Kinematics, Kinetics, Amputee Gait (part 1)

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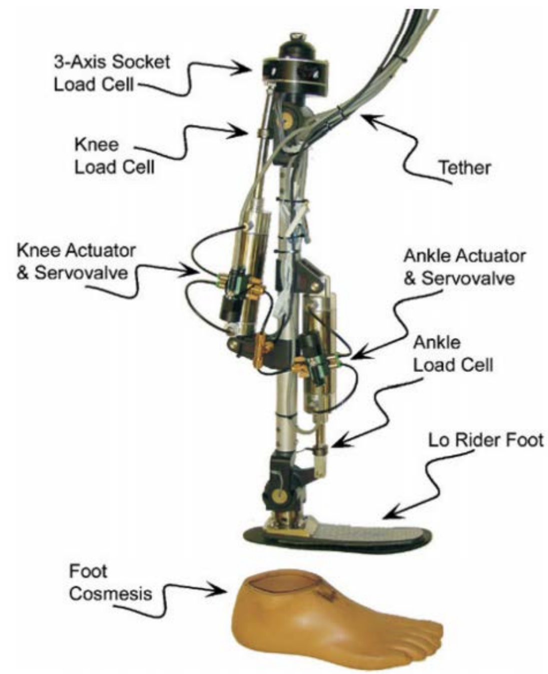
Today

- Calculating joint angles & joint torques
- Design & control of the Vanderbilt prosthesis
- Design of a passive exoskeleton

- Next week:
  - studies of amputee gait

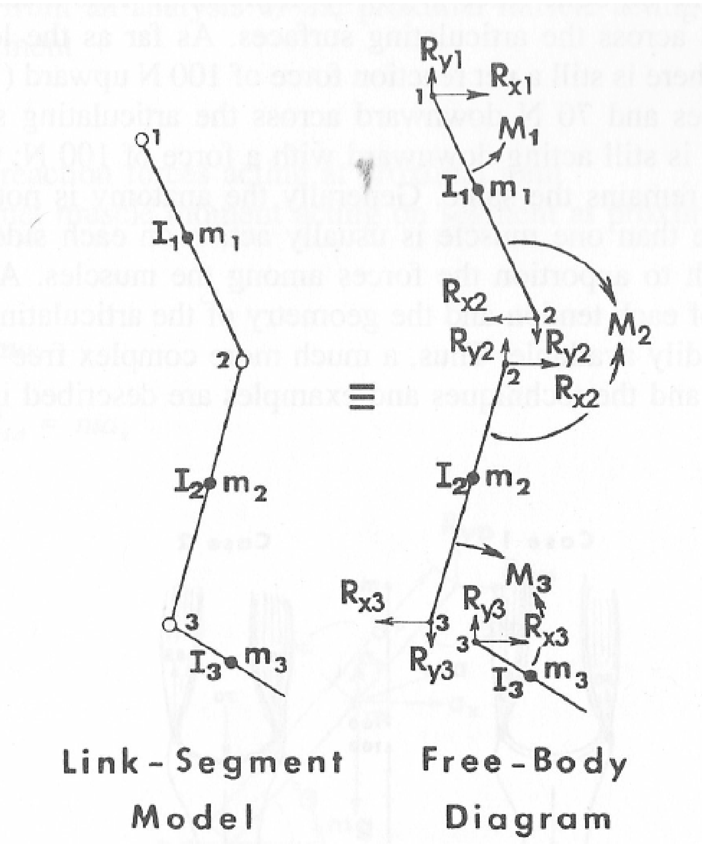


Definitions

- Kinematics: the study of motion
  - positions, velocities, accelerations
  - joint angles
- Kinetics: the study of forces related to motion
  - ground reaction forces
  - joint contact forces
  - joint moments (torques)
  - inverse dynamic analysis

Link-segment Model (Winter)

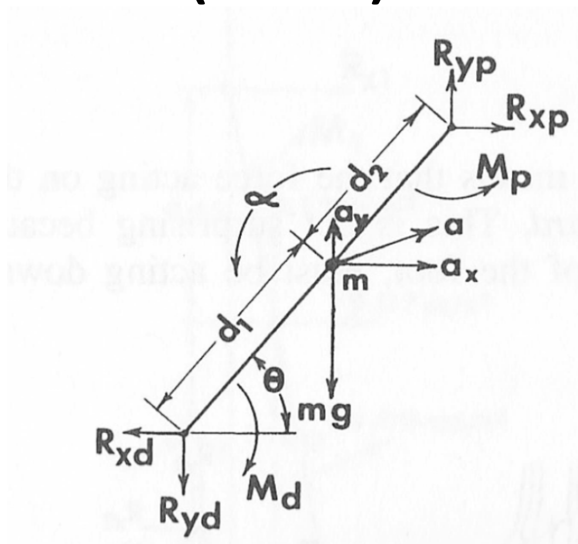
- Body is divided into links, connected by joints
- At each joint, there is a resultant force and a resultant moment between two links
  - This is an abstraction, imagining torque motors at joints



Winter Fig 4.3

Free body diagram (FBD) and link-segment equations

$$\sum F_x = ma_x$$
$$\sum F_y = ma_y$$
$$\sum M = I\alpha$$



include all forces and moments acting on the segment, and no others!

