Modeling and Simulation of Gait (part 2)

MCE 493/593 & ECE 492/592
Prosthesis Design and Control
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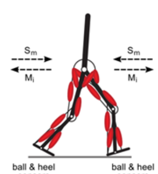
Today

- Optimizing the movement of a simulation model
  - "shooting" approach
  - space-time (collocation) approaches
- Optimization of a hydraulic knee
  - ASME J Biomech Eng 2012
- Optimization of running with a prosthetic foot
  - Int. Soc. Biomech 2009

Optimizing a simulation model

- Goal: produce the "best" movement
- Optimizing the mechanical design parameters
  - mass, length, stiffness
- Optimizing controller parameters (p)
  - u = u(t,x;p)
  - open loop control u = u(t;p)
  - closed loop control parameters(PD control, impedance control) u = u(t,x;p) (not today)
  - autonomous system u = u(x;p) (not today)
- Best done simultaneously!



"Shooting" approach

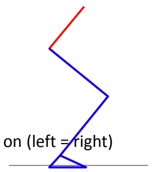
1. Guess system parameters **p**
2. Set initial state (**x**0) (sometimes this is optimized also)
3. Do a simulation with parameters **p**, starting at **x**0
4. Evaluate performance
5. Change the system parameters **p**, to improve performance
6. Repeat from 2, and stop if performance can no longer be improved

Use general purpose unconstrained optimization tools:
PSO, BBO, GA, fminsearch, fminunc, simann.m

Matlab code: jumpopt.m (uses gait2de package)

State at t=0:

```
sim.xinit = [0 0.68 -pi/4+0.1 pi/2 -pi/2 pi/4-0.1 pi/2 -pi/2 pi/4-0.1 ...  % q
            zeros(1,9)   ...                                                %qd
            1.4*ones(1,16) ...           % Lce
            zeros(1,16)];                % a
```



With u=0, model will collapse

Which u(t) will make it jump highest?

8 controller parameters: time at which each muscle switches on (left = right)

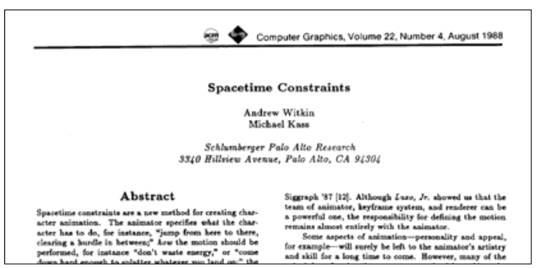
```
function [u] = controller(t,x);
    global sim
    u = zeros(16,1);
    for i=1:8
        if (t > sim.par(i))
            u(i) = 1;                    % turn the muscle on
            u(i+8) = 1;                  % and the one on the other side
        end
    end
end
```


Limitations of the shooting approach

- Optimization can end in a local optimum
  - Especially for complex movements, e.g. gait cycle
  - To minimize risk, use "global" optimization algorithms plato.asu.edu/sub/global.html
- Hard to satisfy endpoint constraints (with open loop control)
  - especially for complex and unstable movements
  - for instance: periodicity (final state = initial state)
  - constrained optimization (fmincon) often fails
    - local optimum
    - not even finding a feasible solution (satisfying the constraints)
- Shooting works well for:
  - optimizing open loop controller for ballistic movements
  - optimizing feedback controller for periodic movements (example)

"Space-time" or collocation approach

physics-based animation



Computer Graphics, Volume 22, Number 4, August 1988

Spacetime Constraints

Andrew Witkin
Michael Kass

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Abstract

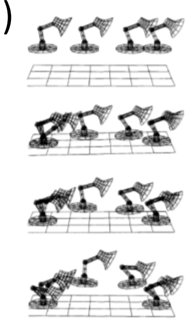
Spacetime constraints are a new method for creating character animation. The animator specifies what the character has to do, for instance, "jump from here to there, clearing a hurdle in between;" *how* the motion should be performed, for instance "don't waste energy," or "come

Siggraph '87 [12]. Although *Luxo, Jr.* showed us that the team of animator, keyframe system, and renderer can be a powerful one, the responsibility for defining the motion remains almost entirely with the animator.

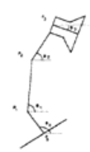
Some aspects of animation—personality and appeal, for example—will surely be left to the animator's artistry and skill for a long time to come. However, many of the

"Because we extend the model through time as well as space, we call the formulation *spacetime constraints*."

