Mechanical Engineering Seminar (U-Grad)
Special Topics in Mechano-Informatics II (Grad)
"Biomechanics of Human Movement"

Dr. Emel Demircan

Lecture 2

Announcements

- Lecture Handouts:

http://www.ynl.t.u-tokyo.ac.jp/lectures/2014/index.html

- HW1 out today – due on May 2nd, by 5pm

Submissions to: **emel@ynl.t.u-tokyo.ac.jp**

- Project Team/Topic selection – today (in class)

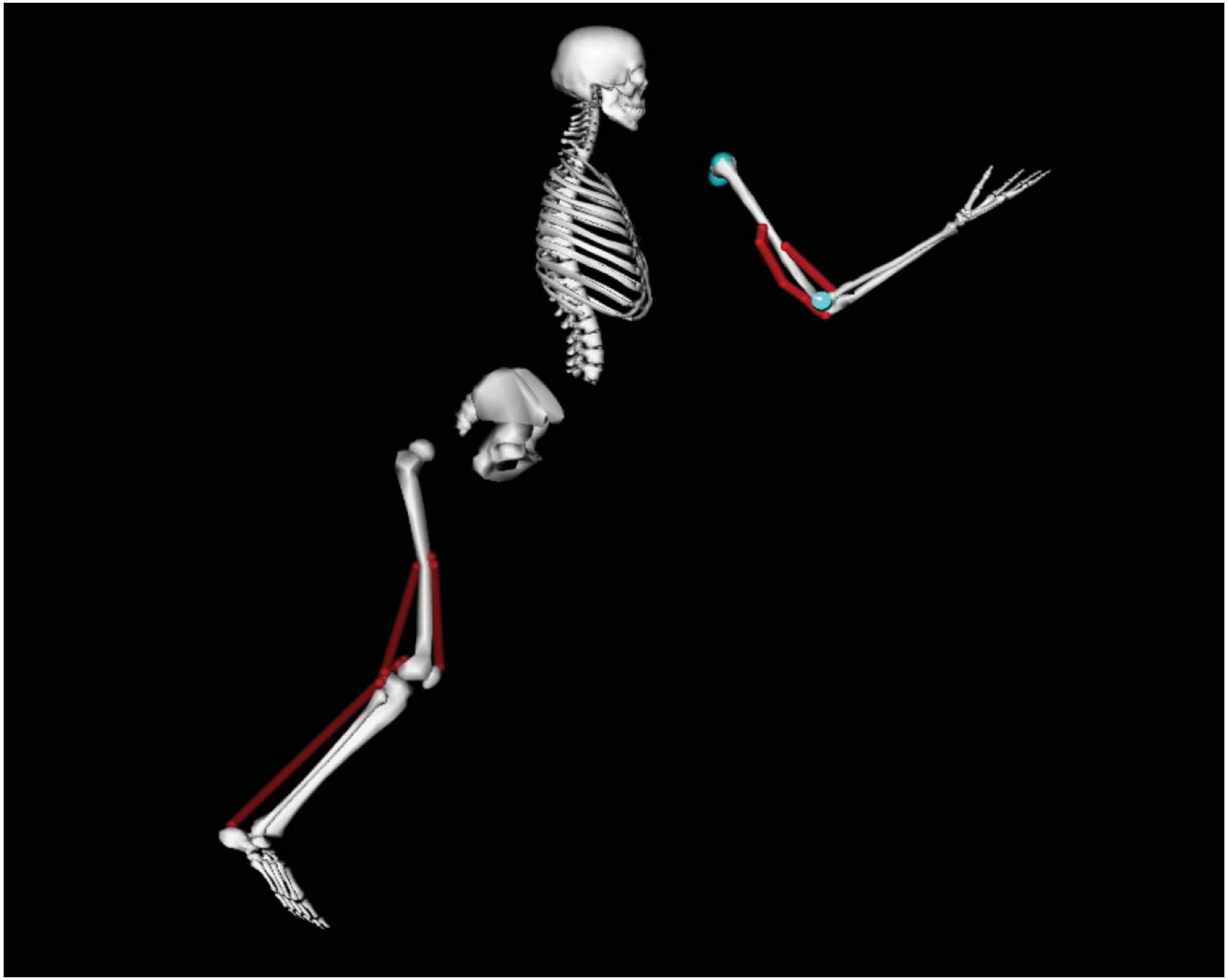
Musculoskeletal Modeling

Skeletal Kinematics

Musculoskeletal Kinematics

Introduction to Biomechanical Simulation

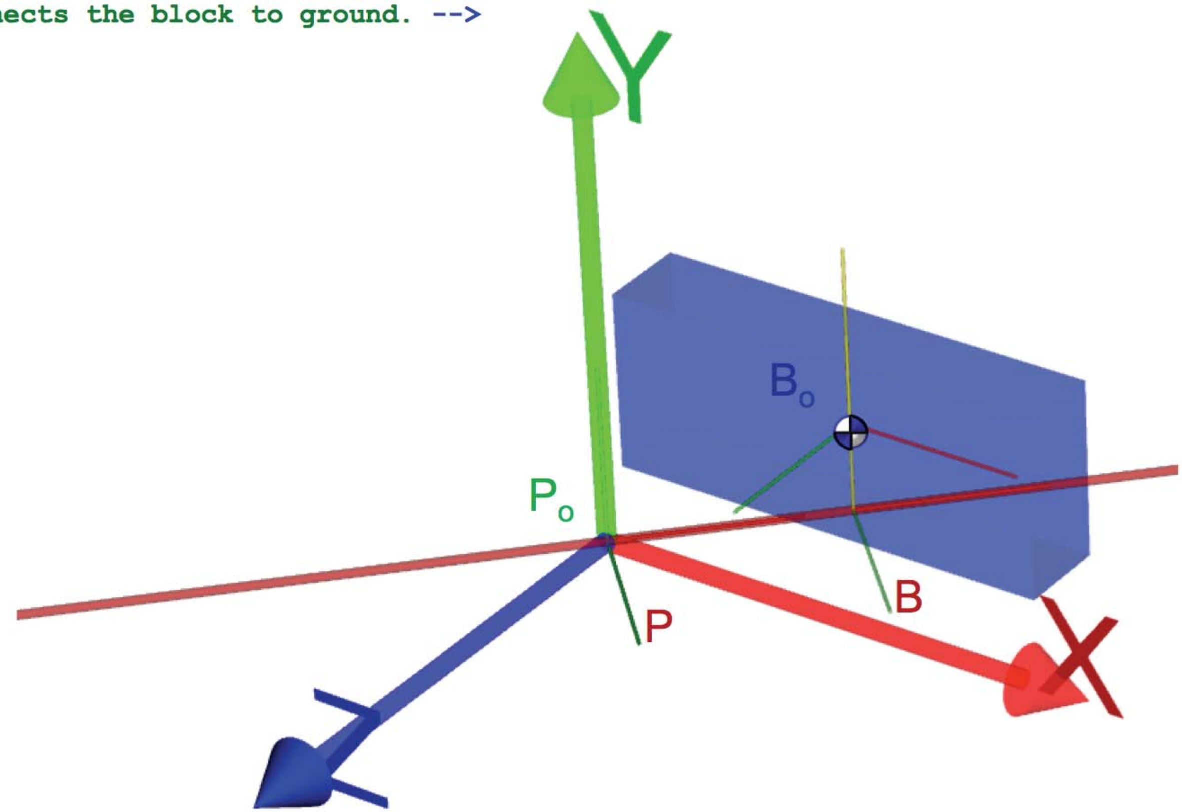
Components of a Musculoskeletal Model



Musculoskeletal Modeling

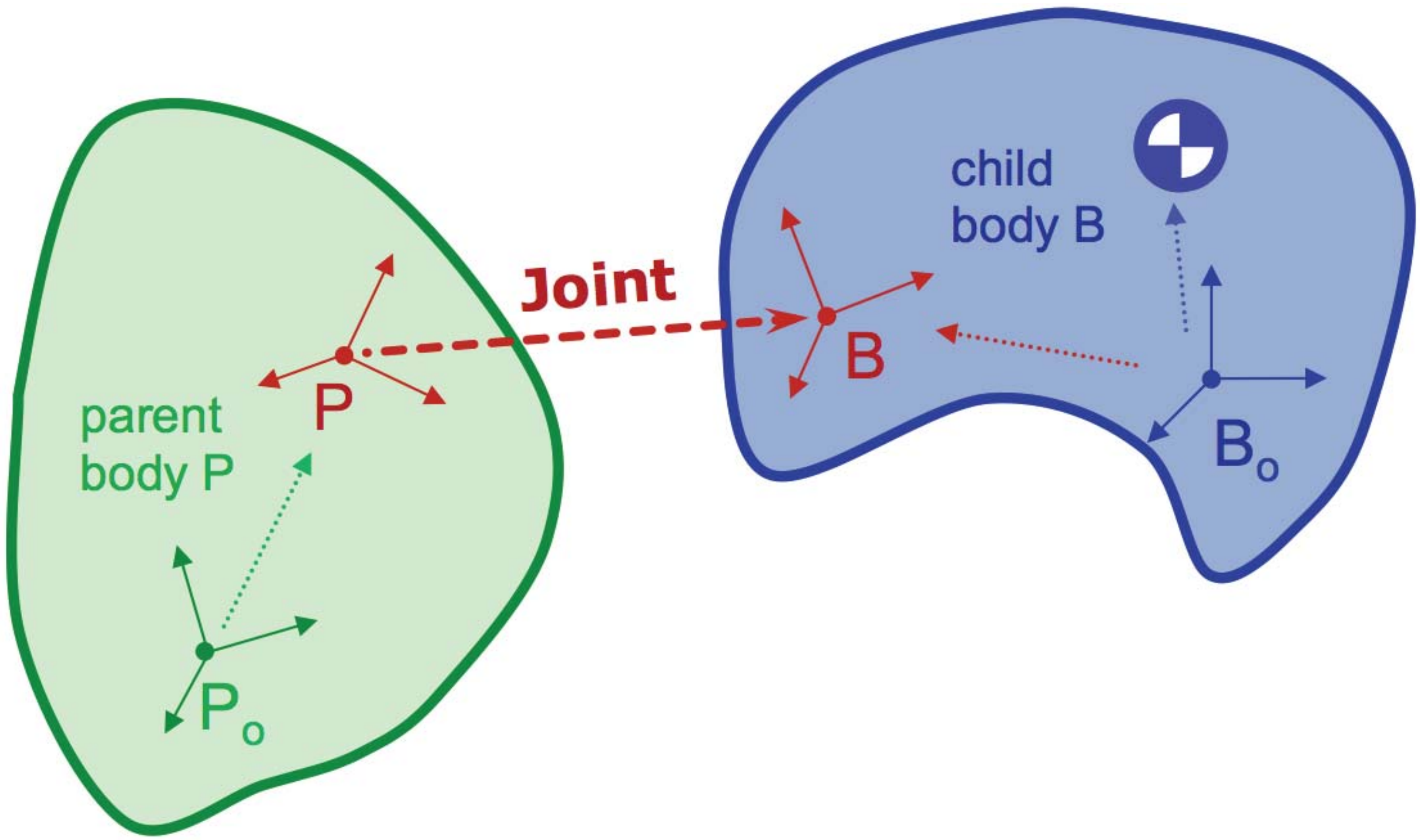
Body Segment | Joint | Muscle

```
<Body name="block">
   <mass>   5.00 </mass>
   <mass_center> 0.0   0.0   0.0 </mass_center>
   <inertia_xx>  0.1 </inertia_xx>
   ...
   <inertia_yz>  0.0 </inertia_yz>
   <!—Joint connects the block to ground. -->
   <Joint>
```



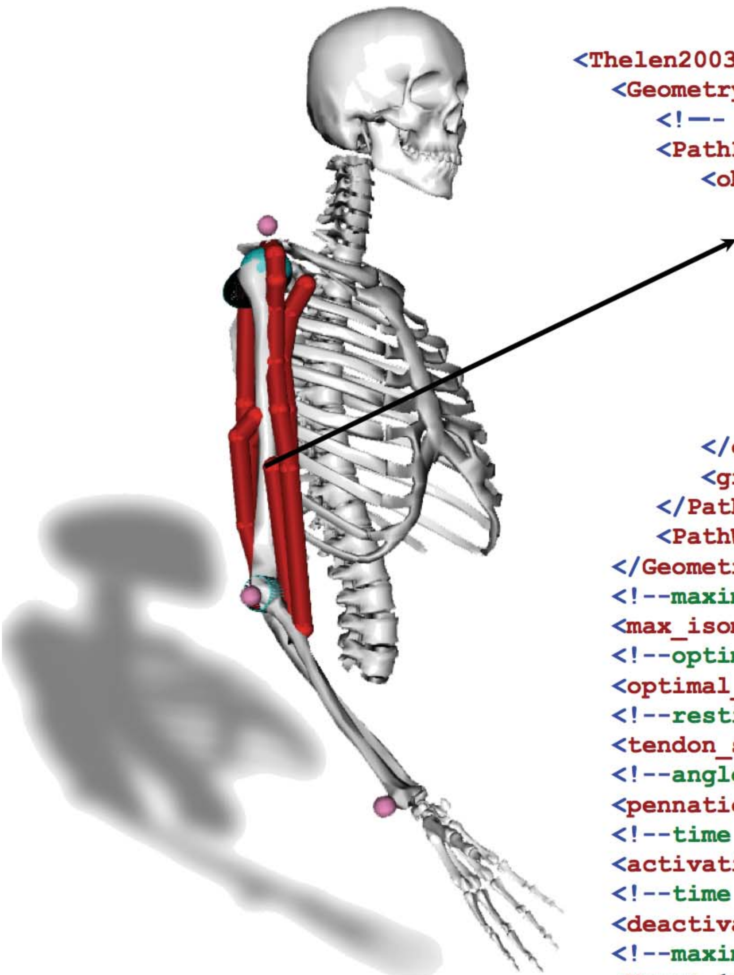
Musculoskeletal Modeling

Body Segment | Joint | Muscle



Musculoskeletal Modeling

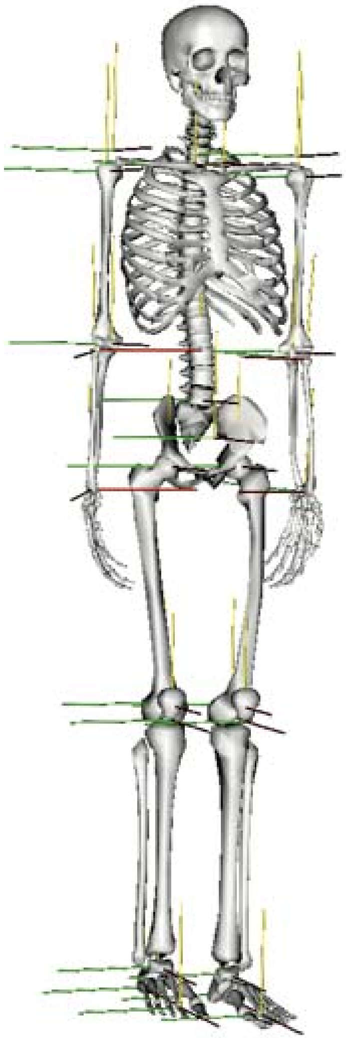
Body Segment | Joint | Muscle

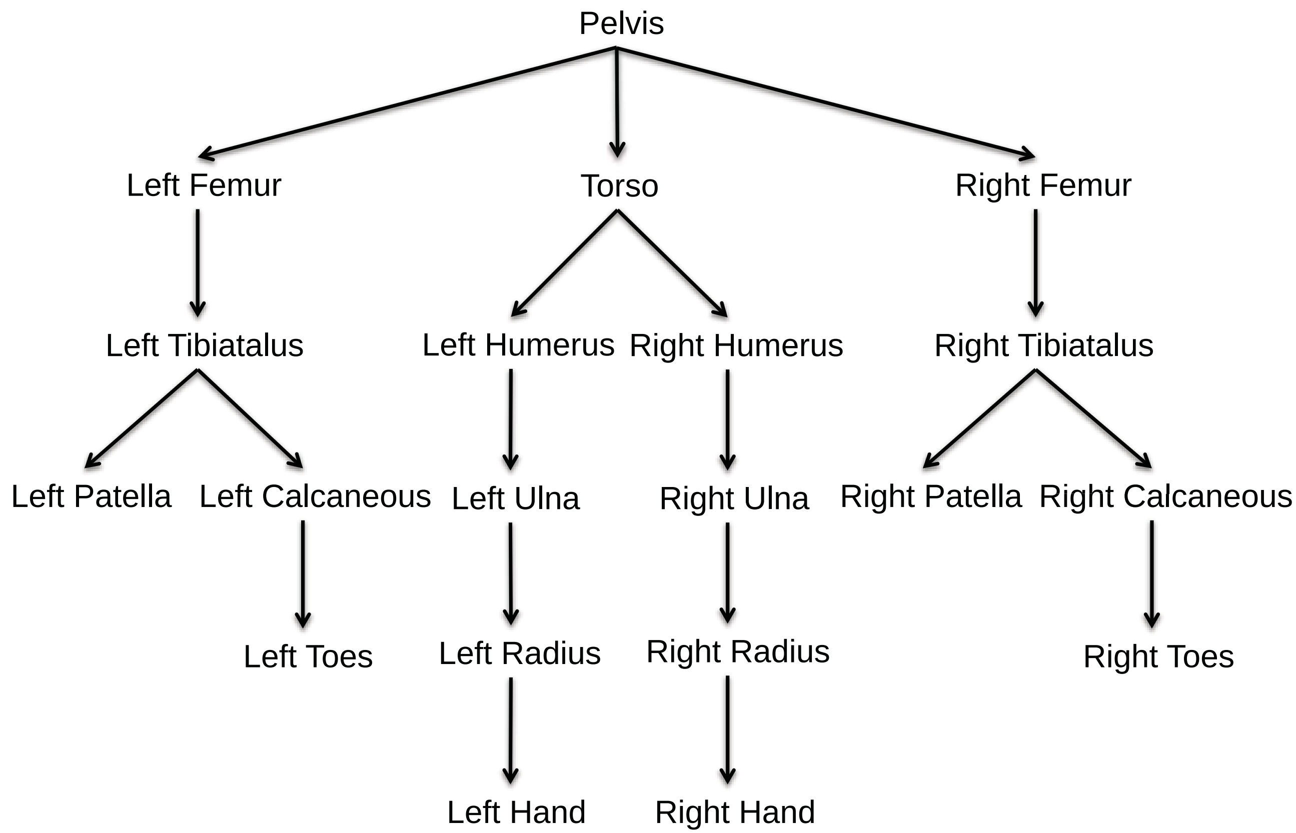


```
<Thelen2003Muscle name=“brachialis_r">
  <GeometryPath name="">
    <!—- points on bodies that define the path of the muscle -->
