Kinematics, Kinetics, Amputee Gait (part 2)

MCE 493/593 & ECE 492/592
Prosthesis Design and Control
October 21, 2014

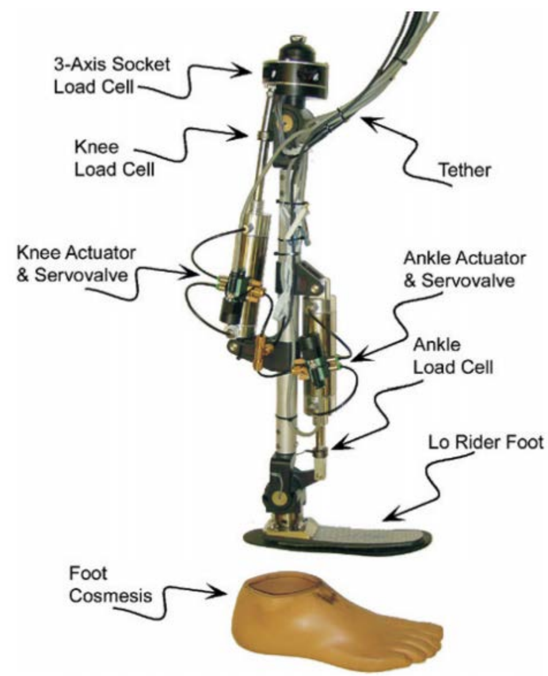
Antonie J. (Ton) van den Bogert
Mechanical Engineering
Cleveland State University

Homework due October 28

- Download the data file and Matlab code for the 2D kinematic/kinetic analysis (links in PDF)
  - Run the invdyn2d program
- Use the data to design impedance controllers for hip, knee and ankle
  - Optimization or trial and error
  - One control law for entire gait cycle
  - Show plots of actual joint moment and "best" controller
- Do this also for the hip joint
  - Will require additional code in invdyn2d.m

Today

- Additional notes on Vanderbilt leg
- Design of a passive exoskeleton
  - based on inverse dynamic data
- Studies of amputee gait

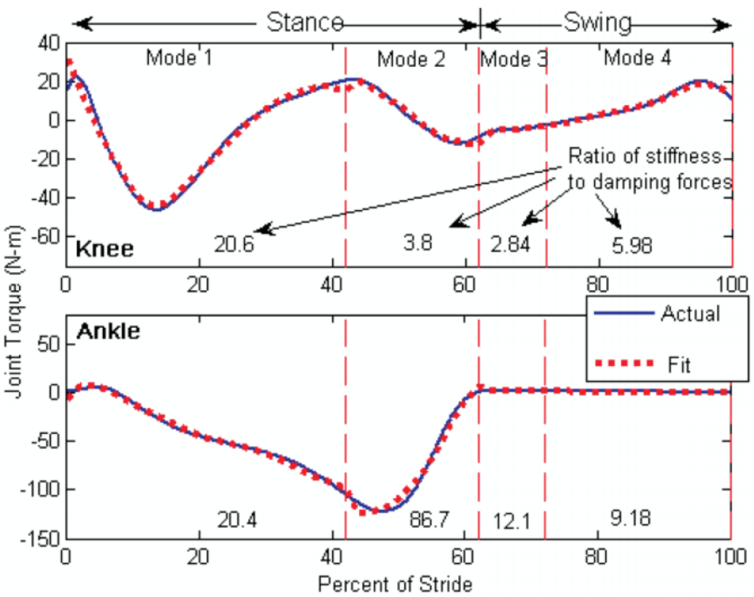


More than 4 phases would give better fit. So why not?

impedance control

$$\tau = k_1 (\theta - \theta_e) + k_2 (\theta - \theta_e)^3 + b\,\dot{\theta}$$

(Sup, Int J Rob Res 2008)

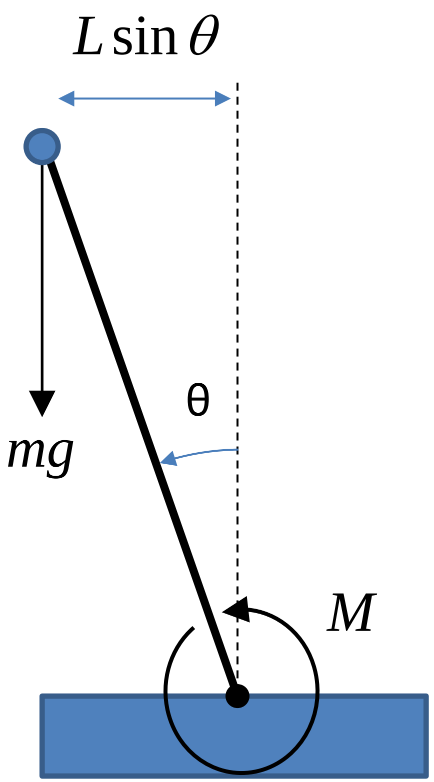


...utilizes an impedance-based approach to generate joint torques. Such an approach [...] generates stable and predictable behavior. The essence of the approach is to characterize the knee and ankle behavior with a series of finite states [...] switching between appropriate equilibrium positions (of the virtual springs) in each finite state. In this manner, **the prosthesis is guaranteed to be passive within each gait mode**, and thus generates power simply by switching between modes. As the user initiates mode switching, the result is a predictable controller that, barring input from the user, will always default to passive behavior.

Some concerns

- Bandwidth of (Winter) gait data is ~6 Hz, so maybe we have ~12 independent samples in the gait cycle.
- 16 parameters is already too many to identify from 12 equations
- Passive does not imply stable
  - it's not really passive when frequently switching
  - slider crank model shows that leg will buckle when knee stiffness is less than 7 Nm/deg
  - fit to Winter data had k1 = 3.78 Nm/deg
  - what to do?

Inverse dynamics is not feedback control!



Inverted Pendulum

Equation of motion:

$$mL^2\ddot{\theta} = mgL\sin\theta + M$$

Small-angle approximation:

$$mL^2\ddot{\theta} = mgL\theta + M$$

Desired movement:

$$\theta = A\sin\omega t$$

Inverse dynamics:

$$\begin{aligned} M &= mL^2\ddot{\theta} - mgL\theta \\ &= -mAL(g + L\omega^2)\sin\omega t \\ &= -mL(g + L\omega^2)\theta \end{aligned}$$

Controller

From inverse dynamics: $M = -k\theta$

$$k = mL(g + L\omega^2)$$

Linear system dynamics with control:

$$mL^2\ddot{\theta} = mgL\theta + M$$

$$= mgL\theta - mL(g + L\omega^2)\theta$$

$$= -mL^2\omega^2\theta + errors\,/\,perturbations$$

Solution:

$$\theta = A\sin\omega t + effect\ of\ errors\,/\,perturbations$$

A controller that might work:

$$M = -k\theta - K_p(\theta - A\sin\omega t) - K_d(\dot{\theta} - A\omega\cos\omega t)$$

inverse dynamics position feedback velocity feedback

Now, the controller also needs to know the desired trajectory (A sin wt), and it needs to know what time it is (t).

This is not ideal either!

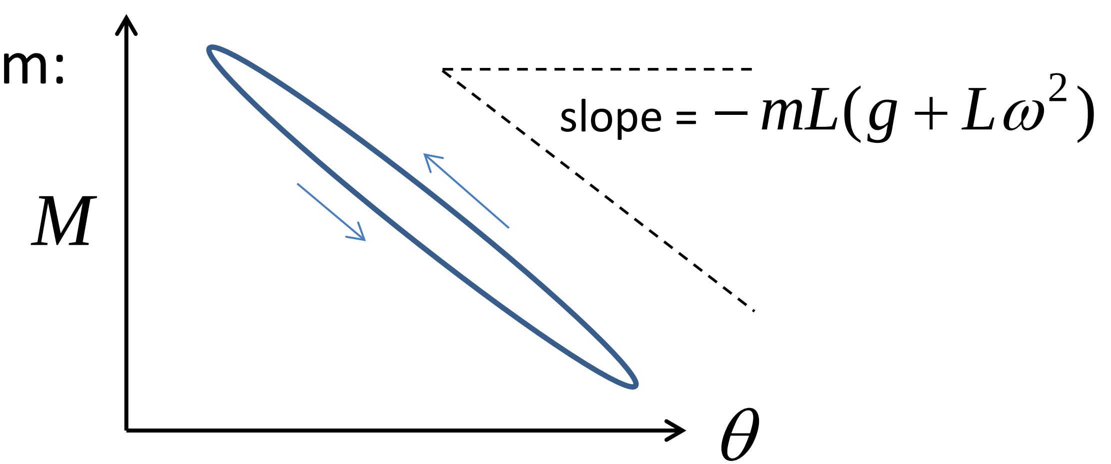
Moment-angle relationship during movement → "pseudo-stiffness"

When system is observed on its nominal trajectory:

$$M = -mAL(g + L\omega^2)\sin\omega t$$

$$\theta = A\sin\omega t$$

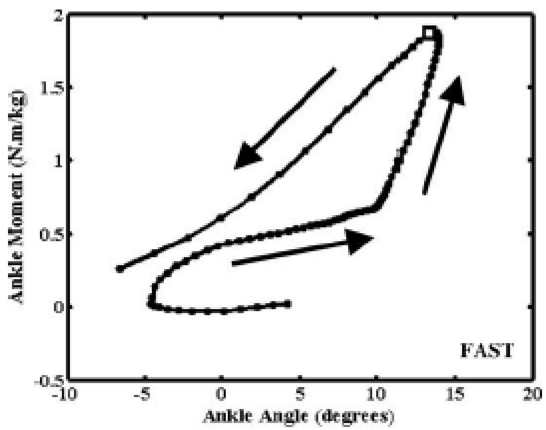
Moment-angle diagram:

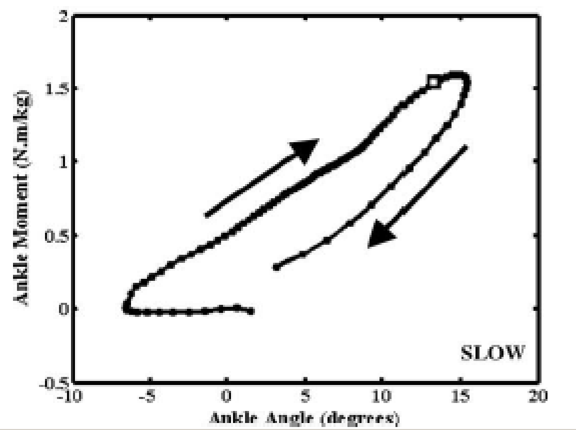


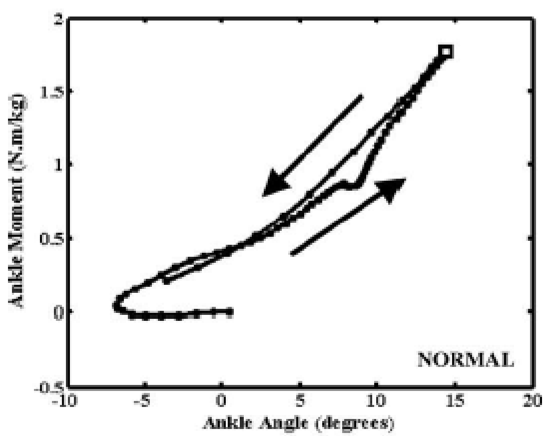
No information about joint stiffness or feedback control!

System needs to be perturbed to identify the feedback gains

Ankle pseudo-stiffness







At normal speed: k ≈ 450 Nm/rad = 8 Nm / deg

Prosthetic feet are designed based on this

Is system still stable when k is too low?

A.H. Hansen et al., J Biomech 2004

Exoskeleton design

2003: Berkeley lower extremity exoskeleton (BLEEX)

hydraulic, powered by internal combustion engine

Ekso Bionics

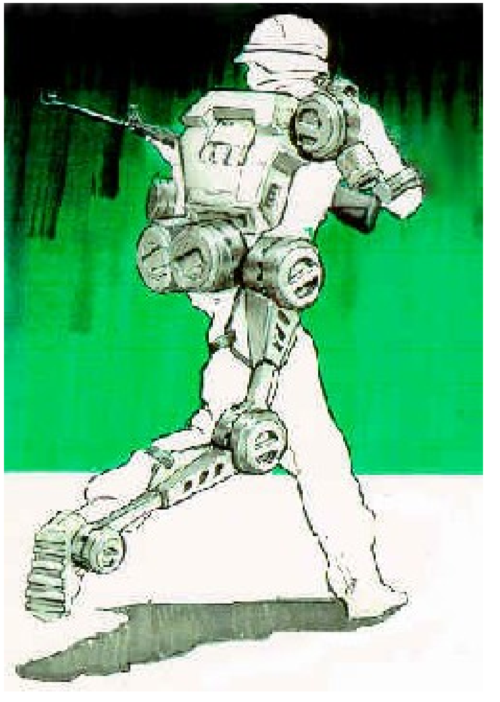
Rewalk

Parker Indego

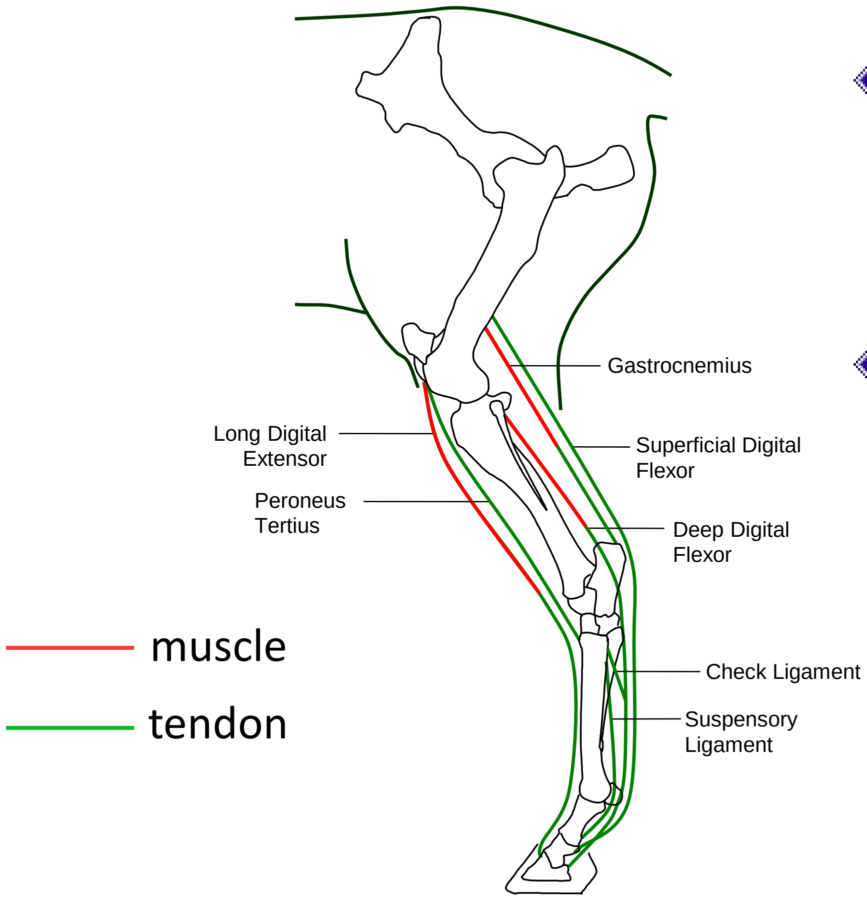
Military applications

- Running speed, backpack
- Estimated steady state power: 600 W
- Peak power 2 kW

Jansen et al., ORNL Technical Report TM-2000/256

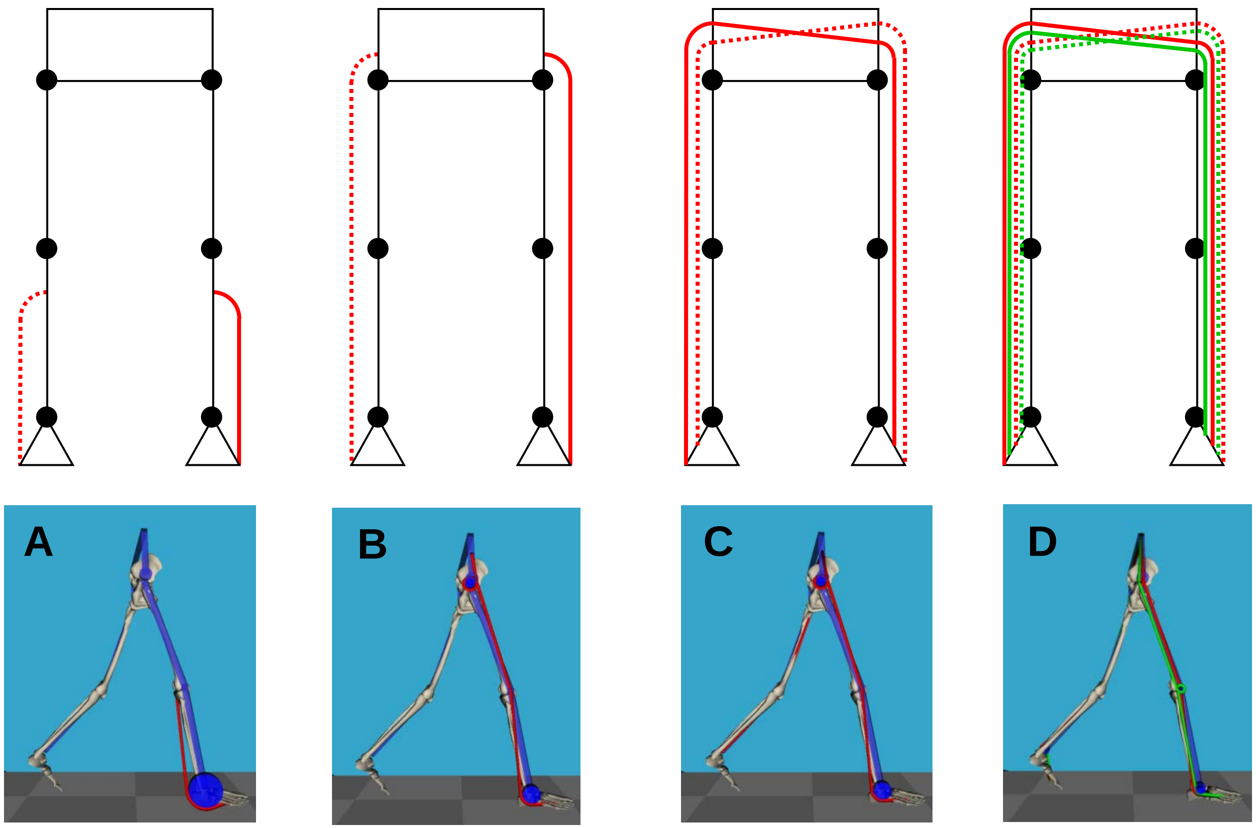


How does nature do it?