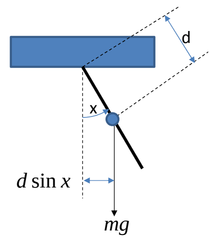
The main idea (open loop)



- Do <u>not</u> use simulation to find **x**(*t*)
- Guess & improve **x**(*t*) and **u**(*t*) until:
  - movement is optimal
  - satisfies task constraints
  - satisfies physics constraints: $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u})$
- Luxo lamp
  - 2D, 6 DOF
  - 3 torque actuators
  - objective: minimal energy
  - task: initial and final state



1-DOF pendulum



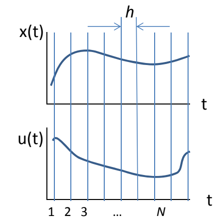
- Variables
  - angle x, torque u
- System dynamics:

$$I\,\ddot{x} = -mgd\sin x + u$$

- Task constraints for swing-up in time T:
  - Initial state $x(0) = 0, \quad \dot{x}(0) = 0$
  - Final state $x(T) = \pi, \quad \dot{x}(T) = 0$
- Cost function: integral of squared torque

$$\int_0^T u(t)^2\,dt$$

Temporal discretization



- Direct collocation: *N* nodes
- Time step $h = T/(N-1)$
- States $x_1, x_2 \ldots x_N$ controls $u_1, u_2 \ldots u_N$
- Diff. eq. becomes N-2 algebraic constraints:

$$I\,\ddot{x} = -mgd\sin x + u \;\Rightarrow\; I\,\frac{x_{i+1} - 2x_i + x_{i-1}}{h^2} = -mgd\sin x_i + u_i$$

- Cost function becomes an algebraic function:

$$\sum_i u_i^2$$

- Time step *h* usually much larger than in ODE solver
  - Convergence study to decide how many nodes are needed
  - For human gait cycle: N=50 or N=100 is typically good enough

Constrained optimization problem

- Unknowns

$$\mathbf{y} = (x_1, x_2 \ldots x_N, u_1, u_2 \ldots u_N)^T$$

- Minimize

$$f(\mathbf{y})$$ cost function

- Subject to

$$\mathbf{c}(\mathbf{y}) = 0$$ task constraints and dynamics constraints

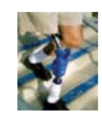
- Matlab solvers for this type of problem:
  - fmincon sequential quadratic programming
  - SNOPT sequential quadratic programming (large scale)
  - IPOPT interior point method (large scale)

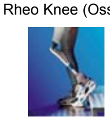
Matlab code:
http://hmc.csuohio.edu/resources/human-motion-seminar-jan-23-2014/test-page

Transfemoral amputees

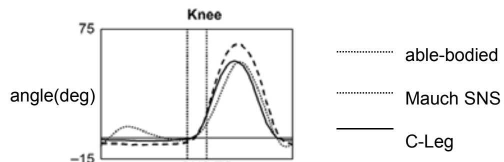
- 30-50% higher metabolic cost
  - Waters et al., JBJS 1976
  - passive hydraulic knees
- Modern knee devices
  - computer-controlled damping
  - only 3-6% metabolic improvement
    - Orendurff et al., JRRD 2006
  - can we do better?


Mauch SNS


Rheo Knee (Ossur)


C-Leg (Otto Bock)

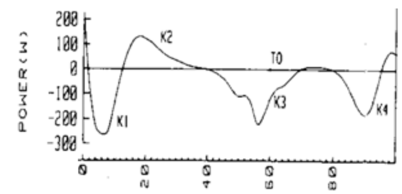
Knee flexion in stance phase



(Segal et al., JRRD 2006)

- One of “six determinants of gait“ is missing
- Cause of high metabolic cost?
- Cause of high mechanical loads?
  - residual limb
  - contralateral limb

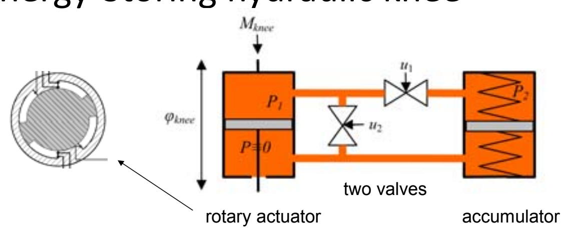
Why no stance phase knee flexion?