Winter Fig. 4.5

R_{xp}, R_{yp}: reaction force vector at p (proximal end)
P_{xp}, P_{yp}: position vector from center of mass to p
and the same variables for distal end (d)

$$R_{xp} + R_{xd} = ma_x$$
$$R_{yp} + R_{yd} - mg = ma_y$$
$$M_p + M_d + \left(P_{xp}R_{yp} - P_{yp}R_{xp}\right) + \left(P_{xd}R_{yd} - P_{yd}R_{xd}\right) = I\alpha$$

Mass properties

For each body segment we need to know:

- mass (kg)
- location of center of mass
- moment of inertia (kg m^2)

Data sources:

- Cadaver studies at Wright-Patterson Air Force Base
  - Dempster 1955, Clauser 1969, Chandler 1975
- Gamma ray absorption studies
  - Vladimir Zatsiorsky, Institute of Physical Culture, USSR, ~1980

Statistical models extracted from data

- Table in Winter's textbook, based on Dempster's data

Table 3.1 Anthropometric Data

		c1	c2		c3			
			Center of Mass/ Segment Length		Radius of Gyration/ Segment Length			
Segment	Definition	Segment Weight/ Total Body Weight	Proximal	Distal	C of G	Proximal	Distal	Density
Hand	Wrist axis/knuckle II middle finger	0.006 M	0.506	0.494 P	0.297	0.587	0.577 M	1.16
Forearm	Elbow axis/ulnar styloid	0.016 M	0.430	0.570 P	0.303	0.526	0.647 M	1.13
Upper arm	Glenohumeral axis/elbow axis	0.028 M	0.436	0.564 P	0.322	0.542	0.645 M	1.07
Forearm and hand	Elbow axis/ulnar styloid	0.022 M	0.682	0.318 P	0.468	0.827	0.565 P	1.14
Total arm	Glenohumeral joint/ulnar styloid	0.050 M	0.530	0.470 P	0.368	0.645	0.596 P	1.11
Foot	Lateral malleolus/head metatarsal II	0.0145 M	0.50	0.50 P	0.475	0.690	0.690 P	1.10
Leg	Femoral condyles/medial malleolus	0.0465 M	0.433	0.567 P	0.302	0.528	0.643 M	1.09
Thigh	Greater trochanter/femoral condyles	0.100 M	0.433	0.567 P	0.323	0.540	0.653 M	1.05
Foot and leg	Femoral condyles/medial malleolus	0.061 M	0.606	0.394 P	0.416	0.735	0.572 P	1.09
Total leg	Greater trochanter/medial malleolus	0.161 M	0.447	0.553 P	0.326	0.560	0.650 P	1.06

Estimating the mass properties

Assume we have measured:

- body mass (BM)
- global coordinates of proximal marker (Xp,Yp)
- global coordinates of distal marker (Xd, Yd)
- segment length L (possibly from markers)

Now we can estimate:

- Segment mass M = c1 * BM
- Center of mass Xcm = (1-c2)*Xp + c2*Xd
  Ycm = (1-c2)*Yp + c2*Yd
- Moment of inertia I = M*(c3*L)^2
  (with respect to center of mass)

Segment kinematics

- Compute in each frame (sample):
  - Center of mass position: Xcm, Ycm (2 slides ago)
  - Segment angle: θ = atan2(Yp-Yd, Xp-Xd)
- Low-pass filter (5-20 Hz)
- Take second derivative at sample i (time interval h)

$$\ddot{x}_i = \frac{\left(\frac{x_{i+1} - x_i}{h}\right) - \left(\frac{x_i - x_{i-1}}{h}\right)}{h} = \frac{x_{i+1} - 2x_i + x_{i-1}}{h^2}$$

