Robotics and Animatronics in Disney

Lecture 7: Human Modeling and Control

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Goals

- Introduce basic physiology and describe how to model it using robotics techniques
- Introduce attempts to understand human motor control principles
- Discussion on differences between simple vs. complex models for human motion analysis

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Human Body Modeling

[Nakamura et al. TRO 2005]
[Yamane et al. ICRA 2005]

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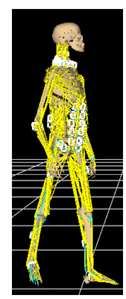
Musculoskeletal Model

Skeleton

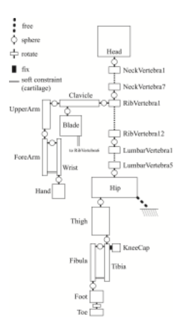
Musculo-tendon network



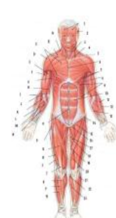
Skeleton

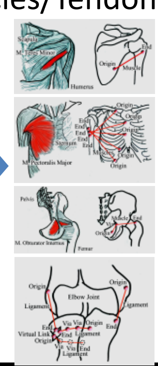
200 bones→53 rigid bodies (no fingers)

155 DOF by mechanical joints



Muscles/Tendons/Ligaments

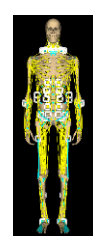




997 muscles

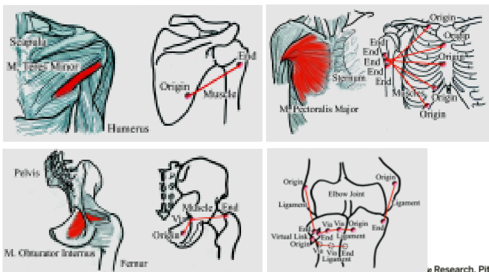
50 tendons

117 ligaments



Musculo-Tendon Network

Mass-less, zero-radius wires with via-points



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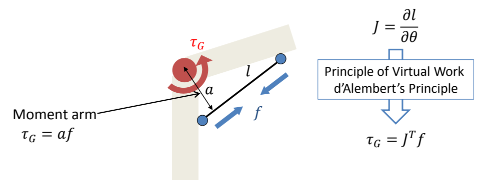
Dynamics

Wire tensions ⇔ Joint torques



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Dynamics Simulation

Wire tensions ⇒ Joint torques

1. Obtain equivalent joint torques $\tau_G = J^T f$
2. Forward dynamics computation for articulated rigid bodies

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Wire Tension Estimation

Wire tensions ⇐ Joint torques

1. Inverse dynamics computation for articulated rigid bodies
2. Solve $\tau_G = J^T f$
   Infinite number of solutions!

Unique solution
Physiological reality

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Wire Tension Estimation

Optimization [Challis 1997] [Rasmussen 2003]

Minimize

$\tau_G - J^T f$ + $f^* - f$

Subject to

$-f_{max} \le f \le 0$

via linear or quadratic programming

Reference muscle tension

$\begin{cases} 0 & \rightarrow \text{numerically optimal tensions} \\ \text{from EMG data} & \rightarrow \text{physiologically realistic tensions} \end{cases}$

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Linear Programming

[Nakamura et al. 2005] [Yamane et al. 2005]

- Consider EMG data for physiological reality
- Linear programming formulation

minimize

$$Z = a_\tau^T \delta_\tau + a_f^T \delta_f \quad (a_\tau, a_f > 0)$$

subject to

$$-\delta_\tau \le \tau'_G - J^T f \le \delta_\tau$$
$$0 \le \delta_\tau$$

Error of the mapping equation

$$-\delta_f \le f - f^* \le \delta_f$$
$$0 \le \delta_f$$

Error from a reference tension

$\begin{cases} f^* = 0 \rightarrow \text{minimizes total force} \\ \text{Compute from EMG data} \end{cases}$

$$-f_{max} \le f \le 0$$

Muscles can only pull

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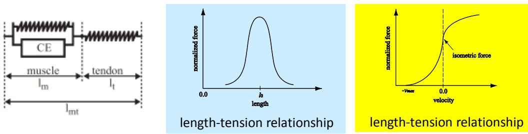
Physiological Muscle Model

