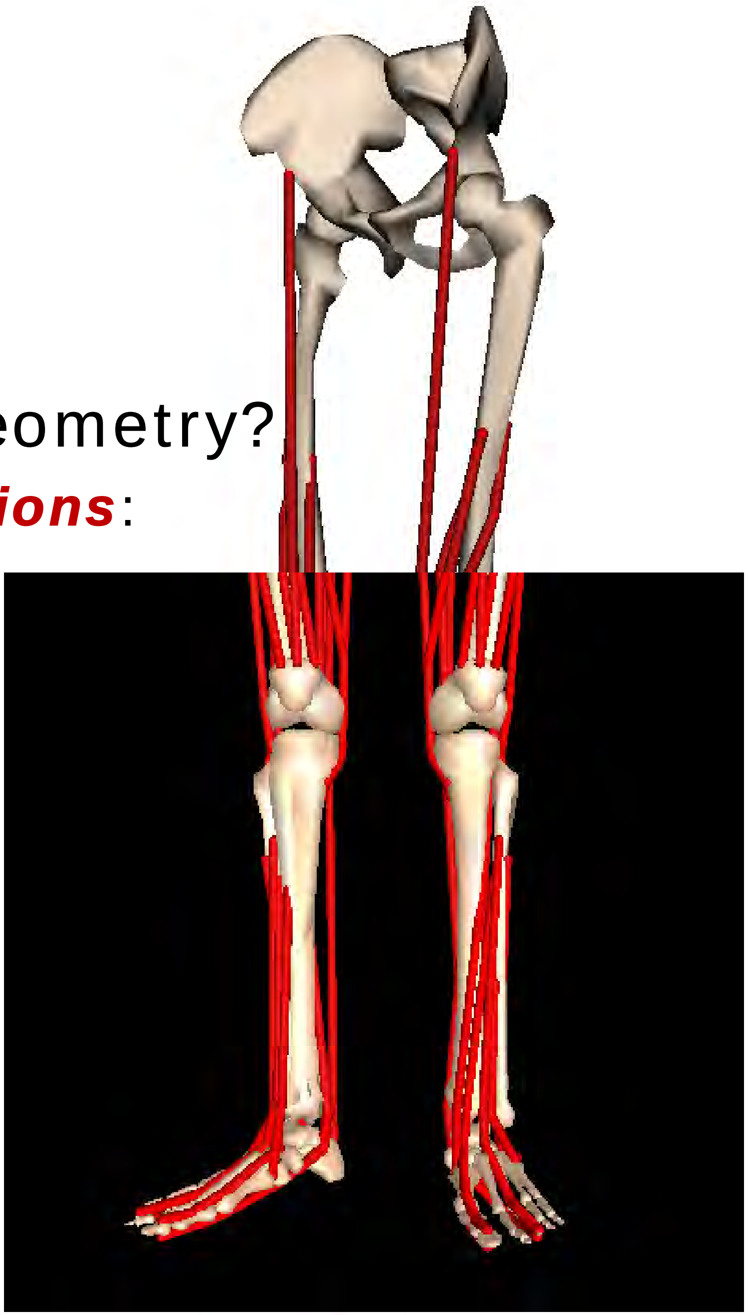
Musculoskeletal Geometry: Moment Arms

Lecture 4

BME 599: Modeling & Simulation of Movement

Question of the Day



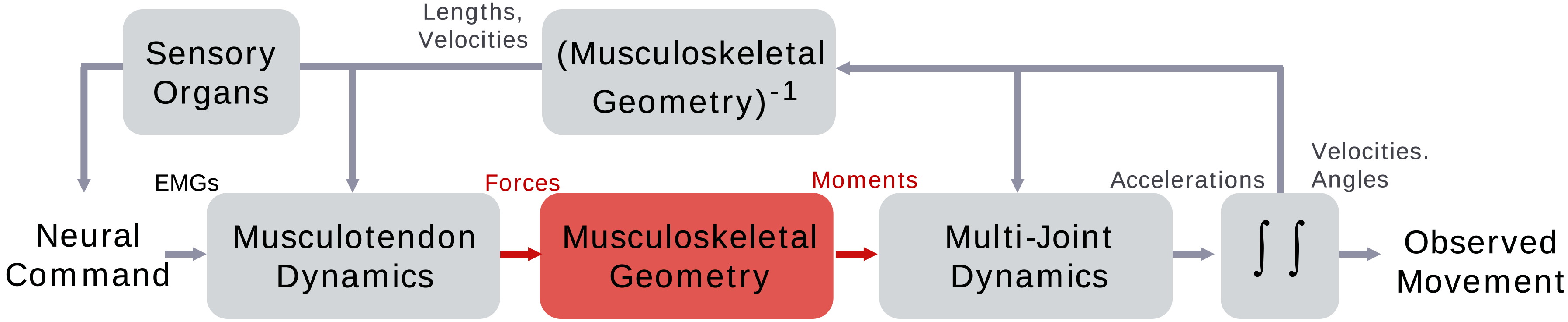
Why study musculoskeletal geometry?

- To ***answer fundamental questions***:
  - Why are we shaped this way?
  - What if we had huge moment arms?
- To ***answer clinical questions***:
  - How is muscle function altered by deformity?
  - How can we design surgical changes in geometry to restore function?

Outline for Today

- Question of the day
- Musculoskeletal geometry
  - Motivation
  - Definition of a moment and moment arm
  - 2D and 3D examples
  - How to measure moment arms
- Modeling of geometry
- Arnold et al., 2000 (similar to Delp et al., 1999)
- Blemker et al., 2007
- Answer your questions!

Musculoskeletal Geometry Transforms Muscle Forces to Joint Moments

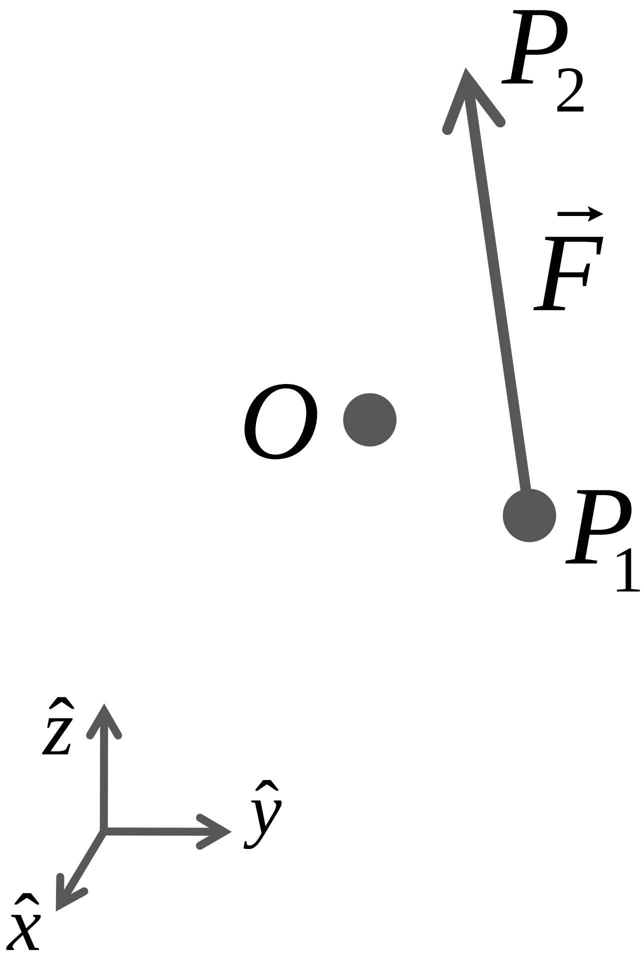


- So far, we've analyzed ***muscle function***
- ***Musculoskeletal geometry*** has a major influence on ***muscle function***
- ***Moment arms*** are the basic ***measure of geometry***

Definition of a Moment

To define a moment you need a point (O) and a fixed vector ($\vec{F}$).

$$\vec{F} = \vec{P}_2 - \vec{P}_1$$



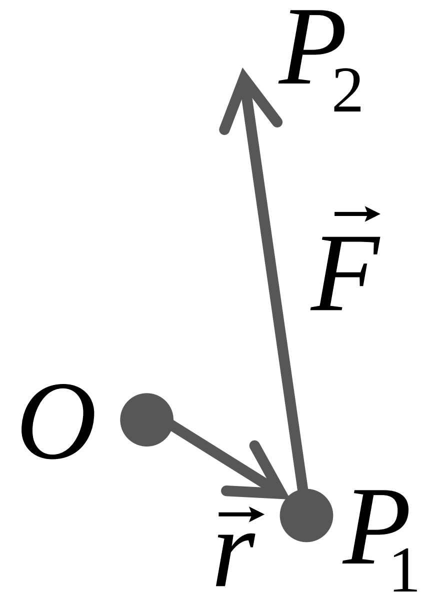
Definition of a Moment

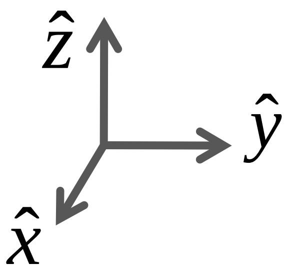
Let $\vec{r}$ be a vector from O to any point on the line of action of $\vec{F}$.

$$\vec{r} = \vec{P}_1 - \vec{O}$$

The moment of $\vec{F}$ about O is defined by the cross product :

$$\vec{M}_o \equiv \vec{r} \times \vec{F}$$

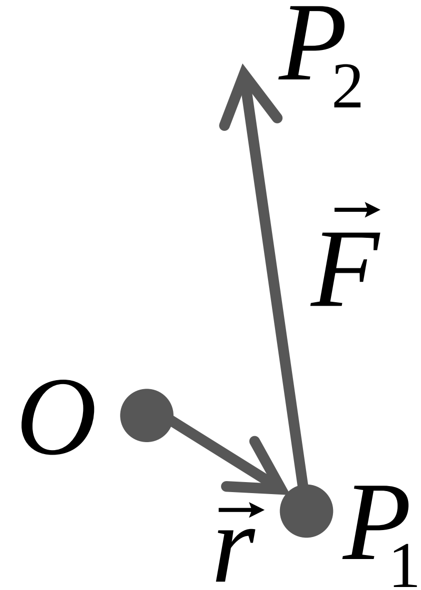


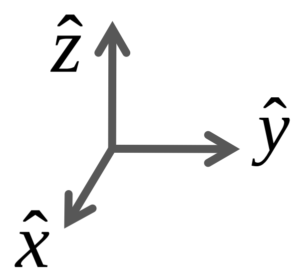


Definition of a Moment Arm

The moment arm of $\vec{F}$ for $\hat{x}$ is defined as:

$$ma_x = \frac{\vec{r} \times \vec{F}}{\left|\vec{F}\right|} \bullet \hat{x}$$





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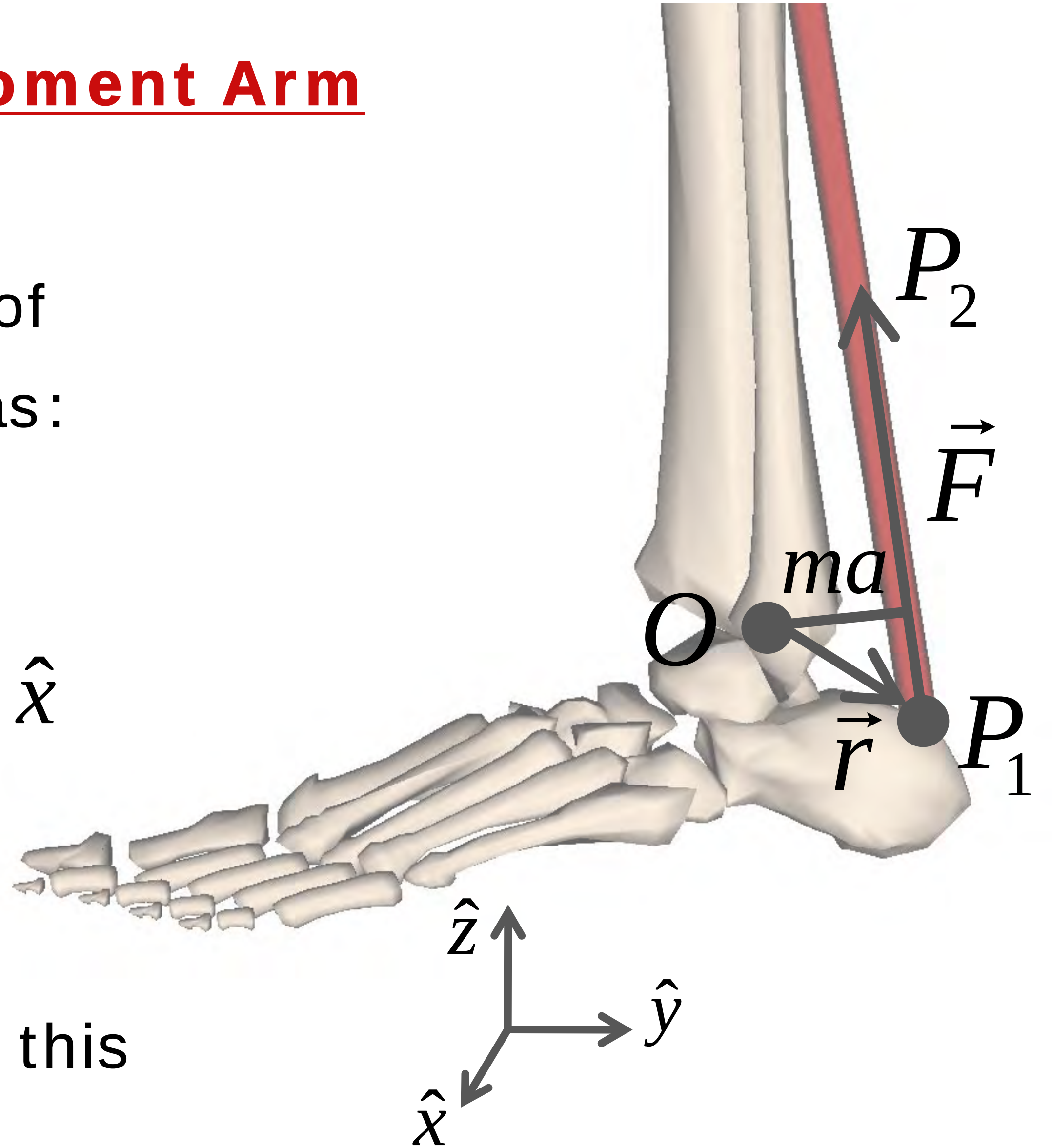
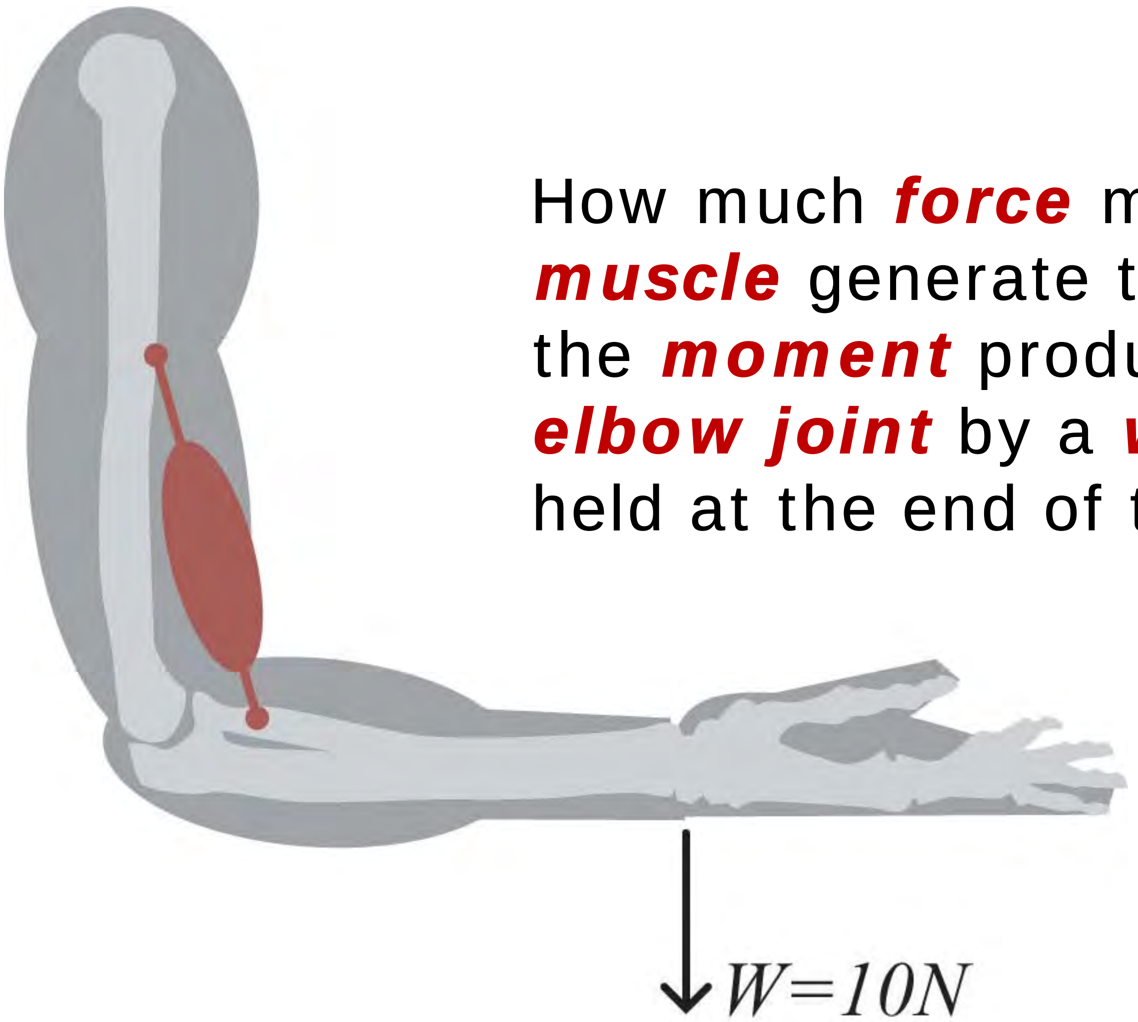
The moment arm of
$\vec{F}$ for $\hat{x}$ is defined as:

$$ma_x = \frac{\vec{r} \times \vec{F}}{\left|\vec{F}\right|} \bullet \hat{x}$$

Where do we get this ***geometry***?

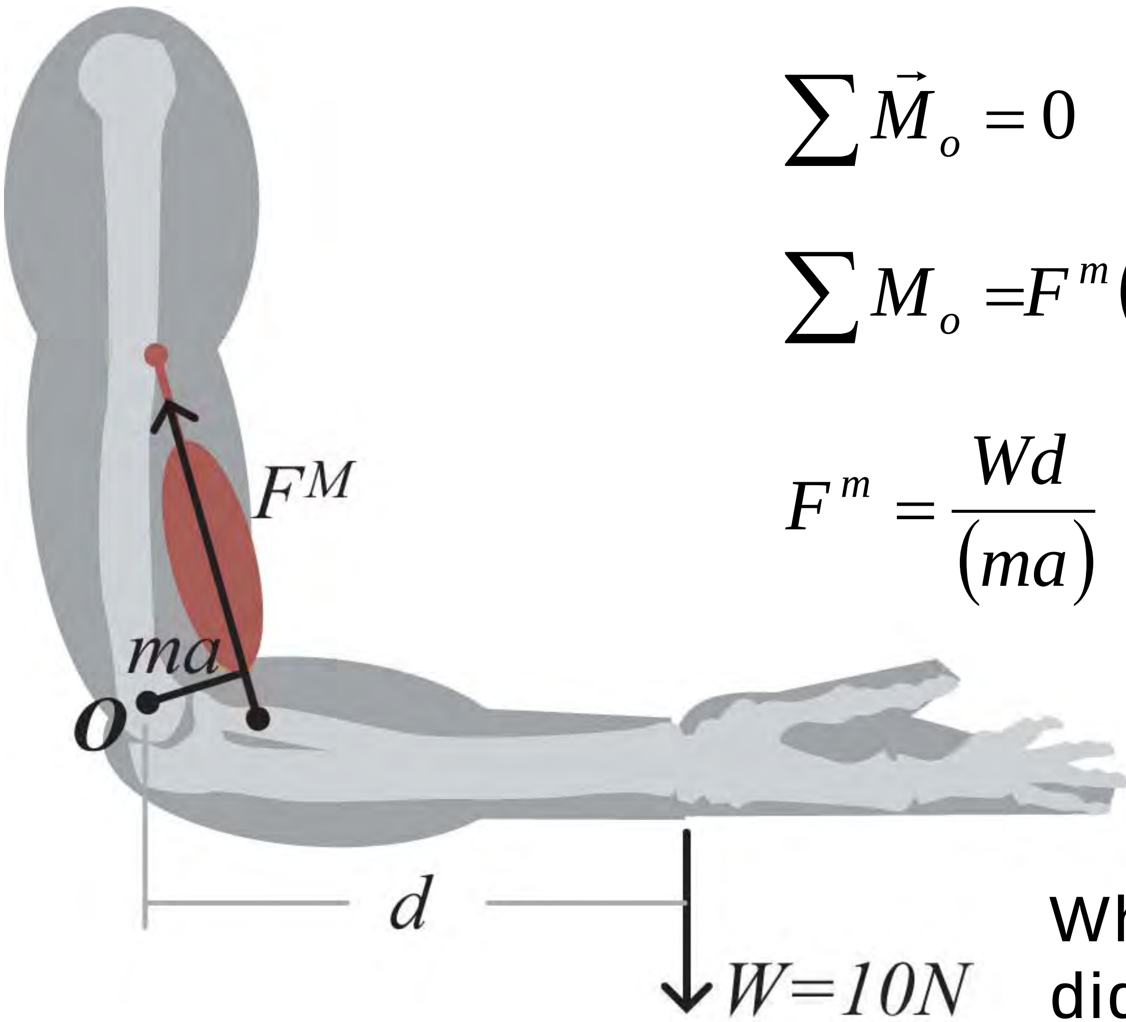


Planar Isometric Analysis



How much ***force*** must a ***muscle*** generate to ***balance*** the ***moment*** produced at the ***elbow joint*** by a ***weight*** being held at the end of the arm?

Planar Isometric Analysis



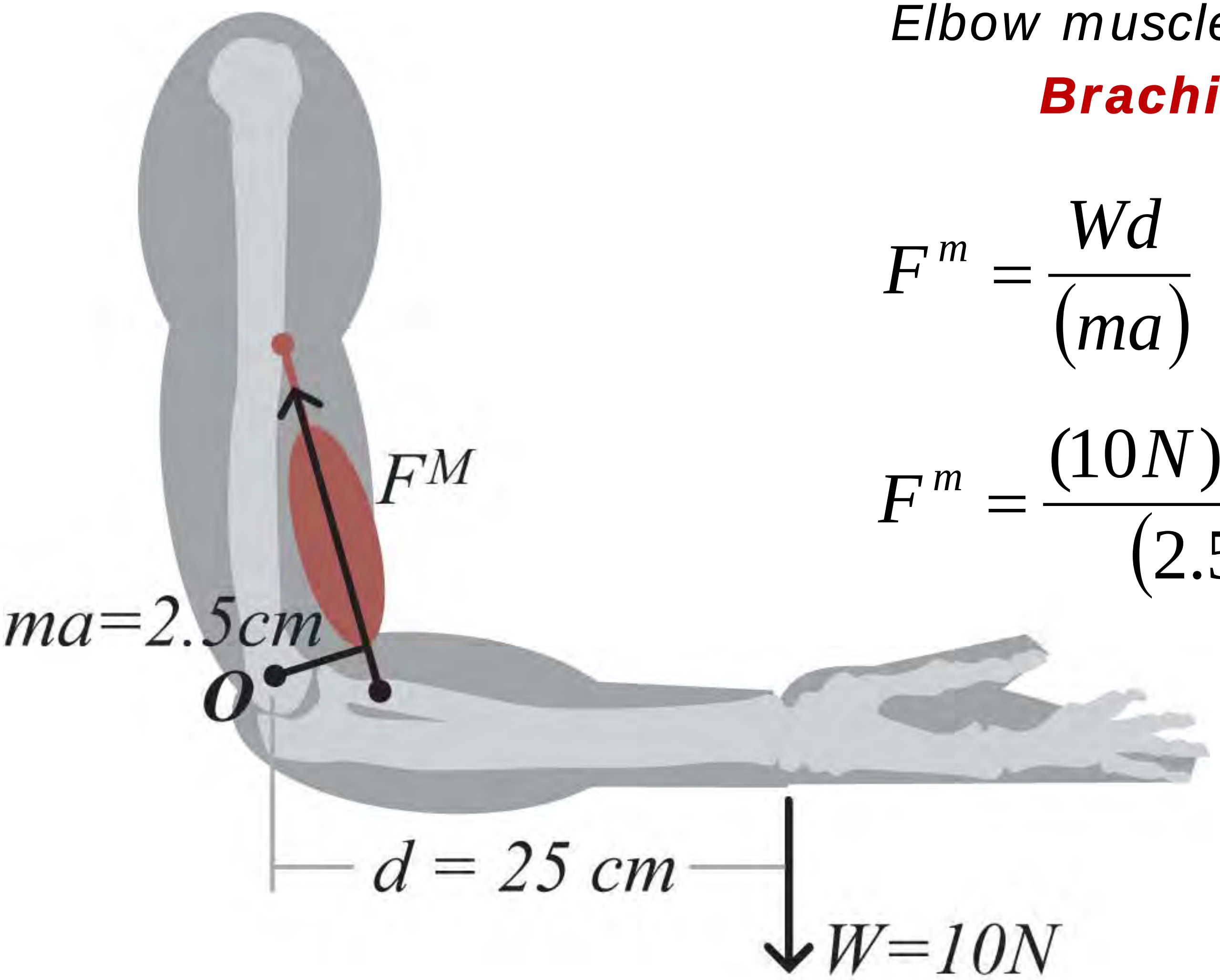
$$\sum \vec{M}_o = 0$$

$$\sum M_o = F^m(ma) - Wd = 0$$

$$F^m = \frac{Wd}{(ma)}$$

What ***assumptions*** did we make?