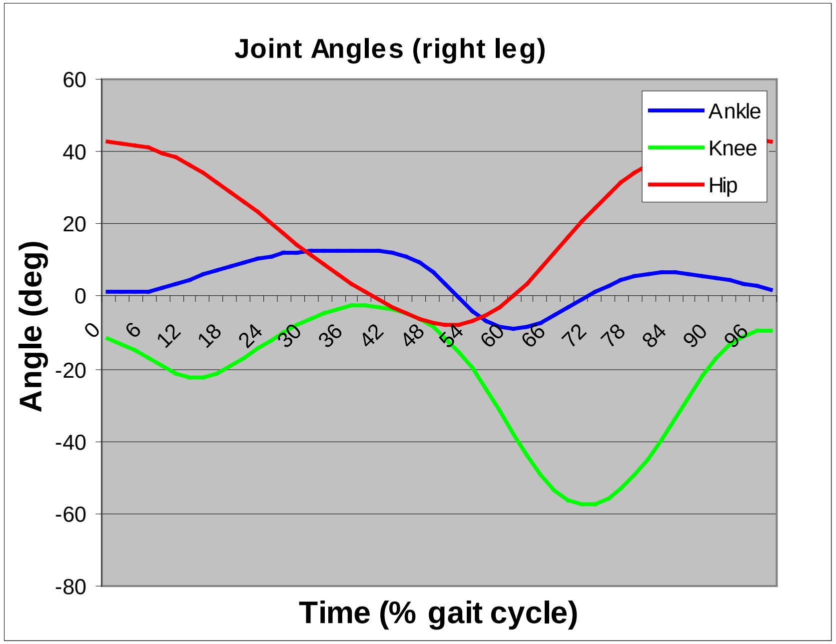
- Muscles span more than one joint!
  - Transfer of energy: when joint requires negative power, power can be transferred to a joint where positive power is needed.
- Long tendons & short muscle
  - Storage of energy: when joint requires negative power, elastic energy can be stored until a time when positive power is needed.
  - Force generation: passive elasticity can contribute to force production without energy cost.

Theoretical "exotendon" designs

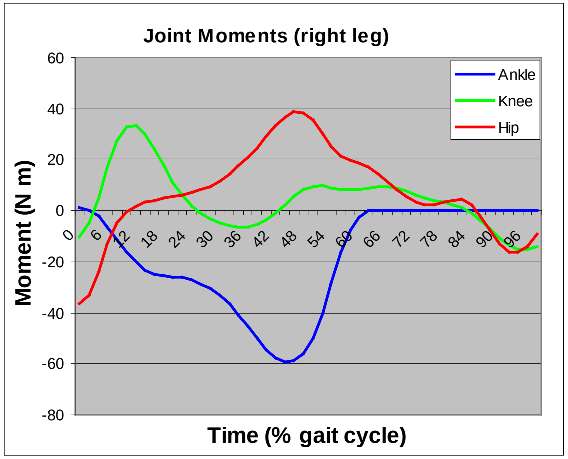


Pulley mechanisms were optimized for maximal contribution to the joint moments or joint powers required for walking

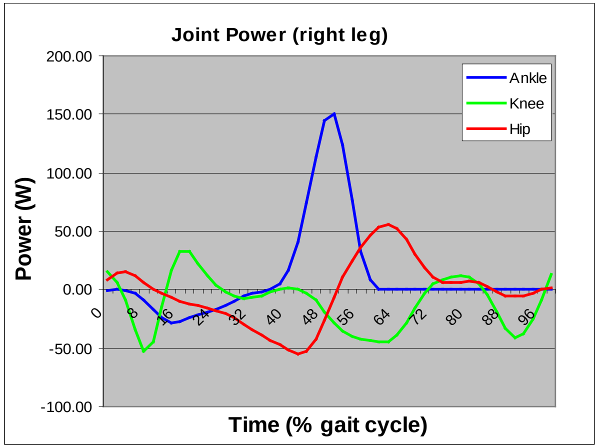
Kinematic/kinetic data



joint movements



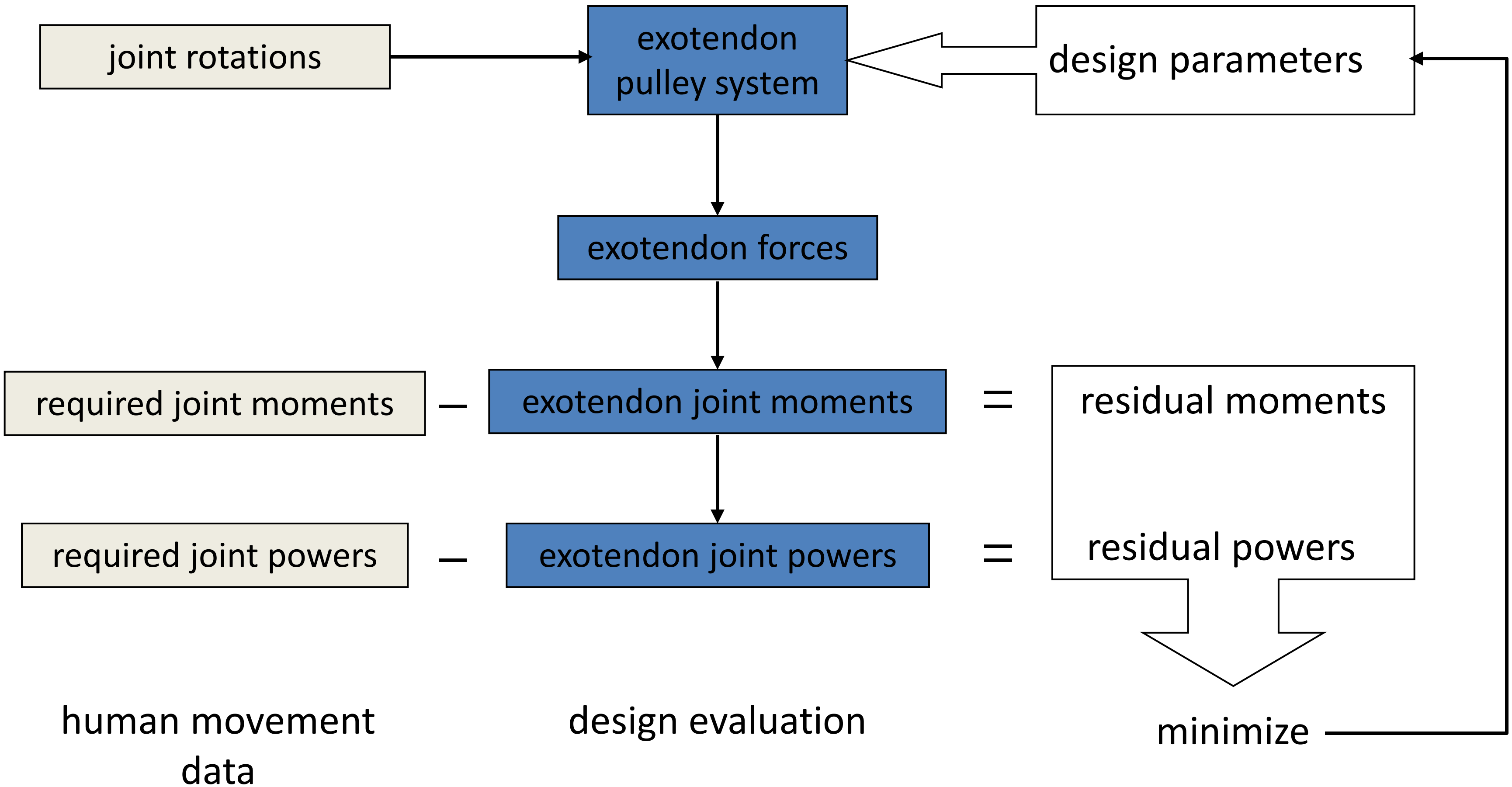
required joint torques



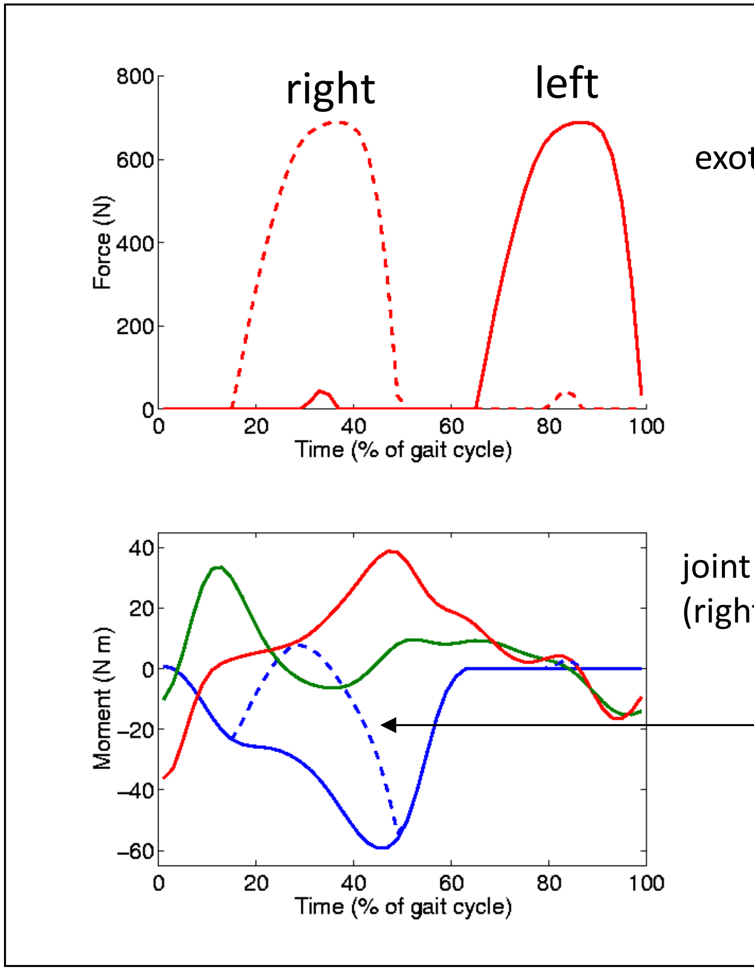
required joint powers

B. Stansfield et al., Gait & Posture 17: 81-87, 2003

Optimization of design



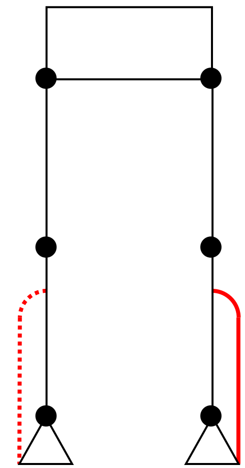
Results: single-joint design optimized for moment