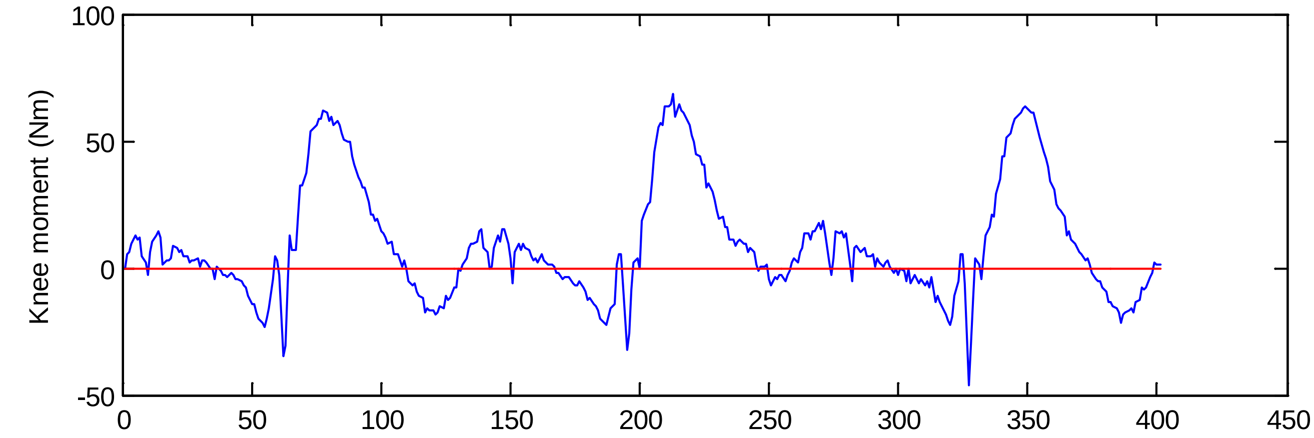
Recursive inverse dynamic analysis

- Start at segment at the end of the leg (foot)
- External force/moment known (force plate)
- Solve ankle force/moment
  - 3 equations, 3 unknowns
- Next segment: lower leg
- Ankle force/moment acting on lower leg = minus ankle force/moment acting on foot
- Solve knee force/moment
  - 3 equations, 3 unknowns
- …and so on

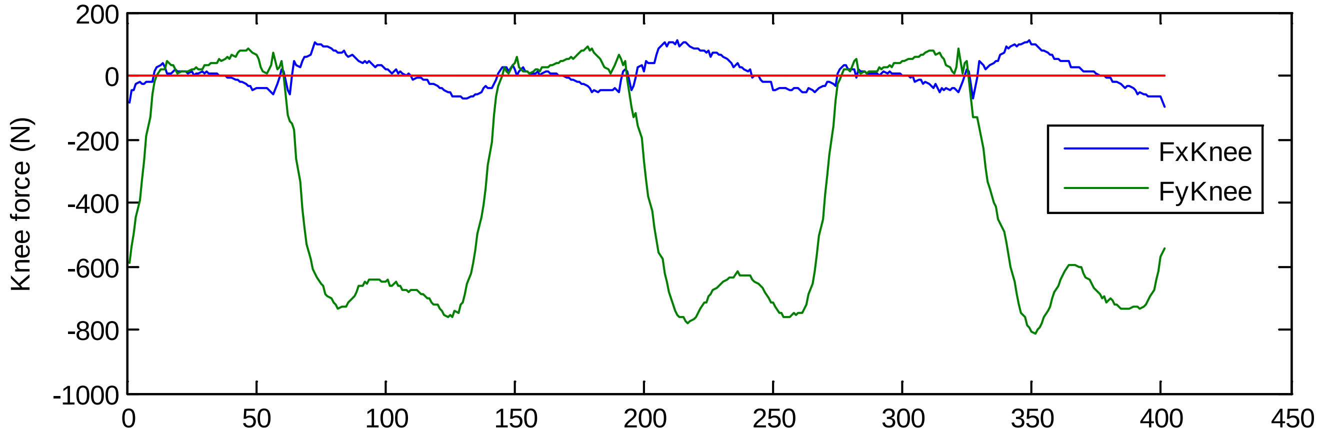
Data file and Matlab code

	A	AW	AX	BF	BG	BO	BP	BU	BV	FN	FO	FQ	FR	FV
1	Time	RGTRO.PosX	RGTRO.PosY	RLEK.PosX	RLEK.PosY	RLM.PosX	RLM.PosY	RMT5.PosX	RMT5.PosY	FP1.CopX	FP1.CopY	FP1.ForX	FP1.ForY	FP1.MomZ
1254	12.52	0.46971	0.95828	0.41164	0.50086	0.27265	0.09972	0.39869	0.04227	0.41506	0	16.82711	741.5053	307.7679
1255	12.53	0.46911	0.95677	0.40686	0.49982	0.26338	0.09996	0.3892	0.04224	0.40731	0	21.06817	745.1191	303.49737
1256	12.54	0.46855	0.95511	0.40235	0.49859	0.25426	0.10033	0.3797	0.04216	0.40082	0	26.37835	750.5475	300.83486
1257	12.55	0.4681	0.95339	0.39824	0.49731	0.2452	0.10073	0.37031	0.04215	0.39167	0	32.35532	755.8463	296.04016
1258	12.56	0.46779	0.95156	0.39456	0.4959	0.23649	0.10105	0.36094	0.04207	0.38571	0	39.92746	761.7033	293.79952
1259	12.57	0.46767	0.94966	0.39133	0.49449	0.2277	0.10151	0.35163	0.04207	0.37846	0	41.5595	769.7909	291.33688

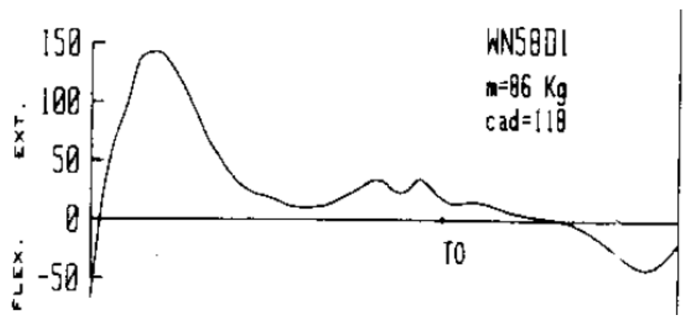
```
d = load('Subject005Trial08.txt');
h = 0.01;                  % time interval between frames
f = 1800:2200; % frames we will look at
HipX   = d(f,26+23);   % RGTRO.PosX
HipY   = d(f,26+24);   % RGTRO.PosY, etc.
KneeX  = d(f,2*26+6);
KneeY  = d(f,2*26+7);
AnkleX = d(f,2*26+15);
AnkleY = d(f,2*26+16);
ToeX   = d(f,2*26+21);
ToeY   = d(f,2*26+22);
```



Do the signs and magnitudes make sense?



