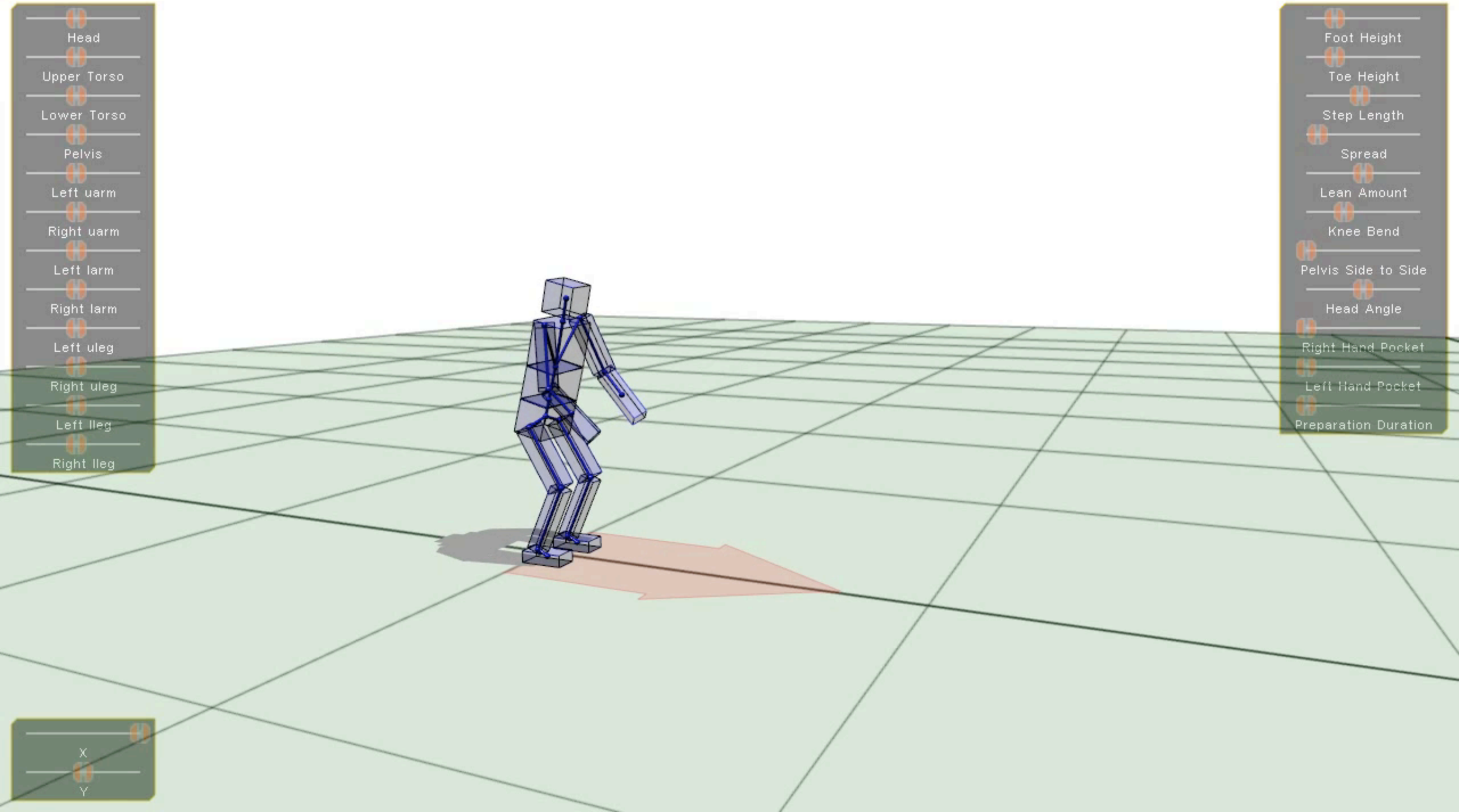
[Herr and Popović, 2004]