Planar Isometric Analysis



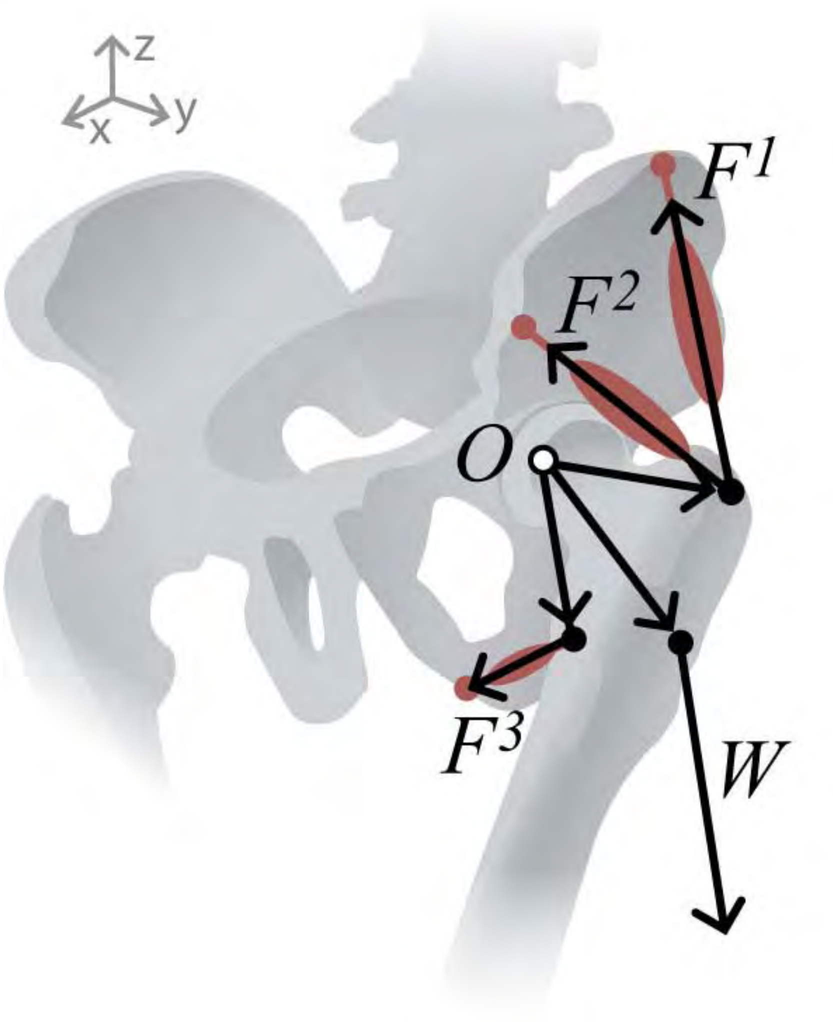
Elbow muscle ***moment arm****:*

Brachialis ~ 2.5 cm

$$F^m = \frac{Wd}{(ma)}$$

$$F^m = \frac{(10N)(25cm)}{(2.5cm)} = 100N$$

3D Isometric Analysis



$$\sum \vec{M}_o = 0$$

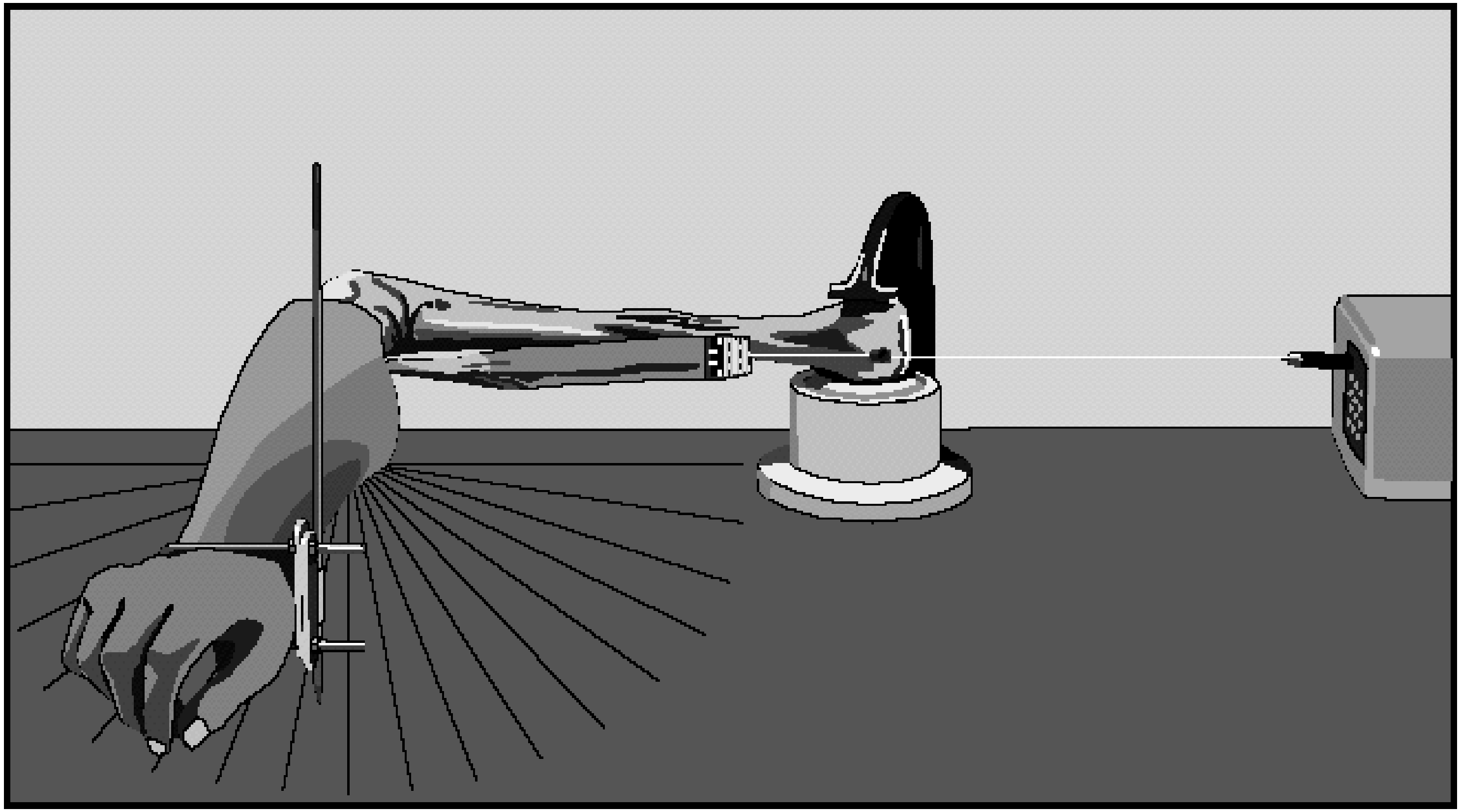
$$\left(\vec{r}_w \times \vec{W}\right) + \sum_{i=1}^{3} \left(\vec{r}_i \times \vec{F}^{\,i}\right) = 0$$

$$\left(\vec{r}_w \times \vec{W}\right) \cdot \hat{x} + \sum_{i=1}^{3} \left(\vec{r}_i \times \vec{F}^{\,i}\right) \cdot \hat{x} = 0$$

$$\left(\vec{r}_w \times \vec{W}\right) \cdot \hat{y} + \sum_{i=1}^{3} \left(\vec{r}_i \times \vec{F}^{\,i}\right) \cdot \hat{y} = 0$$

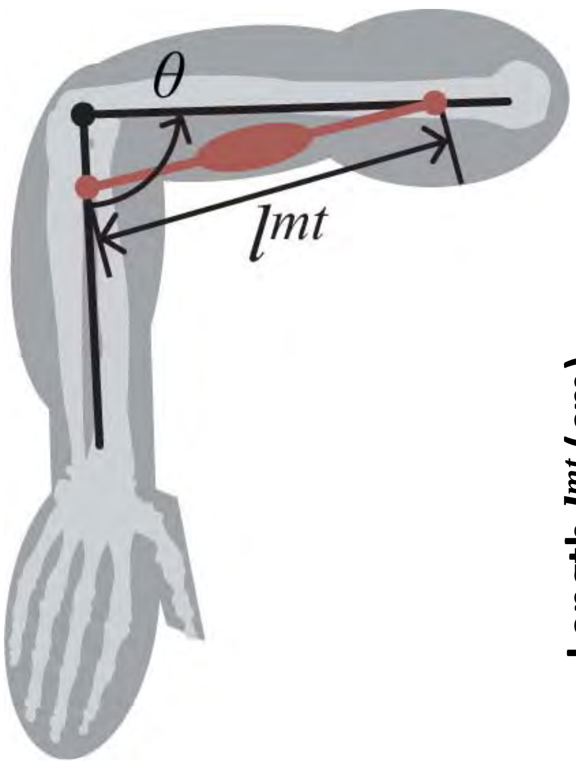
$$\left(\vec{r}_w \times \vec{W}\right) \cdot \hat{z} + \sum_{i=1}^{3} \left(\vec{r}_i \times \vec{F}^{\,i}\right) \cdot \hat{z} = 0$$

How Do We Measure Moment Arms?



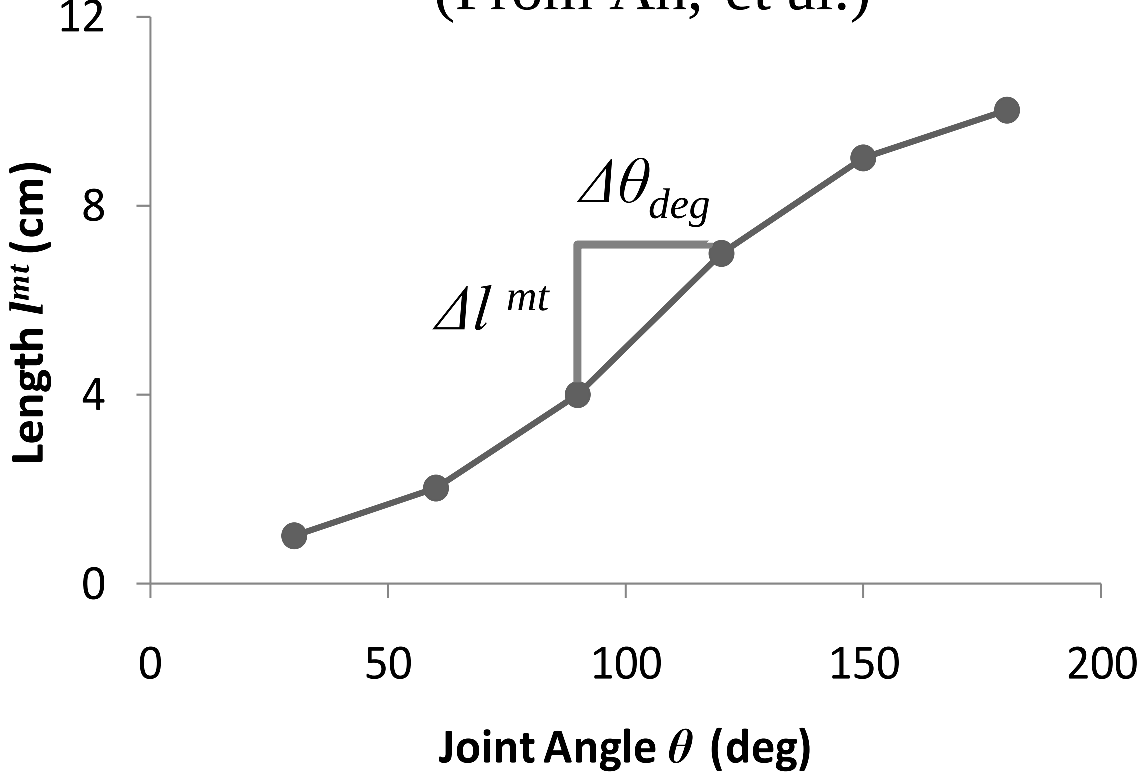
Murray, Delp and Buchanan, 1995

Muscle-tendon Length vs. Joint Angle

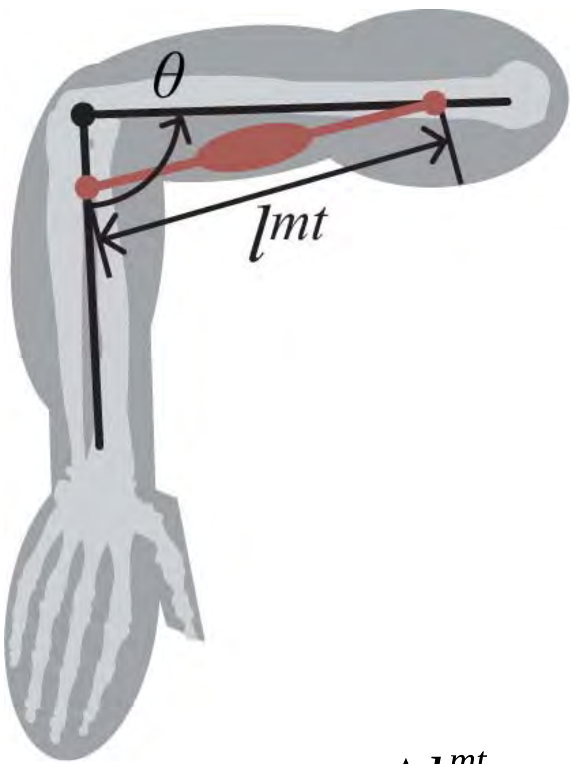


$$ma = \frac{\Delta l^{mt}}{\Delta \theta_{rad}}$$

(From An, et al.)