How do these curves compare to literature?



D.A. Winter (1983) Energy generation and absorption... Clin Orthop Rel Res.

Vanderbilt prosthetic leg

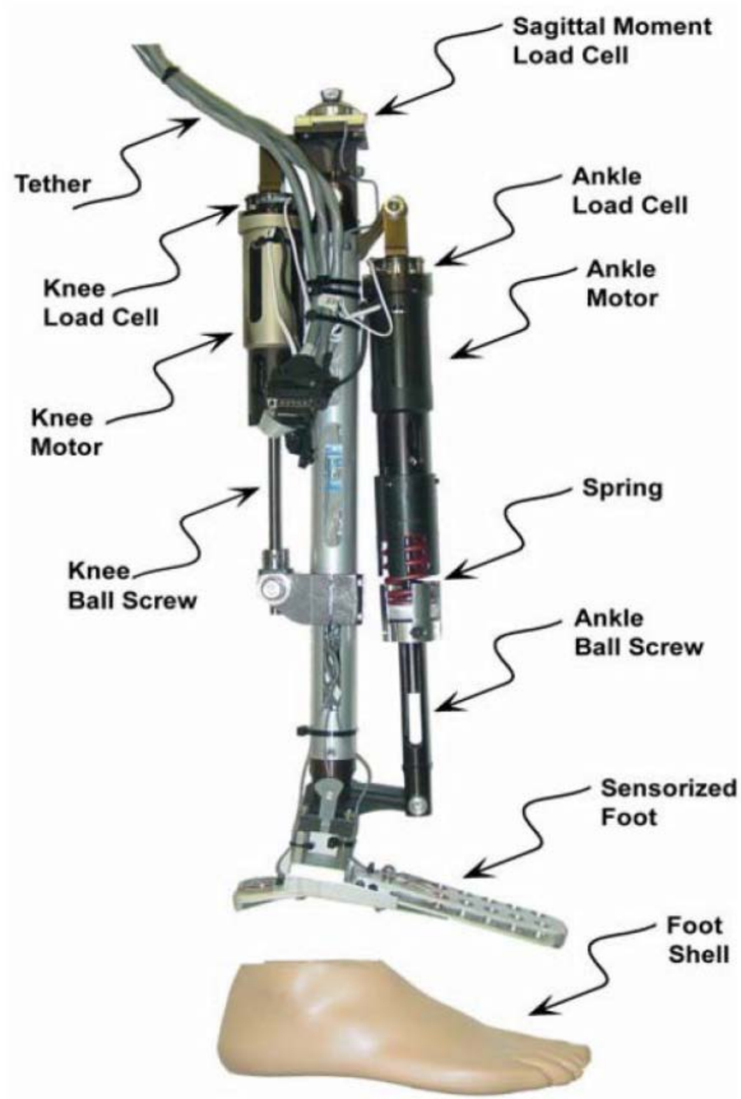
Knowing able-bodied joint rotations and joint torques, we can use motors to produce:

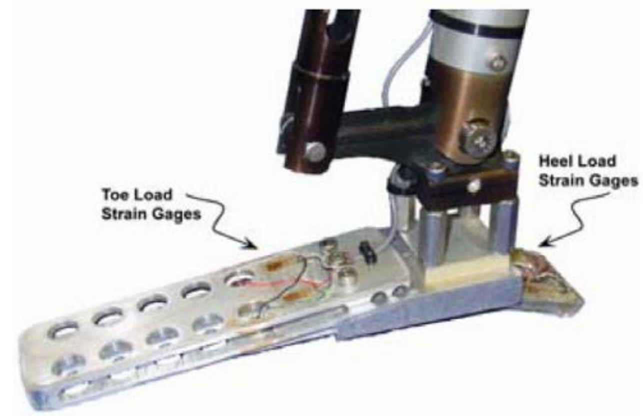
- joint angle as a function of time (not a good idea)
- joint torque as a function (not a good idea)
- a relationship between angle and torque (great idea!)