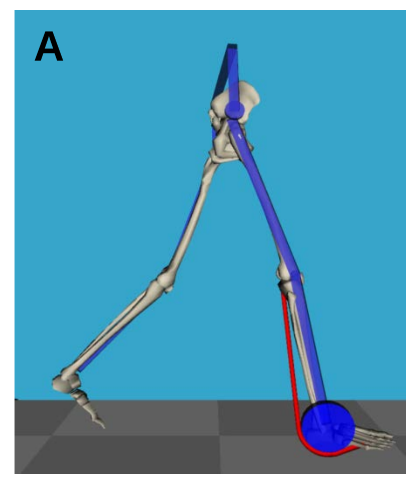


exotendon forces

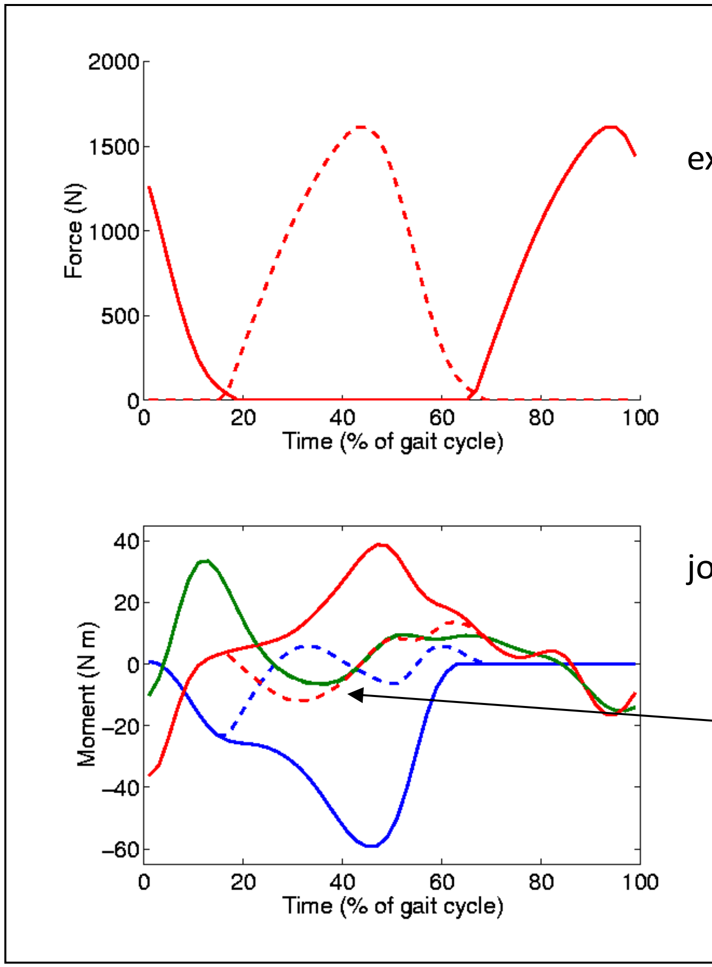
joint moments (right side)

residual ankle moment





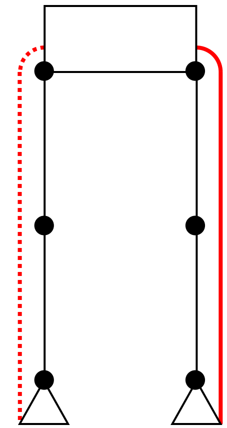
Results: three-joint design optimized for moment

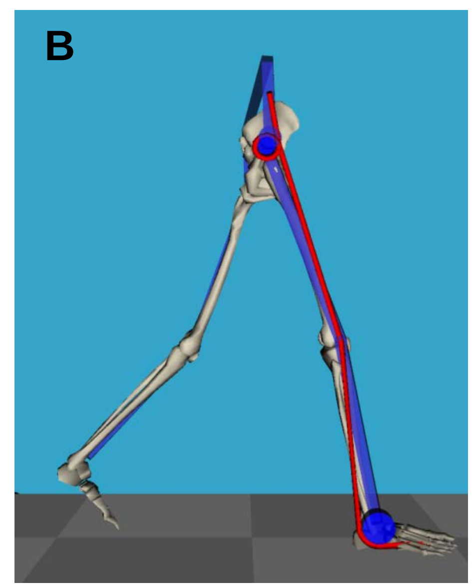


exotendon forces

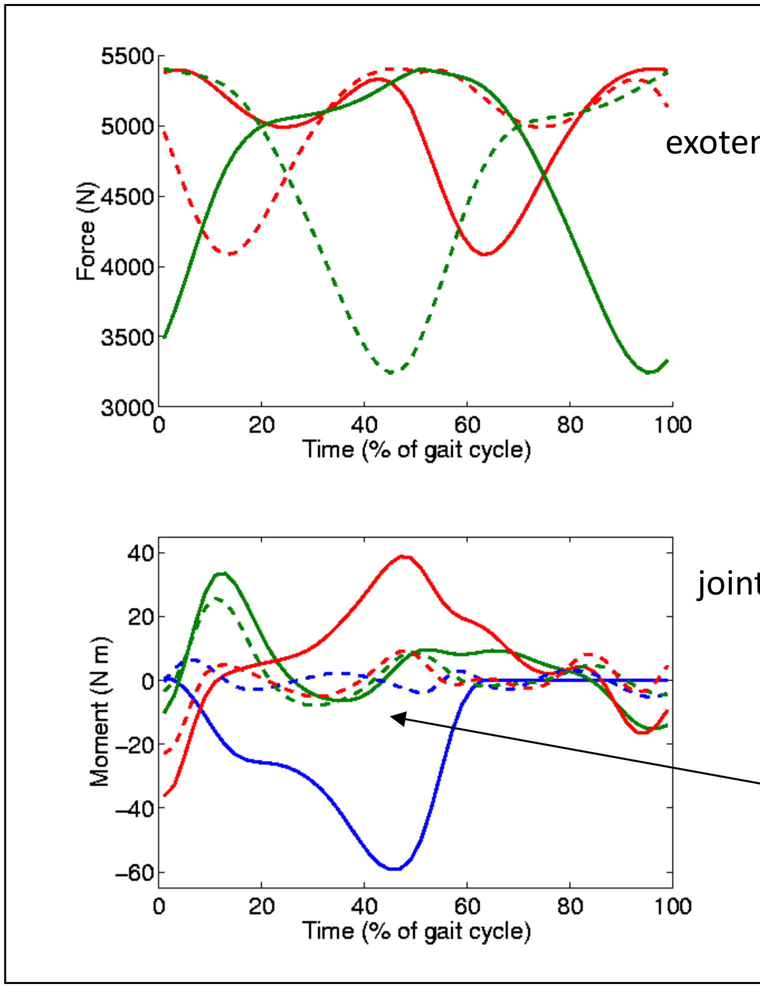
joint moments

residual moments





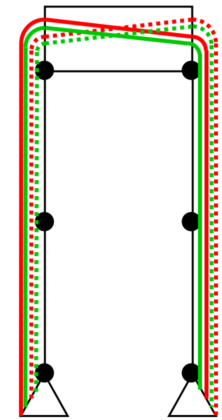
Results: double six-joint design optimized for moment