Sample Data: Joint Angle and Length



θ_{deg}	$\Delta\theta_{deg}$	$\Delta\theta_{rad}$	l^{mt} cm	Δl^{mt} cm	ma cm
30			1		
60			2		
90			4		
120			7		
150			9		
180			10		

$$ma = \frac{\Delta l^{mt}}{\Delta \theta_{rad}}$$

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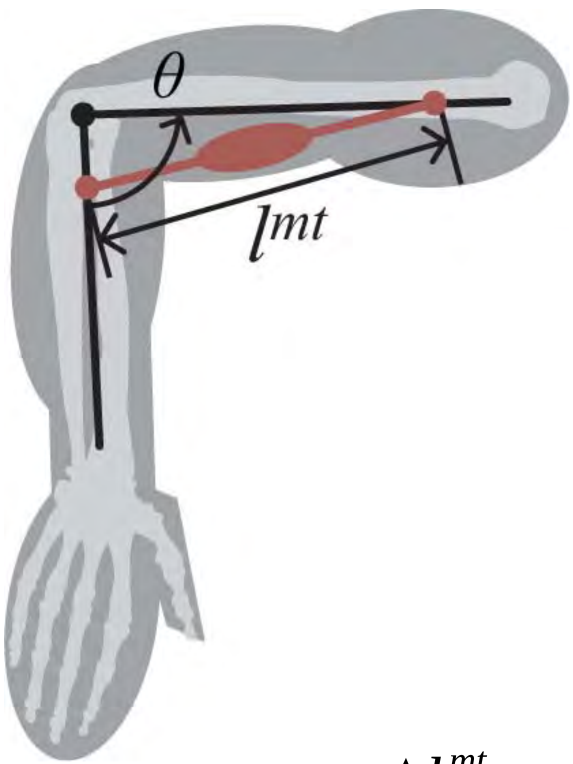
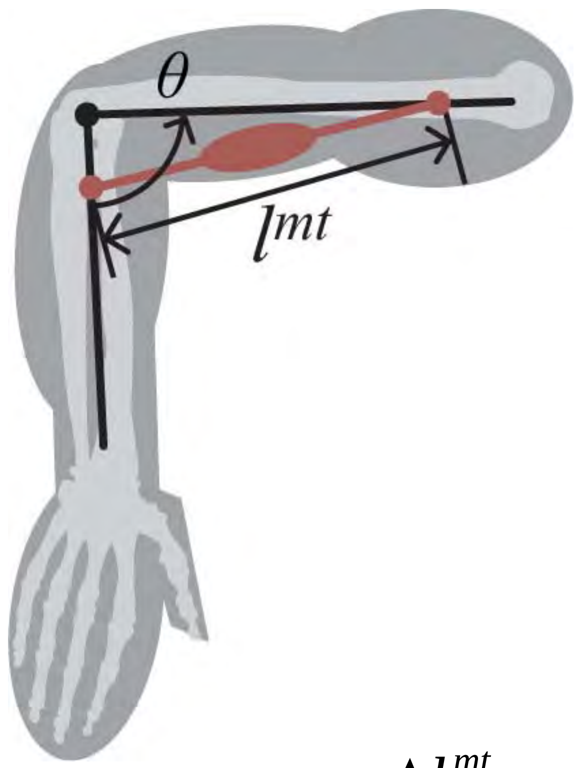


θ_{deg}	$\Delta\theta_{deg}$	$\Delta\theta_{rad}$	l^{mt} cm	Δl^{mt} cm	ma cm
30			1		
60	30		2	1	
90	30		4	2	
120	30		7	3	
150	30		9	2	
180	30		10	1	

$$ma = \frac{\Delta l^{mt}}{\Delta\theta_{rad}}$$

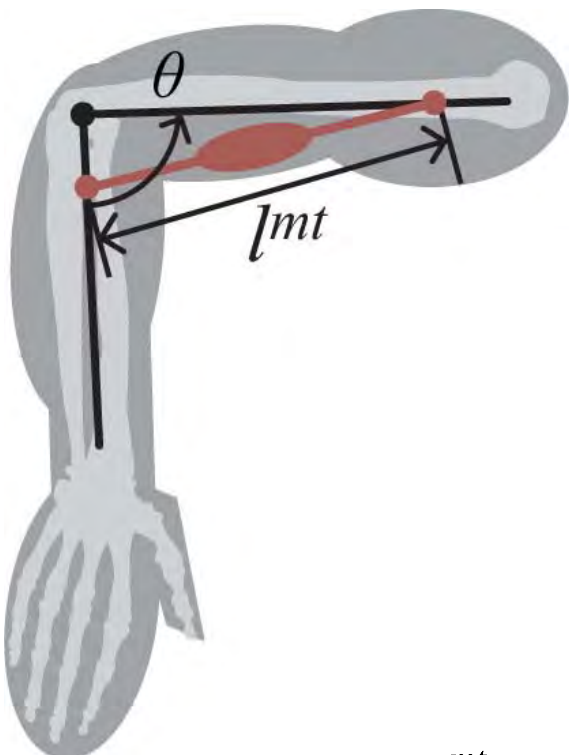
Sample Data: Joint Angle and Length



θ_{deg}	$\Delta\theta_{deg}$	$\Delta\theta_{rad}$	l^{mt} $_{cm}$	$\Delta l^{mt}{}_{cm}$	ma $_{cm}$
30			1		
60	30	0.5	2	1	
90	30	0.5	4	2	
120	30	0.5	7	3	
150	30	0.5	9	2	
180	30	0.5	10	1	

$$ma = \frac{\Delta l^{mt}}{\Delta\theta_{rad}}$$

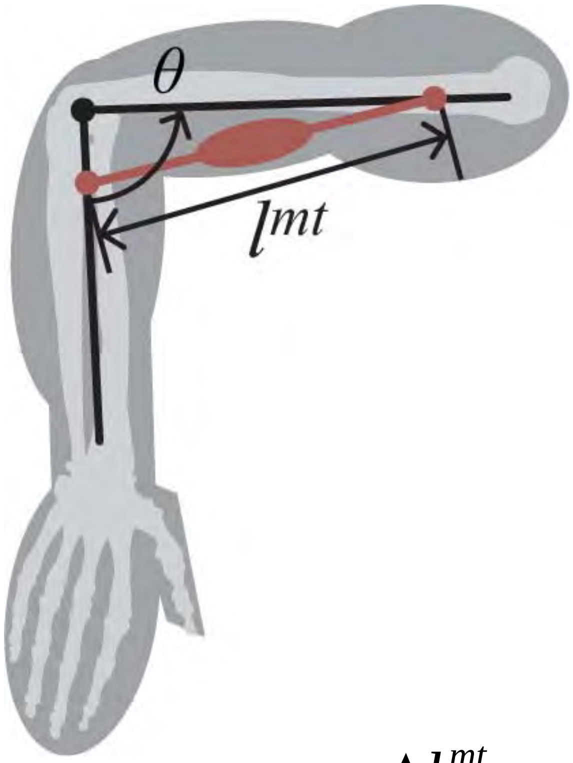
Sample Data: Joint Angle and Length

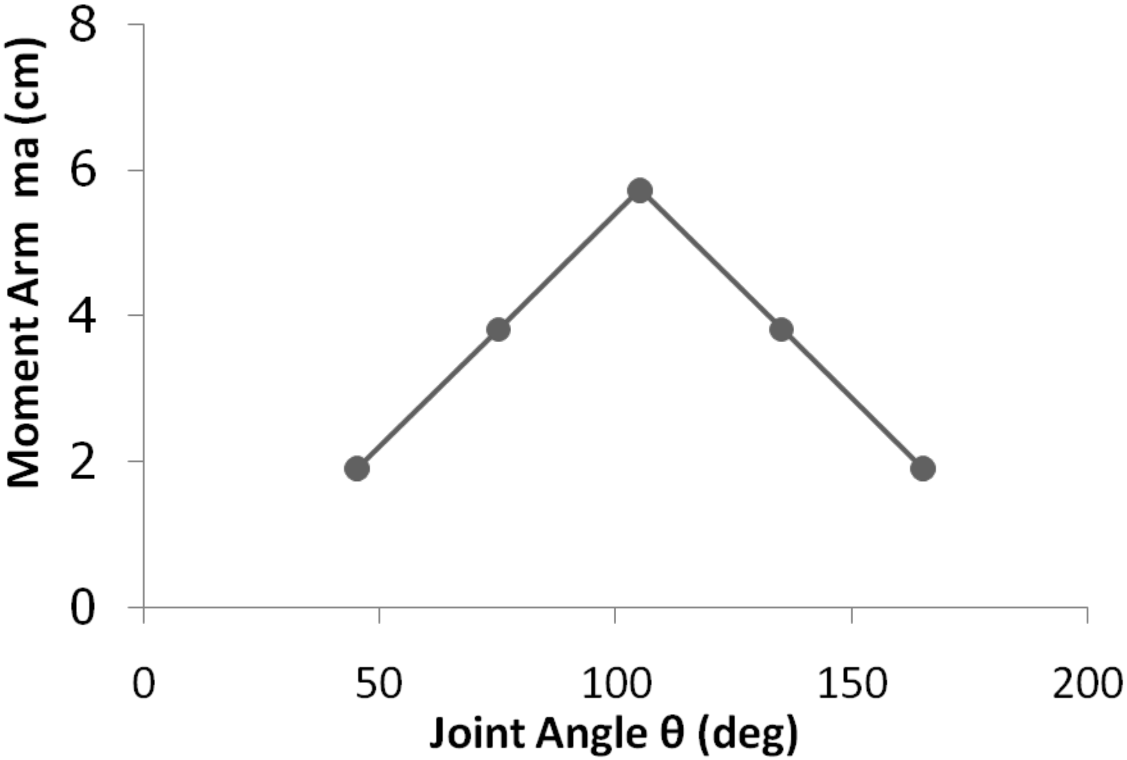


θ_{deg}	$\Delta\theta_{deg}$	$\Delta\theta_{rad}$	l^{mt} cm	Δl^{mt} cm	ma cm
30			1		
60	30	0.5	2	1	2
90	30	0.5	4	2	4
120	30	0.5	7	3	6
150	30	0.5	9	2	4
180	30	0.5	10	1	2

$$ma = \frac{\Delta l^{mt}}{\Delta \theta_{rad}}$$

Moment Arm vs. Joint Angle

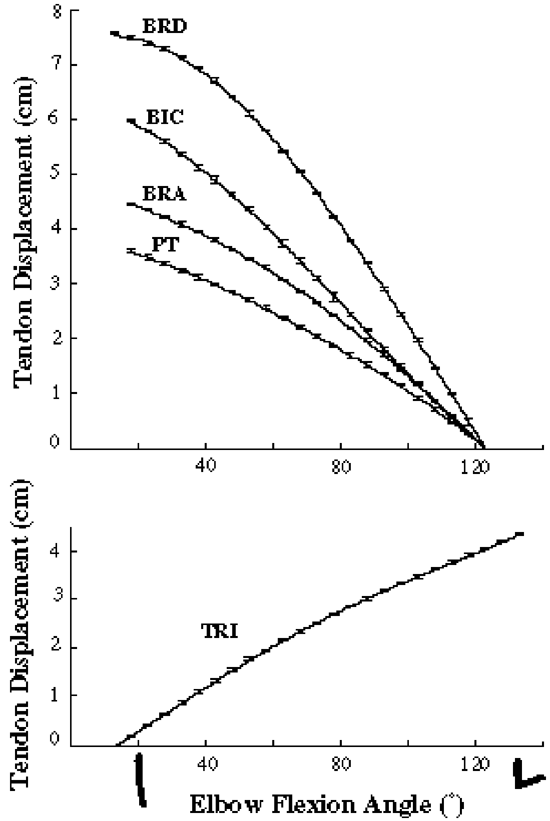




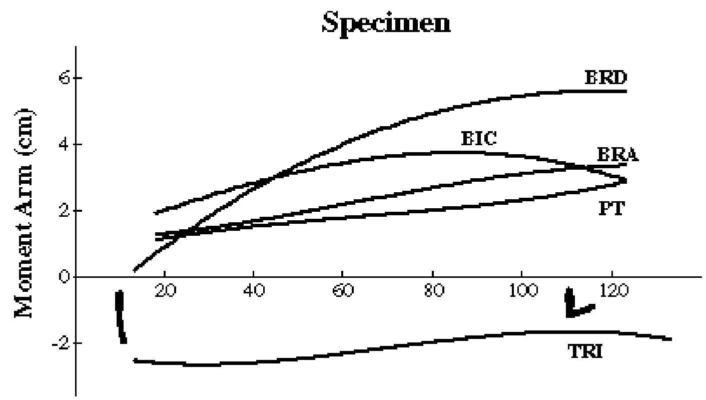
$$ma = \frac{\Delta l^{mt}}{\Delta \theta_{rad}}$$