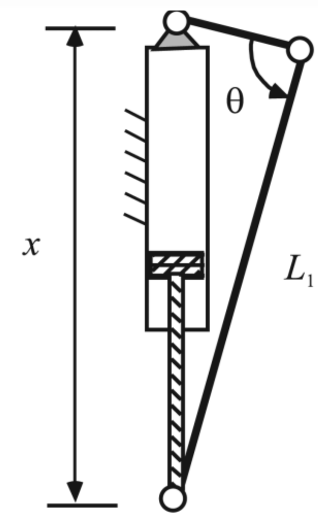
Sources:

- Sup FC, Bohara A, Goldfarb M (2008) Design and Control of a Powered Transfemoral Prosthesis. Int J Rob Res 27(2): 263–273. **(pneumatic)**
- Sup FC, Varol HA, Mitchell J, Withrow T, Godlfarb M (2008) Design and Control of an Active Electrical Knee and Ankle. Proc IEEE RAS EMBS Int Conf Biomed Robot Mechatron. pp. 523-528.

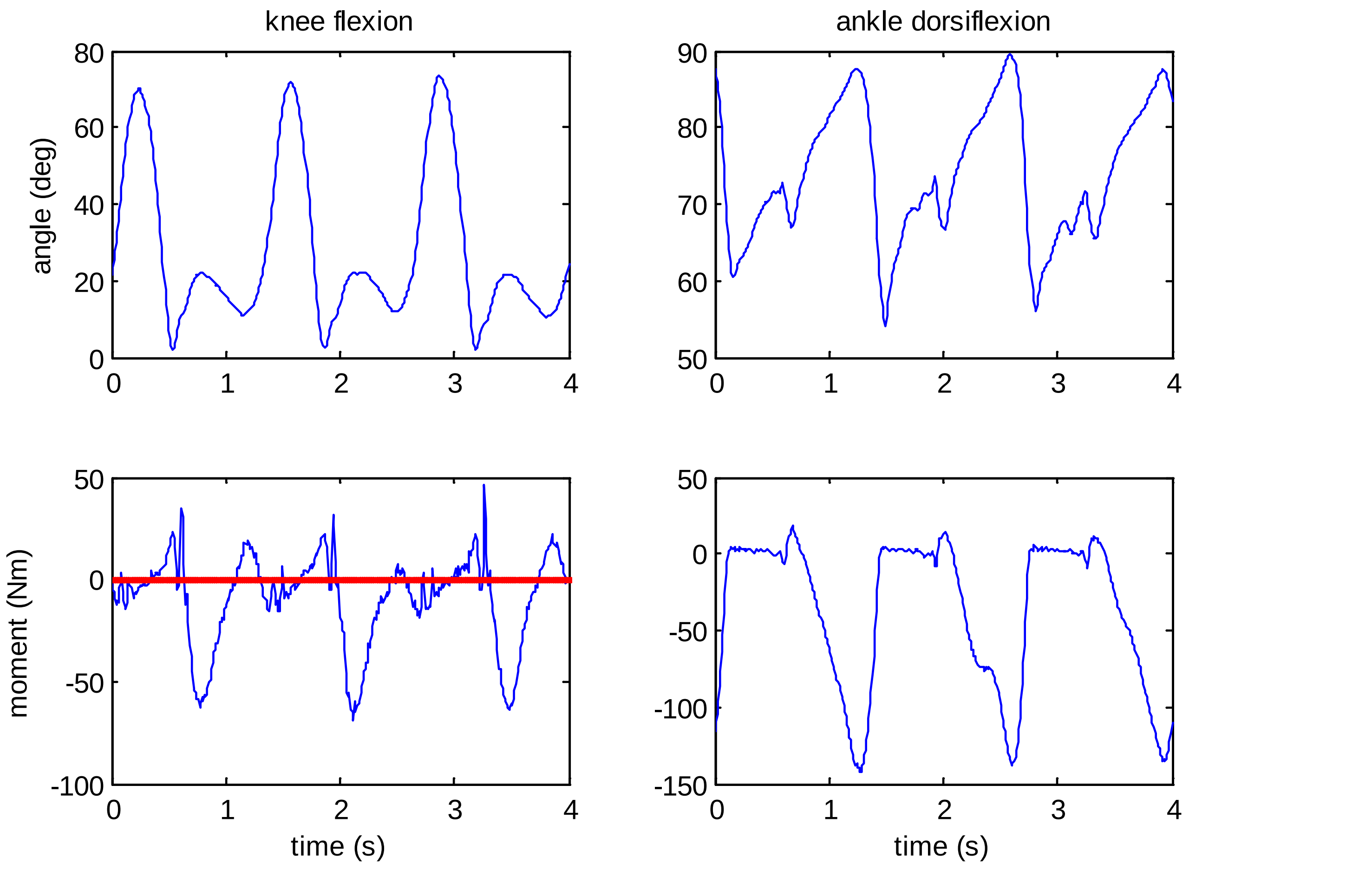
Hardware


Sagittal Moment
Load Cell
Tether
Ankle
Load Cell
Knee
Load Cell
Ankle
Motor
Knee
Motor
Spring
Knee
Ball Screw
Ankle
Ball Screw
Sensorized
Foot
Foot
Shell