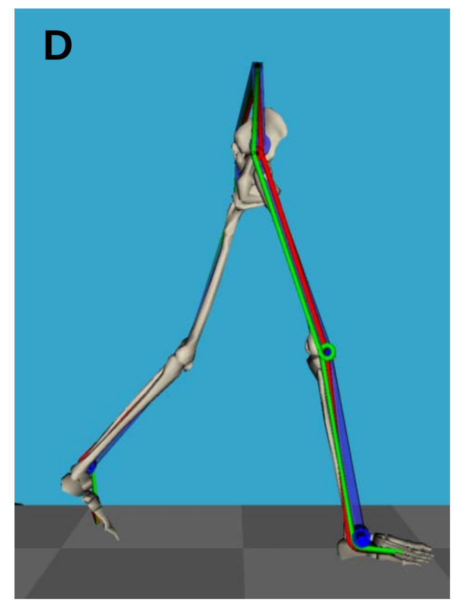


exotendon forces

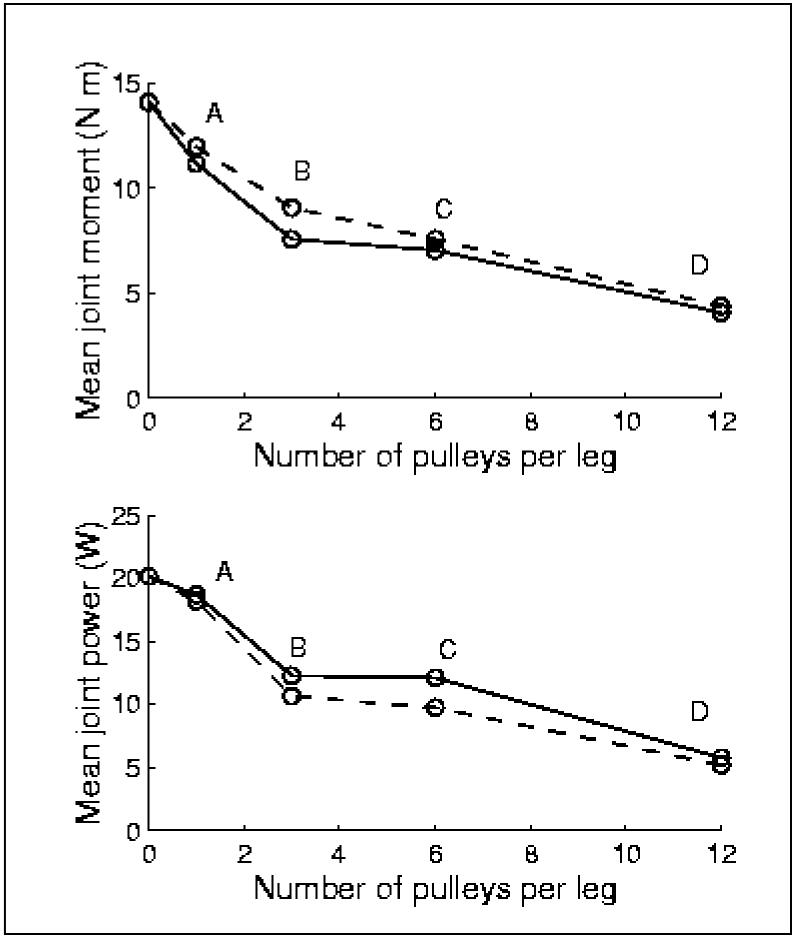
joint moments

residual moments

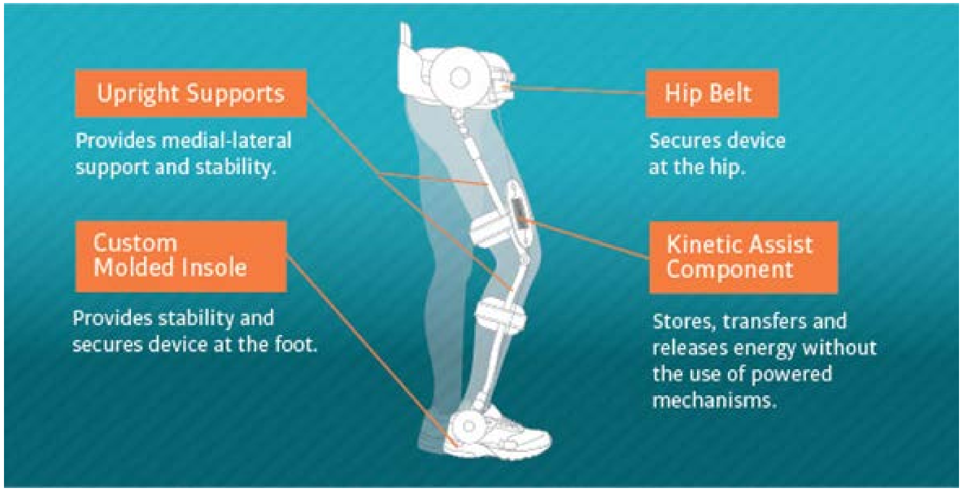




Results: summary of all design optimizations



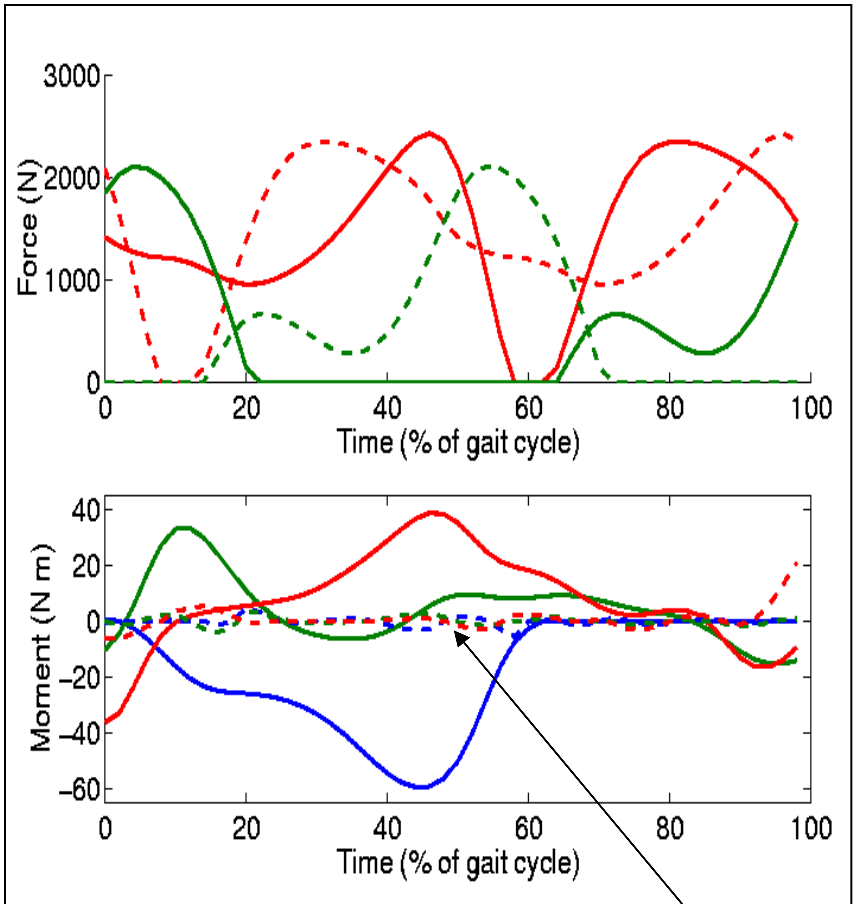
70% reduction in joint moment and joint power is possible with a passive elastic cable-pulley system



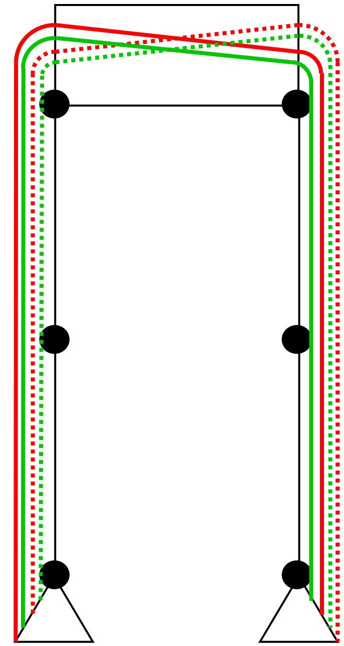
www.cadencebiomedical.com

van den Bogert, Biomed Eng Online, 2003

Results: spiral pulleys



residual moments



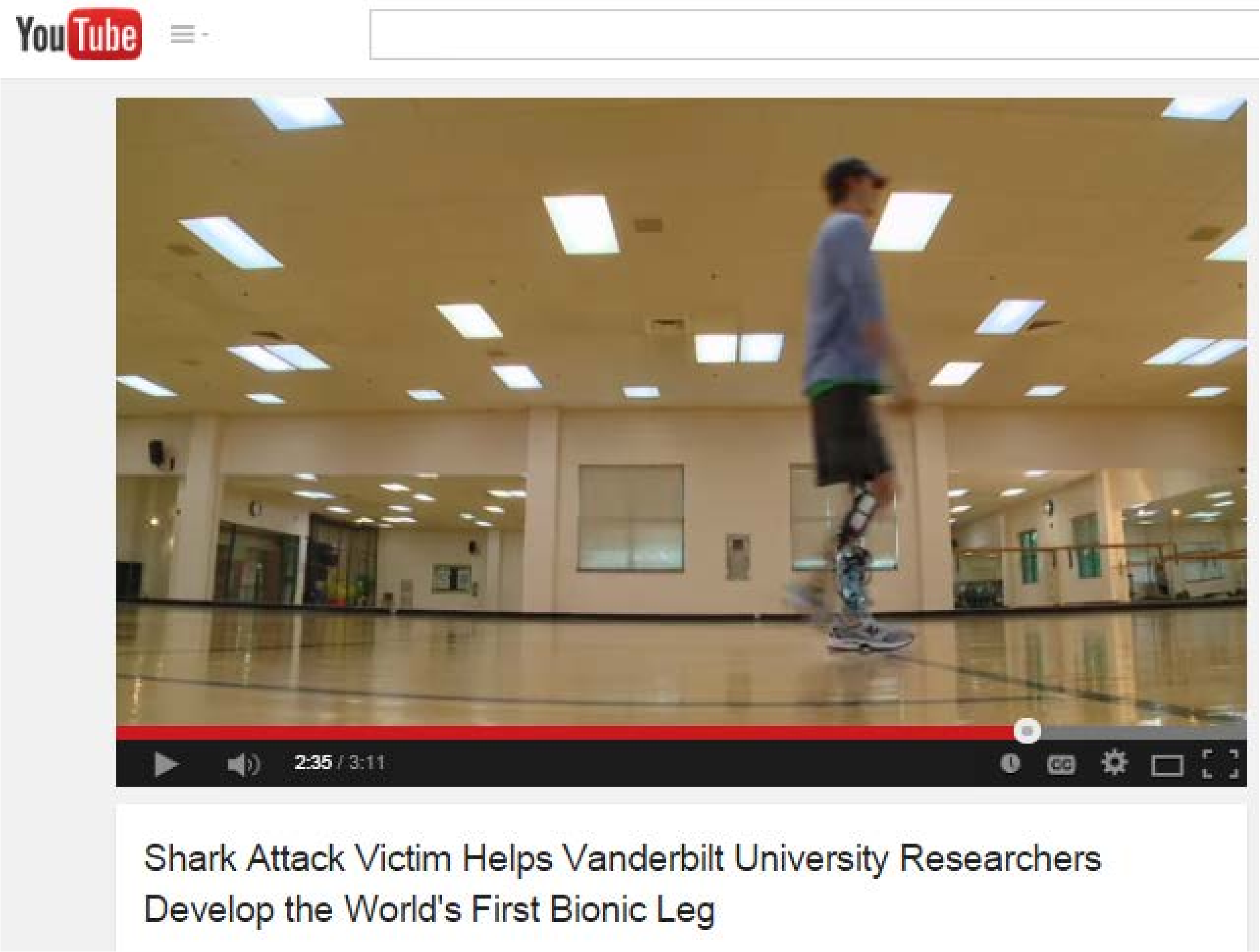
- 26 design parameters
- optimized with simulated annealing
- $50 \cdot 10^9$ designs evaluated
- mean residual moment is only **10.15%** of original moment

Inverse dynamics is not control!