Muscle model [Hill 1938]



Numerical model [Stroeve 1999]

$$F_l(l) = \exp\left(-\left(\frac{l-l_0}{l_{sh}}\right)^2\right)$$

$$F_v(\dot{l}) = \begin{cases} 0 & (\dot{l} \le -v_{max}) \\ V_{sh}(v_{max}+\dot{l})/V_{sh}v_{max}-\dot{l} & (-v_{max} \le \dot{l} \le 0) \\ V_{sh}V_{shl}v_{max}+V_{ml}\dot{l}/V_{sh}V_{shl}v_{max}+\dot{l} & (0 \le \dot{l}) \end{cases}$$

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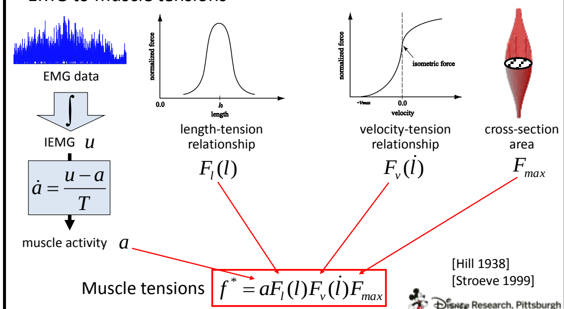
Physiological Muscle Model

EMG to muscle tensions



[Hill 1938]
[Stroeve 1999]

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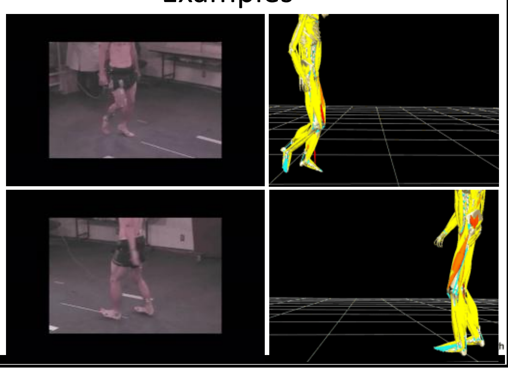
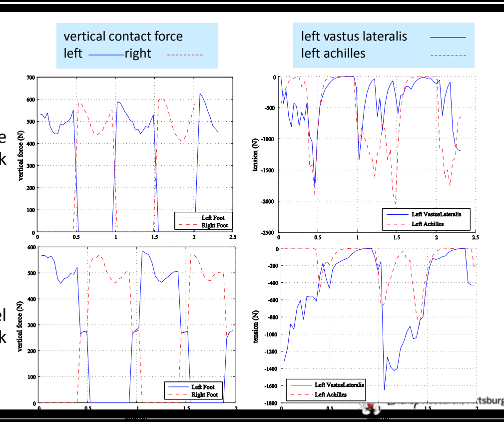
Examples

toe walk

heel walk





Realtime Interface

[Murai et al. EMBC 2009]

Neuromuscular Control

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[Murai, Yamane, Nakamura EMBC 2007]
[Murai and Yamane ICRA2011]

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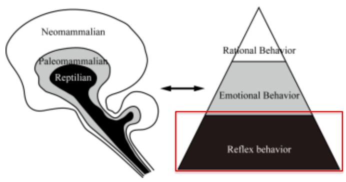
Understanding Motor Control

How motor commands are generated



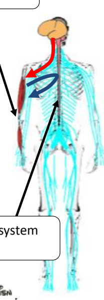
[MacLean 1990]

Modeling the Reflex Behavior

- Neuromuscular network model
- Parameter identification
- Evaluation
  - Simple reflex
  - Reflex in walking motion

Neuromuscular Network Model

- Inputs and outputs
  - Inputs: motor command signals at spinal nerve rami
  - Outputs: muscle tensions
- Two paths:
  - CNS→PNS: descending pathway
  - PNS→PNS: ascending and descending pathways (somatic reflex network)



Motor Command Signals

[Murai, Yamane, Nakamura EMBC 2007]