    <PathPointSet name="">
      <objects>
        <PathPoint name=“brachialis_r-P1">
          <location> -0.00240000 -0.15330000 0.00710000 </location>
          <body> humerus_r </body>
        </PathPoint>
        <PathPoint name="brachialis_r-P2">
          <location> 0.00000000  0.03100000 -0.00530000 </location>
          <body> r_ulna_radius_hand </body>
        </PathPoint>
      </objects>
      <groups/>
    </PathPointSet>
    <PathWrapSet name=""> ...
  </GeometryPath>
  <!--maximum isometric force of the muscle fibers-->
  <max_isometric_force> 972.00000000 </max_isometric_force>
  <!--optimal length of the muscle fibers-->
  <optimal_fiber_length> 0.08580000 </optimal_fiber_length>
  <!--resting length of the tendon-->
  <tendon_slack_length> 0.05300000 </tendon_slack_length>
  <!--angle between tendon and fibers at optimal fiber length-->
  <pennation_angle> 0.00000 </pennation_angle>
  <!--time constant for ramping up of muscle activation-->
  <activation_time_constant> 0.01000000 </activation_time_constant>
  <!--time constant for ramping down of muscle activation-->
  <deactivation_time_constant> 0.04000000 </deactivation_time_constant>
  <!--maximum contraction velocity at full activation (fiber length/s)-->
  <Vmax> 10.00000000 </Vmax>

  ...
</Thelen2003Muscle>
```