Experimental Results

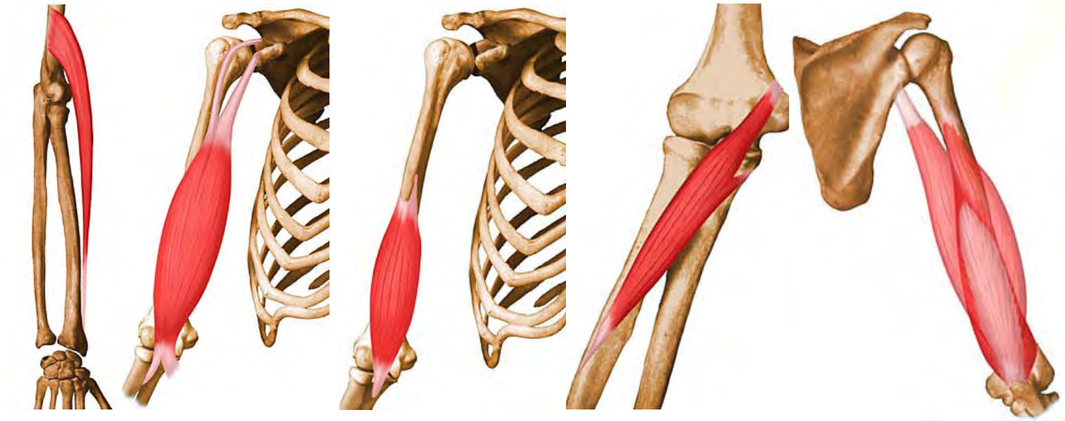
Displacements



Moment Arms



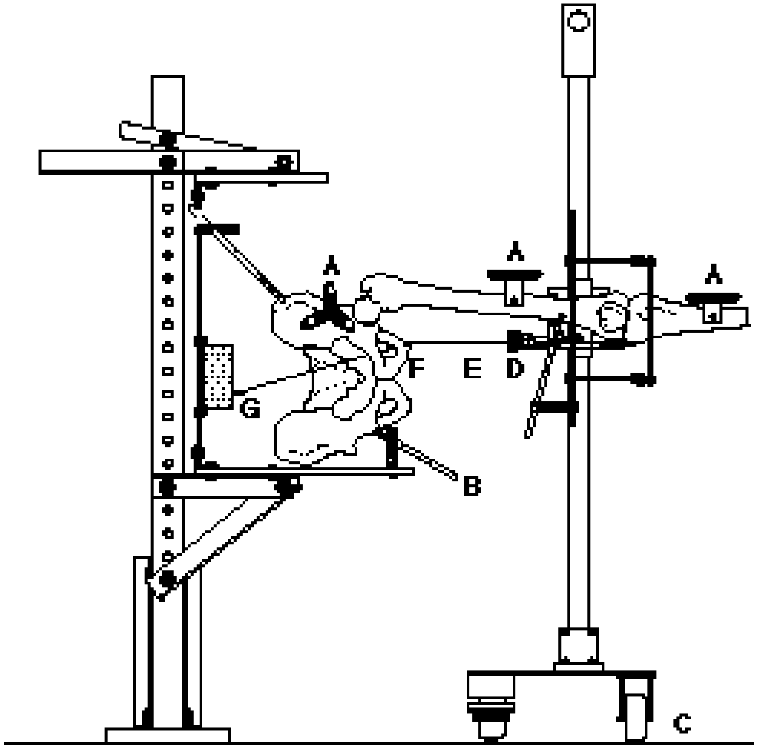
University of Washington

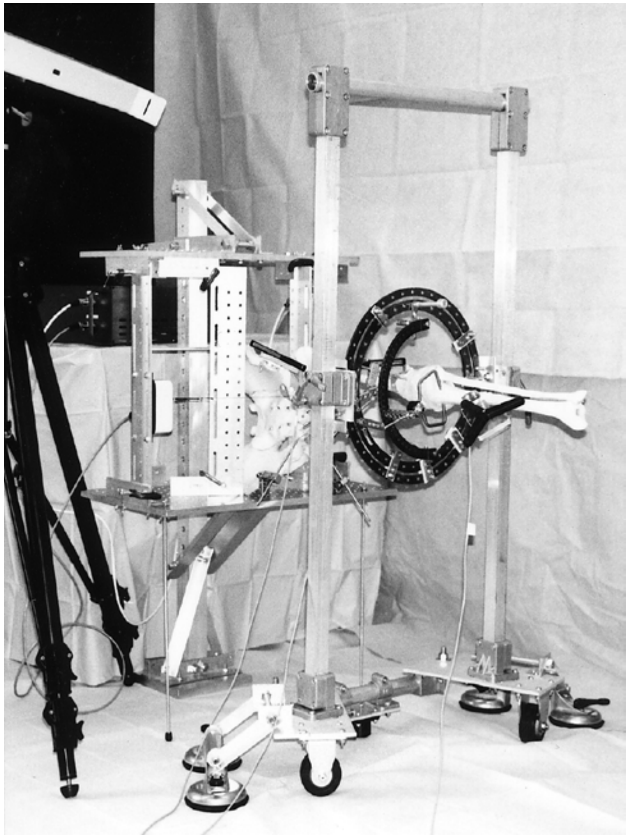


BRD BIC BRA PT TRI

Murray, Delp and Buchanan, 1994

Measuring Moment Arms



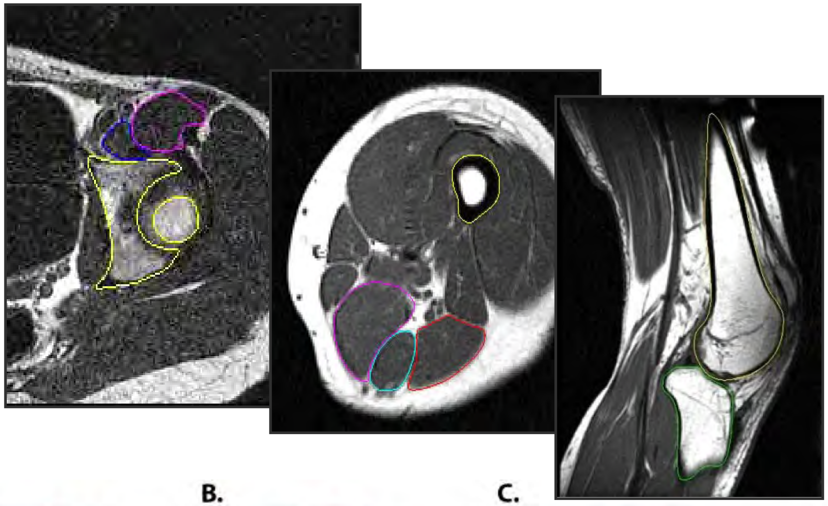


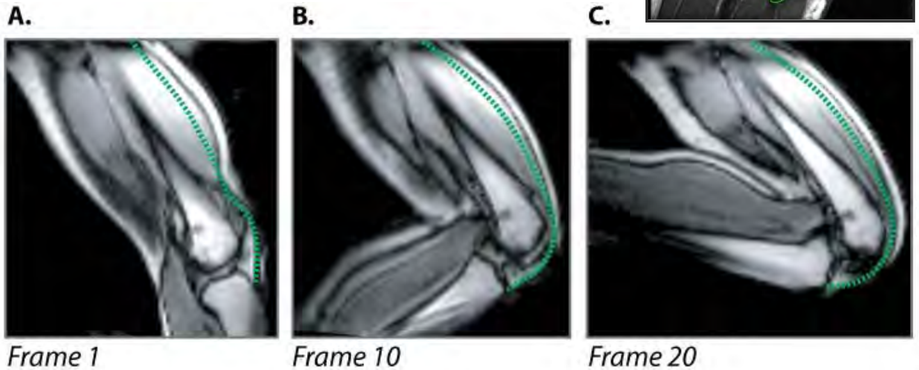
At the hip joint: ***three degrees of freedom***!

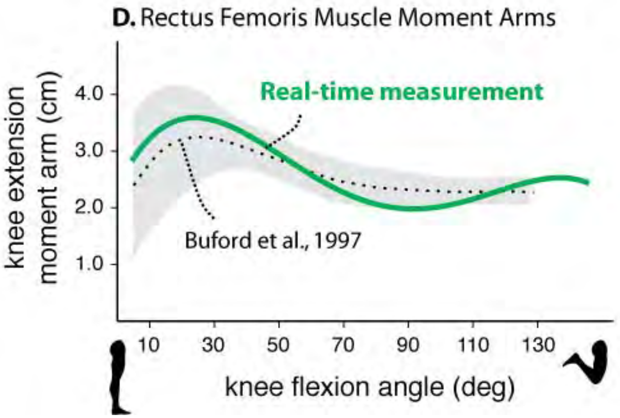
Measuring Moment Arms

What are ***other ways*** to ***determine moment arm***?

Is ***moment arm*** defined for a ***translational degree of freedom***?







Concept Test

Muscles with ***large moment arms*** undergo a ***larger change in length*** with joint rotation.

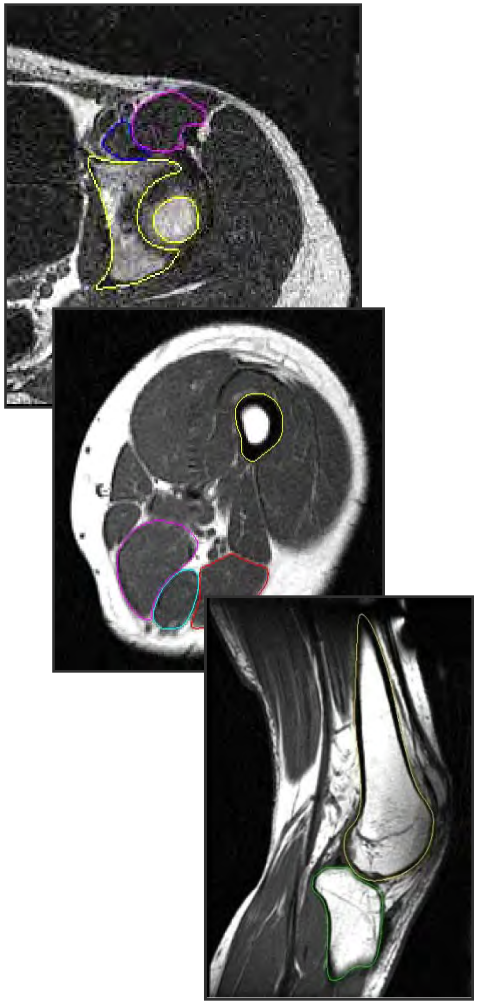
True or ***False***?

Draw this and ***convince yourself*** and your neighbor

Outline for Today

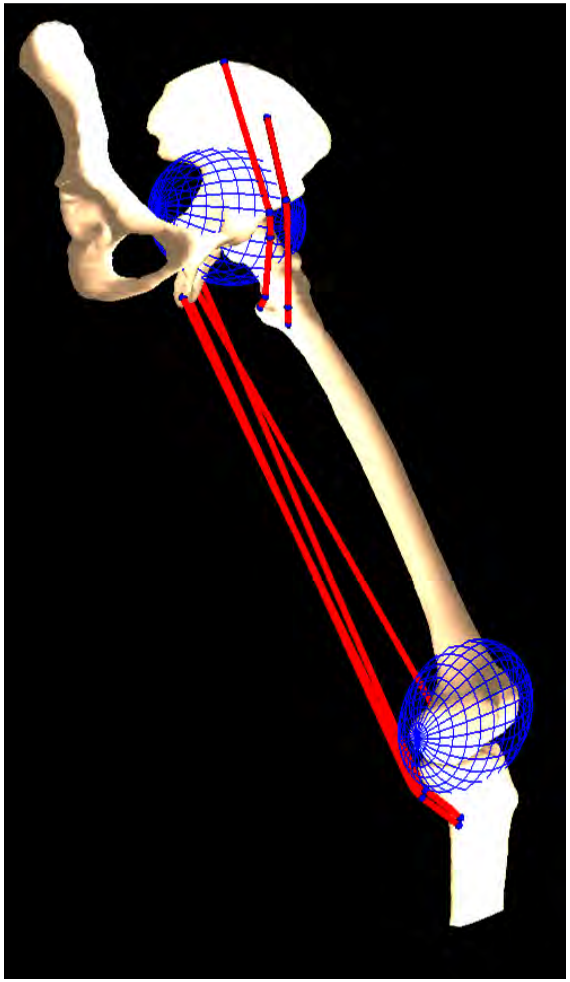
- Question of the day
- Musculoskeletal geometry
  - Motivation
  - Definition of a moment and moment arm
  - 2D and 3D examples
  - How to measure moment arms
- Modeling of geometry
- Arnold et al., 2000 (similar to Delp et al., 1999)
- Blemker et al., 2007
- Answer your questions!