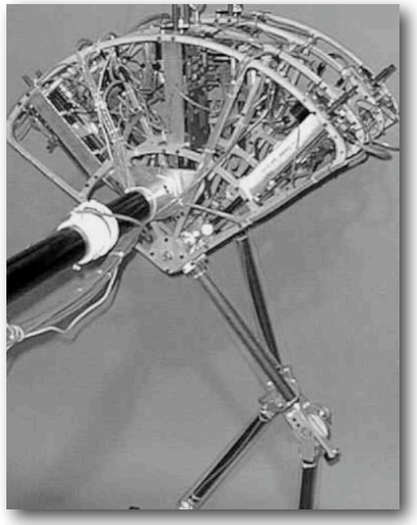


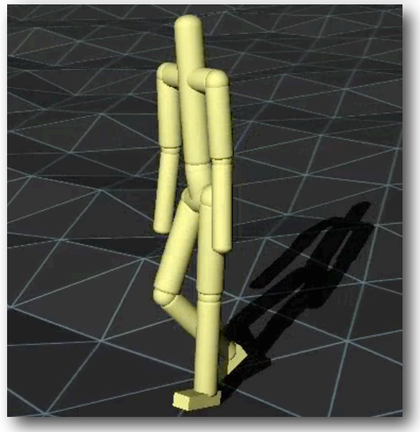

Basic "Relaxed" Style




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
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
X
Y

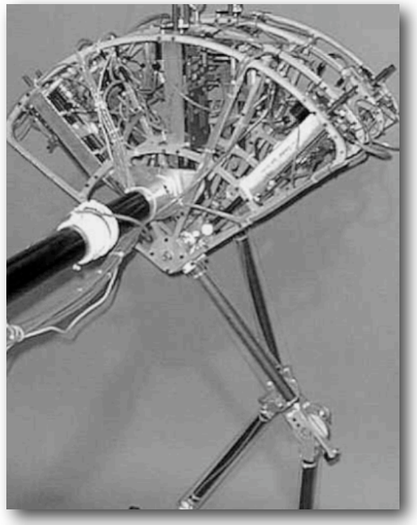


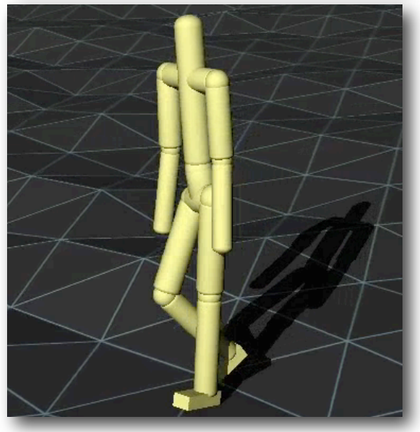


Virtual Model Control

Previous Work

- Pratt et al. 1995-2001
- Coros, Beaudoin, van de Panne 2010
- Wu and Popović 2010





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Pros

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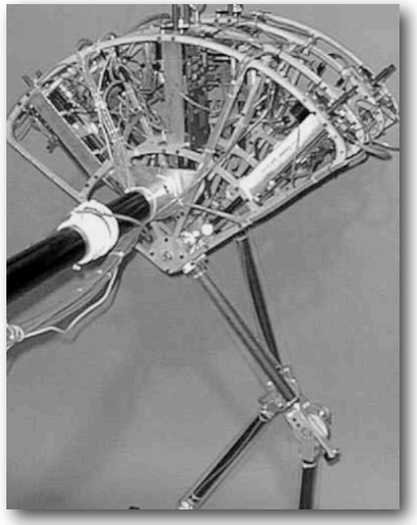
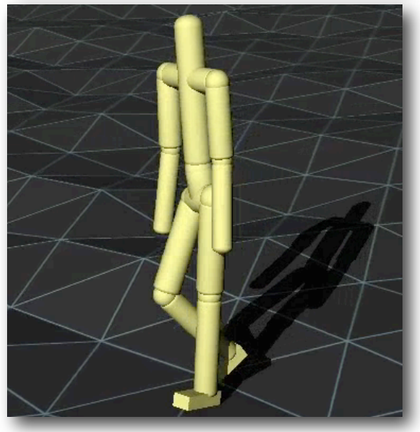
- No dynamics model required





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Pros

- Fast to evaluate
- No dynamics model required

Cons

- Whole-body tasks are hard to express
- Doesn’t handle goal interference

Limitations/Future Work

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Performance varies 50-100% realtime

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Can’t generate motions such as flips/cartwheels