WInter, CORR 1983

- Controlled damper can dissipate (K1,K3,K4) but not generate energy (K2)
- Patients may avoid K1, even if device allows it

Energy-Storing hydraulic knee

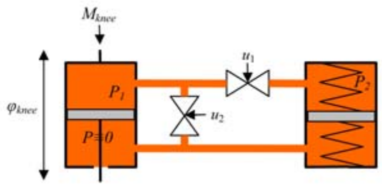


- Equivalent to controlled damper device when accumulator is not used (valve 1 closed)
- Should improve function during gait and stand-sit-stand tasks

Purpose

- Computational model of device
- Optimization of hardware parameters and valve control patterns for:
  - normal walk
  - slow run
  - stand-sit-stand
- Quantify performance

Model of hydraulic circuit



Valve controls:

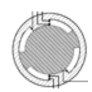
$u_1(t)$, $u_2(t)$

$0 \leq u \leq 1$
(closed) (open)

Differential-algebraic equations:

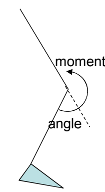
$$V\dot{\varphi} - v_1 - v_2 = 0$$
$$\dot{P}_2 - k v_1 = 0$$
$$u_1(t)^2 C_1^2 \left(\frac{M}{V} - B_1 v_1 - P_2\right) - v_1|v_1| = 0$$
$$u_2(t)^2 C_2^2 \left(\frac{M}{V} - B_2 v_2\right) - v_2|v_2| = 0$$

Actuator constant:
$V = 7.3\ \mathrm{cm}^3$



Human movement data

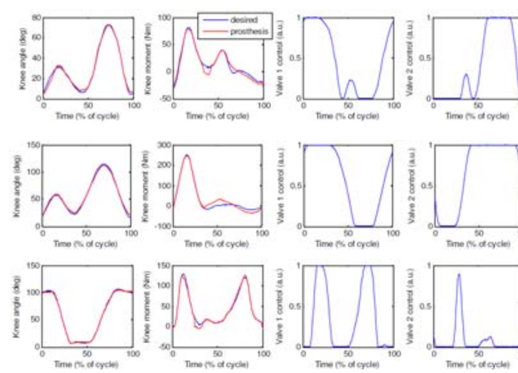
- 3 able-bodied subjects
- 3 activities
  - walk, run, sit-stand-sit
- knee moment and knee angle (Orthotrak, Motion Analysis Corp.)



Design optimization
→ optimal control problem

- Find:
  - valve control signals $u_1(t)$ and $u_2(t)$
  - accumulator stiffness k
- To achieve:
  - best fit to able-bodied angle/moment data
  - smooth valve controls $u(t)$
  - periodic boundary conditions
- Method:
  - direct collocation
  - Ackermann & van den Bogert, *J Biomech* 2010

Results – Subject 1 movement data



NORMAL WALK

$k = 4.2\ \mathrm{MPa\ cm}^{-3}$

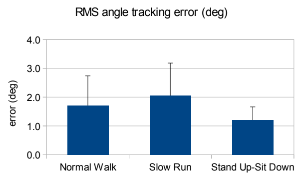
SLOW RUN

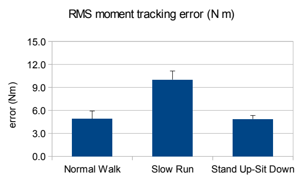
$k = 7.6\ \mathrm{MPa\ cm}^{-3}$

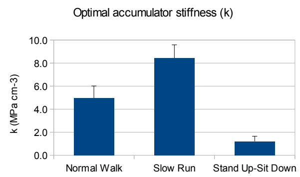
SIT-STAND-SIT

$k = 1.7\ \mathrm{MPa\ cm}^{-3}$

Results: summary
(mean ± SD, N=3 subjects)





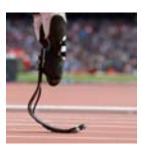


Notes

- Dynamics of the prosthetic system was simulated
  - human motion was not simulated
- Open loop controls were found that resulted in the best agreement with normal human motion / torques
- Controlled energy storage mechanism was sufficient to get close to able-bodied performance
  - theoretically...
  - different tasks require different accumulator stiffness
  - shows feasibility only, open loop control is not a controller!

Running with below-knee prosthetsis

- Bilateral transtibial amputee can compete with able-bodied athletes
- Does the device provide an unfair advantage?
- Still controversial:
  - banned by IAAF, December 2007
  - allowed, Court for Arbitration in Sport, May 2008


Cheetah foot (Ossur)

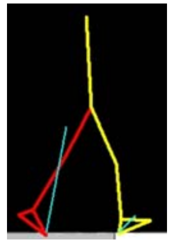

Oscar Pistorius

Previous work

- Brüggemann et al., *Sports Technol,* 2008
  - lower metabolic cost
  - lower joint moments
- Weyand et al., *J Appl Physiol*, 2009
  - similar metabolic cost
  - higher step frequency
- Observational studies
- Controlled experiment is only possible in computer model

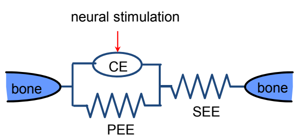
Musculoskeletal model

based on Gerritsen et al., Motor Control 1998



- 2D, 7 segments, 9 DOF
  - SDFast for multibody dynamics
- Viscoelastic ground contact
- Air drag F=.2128·v^2 (Quinn, 2004)
- 16 muscles
  - Hill based contraction dynamics (ODE)
  - first order activation dynamics (ODE)
- 50 states **x**, 16 controls **u**, dynamics

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u})$$



How fast can it run?

