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

<table>
<thead>
<tr>
<th>Section</th>
<th>Mass (g)</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Notes</th>
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<td>Head</td>
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<td>Lower Part of Trunk</td>
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<td>Upper Arm</td>
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<td>Forearm</td>
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<tr>
<td>Thigh</td>
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<td></td>
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<tr>
<td>Shank</td>
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<td>393.4</td>
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</table>
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?
Stance leg  Swing leg

[Muybridge 1887]
Heel-strike
Heel-off
Heel-strike
Toe-off
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 Oijambo Mang’Eni & Yannis Pitsiladis

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

Abstract

Humans have engaged in endurance running for millions of years, 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)

\[ c = \frac{\sum_i x_i m_i}{\sum_i m_i} \]
Newton’s 2nd Law: \( f = m\ddot{x} \)

\[
\begin{align*}
\mathbf{f} & = m\ddot{\mathbf{x}} \\
\mathbf{f} & = m\ddot{\mathbf{c}} \\
\mathbf{f} & = \mathbf{f}_g + \mathbf{f}_c \\
\mathbf{f}_g & = -mg\mathbf{u}
\end{align*}
\]
Ballistic motion

\[ m\ddot{c} = f_g \]
\[ = -mgu \]
\[ \ddot{c} = -gu \]

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

\[ \tau = I \dot{\omega} \]
\[ \tau = \tau_c \]

In ballistic motion, \( \tau = 0 \)

A character in flight has constant angular momentum.

\[ \mathbf{L} = I \omega \]
Conservation of Angular momentum

\[ L = I\omega \]

\[ I_1\omega_1 = I_2\omega_2 \]
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 Tomkins, 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...
Balance

Support polygon
Keeping the COM over the support aids balances
Center-of-pressure (COP):

Weighted average position of forces on foot

If the COP reaches the edge of support, the body may tip
Balancing objective terms:

1. Keep COM above support
2. Regulate COP or angular momentum
3. Reach target pose
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
Genetic algorithm optimizing morphology and controller
Unexpected outcomes: “Maximize ground velocity in 2 seconds”
Unexpected outcomes: “Maximize ground velocity in 2 seconds”
The Surprising Creativity of Digital Evolution: A Collection of Anecdotes from the Evolutionary Computation and Artificial Life Research Communities


(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 nature. Indeed, many researchers in the field of digital evolution have observed their evolving systems producing designs that are unexpected...
Measuring effort

Want to measure metabolic energy
Mechanical power: \( Power = Force \cdot Velocity \)
\[ = \tau \dot{q} \]
\[ E = \sum \tau \dot{q} \]
Squared torques: \[ E = \sum \tau^2 \]
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
\[ \tau = \tau_m + \tau_p \]
\[ E(Q) = \sum_{ti} \alpha_i \tau_{ti}^2 \]

Constraints \( C \)

\[ Q^* = \arg \min_Q E(Q) \]
\[ s.t. \ C(Q) = 0 \]

147 model parameters, very hard to set
Inverse optimization

mocap
Synthesis
Validation
Motion warping
Training data
Synthesized motion
Features in walking
Humans don’t keep static balance in walking

Support

COM projection
Center-of-Mass (COM)

Propel forward, shift weight to maintain balance

M. Popovic et al 2004
Angular momentum in walking

Pigeon movement

Simplified Models
Passive toys by Peter Steinkamp
Passive toys by Peter Steinkamp
Inverted Pendulum
Passive Dynamic Walker

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

DCT: 1.6

DCT: 0.05

DCT: 0.055
Other simplified models


Make policies for neuromechanical control

Collapse dimensions by trimming away degrees of freedom (seek synergies and symmetries)

Use as a guide or target for control

Add degrees of freedom (joints, muscles) from animal to reveal mechanisms

Spring-loaded inverted pendulum (SLIP)

Lateral leg spring (LLS)

Multiple legs, joints and muscles

Multiple legs, joints and muscles
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
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.
Controllers
Controller:

Mapping from state to joint torques:

\[ \mathbf{\tau} = f(q, \dot{q}, S) \]
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

Objectives

\[ R(s_{1:T}) = \sum_i w_i E(s_{1:T}) \]
Optimization

Initial Controller
Our Result

SIMBICON
(our implementation)
Head Stabilization Term

\[ E_{\text{head}} \]

With  

Without
Angular Momentum Term

\[ E_{\text{ang}} \]

(note the relationship between arms and legs)
The role of uncertainty

Many elements of natural environments are unpredictable

External disturbances
The role of uncertainty

Many sources of uncertainty:

- Environment
- External forces
- User control
- Motor noise [Harris and Wolpert, Nature 1998]
Define a probability distribution:

\[ p(s_{1:T}) \]

Want to optimize:

\[ E_{p(s_{1:T})}[R(s_{1:T})] \]

Monte Carlo approximation:

\[ \frac{1}{N} \sum_{j} R(s_{1:T}^{(j)}) \quad s_{1:T}^{(j)} \sim p(s_{1:T}) \]
Optimizing controllers with uncertainty

External disturbances
Optimizing controllers with uncertainty

Slippery surface
Optimizing controllers with uncertainty

Walking on top of a tall wall
Biology-based actuators and objectives

J.M. Wang et al. SIGGRAPH 2012
Deep controllers with symmetry

Yu, Turk, Liu. SIGGRAPH 2018
At each time step, optimize torques:

\[ \tau^* = \arg \min E(\tau) \]

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

Features

Contact

COM

AM

Posture
COM Control

Features
- Contact
- COM
- AM
- Posture

Diagram showing BOS Center and COM Projection.
Contact Control

Features
- Contact
- COM
- AM
- Posture
AM Control

Features
- Contact
- COM
- AM Posture

Diagram: A figure illustrating the concept of AM Control with a focus on posture and balance.
Features \xrightarrow{E_i(x)} \text{Prioritized Optimization} \xrightarrow{\tau} \text{Simulation}
Walking

Features

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

Features
- Contact
- COM
- Trunk
- AM
- Postur
- Foot
- Arms

COM
Walking: AM Control

Features

- Contact
- COM
- Postur
- Trunk
- Foot
- Arms
- AM

Arms
Walking: State-Machine

Features
- Contact
- COM
- Trunk
- AM
- Postur
- Foot
- Arms

State Machine Diagram:
- ΔT
- ≥ 1 Contacts
- 4 Contacts
- 60% of Swing

States:
- SUPPORT
- HEELOFF
- SWING
- PLANT
- SUPPORT
- HEELOFF
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

Next Foot Contact
Walking
Walking

Next Foot Contact
Walking
Walking
Running
Running
Running
General Gaits:
sequence of single/double SLIP and flight phases
Optimize $U^*$ to satisfy goals:

$$U^* = \arg\min \sum_i w_i g_i(S(t))$$
Optimize $U^*$ to satisfy goals:

$$U^* = \arg\min_U \sum_i w_i g_i(S(t))$$

General nonlinear optimization
23-dimensional
Solved using CMA [Hansen 2006]
Step Distance
Pushes
Projectile Avoidance
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

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<tr>
<th>Fundamentals</th>
<th>Applications</th>
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<td>Other animals</td>
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<td>Contact and foot models</td>
<td>Clothing</td>
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<td>Perceptual uncertainty</td>
<td>Climbing</td>
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<td>Eye movements/sensing</td>
<td>Bicycle stunts</td>
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<td>Planning</td>
<td>Soft creatures</td>
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<td>Evolution of Morphology</td>
<td>Crowds</td>
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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