Modeling Pipeline



MR images

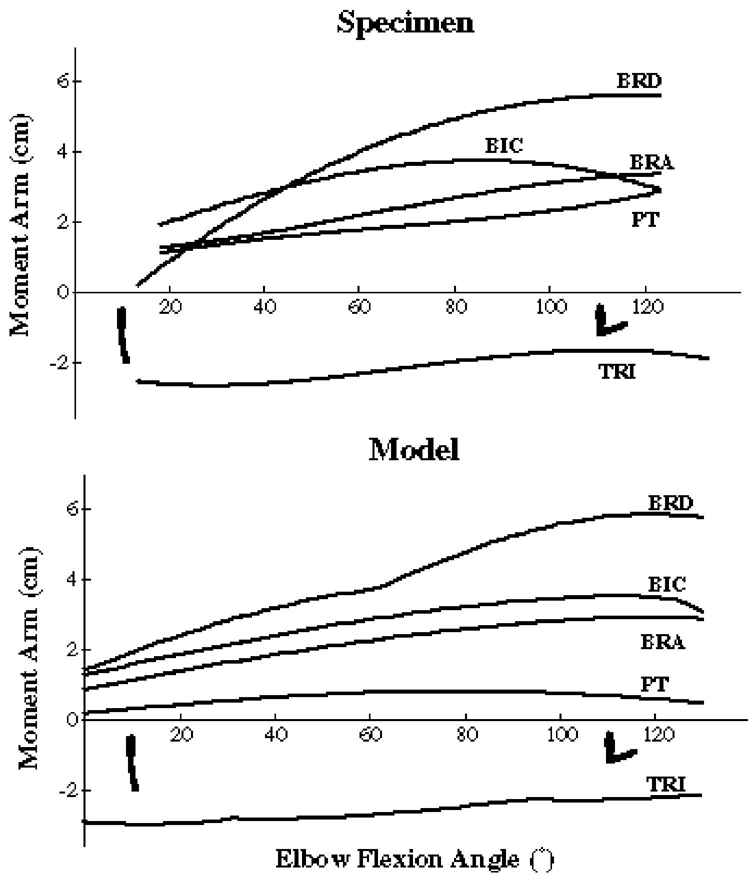
3D reconstruction

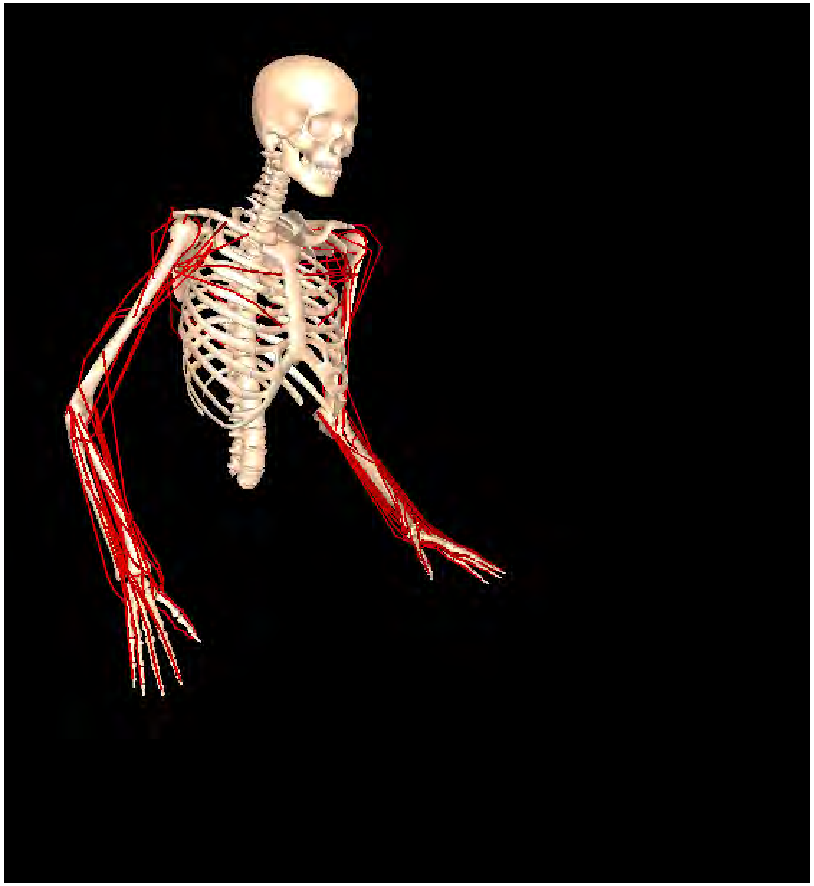


line muscles combined with geometric assumptions

Arnold et al., 2000

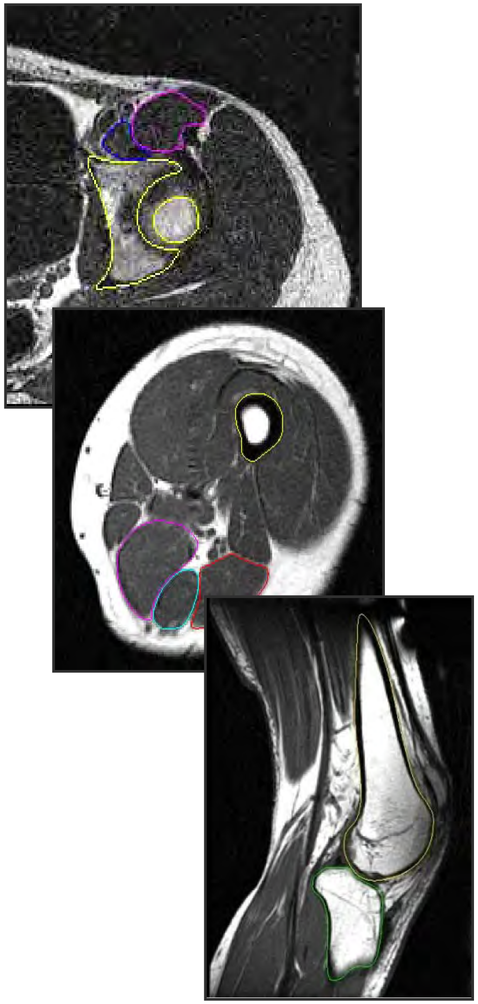
Measured vs Model Moment Arms





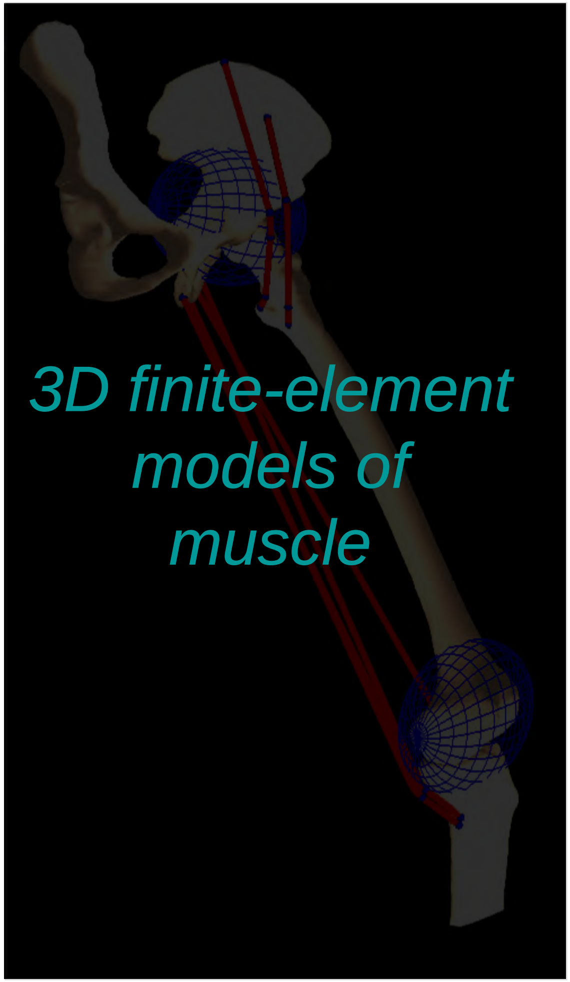
Murray, Delp and Buchanan, 1994

Future Modeling Pipeline



MR images

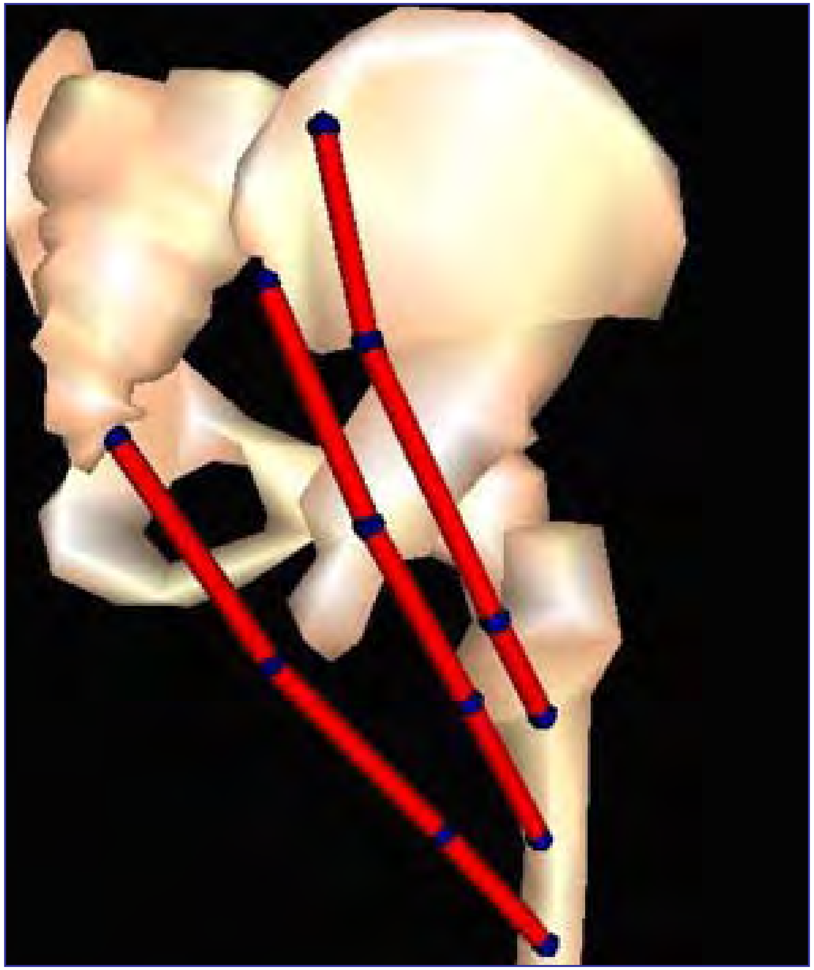
3D reconstruction



Arnold et al., 2000

Gluteus Maximus and Medius

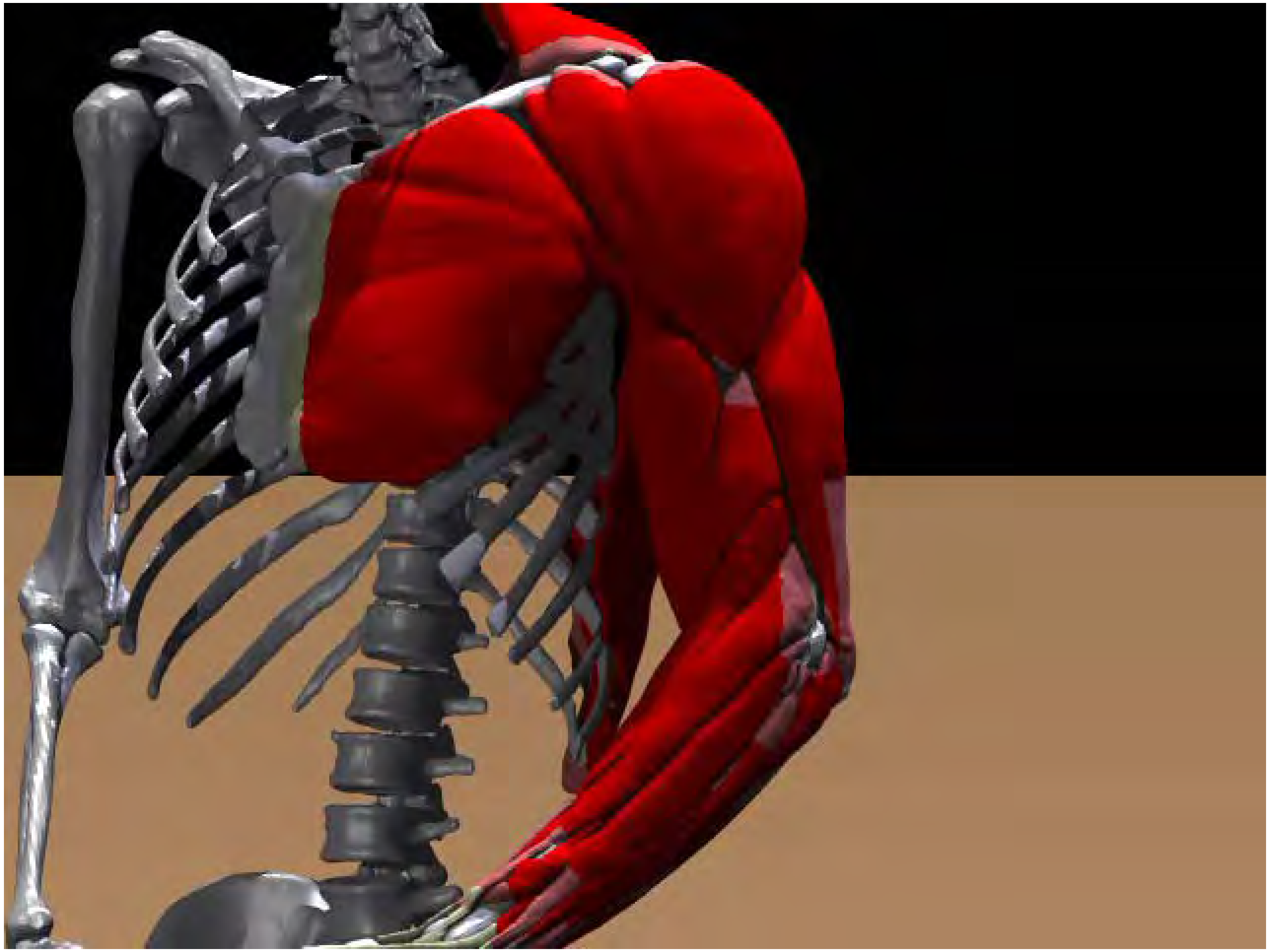
Current



Future

Blemker et al., 2005

Many Muscles, High Speed



Fedkiw Lab

Summary

- ***Questions*** we can answer:
  - ***What*** are ***moments*** and ***moment arms***?
  - ***How*** do we ***measure moments*** and ***moment arms***?
  - ***How*** do we ***model musculoskeletal geometry***?