Musculoskeletal Modeling





Musculoskeletal Modeling

Assumptions & Limitations

- Scaling
- Muscle modeling:
  - Musculo-tendon parameters vary among subjects with different musculoskeletal geometry
  - Muscle capacity
- Complex Joints (custom joints)
  - Shoulder
  - Knee
- Testing the simulations!

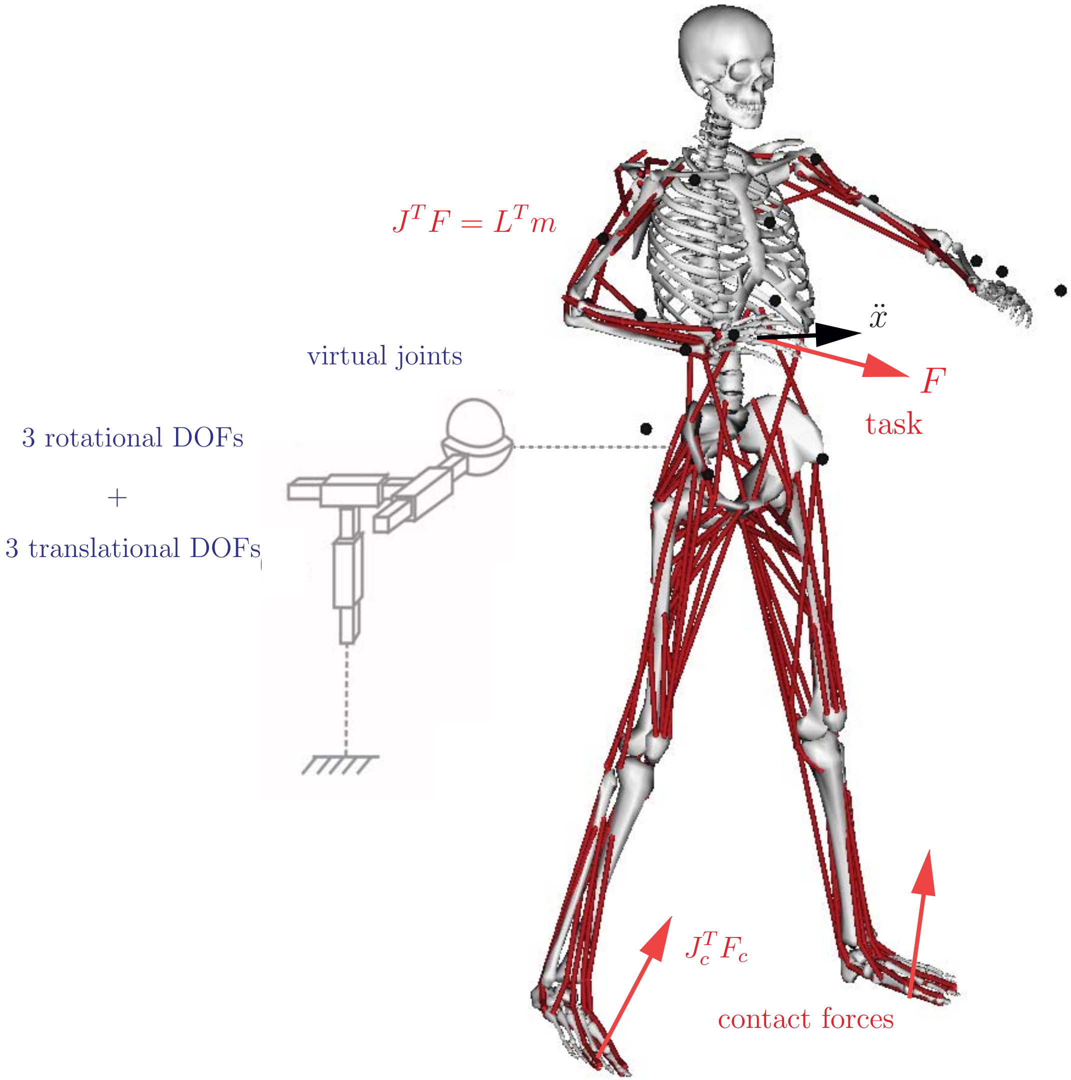
Musculoskeletal Modeling

Skeletal Kinematics

Musculoskeletal Kinematics

Introduction to Biomechanical Simulation

Skeletal Kinematics



Skeletal Kinematics

Definition: Skeleton Generalized Coordinates. *The skeletal system is considered as a system of constrained rigid bodies represented by a set of n independent configuration parameters or generalized coordinates, q. The generalized coordinates are usually given in terms of the joint angles between the body segments.*

Definition: Skeleton Jacobian. *The Jacobian, J, of a body is the partial velocity matrix, which maps the generalized velocities to the resulting Cartesian space velocities of the body segment.*

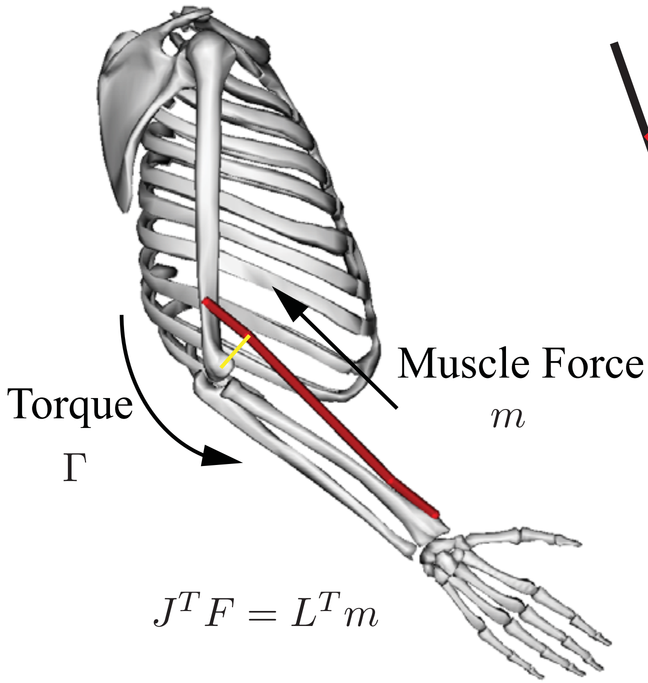
Musculoskeletal Modeling

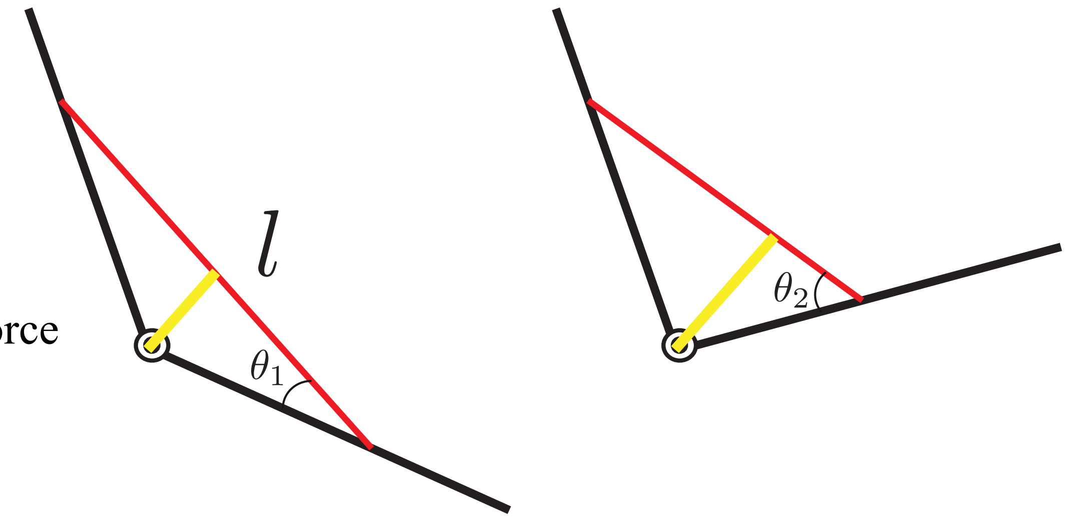
Skeletal Kinematics

Musculoskeletal Kinematics

Introduction to Biomechanical Simulation

Musculoskeletal Kinematics





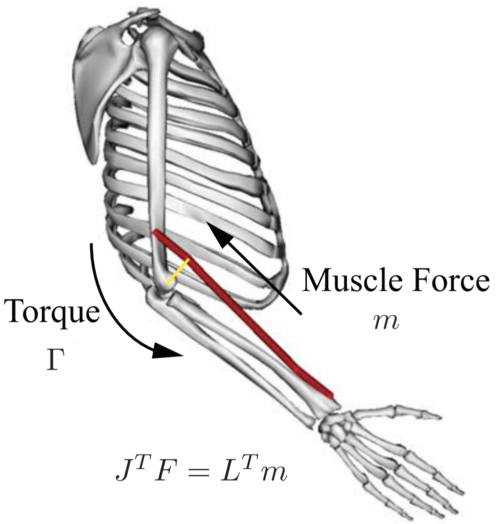
Definition: Muscle Jacobian, L. *In human musculoskeletal models all musculo-tendon lengths, l, can be uniquely determined from the joint angle, θ, and differential changes, dl, are given by:*