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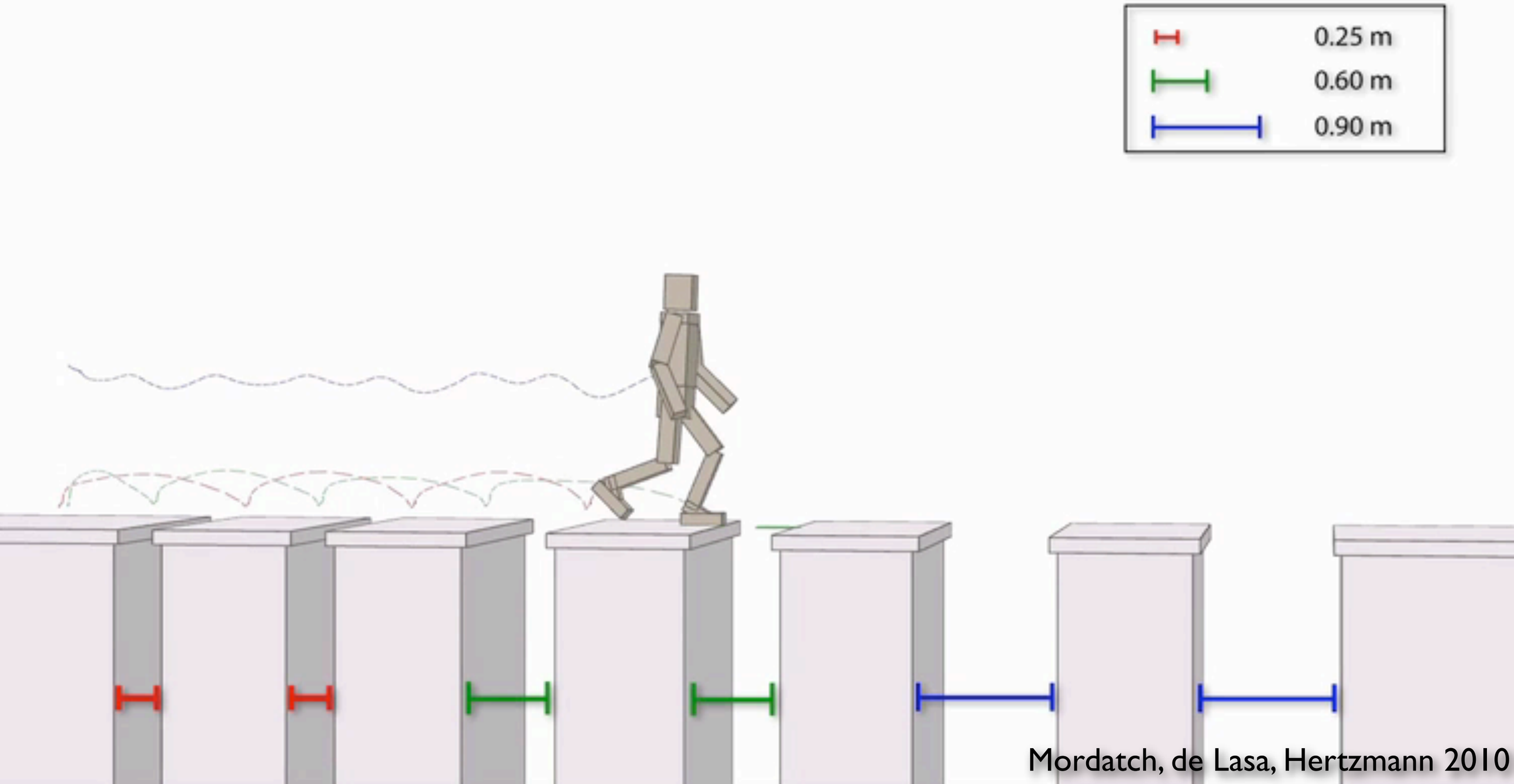
Performance varies 50-100% realtime