- Remember, the elastic system does not replace all of the required moments
  - remainder can be used to provide control
- This would work for certain applications
  - military
  - patients who still have some muscular control (stroke, MS, incomplete spinal cord injury)
    - elastic forces assist and guide the movement
  - paralyzed patients, if there are additional motors that provide control
    - motors can be half the size

- Electric motors might replicate these multi-DOF elastic force fields, and do the energy storage/transfer

Video (Vanderbilt leg test subject)

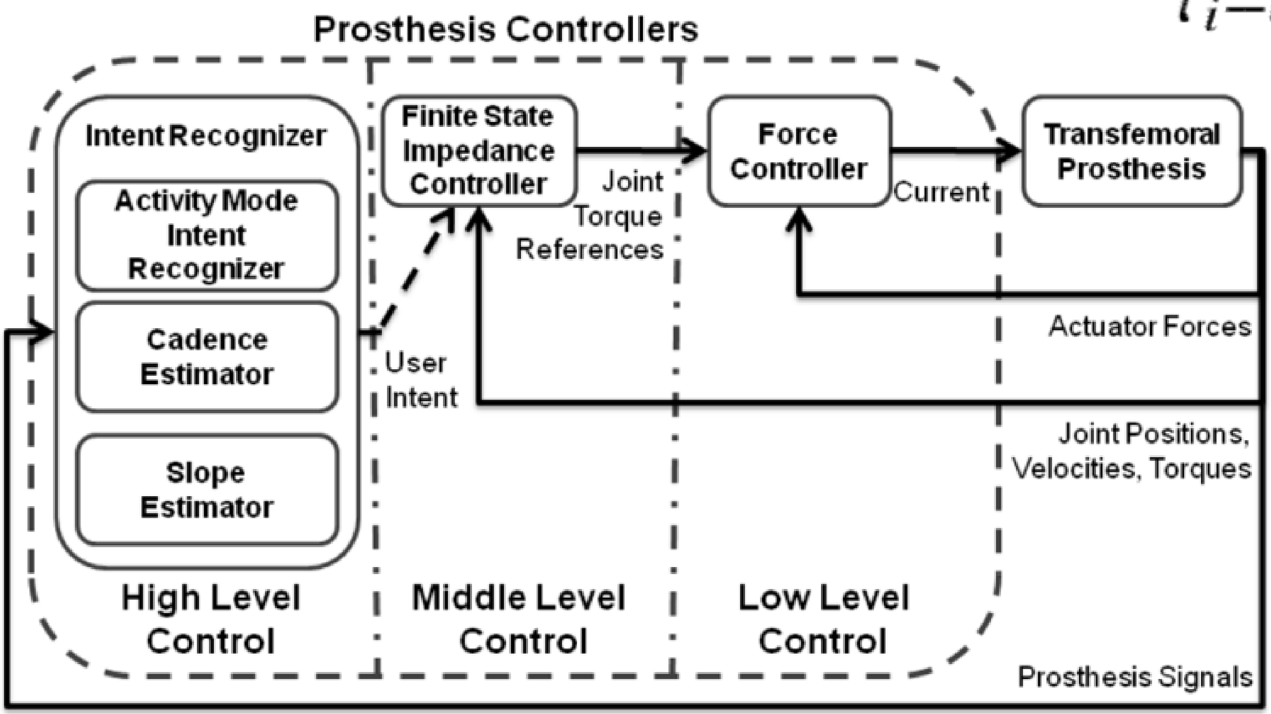


https://www.youtube.com/watch?v=tj1Y5eEU-j4

Evaluation in amputee

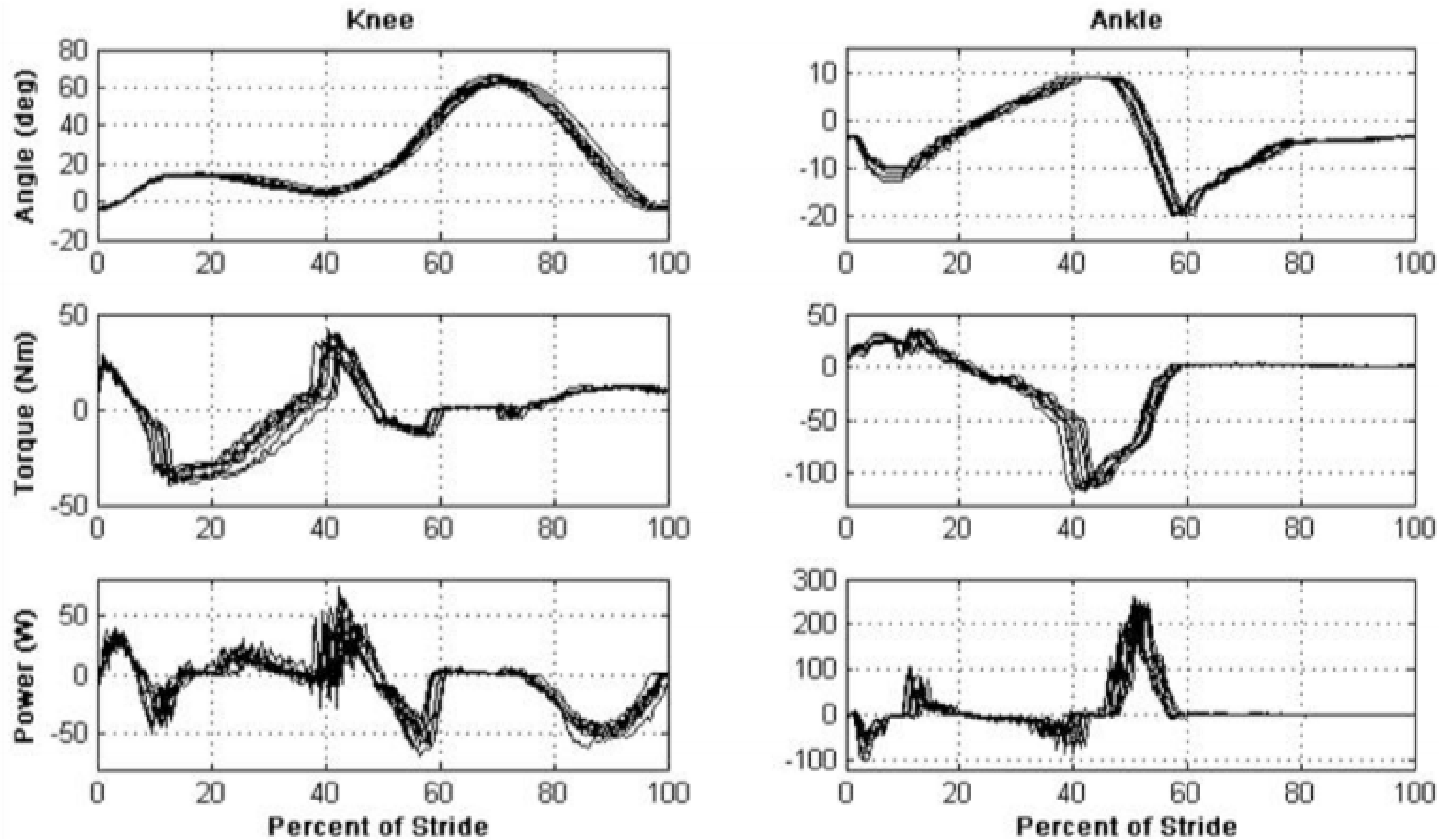
- Sup et al., Self-Contained Powered Knee and Ankle Prosthesis: Initial Evaluation on a Transfemoral Amputee. IEEE Int Conf Rehabil Robot. 2009 June 23; 2009: 638–644. doi:10.1109/ICORR.2009.5209625

$$\tau_i = k_i(\theta - \theta_{ki}) + b_i\,\dot{\theta}$$



k_{knee} = 4.5 Nm/deg

Gait analysis results



This is not a clinical trial. Why not?

Amputee gait studies

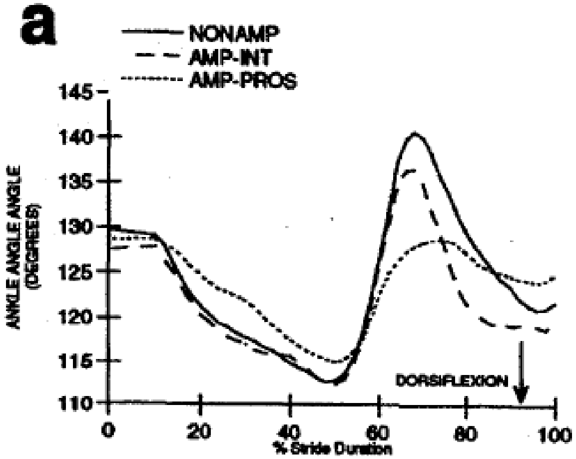
- No studies on the Vanderbilt leg yet (clinicaltrials.gov)
- Below knee
  - Sanderson & Martin, Gait & Posture 1997
    - flex-foot, compared to other leg and to able-bodied
- Above knee
  - Johansson et al., Am J Phys Med Rehabil 2005
    - Mauch, Rheo, C-leg compared to each other
  - Segal et al., J Rehab Res Devel 2006
    - Mauch, C-Leg compared to other leg and able-bodied