$$dl = L d\theta$$

Muscle/Task Relationship

Task Dynamics: $$\Gamma = J^T F$$

Muscle Dynamics: $$\Gamma = L^T m$$



Muscle-induced Joint Torques / Task:

$$J^T F = L^T m$$

where
J : skeleton Jacobian
F : task Forces
L : muscle Jacobian
m : muscle Forces

Introduction to Biomechanical Simulation

https://simtk.org/home/opensim

Purpose of Modeling and Simulation

- Visualize complex movement patterns
- Perform “what-if” studies
- Probe parameters that are difficult to measure
- Identify cause-effect relationship

Key Concepts

- <u>Kinematics:</u> coordinates and their velocities and accelerations
- <u>Kinetics:</u> forces and torques
- <u>Dynamics:</u> equations of motion

$$\underbrace{A(q)\ddot{q} + b(q,\dot{q}) + g(q) + F}_{\text{known}} = \underbrace{\Gamma}_{\text{unknown}}$$

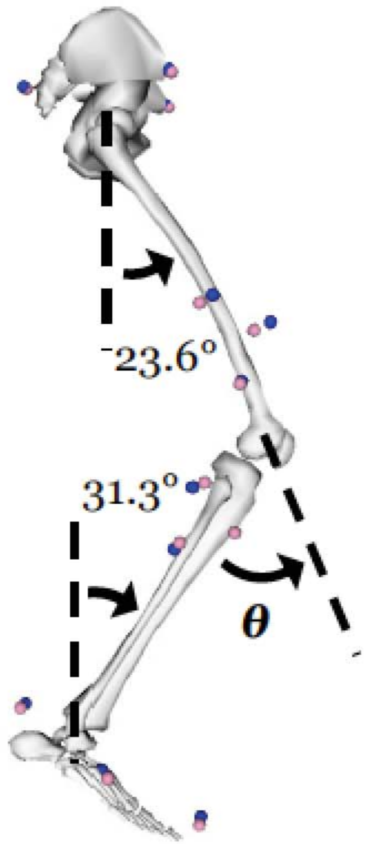
Quiz

1. For the model shown on the right, what is the value (θ) of the knee coordinate (*Note: extension is +*)?

   A. 23.6° B. -54.9° C. 31.3° D. -125.1°

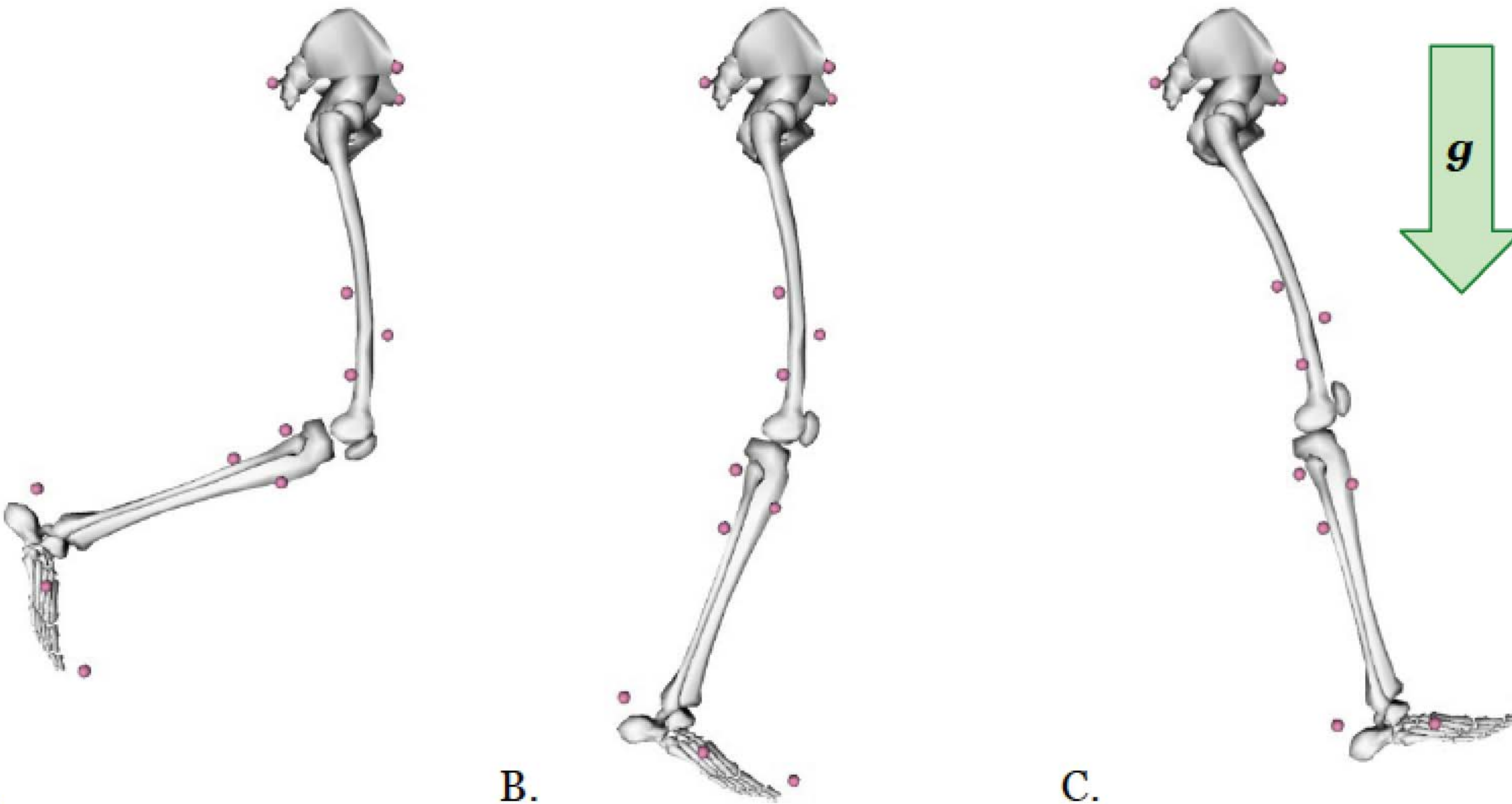
2. Given that the model shown on the right is at rest, what is the velocity of the knee?

   A. 23.6°/s B. -54.9°/s C. 3.89°/s D. 0°/s



Quiz

3. For the model poses shown below at rest and with gravity ($\boldsymbol{g}$) as the only force acting on the model, which pose requires the largest torque at the knee joint?



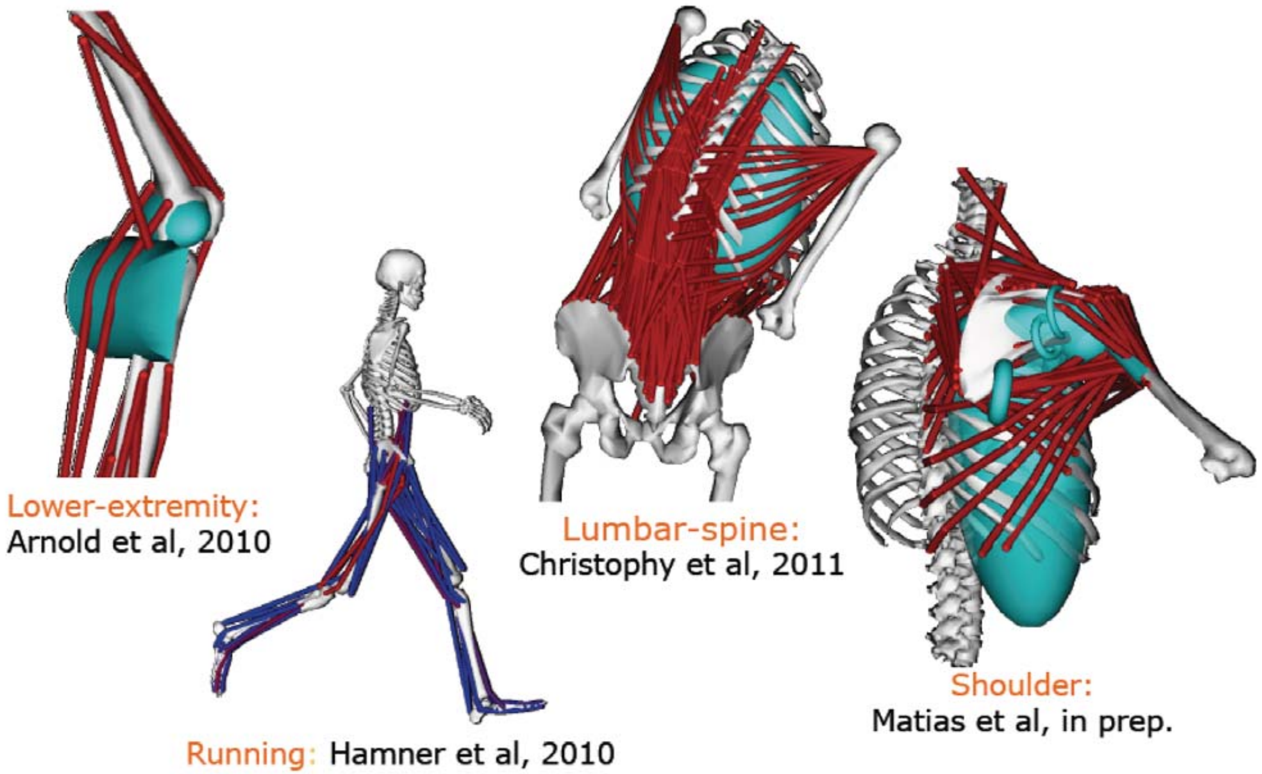
A. B. C.