- 997 muscles: 997 independent control signals?
- A lot of work suggests that human motions are confined in smaller space
  - Joint trajectories [Safonova et al. 2004]
  - Muscle synergy [Bernstein 1967]
- Hypothesis: muscles are controlled by fewer independent signals

Motor Command Signals

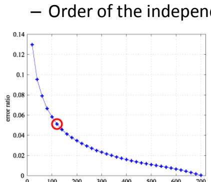
[Murai, Yamane, Nakamura EMBC 2007]

- Independent component analysis (ICA)

$$f = W_{ICA} s$$

Muscle tensions — Independent signals

  - Estimate mutually independent signal sources
  - Order of the independent signals is undefined

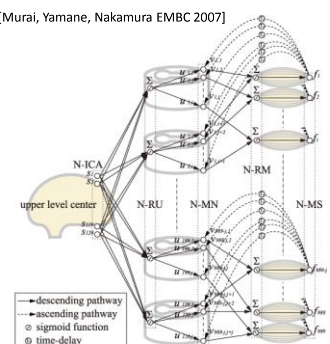


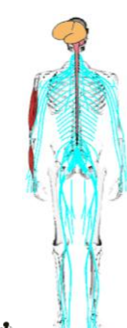
Dimension of s?

120, the number of relevant spinal nerve rami, is enough!

Neuromuscular Network Model

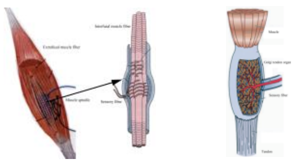
[Murai, Yamane, Nakamura EMBC 2007]



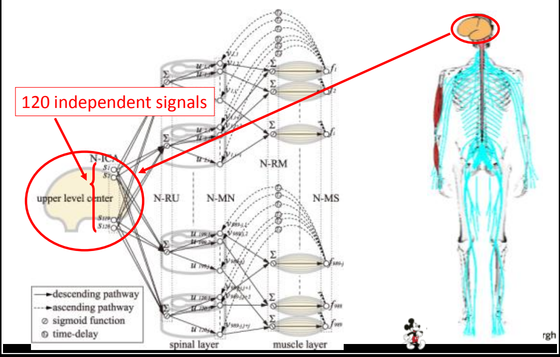


Somatosensory Information

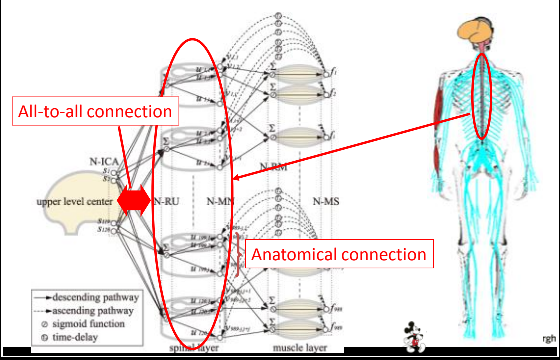
- Somatosensory information for reflex:
  - Muscle spindle: senses muscle length and velocity, induces stretch reflex, antagonistic inhibition, etc.
  - Golgi tendon organ: senses muscle tension, induces Ib inhibition