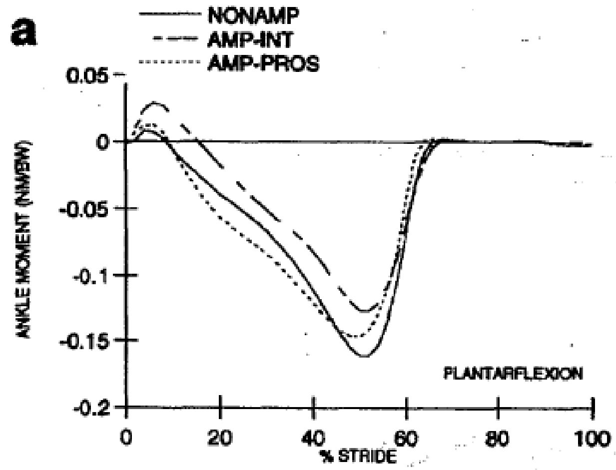
Sanderson & Martin 1997

www.ossur.com

- Methods
  - 6 able-bodied, 6 unilateral below knee amputees
  - amputees used the flex-foot
  - 1.2 m/s and 1.6 m/s, three trials at each speed
  - AMTI force plate sampled at 240 Hz
  - Single-camera (2D) video at 60 Hz
  - double 2nd order Butterworth filter (5 Hz for foot markers, 4 Hz knee, 3 Hz hip)
  - conventional 2D kinematics and inverse dynamics

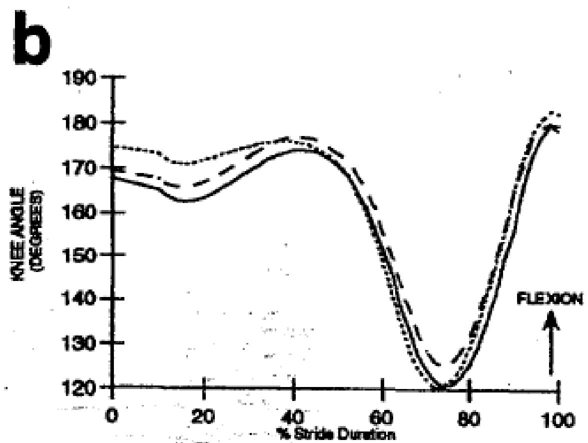
1.2 m/s

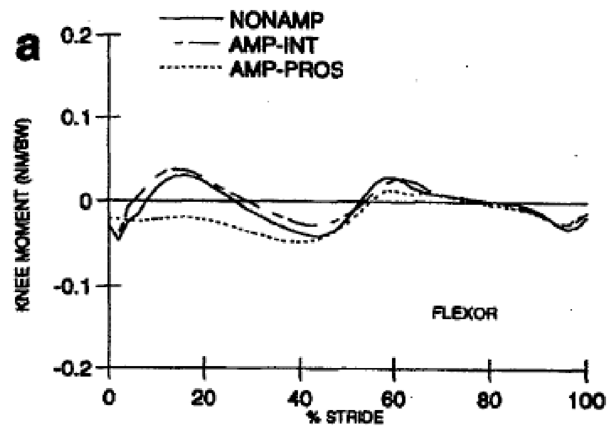




ankle

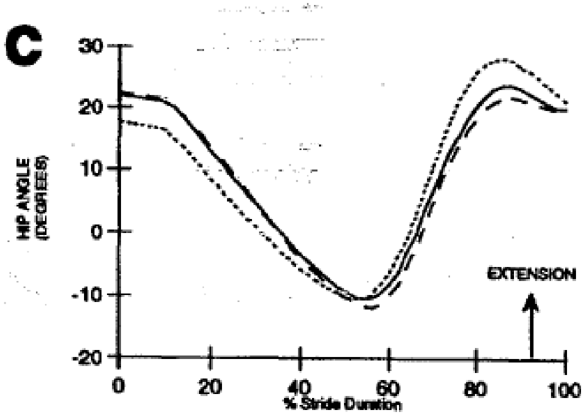
angle & moment

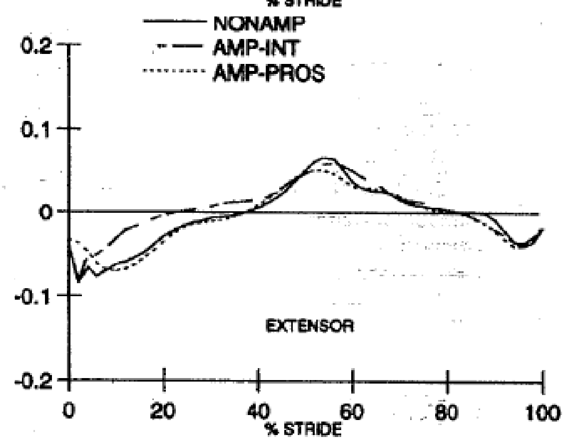




knee

angle & moment

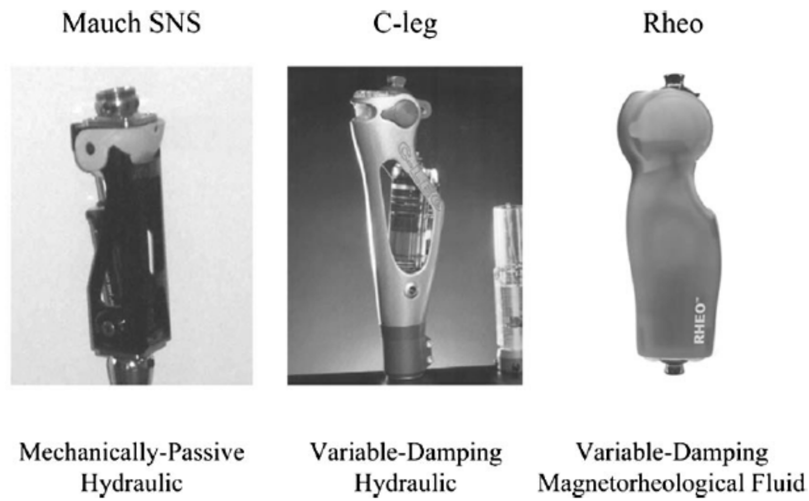




hip

angle & moment

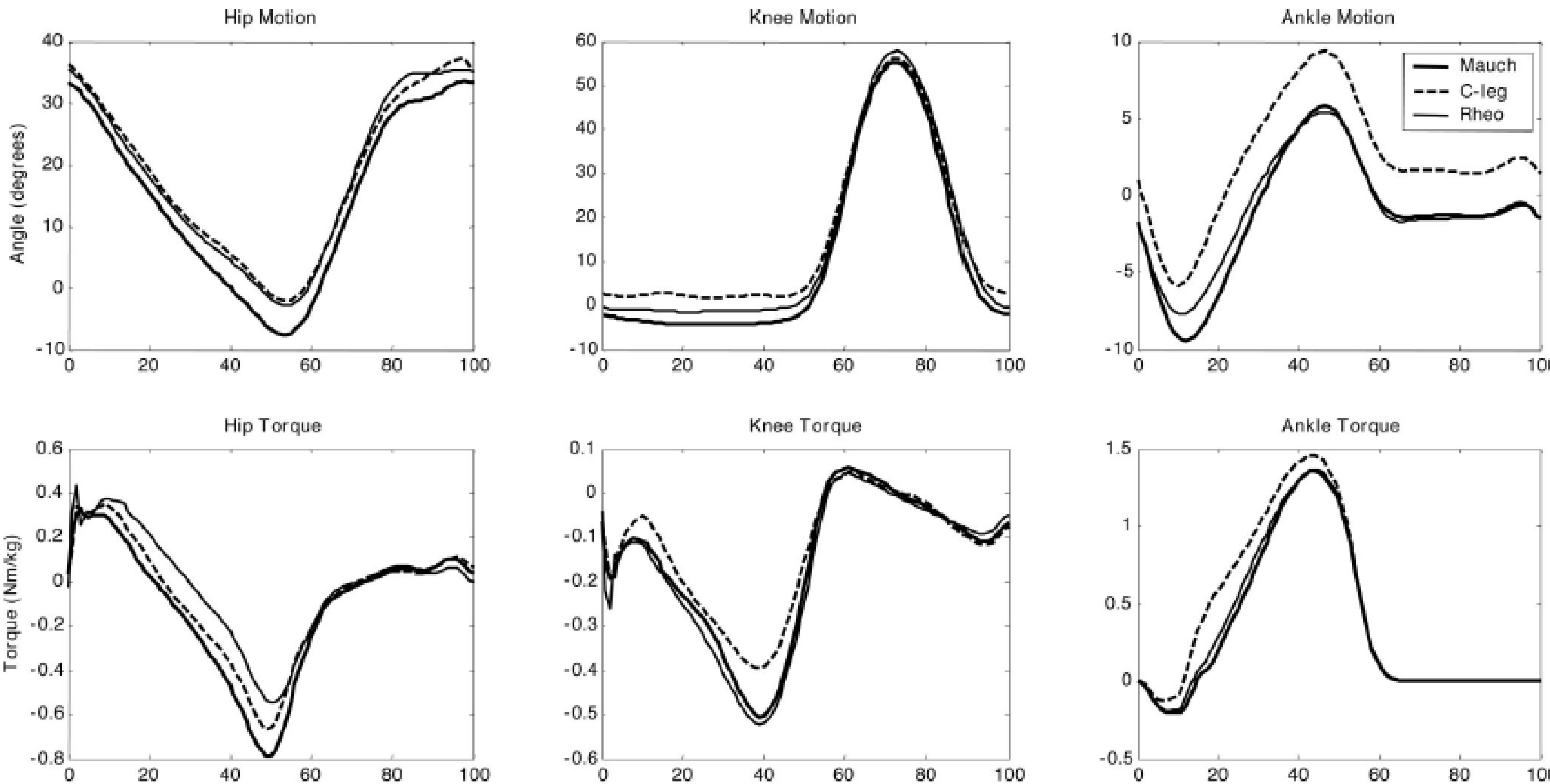
Johansson et al., 2005



- 8 unilateral AK amputees
- 4 C-leg users, 1 Mauch, 1 endolite, 1 Rheo, 1 4-bar
- all were tested with Mauch, C-leg, Rheo in random order
  - 10 hours of getting used to new prosthesis
  - Allurion foot used during all tests