What is OpenSim?

OpenSim is a freely available software package that enables you to **build**, **exchange**, and **analyze** computer models of the musculoskeletal system and dynamic simulations of movement.

Some Features

- Standard format for exchanging models
- General purpose inverse dynamics
- Optimization to estimate muscle and joint forces
- Methods to create simulations from motion capture
- Tools to analyze simulations



Some Features

- Standard format for exchanging models
- General purpose inverse dynamics
- Optimization to estimate muscle and joint forces
- Methods to create simulations from motion capture
- Tools to analyze simulations

OpenSim Tools:

- Scaling a Model
- Performing Inverse Kinematics Analyses
- Performing Inverse Dynamics Analyses
- Performing Static Optimization Analyses
- Generating Forward Dynamics Simulations
- Analyzing Dynamic Simulations
- Plotting Results
- Creating Snapshots and Making Animations

Final Project Teams

- Group 1 -> please split into two groups:
  - Itsuki Ichikawa M1
  - Veerachart Srisamosorn M1
  - Wu Cheng B4
  - Liang Boshen B4
  - Park Huijun B4
- Group 2 -> please split into two groups:
  - Emiko Uchiyama M1
  - Rie Hitsuyu M1
  - Akihiro Sanada M2
  - Heewon Park M1
  - Tomoyuki Maekawa M1
- Group 3 -> please split into two groups:
  - Yumiko Furuhata B4
  - Tatsuya Ishikawa B4
  - Haruguki Sanuki B4
  - Taira Miyatake B4
  - Shunsuke Sato B4

In total:
6 Groups

Final Project

Please select your team leader and one topic from the list below:

- Exoskeleton Robots & Rehabilitation Robotics
- Human Performance Augmentation
- Animation and Simulation
- Human & Humanoid in Aging Society
- Human & Humanoid Skills/Cognition
- Human Motion Tracking
- Gait Analysis & Rehabilitation
- Human Musculoskeletal Modeling
- Socially Assistive Robots
- Natural Motion Generation in Humanoid Robotics
- Motion Analysis for Workspace Ergonomics
- Children Gait and Posture Rehabilitation
- Real-time Feedback Modalities for Motion Training

Paper Selections

Please use the following references to select the papers about your topic:

Journals (Biomechanics):
Annals of Biomedical Engineering
Computer Aided Surgery
Gait and Posture
Journal of Biomechanical Engineering
Journal of Biomechanics
Journal of Physiology
Journal of Orthopeadic Research
Nature
Science

Journals/Books (Robotics):
IJRR
IJHR
TRO
STAR: Springer Tracts on Advanced Robotics
Advanced Robotics
International Journal of Social Robotics
IEEE Robotics and Automation Magazine
Springer Handbook of Robotics

Societies/Conferences (Biomechanics):
American Society of Biomechanics (ASB)
ASME Bioengineering Division
Biomedical Engineering Society
Gait and Clinical Movement Analysis Society
International Society of Biomechanics (ISB)
Medical Image Computing
Orthopeadic Research Society…

Societies/Conferences (Robotics):
IEEE Robotics and Automation Society
RSJ The Robotics Society of Japan
IEEE ICRA
IEEE/RSJ IROS
EURON: European Robotics Research Network
RSS Robotics Science and Systems
ISER, Humanoids…

Literature Searching
Bmesource.org
Lane Medical Library
PubMed

Final Project Presentation: Example

Learning about human motion using operational space ideas

CS327A Symposium Presentation

Chris Dembia

References

Demircan, E., Sentis, L., Sapio, V. De, & Khatib, O. (2008). Human Motion Reconstruction by Direct Control of Marker Trajectories, 263–272.

Khatib, O., Demircan, E., De Sapio, V., Sentis, L., Besier, T., & Delp, S. (2009). Robotics-based synthesis of human motion. *Journal of physiology, Paris*, *103*(3-5), 211–9. doi:10.1016/j.jphysparis.2009.08.004

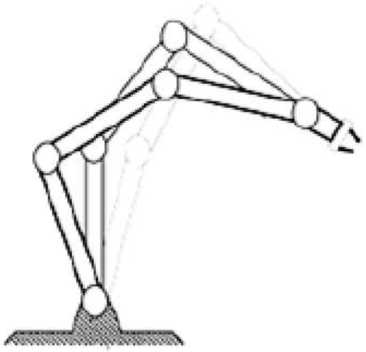
Ott, C., Lee, D., & Nakamura, Y. (2008). Motion capture based human motion recognition and imitation by direct marker control. *Humanoids 2008 - 8th IEEE-RAS International Conference on Humanoid Robots*, 399–405. doi:10.1109/ICHR.2008.4755984