Toe Load
Strain Gages
Heel Load
Strain Gages


θ
x
L_1

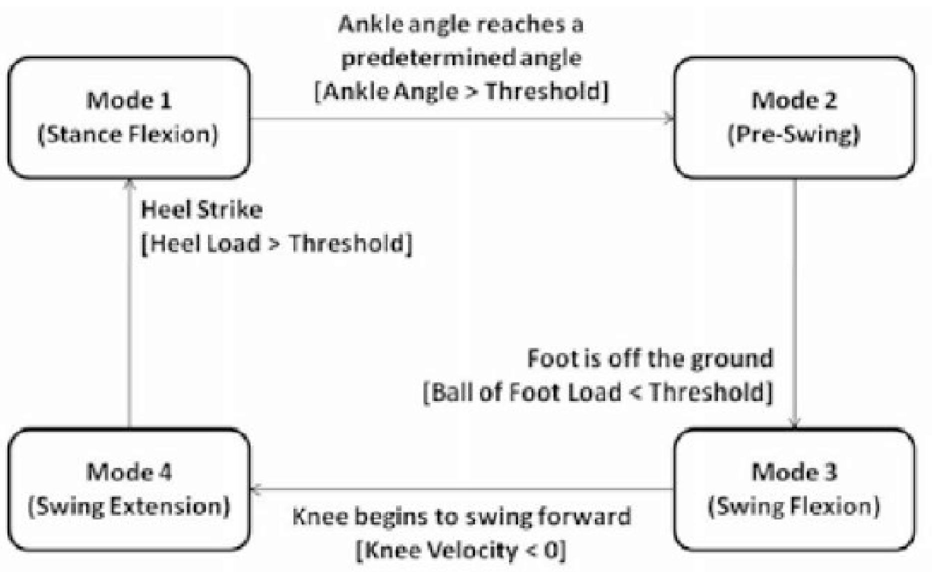
Control based on able-bodied gait

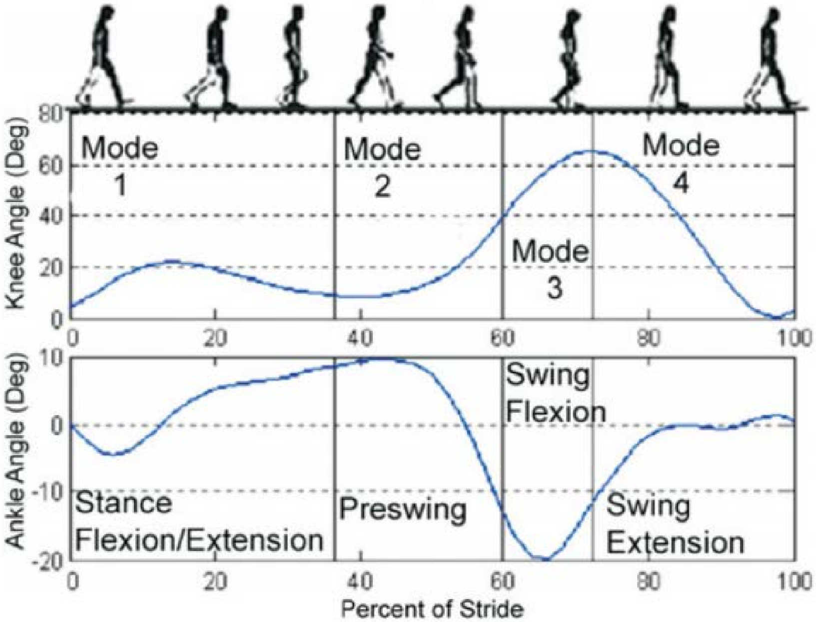


Relationship between joint motion and joint torque:
sometimes spring-like, sometimes damper-like

Four phases in the gait cycle

Finite state machine



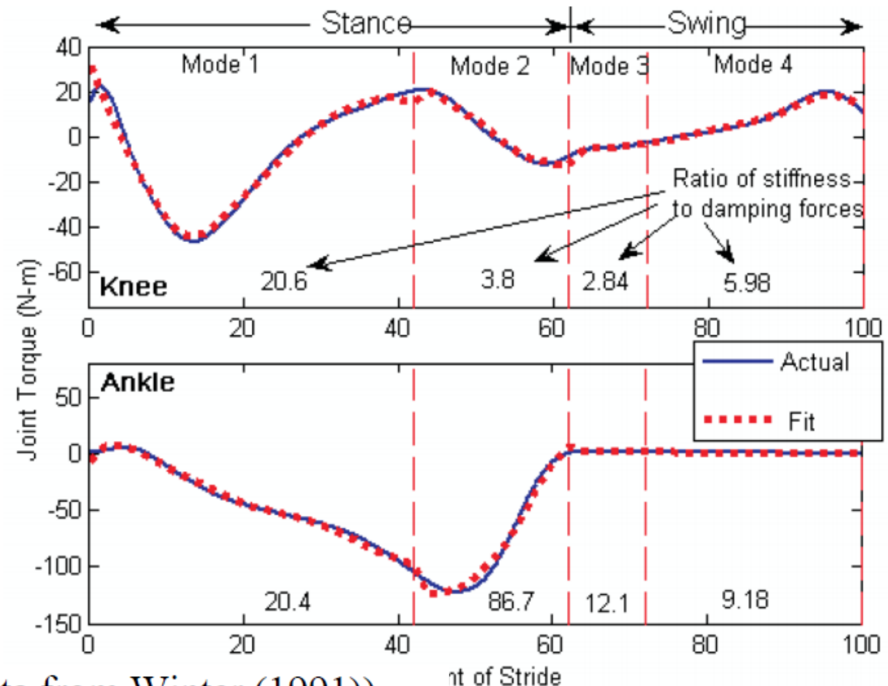


In each phase, fit a spring-damper model to Winter's angle-torque data

impedance control"

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

(Sup, IJRS 2008)



Impedance Parameters for Prototypical Gait (Gait Data from Winter (1991)).