- ***Problems*** we can solve:
  - ***Calculating muscle force*** from measurements of ***moment*** and ***moment arm***
  - ***Understanding*** how ***moment arm*** changes ***muscle function***

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- Blemker et al., 2007
- Answer your questions!

Arnold et al., 2000

Accuracy of Moment Arms

How did they evaluate ***accuracy*** of ***moment arms*** estimated from ***MRI***-based musculoskeletal models?

1. Develop geometric/kinematic ***models from MR images***
2. Experiment: ***tendon excursion measurements***
3. The ***moment arms*** of ***models compared to experiments***

Computer Aided Surgery 5:108–119 (2000)

Biomedical Paper

Accuracy of Muscle Moment Arms Estimated from MRI-Based Musculoskeletal Models of the Lower Extremity

Allison S. Arnold, Ph.D., Silvia Salinas, M.S., Deanna J. Asakawa, M.S., and Scott L. Delp, Ph.D.
Biomechanical Engineering Division, Mechanical Engineering Department, Stanford University

ABSTRACT **Objective:** Biomechanical models that compute the lengths and moment arms of soft tissues are broadly applicable to the treatment of movement abnormalities and the planning of orthopaedic surgical procedures. The goals of this study were to: (i) develop methods to construct subject-specific biomechanical models from magnetic resonance (MR) images, (ii) create models of three lower-extremity cadaveric specimens, and (iii) quantify the accuracy of muscle-tendon lengths and moment arms estimated using these models.

Materials and Methods: Models describing the paths of the medial hamstrings and psoas muscles for a wide range of body positions were developed from MR images in one joint configuration by defining kinematic models of the hip and knee, and by specifying "wrapping surfaces" that simulate interactions between the muscles and underlying structures. Our methods for constructing these models were evaluated by comparing hip and knee flexion moment arms estimated from models of three specimens to the moment arms determined experimentally on the same specimens. Because a muscle's moment arm determines its change in length with joint rotation, these comparisons also tested the accuracy with which the models could estimate muscle-tendon lengths over a range of hip and knee motions.

Results: Errors in the moment arms calculated with the models, averaged over functional ranges of hip and knee flexion, were less than 4 mm (within 10% of experimental values).

Conclusion: The combination of MR imaging and graphics-based musculoskeletal modeling provides an accurate and efficient means of estimating muscle-tendon lengths and moment arms in vivo. Comp Aid Surg 5:108–119 (2000).

Key words: musculoskeletal model, magnetic resonance imaging, muscle, moment arm, hip, knee

INTRODUCTION

Surgeons frequently lengthen "tight" muscles in persons with cerebral palsy in an attempt to improve ambulation.[4,24] For example, children who walk with excessive flexion of their knees often have their hamstrings lengthened in an effort to diminish the crouched posture, increase the efficiency of movement, and prevent the progression of deformities. Exaggerated hip flexion during walking is commonly treated by surgical lengthening of the psoas muscle at the pelvic brim. Unfortunately, the outcomes of soft-tissue procedures to correct crouch gait and other movement abnormalities in persons with neuromuscular disorders are unpredictable and sometimes unsatisfactory.[24] We

Address correspondence/reprint requests to: Scott L. Delp, Biomechanical Engineering Division, Mechanical Engineering Department, Stanford, CA 94305-3030; Telephone: (650) 723-1230; Fax: (650) 725-1587; E-mail: delp@leland.stanford.edu.

Final paragraph of Introduction and in Methods

Arnold et al., 2000

MS Model Development

What is the process to go ***from MR images to graphics-based model***?

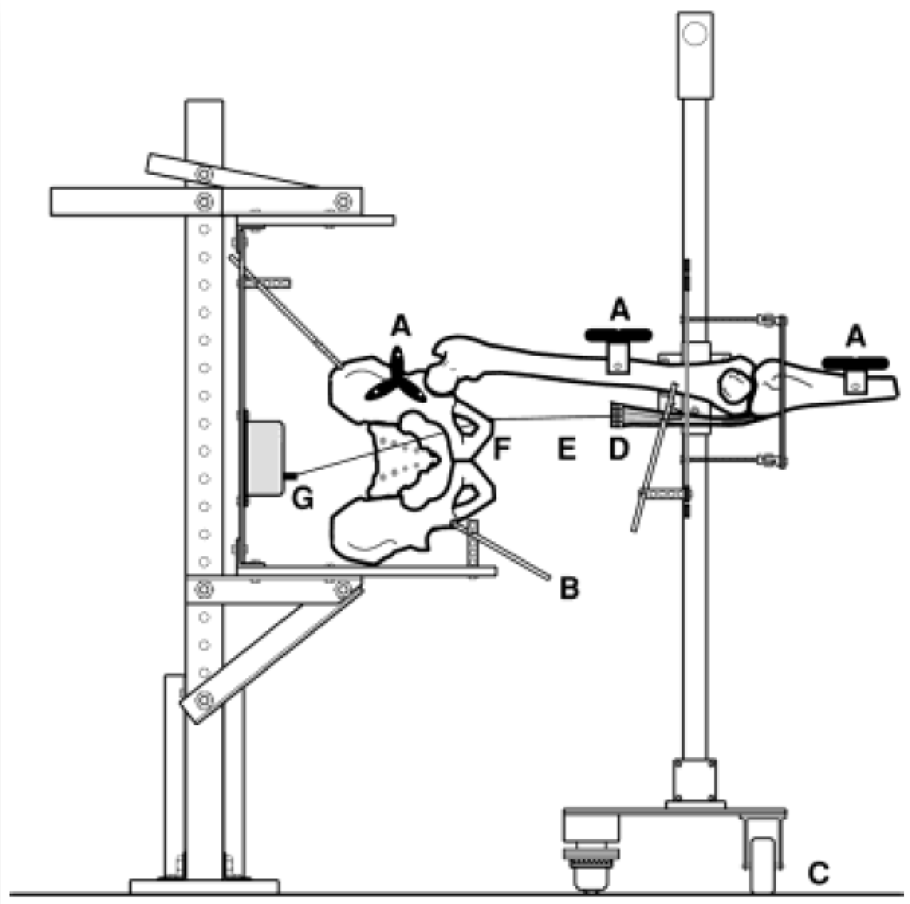
1. Acquire MR images (250)
2. Identify and outline anatomical structures (pelvis, femur, tibia, psoas, semitendinosus, and semimembranosus) in each image
3. Generate 3D surfaces from 2D outlines
4. Register surfaces from adjacent images
5. Scale models to each cadaver specimen
6. Specify muscle-tendon paths

First four sections of Methods

Arnold et al., 2000

Tendon Excursion Measurements

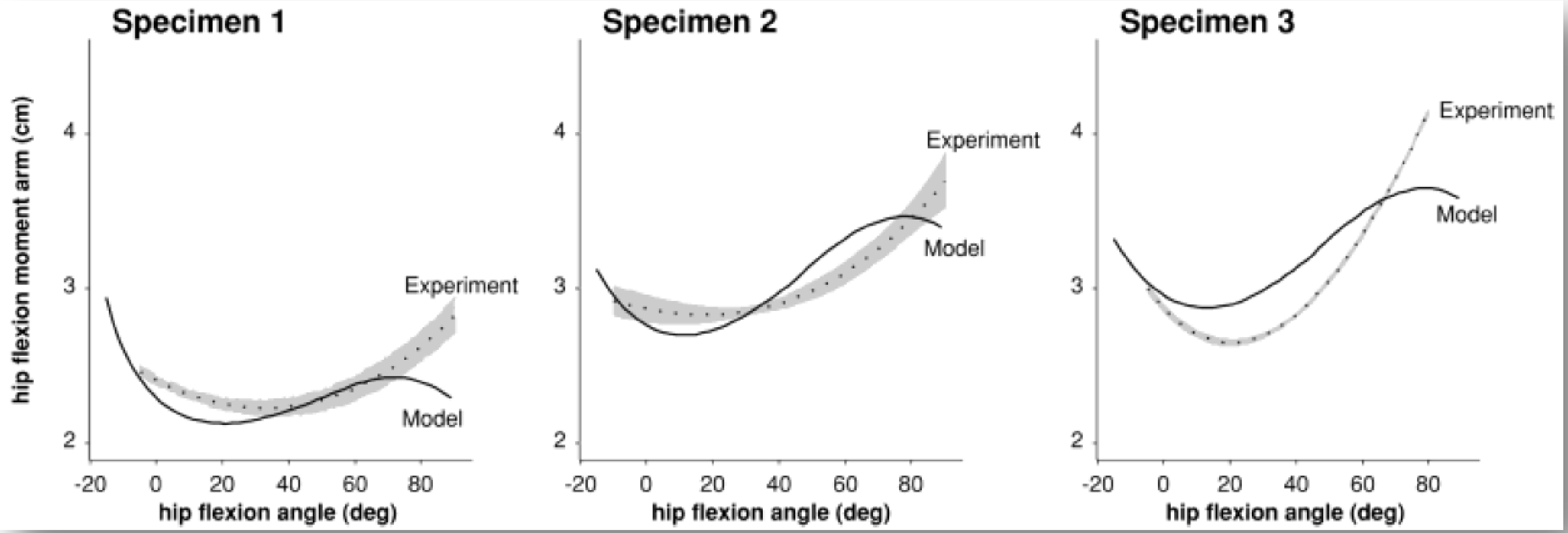
- ***Measure length changes of muscles*** through range of hip and knee angles
- Muscle ***moment arms*** computed as ***partial derivative*** of muscle-tendon ***length with respect to joint angle***



Fifth section of Methods

Arnold et al., 2000

Moment Arms of Models Compared to Experiments



- ***Psoas*** errors averaged 1.1 to 2.7 mm (5 to 8%)