Motion capture

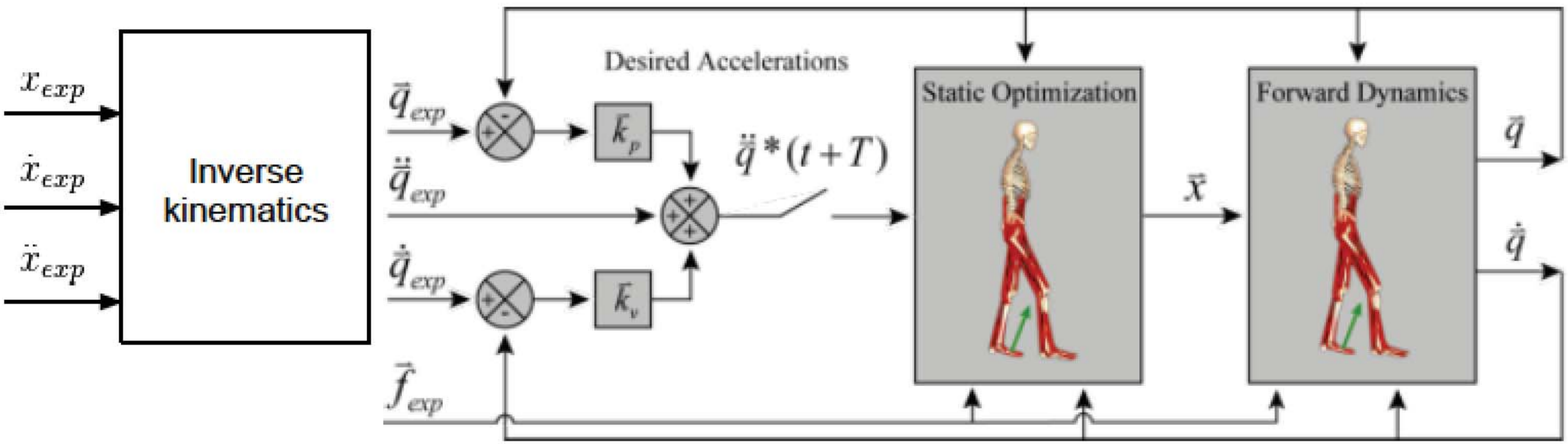
Animation

Biomechanics

Robot control

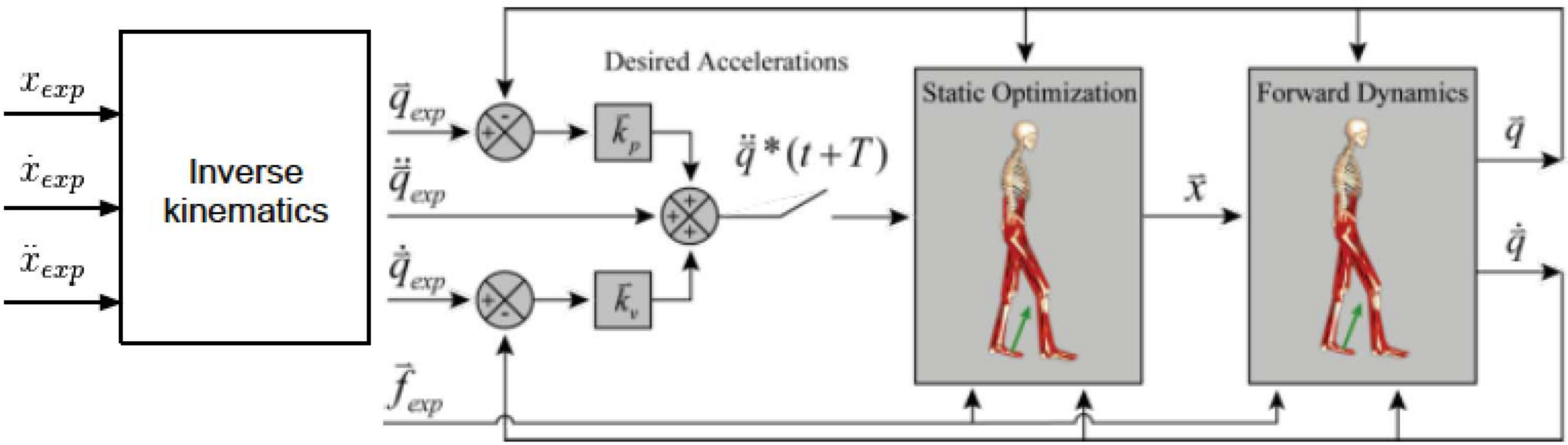


Biomechanics



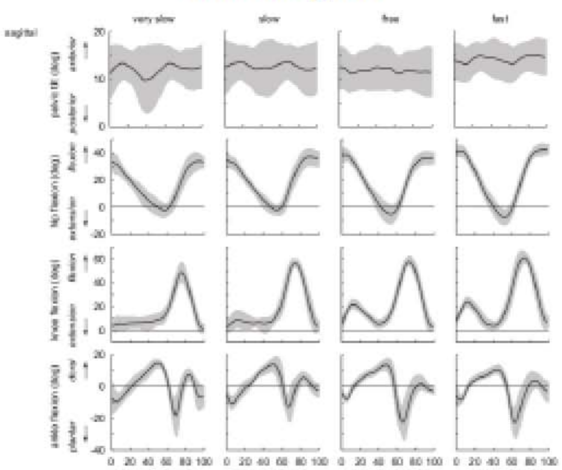
OpenSim

Biomechanics

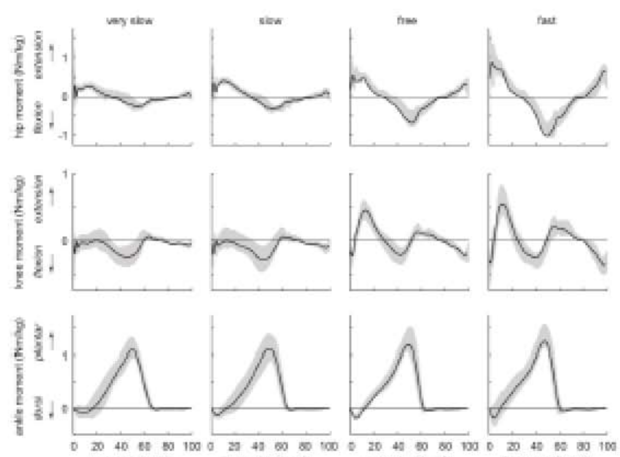


OpenSim

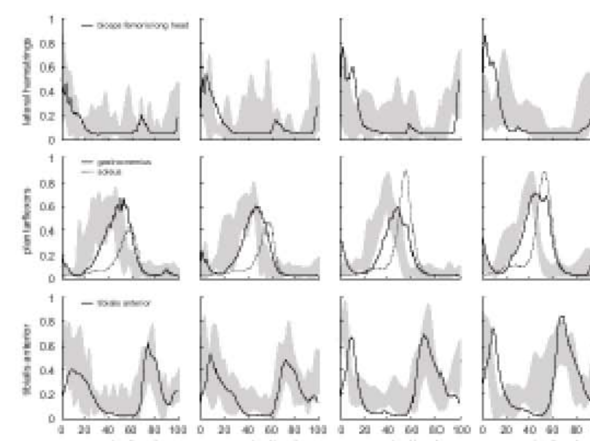
Joint angles



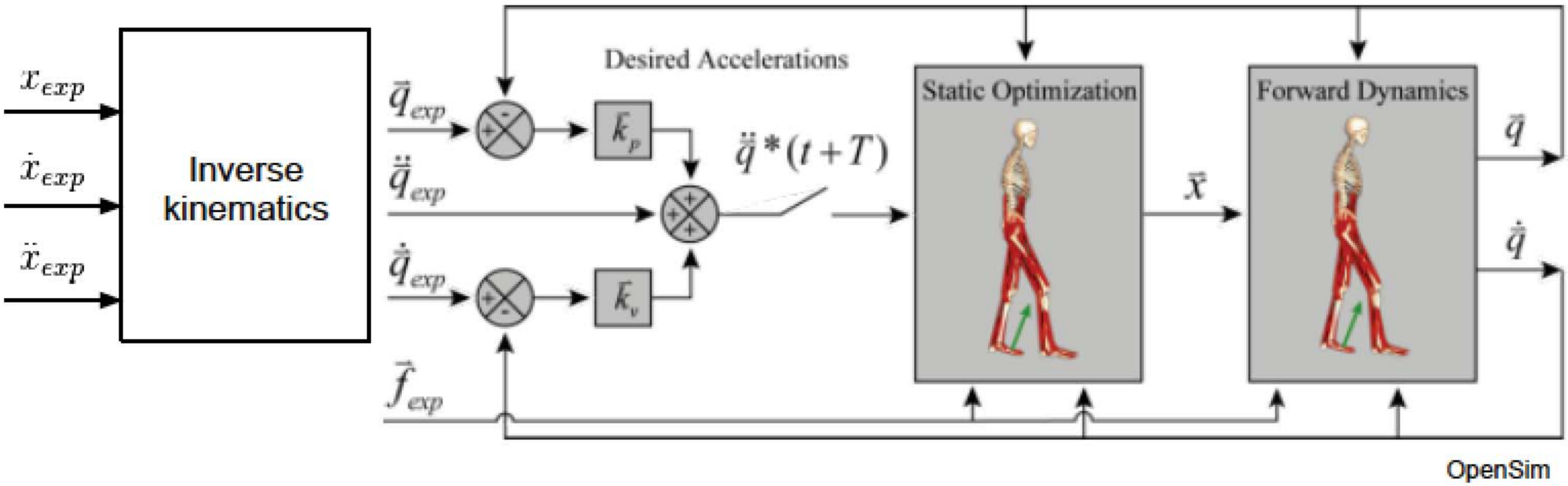
Joint moments



Muscle forces



Inverse kinematics in biomechanics



$$x = G(q)$$

marker position

marker pos. on model

$$\min_q \left(\sum_m w_i ||x_i^m - x_i(q)||^2 \right)$$

for all markers

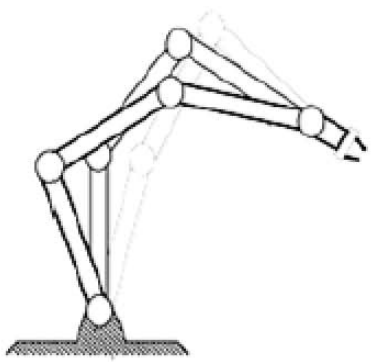
weight (importance of this marker)

$$x_i = G_i(q)$$

"End-effector" inverse kinematics

Resolved motion rate control

$$\dot{q} = J^{\#}\dot{x}$$



minimize norm:

$$J^{\#} = J^{+} = J^{T}(JJ^{T})^{-1}$$

minimize instantaneous kinetic energy:

$$J^{\#} = A^{-1}J^{T}(JA^{-1}J^{T})^{-1}$$

"End-effector" inverse kinematics

Resolved motion rate control

$$\dot{q} = J^{\#}\dot{x}$$

minimize norm:

$$J^{\#} = J^{+} = J^{T}(JJ^{T})^{-1}$$

minimize instantaneous kinetic energy:

$$J^{\#} = A^{-1}J^{T}(JA^{-1}J^{T})^{-1}$$

Closed-loop inverse kinematics (CLIK)

marker position

$$\dot{q} = J^{\#}(\dot{x} + K(x - x^{m}))$$

matrix of gains

rejects steady-state error

Direct marker control

Dynamics, solve for q:

$$A\ddot{q} + b + g = \Gamma \Longrightarrow \ddot{q} = A^{-1}(\Gamma - b - g)$$

Specify control in task space:

$$\Gamma = J^T F$$

Feed-forward linearization:

$$F = \hat{\Lambda} F^* + \hat{\mu} + \hat{p}$$

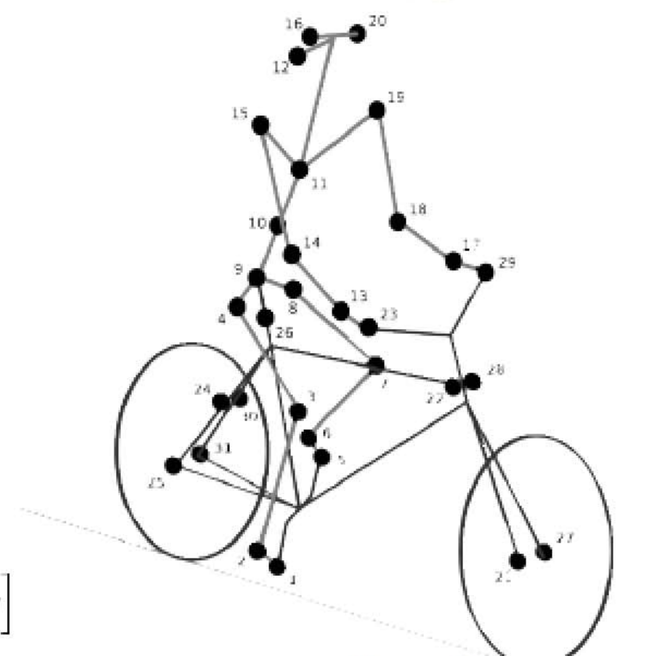
Marker tracking control law:

$$F^* = \ddot{x}^m - k_v(\dot{x} - \dot{x}^m) - k_p(x - x^m)$$

All together now:

$$\ddot{q} = A^{-1}\left[J^T[\hat{\Lambda}(\ddot{x}^m - k_v(\dot{x} - \dot{x}^m) - k_p(x - x^m)) + \hat{\mu} + \hat{p}] - b - g\right]$$