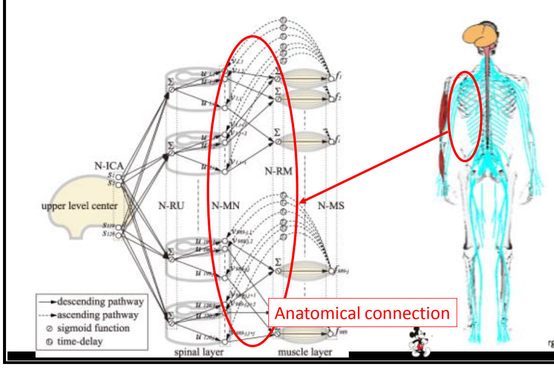
Neuromuscular Network Model



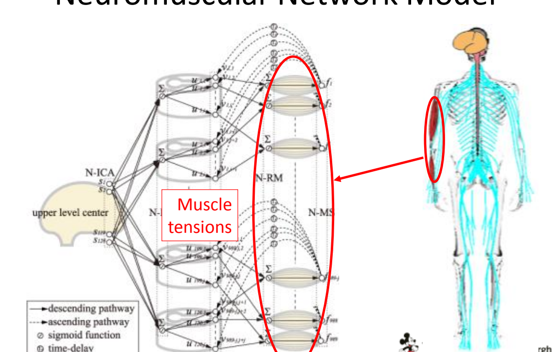
Neuromuscular Network Model



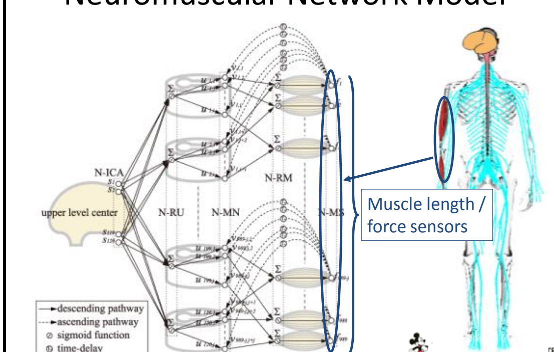
Neuromuscular Network Model



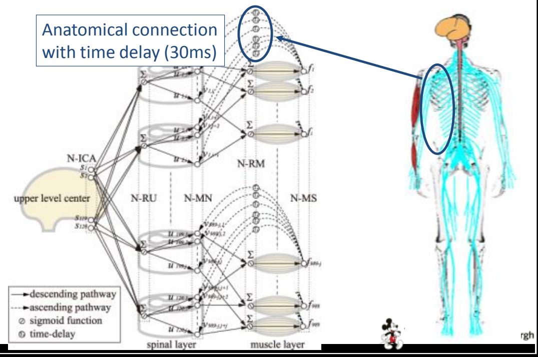
Neuromuscular Network Model



Neuromuscular Network Model

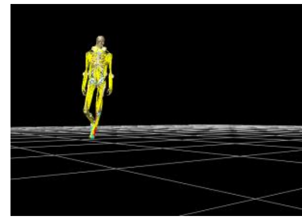


Neuromuscular Network Model



Experiment

- Parameter identification
  - 5000 cycles
  - Error
    - average: 2.59%
    - variance: 0.34%



training data (2000 frames/10 seconds)

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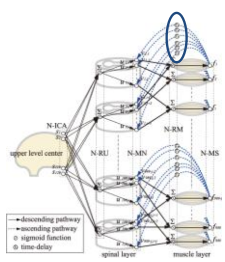
Weight Parameter of Reflex Loop

from **Iliacus** (hip flexion) to	
muscle	*weight*
Iliacus	4.20E+00
Sartorius	2.60E-01
Rectus Femoris	3.94E+00
Pectineus	4.60E-01
Gracilis	-4.06E-01
Adductor Longus	-1.69E-01
Adductor Brevis	-3.59E-01
Adductor Magnus	-4.10E-02



hip flexion muscles

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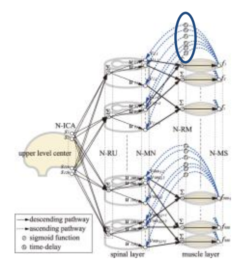
Weight Parameter of Reflex Loop

from **Tensor Fasciae Latae** (hip flexion) to	
muscle	*weight*
Tensor Fasciae Latae	2.93E-01
Gluteus Maximus	-1.28E-01
Biceps Femoris	-4.53E-01
Semitendinosus	-1.02E+00
Semimembranosus	-1.13E+00
Gluteus Medius	-4.94E-02
Gluteus Minimus	-9.30E-01



hip extension muscles

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Patellar Tendon Reflex

hit!

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Reflex in Walking Motion

[Murai and Yamane 2011]

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Further Validation of Reflex Model

More complex behavior: walking

Videos from [Cham 2009]

Human response to trips [Eng et al. 1994]

- Elevating strategy:
  - Trip at early stage of swing(5-25%)
  - Swing leg is lifted for collision avoidance

- Lowering strategy:
  - Trip at later stage of swing(55-75%)
  - Swing leg is lowered for immediate contact

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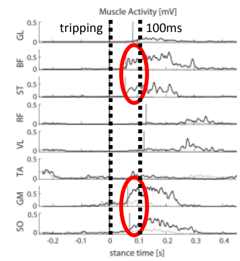
Human Response to Trips

[Pijnappels et al.05]

- EMG within 100ms is observed → involuntary response
- Induced by reflex system?