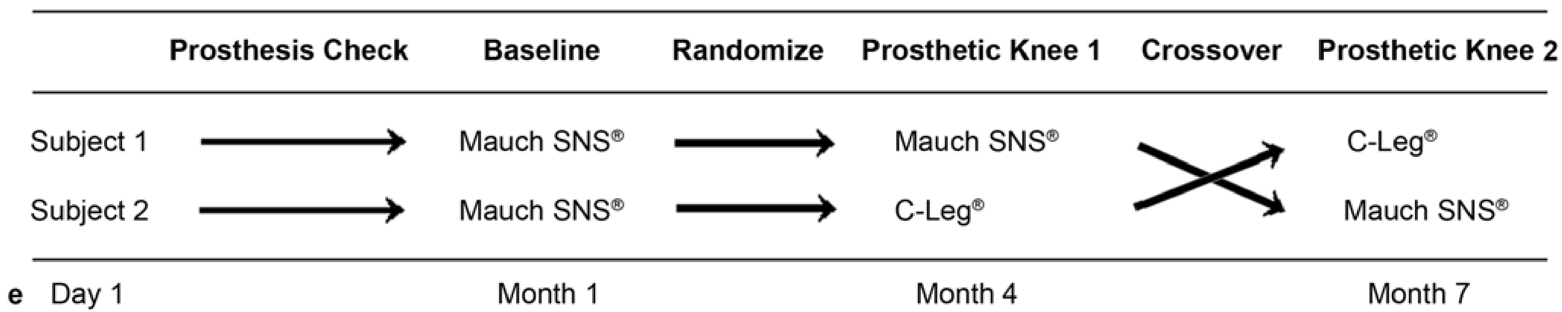
- Vicon 3D mocap, AMTI force plate
- Bodybuilder software for kinematics/kinetics (3D?)

Prosthetic side



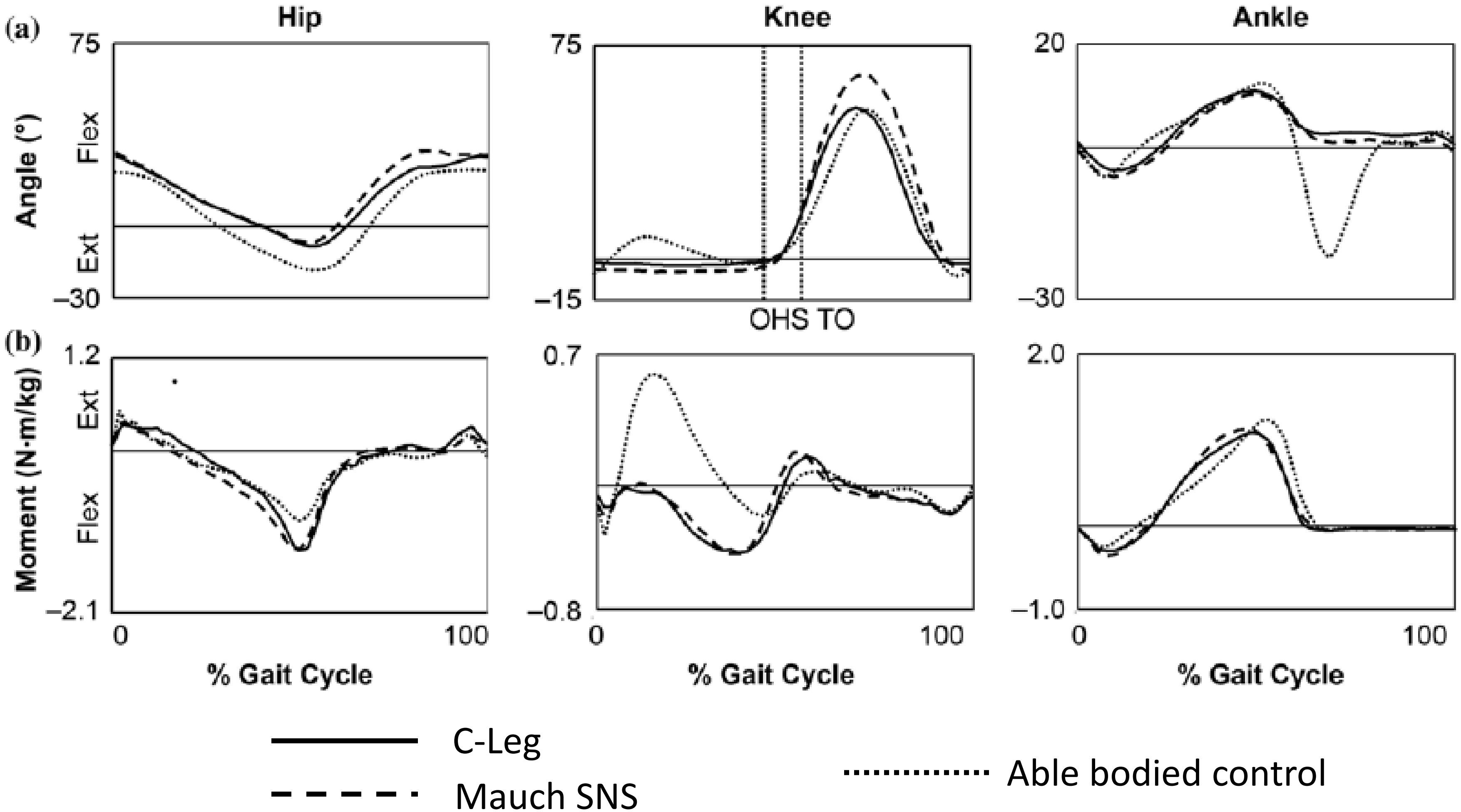
Segal et al., 2006

- 8 above-knee amputees, Mauch users
- 9 able-bodied controls
- amputees were tested with C-Leg and Mauch knee

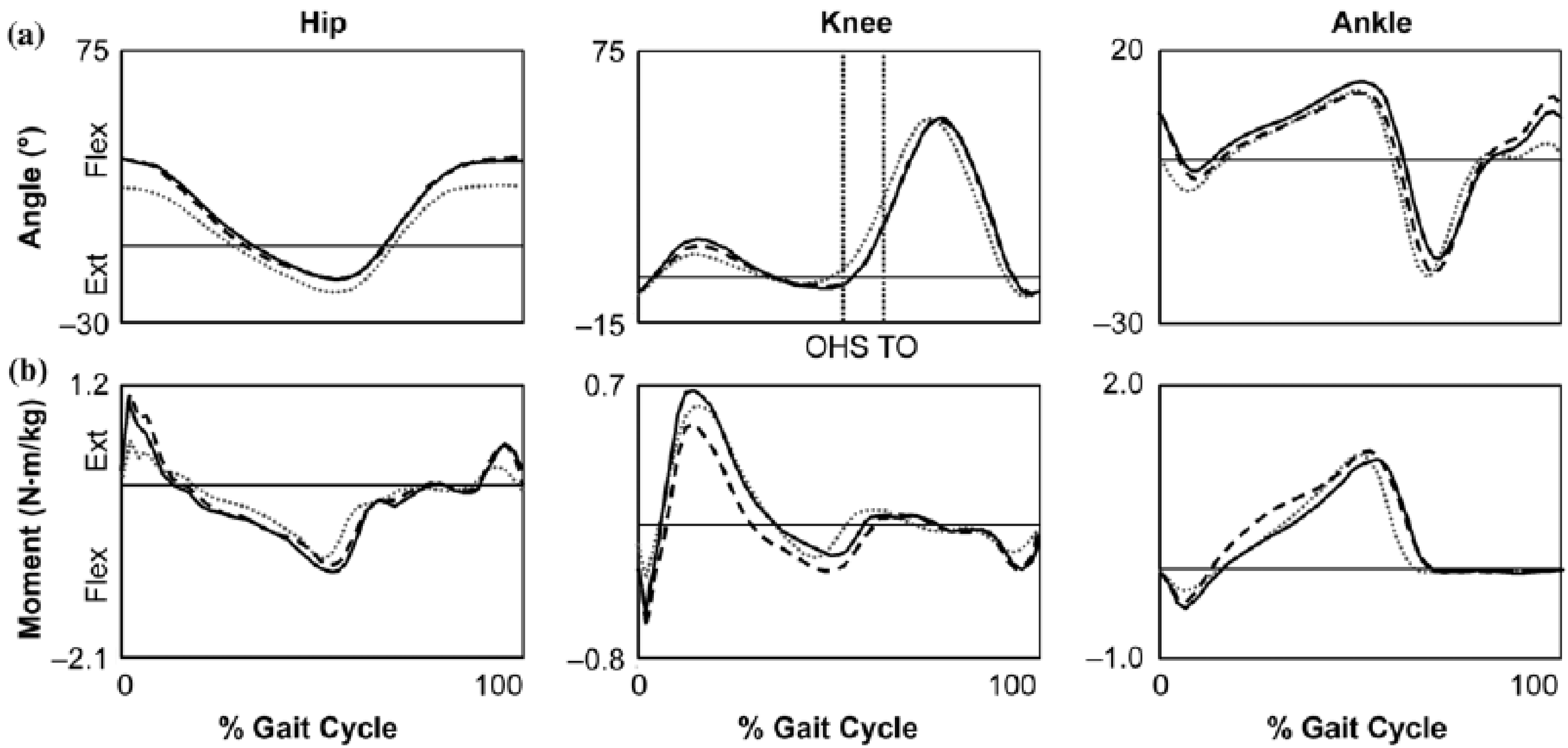


- 10 Vicon cameras, 120 Hz; Kistler force plate 600 Hz
- Vicon Plug-in Gait software for 3D kinematics/kinetics

Prosthetic side



Intact side



C-Leg

Mauch SNS

Able bodied control

What did I learn from the gait studies?

- All prosthetic knees show
  - almost no knee flexion in stance
  - no knee extension moment in stance
  - (except for the Vanderbilt test subject)
- Below-knee amputees also did this!
  - So maybe it's caused by the foot
- C-Leg and Rheo knee perform similar to Mauch knee
  - Is extra cost justified?
  - Normal gait tests may not reveal certain benefits (active stumble recovery)