OpenSim



Moore, 2012

Direct marker control: priorities

Highest-priority marker set:

$$F^*_{m1} = \ddot{x}^m_{m1} - k_v(\dot{x}_{m1} - \dot{x}^m_{m1}) - k_p(x_{m1} - x^m_{m1})$$

$$F_{m1} = \hat{\Lambda} F^*_{m1} + \hat{\mu}_{m1} + \hat{p}_{m1}$$

Second priority marker set:

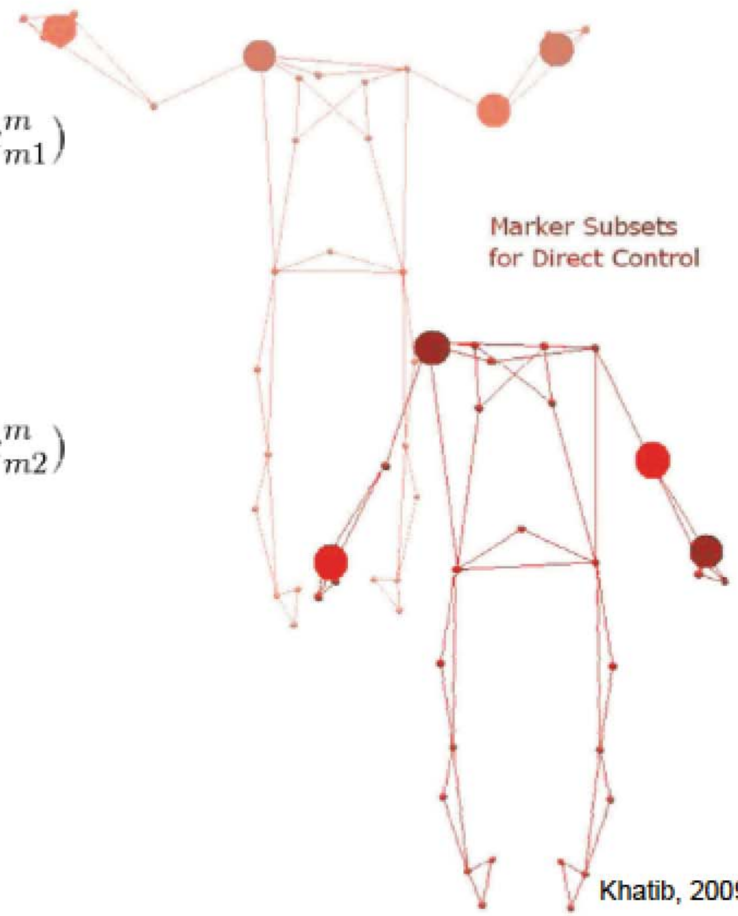
$$F^*_{m2} = \ddot{x}^m_{m2} - k_v(\dot{x}_{m2} - \dot{x}^m_{m2}) - k_p(x_{m2} - x^m_{m2})$$

$$F_{m2|m1} = \hat{\Lambda} F^*_{m2} + \hat{\mu}_{m2|m1} + \hat{p}_{m2|m1}$$

$$J_{m2|m1} = J_{m2}(I - \bar{J}_{m1} J_{m1}) = J_{m2} N_{m1}$$

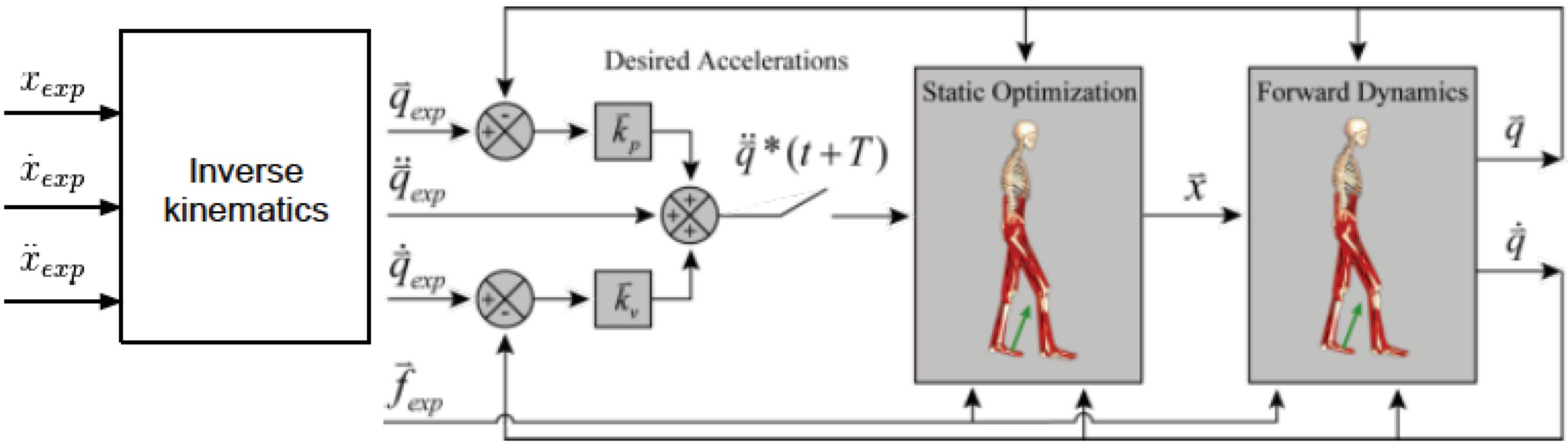
Computing combined joint torques:

$$\Gamma = J^T_{m1} F_{m1} + J^T_{m2|m1} F_{m2|m1}$$



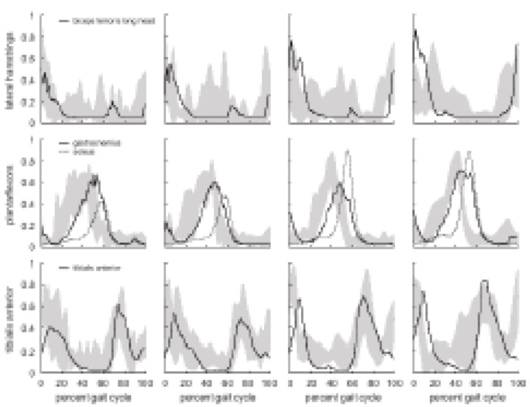
Khatib, 2009

Doing something with q: biomechanics



OpenSim

Muscle forces



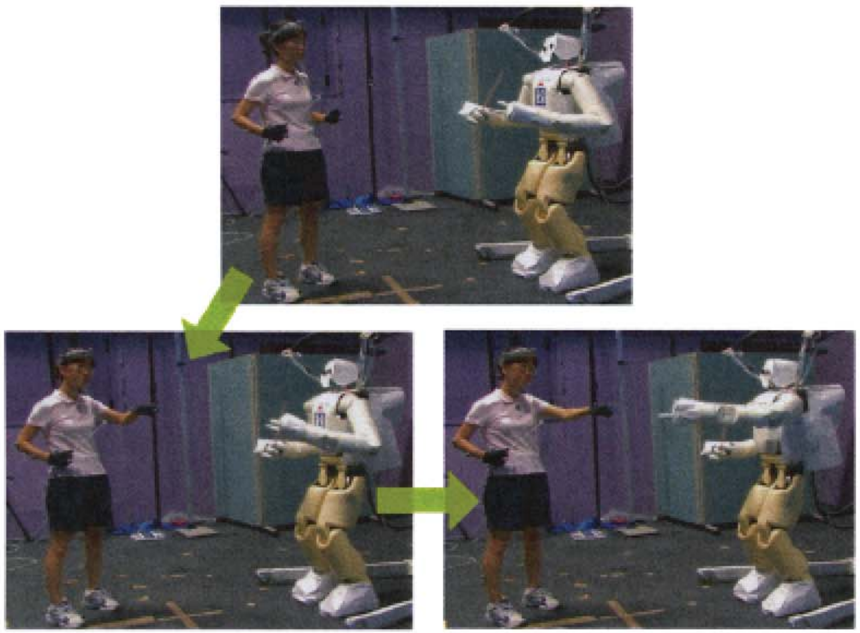
$$\Gamma' = \ddot{q}^m - k_v(\dot{q} - \dot{q}^m) - k_p(q - q^m)$$ joint space control law