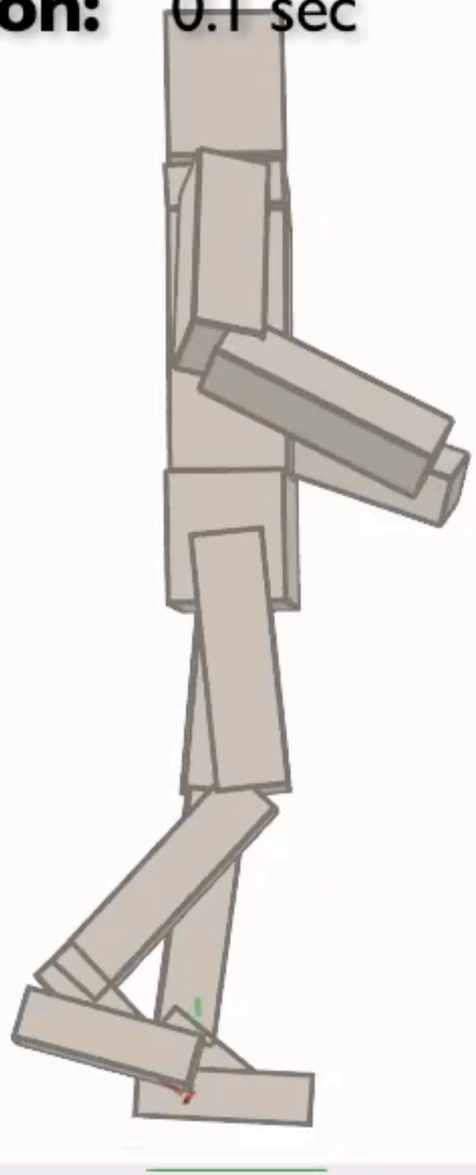
Can’t generate motions such as flips/cartwheels

Limited robustness to pushes

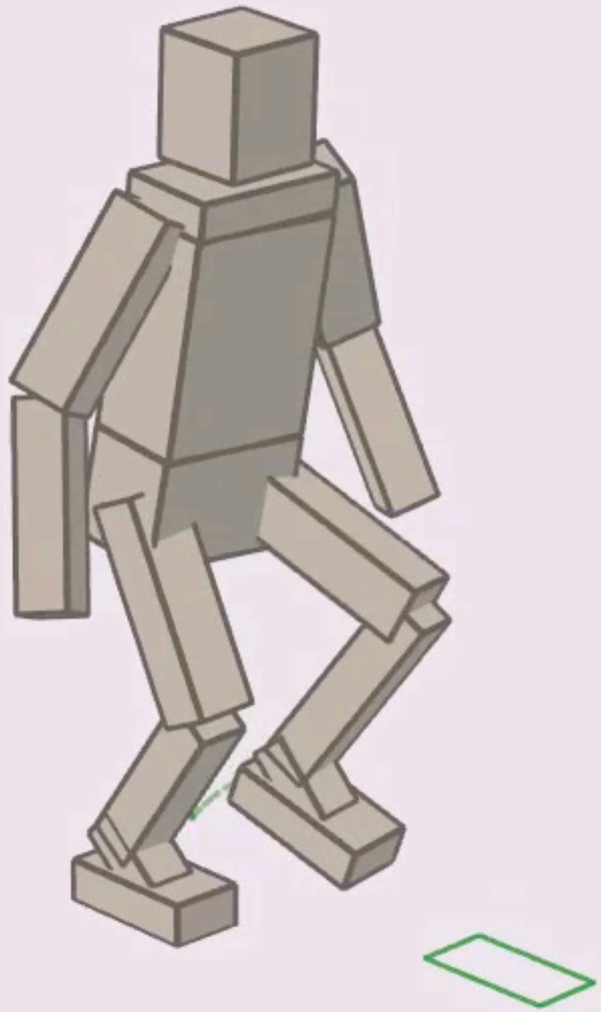


Mordatch, de Lasa, Hertzmann 2010

Force: 100 N
Duration: 0.1 sec



Mordatch, de Lasa, Hertzmann 2010



Gcomapex
Gheading
Gstepdir
Gstepdist
Gsteptime
Wacceleration
Wcomapex
Wheading
Whip
Wleg
Wstepdist
Wsteptime
Wterrain
pushdir
pushforce
stepheight

COM Height

Conclusions

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Design control using high-level goals

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New Prioritized Optimization algorithm

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Walking controller with new capabilities

Until very recently, just making a character walk without falling over was incredibly hard.

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Now it is not.

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Now it is not.

Together with other exciting results from this year, the opportunities to create new control capabilities are wide open!