(open loop optimal control problem)

Find:

- trajectory $\mathbf{x}(t)$, controls $\mathbf{u}(t)$
- duration T of half a gait cycle
- speed V

Such that

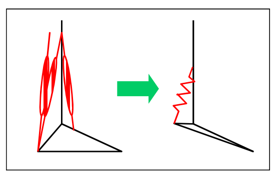
1. Speed V is maximized
2. System dynamics is satisfied: $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u})$
3. Trajectory is symmetric & periodic with forward translation:

$$\mathbf{x}(T) = \mathbf{x}(0)^{\text{mirror}} + V \cdot T \cdot \hat{\mathbf{x}}^*$$

*state space unit vector for forward translation

solved by direct collocation

Protocol



- Able-bodied model
  - How fast can it run?
- Amputee model
  - Remove ankle muscles, remove heel
  - Add passive torsional spring-damper

$$M = k(\varphi - \varphi_0) + b\dot{\varphi}$$

$k = 800$ Nm/rad

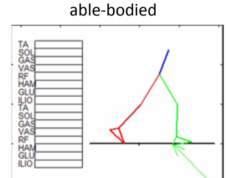
$b = 0.35$ Nms/rad

(Brüggemann et al., 2008)

  - No change in limb mass
  - How fast can it run?
  - And what is different about its motion?

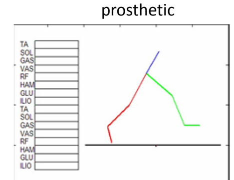
Optimization results

able-bodied



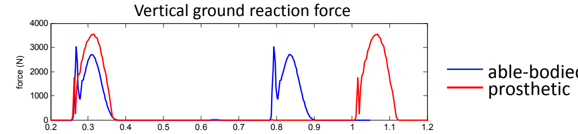
speed: 7.45 m/s
gait cycle: 526 ms
stance time: 114 ms

prosthetic



speed: 9.02 m/s
gait cycle: 753 ms
stance time: 111 ms

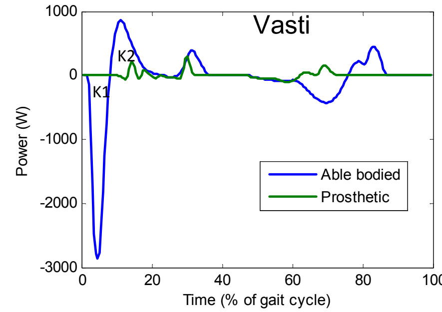
Vertical ground reaction force

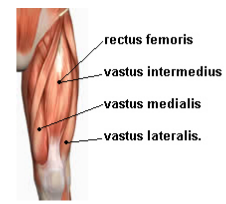


Mechanical energy balance

	Able-bodied	Prosthetic	
Ankle muscles pos. work (W)	746	0	
Ankle muscles neg. work (W)	–566	0	
Net prosthesis work (W)	0	–60	
Other muscles pos. work (W)	907	654	advantage
Other muscles neg. work (W)	–810	–324	
Air drag losses (W)	–88	–156	
Contact losses (W)	–189	–114	advantage
Totals	0	0	

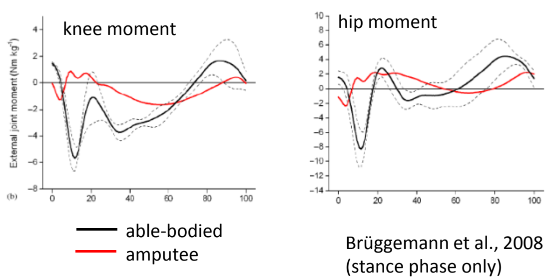
Vasti power during gait cycle





- Less use of muscles with prosthesis
- Prosthetic foot/ankle alters knee muscle function!

Compare to gait lab measurements



Brüggemann et al., 2008
(stance phase only)

Pistorius did not have the extreme "bouncy" gait that the model predicted.
Maybe this movement is too hard to control.

Could able-bodied sprinters run like this?

moment & angular velocity at prosthetic ankle
force-velocity properties of plantarflexor muscles