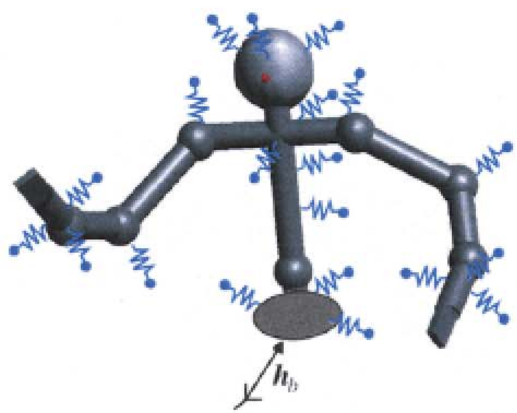
$$\Gamma = \hat{A}\Gamma' + \hat{b} + \hat{g}$$ feed-forward linearization

$$\min_P \sum P_i(q), \text{ s.t. } \Gamma = L^T P$$ solve muscle redundancy

$$\ddot{q} = A^{-1}(\Gamma - b - g)$$ integrate forward

Doing something with q:
Robot imitation of human motions





Task-space spring potential field:

$$U_i = \frac{1}{2} k_i \|x_i^m - x_i\|^2$$

$$F_i = k_i(x_i^m - x_i)$$

$$\Gamma_i = J_i^T F_i$$

Joint-space damping (wow!):

$$\Gamma = \sum \Gamma_i - D(q)\dot{q}$$

Center of mass control:

$$\min_{q_{lower}} \|x_{cm}^{des} - x_{cm}(q)\|^2$$

Learning within operational space framework: Effort minimization

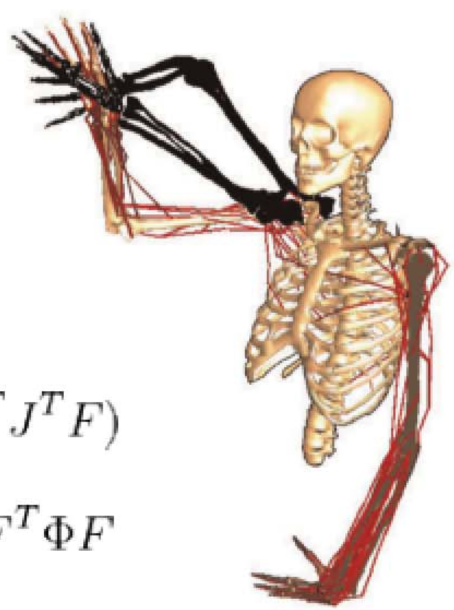
$$E = cP^2$$

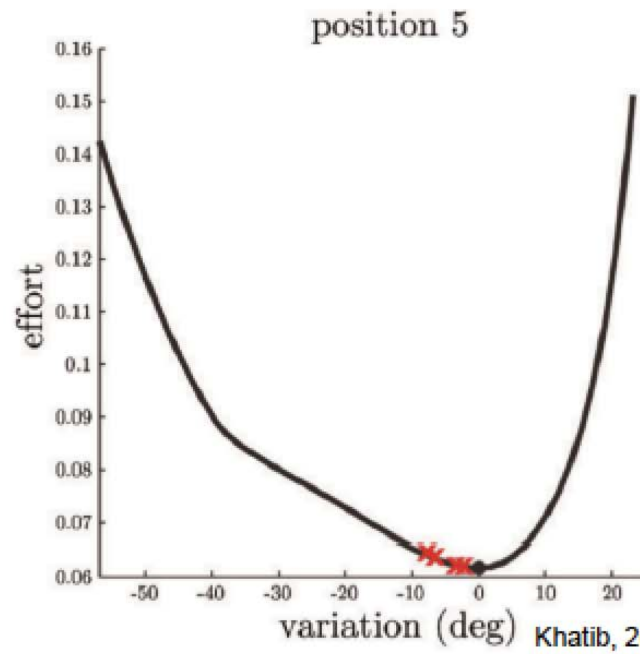
$$E = (N_c^{-1} P)^T (N_c^{-1} P)$$

$$\Gamma = L^T(q) P$$

$$E = (N_c^{-1} L^{-T} J^T F)^T (N_c^{-1} L^{-T} J^T F)$$

$$E = F^T J (L^T N_c^2 L)^{-1} J^T F = F^T \Phi F$$

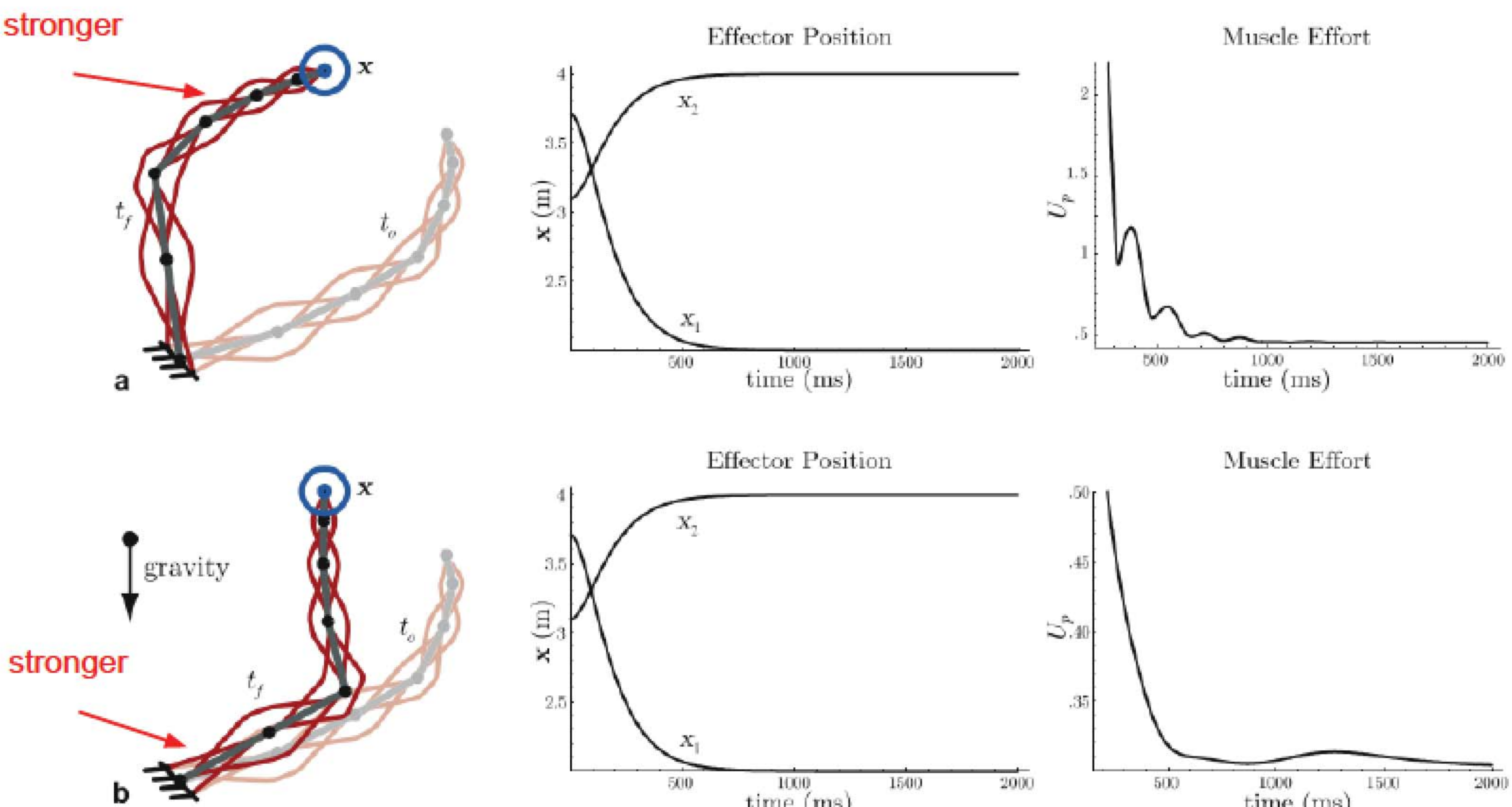




Khatib, 2009

Humans do minimize an effort, based on musculoskeletal physiology , for which we can obtain an approximate expression, which choosing their configuration during a task

Within op. space: Effect of muscle strength on optimal configuration



De Sapio, 2005

The relative strength of muscles along a linkage affects which configuration possesses minimal effort.

Final Project Presentation

- Review an academic paper and present to the class:
  - General information about the topic & key concepts
  - Motivation and problem statement
  - Technical approach
  - Main results
  - Main experimental insights and contributions
  - Future directions

Schedule

4/18: Introduction
4/25: Spatial Descriptions, Kinematics, Introduction to Biomechanical Simulation
5/2: Skeletal Muscle Structure, Force Generation, Musculoskeletal Geometry
5/9: Production of Movement
5/23: Motion Tracking Techniques
6/6: Inverse Dynamics, Control, Operational Space Formulation
6/27: Human Articulated Body Model, Dynamics, and Motion Control
7/4: Advanced Topics in Human Motion Analysis, Student Presentations

Next Week

- Instructor Extra Office Hours:
  - Monday, 28th: 10am-12pm
  - Monday, 28th: 3pm-5pm
  - Tuesday, 29th: 10am-12pm
  - Tuesday, 29th: 3pm-5pm

- Please **select one time slot** and mark the team leader name on the sheet to meet with the instructor for paper selections.

- Please **bring at least 3 papers** to the instructor office hour. 2 papers will be selected for each team.

- Have a Nice Weekend!

Mechanical Engineering Seminar (U-Grad)
Special Topics in Mechano-Informatics II (Grad)
"Biomechanics of Human Movement"

Dr. Emel Demircan

Lecture 2