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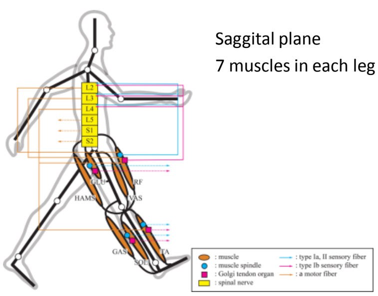
Simplified Model



Saggital plane

7 muscles in each leg (14 muscles)

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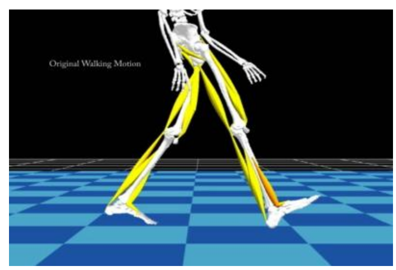
Parameter Identification



(x0.03)

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Identified Parameters

	HAM	GLU	TA	GAS	RF	VAS	SOL
HAM	1.02	0.05	-	-	0.40	-	-
GLU	0.39	0.36	-	-	0.59	-	-
TA	-	-	1.27	-0.52	-0.17	-0.13	-0.02
GAS	-	-	-0.02	0.88	0.16	0.07	0.27
RF	0.07	-0.31	-0.04	0.13	0.00	0.01	0.03
VAS	-	-	0.01	0.13	0.07	0.15	0.23
SOL	-	-	-0.02	0.12	0.06	0.24	0.18

Positive force feedback for synergistic muscle

Negative force feedback for antagonistic muscle

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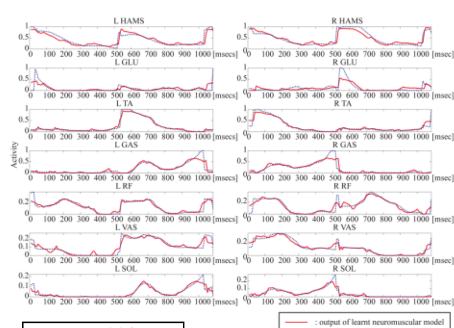
Reconstruction Accuracy



average error: 2.0%

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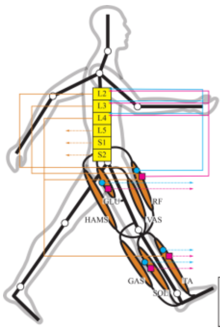
Additional Controller



Upper body control:
Apply PD controller to fixed posture

Mechanical joint limit:
Strong spring is applied at knee joint limit

Swing leg PD control:
Ankle joint has weak spring and damper during swing phase

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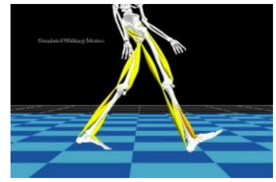
Dynamic Simulation of Locomotion



- Model cannot continue walking
- Similar to original joint motions despite
  - lack of reference trajectory
  - difference in the contact condition

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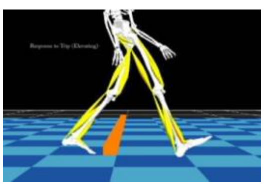
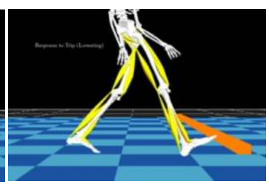
Simulation of Trip Response



13% of swing phase



55% of swing phase

- Qualitatively similar to elevating / lowering strategies
- Simulated muscle activities match reported EMG in GAS, SOL, and GM [Pijnappels et al.'05]

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Summary

- Detailed musculoskeletal model
  - Modeling
  - Dynamics
- Neuromuscular network model
  - Control signal from ICA
  - Patellar tendon reflex
- Reflex in Walking
  - Simplified model for simulation
  - Trip responses

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Discussion

- Level of details
  - We started from a very detailed human model
  - Then used simpler model for further validation
  - Many researchers work with simple models
- Which model makes sense?
  - Simple models can miss details?
  - Parameter identification?
  - Signal/noise ratio?

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