	Knee impedance			
Mode	k_1 **(Nm/deg)**	k_2 **(Nm/deg^3)**	b **(N s m^{-1})**	θ_e **(deg)**
1	3.78	73×10^{-3}	25×10^{-3}	12
2	0	9×10^{-6}	30×10^{-3}	37
3	0	9×10^{-3}	16×10^{-3}	52
4	0.093	2×10^{-6}	13×10^{-3}	44

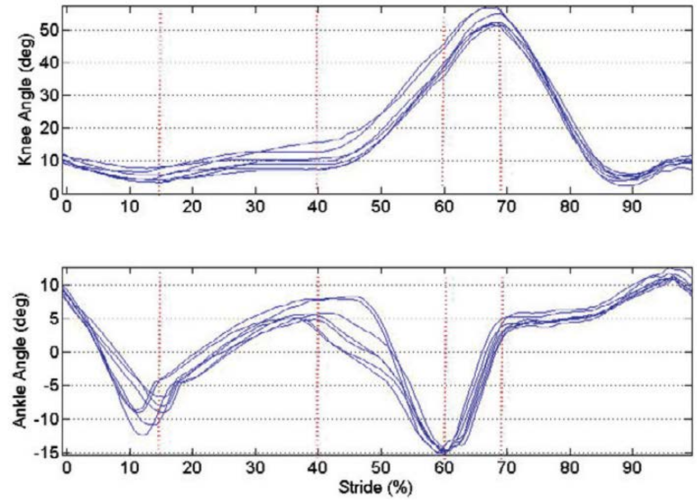
Experimental tuning

Impedance Parameters Derived by Experimental Tuning

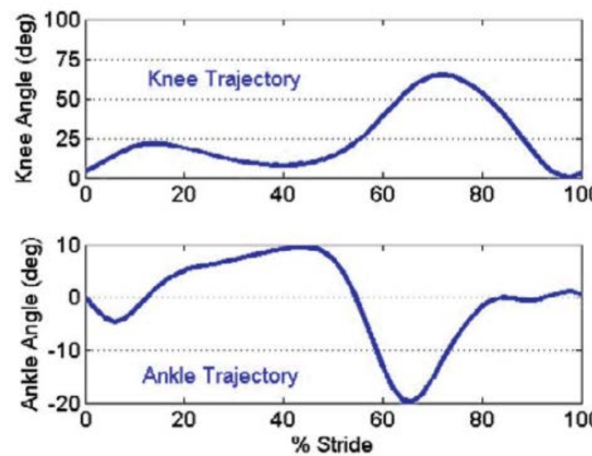
	Knee Impedance			
Mode	**k_1 (Nm/deg)**	**k_2 (Nm/deg^3)**	**b (N s m^{-1})**	**θ_e (deg)**
1	7.5	0	0	14
2	1.0	0.006	0	16
3	0	0	0.005	0
4	0.08	0	0.08	30

Able-bodied testing with "bent-knee adapter"

What it did:



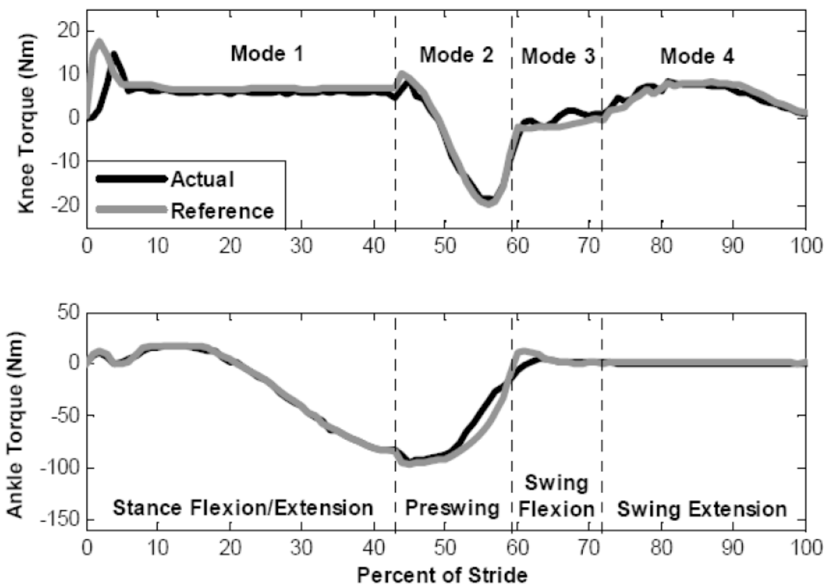
What it was designed to do:

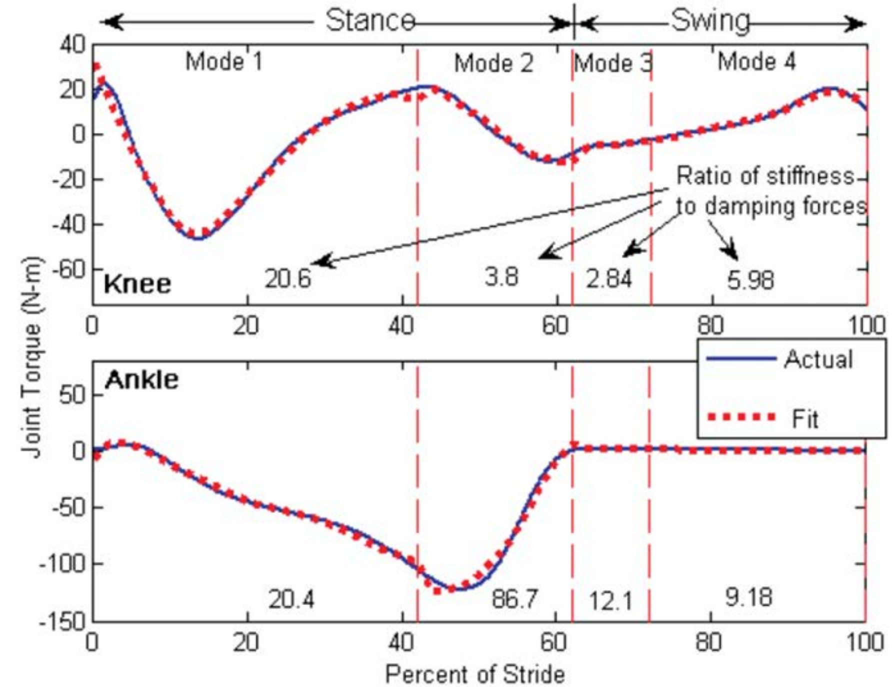


Joint torques

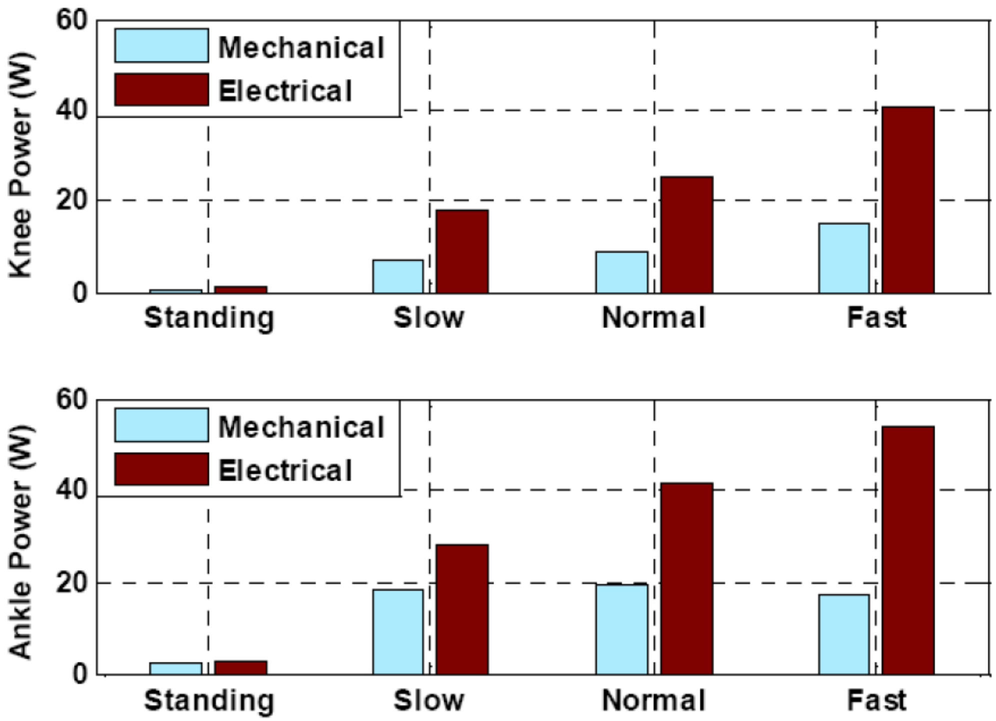
What it was designed to do:

What it did:





Power consumption and mechanical energy generated



60 Wh laptop battery
$140
weight 1 lb

60 W electric power
needed for normal walking

Discussion

- Impedance control is very appealing
- Initial tests for gait:
  - Knee function during stance was abnormal
  - The knee did not do much that a C-leg could not do
  - The ankle generated power (unlike a passive foot)
  - C-leg + BIOM could be equivalent
  - Integrated knee-ankle device has advantages
- There aren't any clinical studies yet (that I know of)