Arnold et al., 2000

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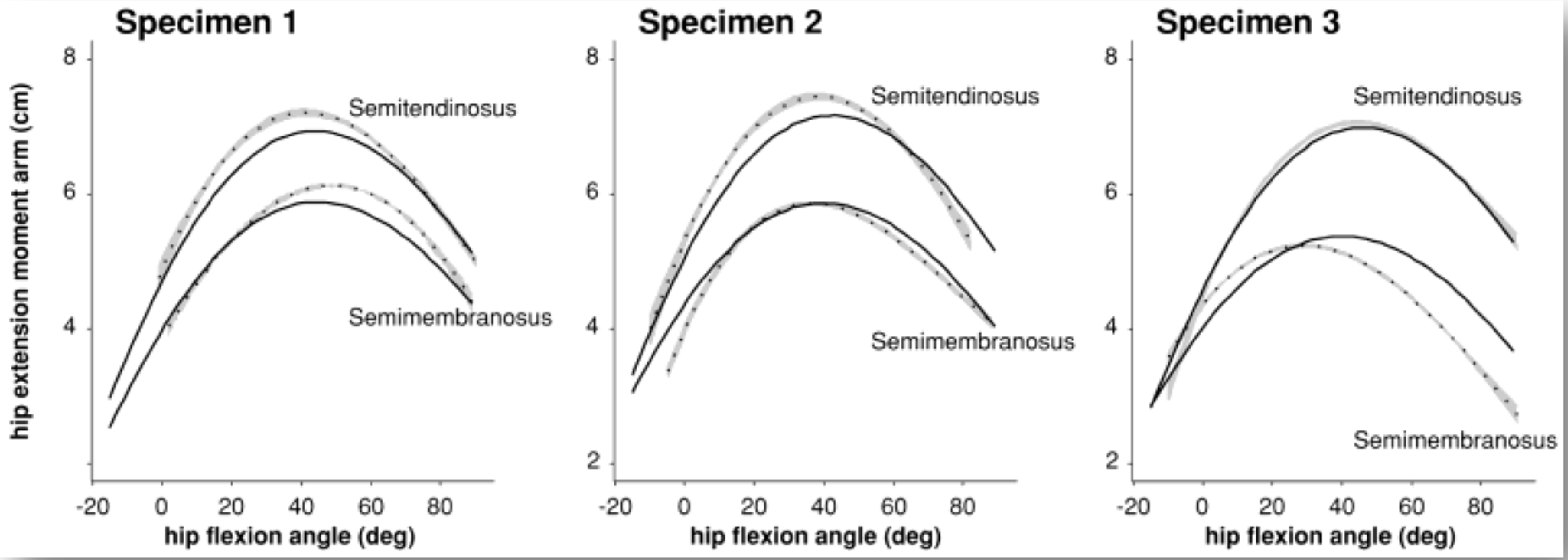
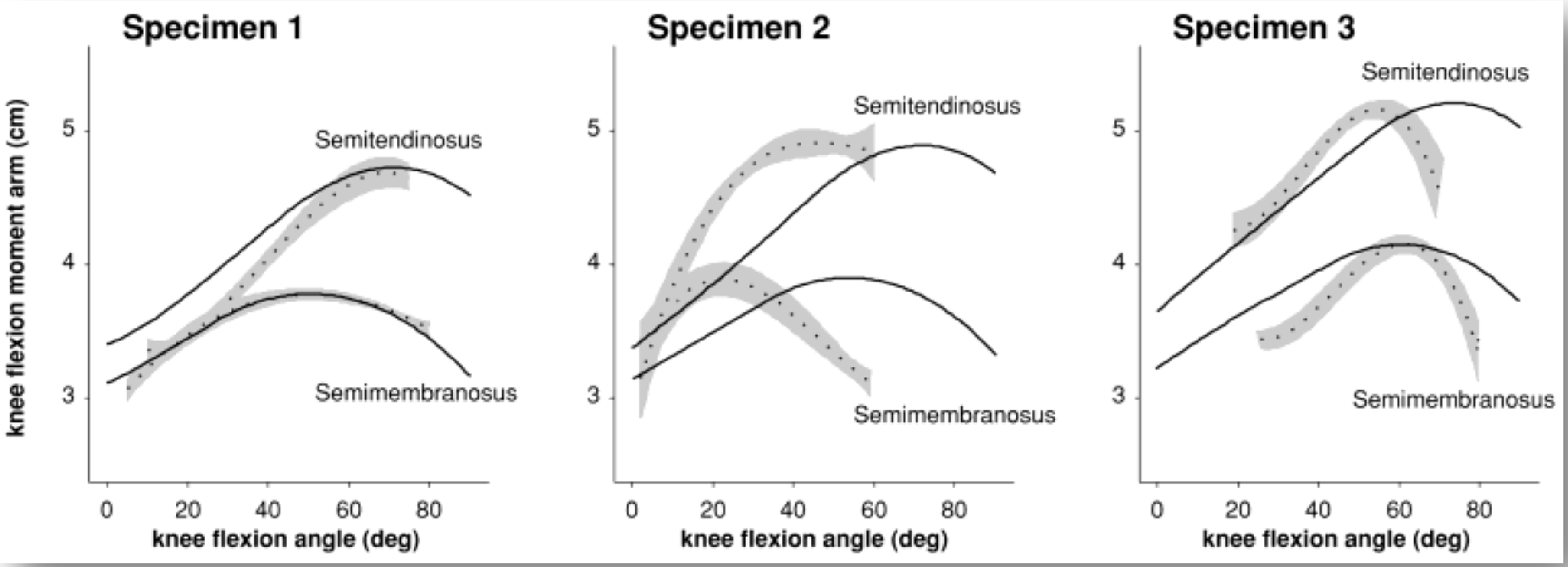


- ***Semimembranosus*** errors averaged 1.0 to 3.8 mm (2 to 9%)
- ***Semitendinosus*** errors averaged 1.3 to 2.5 mm (2 to 4%)

Arnold et al., 2000

Moment Arms of Models Compared to Experiments



- ***Semimembranosus*** errors averaged 0.1 to 3.5 mm (<1 to 10%)
- ***Semitendinosus*** errors averaged 1.8 to 3.9 mm (5 to 9%)

Arnold et al., 2000

Assumptions and Limitations

What are some ***critiques*** of procedures in this study?

1. Hip is a ball-and-socket (not subluxed or dislocated)
2. Knee motion from literature (not subject specific)
3. Line segment muscles with paths from scanned positions (not the full range of motion)
4. Experimental errors (muscle-tendon-suture stretching, speciment alignment, etc.)

Fifth paragraph of Discussion

Computer Aided Surgery 5:108–119 (2000)

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Materials and Methods: Models describing the paths of the medial hamstrings and psoas muscles for a wide range of body positions were developed from MR images in one joint configuration by defining kinematic models of the hip and knee, and by specifying "wrapping surfaces" that simulate interactions between the muscles and underlying structures. Our methods for constructing these models were evaluated by comparing hip and knee flexion moment arms estimated from models of three specimens to the moment arms determined experimentally on the same specimens. Because a muscle's moment arm determines its change in length with joint rotation, these comparisons also tested the accuracy with which the models could estimate muscle-tendon lengths over a range of hip and knee motions.

Results: Errors in the moment arms calculated with the models, averaged over functional ranges of hip and knee flexion, were less than 4 mm (within 10% of experimental values).

Conclusion: The combination of MR imaging and graphics-based musculoskeletal modeling provides an accurate and efficient means of estimating muscle-tendon lengths and moment arms in vivo. Comp Aid Surg 5:108–119 (2000). ©2000 Wiley-Liss, Inc.

Key words: musculoskeletal model, magnetic resonance imaging, muscle, moment arm, hip, knee

INTRODUCTION

Surgeons frequently lengthen "tight" muscles in persons with cerebral palsy in an attempt to improve ambulation.[4,24] For example, children who walk with excessive flexion of their knees often have their hamstrings lengthened in an effort to diminish the crouched posture, increase the efficiency of movement, and prevent the progression of deformities. Exaggerated hip flexion during walking is commonly treated by surgical lengthening of the psoas muscle at the pelvic brim. Unfortunately, the outcomes of soft-tissue procedures to correct crouch gait and other movement abnormalities in persons with neuromuscular disorders are unpredictable and sometimes unsatisfactory.[24] We

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Outline for Today

- Question of the day
- Musculoskeletal geometry
  - Motivation
  - Definition of a moment and moment arm
  - 2D and 3D examples
  - How to measure moment arms
- Modeling of geometry
- Arnold et al., 2000 (similar to Delp et al., 1999)
- Blemker et al., 2007
- Answer your questions!

Blemker et al., 2007

Problems with Current Paradigm

What are two important ***problems for using models*** to study individual patients?

1. Models ***represent anatomy and function of average adult*** subjects
   - no deformities, altered joint kinematics, age differences, etc.
2. Models make ***simplifying assumptions***
   - all muscle fibers shorten uniformly

JOURNAL OF MAGNETIC RESONANCE IMAGING 25:441–451 (2007)

Invited Review

Image-Based Musculoskeletal Modeling: Applications, Advances, and Future Opportunities

Silvia S. Blemker, PhD,[1,5*] Deanna S. Asakawa, PhD,[2] Garry E. Gold, MD,[4] and Scott L. Delp, PhD[2,3]

Computer models of the musculoskeletal system are broadly used to study the mechanisms of musculoskeletal disorders and to simulate surgical treatments. Musculoskeletal models have historically been created based on data derived in anatomical and biomechanical studies of cadaveric specimens. MRI offers an abundance of novel methods for acquisition of data from living subjects and is revolutionizing the field of musculoskeletal modeling. The need to create accurate, individualized models of the musculoskeletal system is driving advances in MRI techniques including static imaging, dynamic imaging, diffusion imaging, body imaging, pulse-sequence design, and coil design. These techniques apply to imaging musculoskeletal anatomy, muscle architecture, joint motions, muscle moment arms, and muscle tissue deformations. Further advancements in image-based musculoskeletal modeling will expand the accuracy and utility of models used to study musculoskeletal and neuromuscular impairments.

Key Words: skeletal muscle; biomechanics; human movement; muscle architecture; magnetic resonance imaging; dynamic imaging; musculoskeletal modeling
J. Magn. Reson. Imaging 2007;25:441–451.

THE OUTCOMES OF SURGERIES to correct disabling movement abnormalities are unpredictable, and sometimes unsuccessful. Theoretically, patients' abnormal movement patterns can be improved by identifying the biomechanical factors that contribute to abnormal movement and designing treatments accordingly. However, many factors can contribute to the abnormal movement. For example, persons with cerebral palsy exhibit disturbances in voluntary control (1), muscle spasticity (2), static muscle contractures (3), bone deformities that alter muscle paths (4), and limb malalignment (5). Current diagnostic methods do not allow clinicians to reliably differentiate between the potential causes of abnormal movement to determine the most appropriate treatment.

We believe that computer models of the musculoskeletal system can help provide a scientific basis for treating movement disorders. Models allow us to answer "what if" questions, isolate individual sources for impairment, and estimate parameters, such as muscle forces, that are difficult to measure experimentally. In recent years, computational models that characterize the three-dimensional surface geometry of bones, kinematics of joints, and the force-generating capacity of muscles have emerged as powerful tools for investigating muscle function. Models have been used to simulate orthopedic procedures, such as osteotomies (6,7), tendon transfers (8–11), tendon lengthenings (12,13), and total joint replacements (14–16). Musculoskeletal models, combined with dynamic simulation, have been used to understand normal (17) and pathological human movement (18).

These model-based studies have provided clinically useful insights and general guidelines; however, the results may have limited applicability to the treatment of individual patients. There have been limited sources for data that can be used to create musculoskeletal models and to test the predictions made by simulating treatments. The input parameters are typically based on an accumulation of cadaveric measurements from a range of studies. The predictions made by musculoskeletal models are tested with average data from unimpaired adult populations. These traits pose two important problems for using models to study individual patients.

First, the models generally represent the musculoskeletal anatomy and function of average adult subjects [e.g., Delp et al (19)]. It is not clear how musculoskeletal deformities or even simply variations in size

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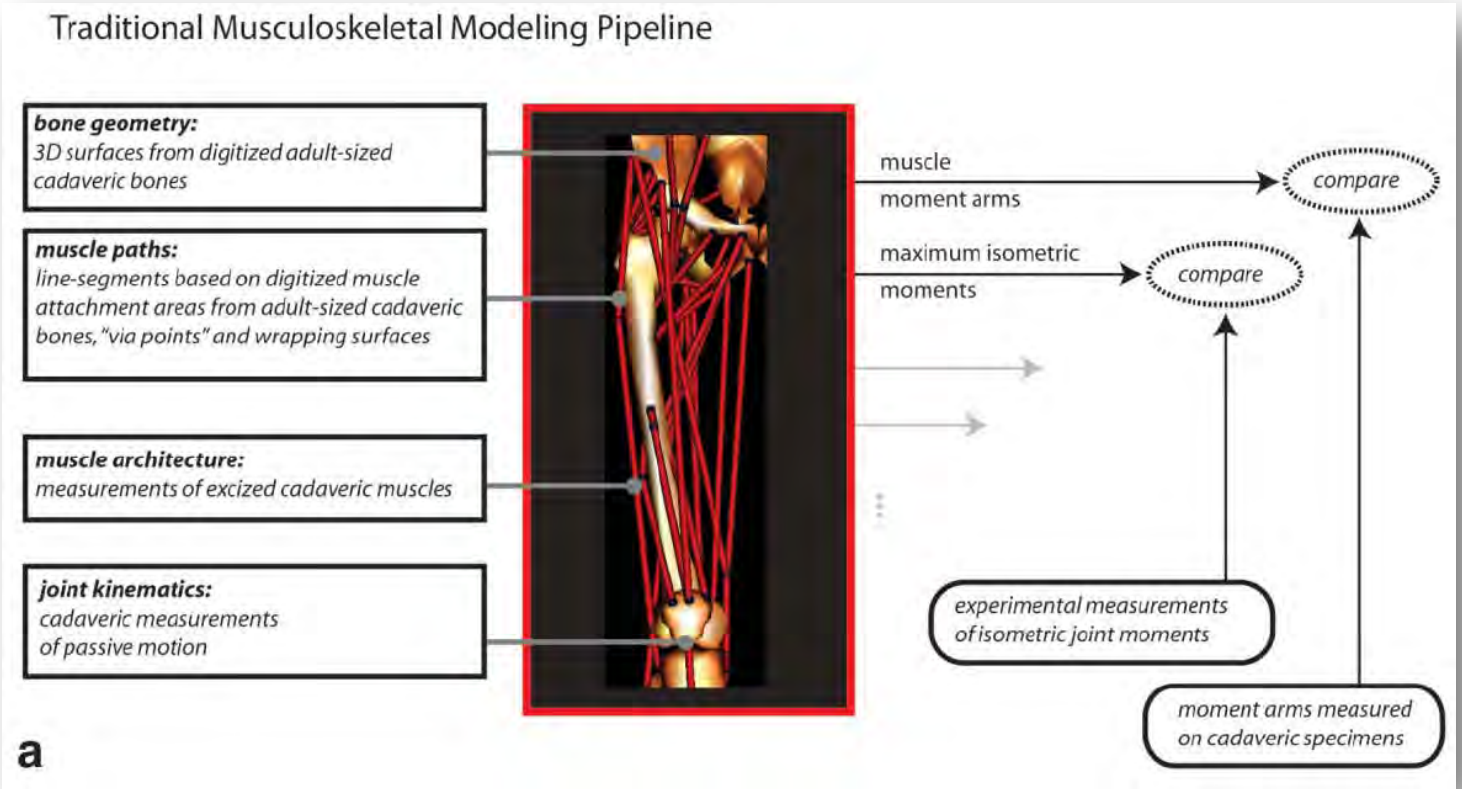
Fourth and fifth paragraphs of first section

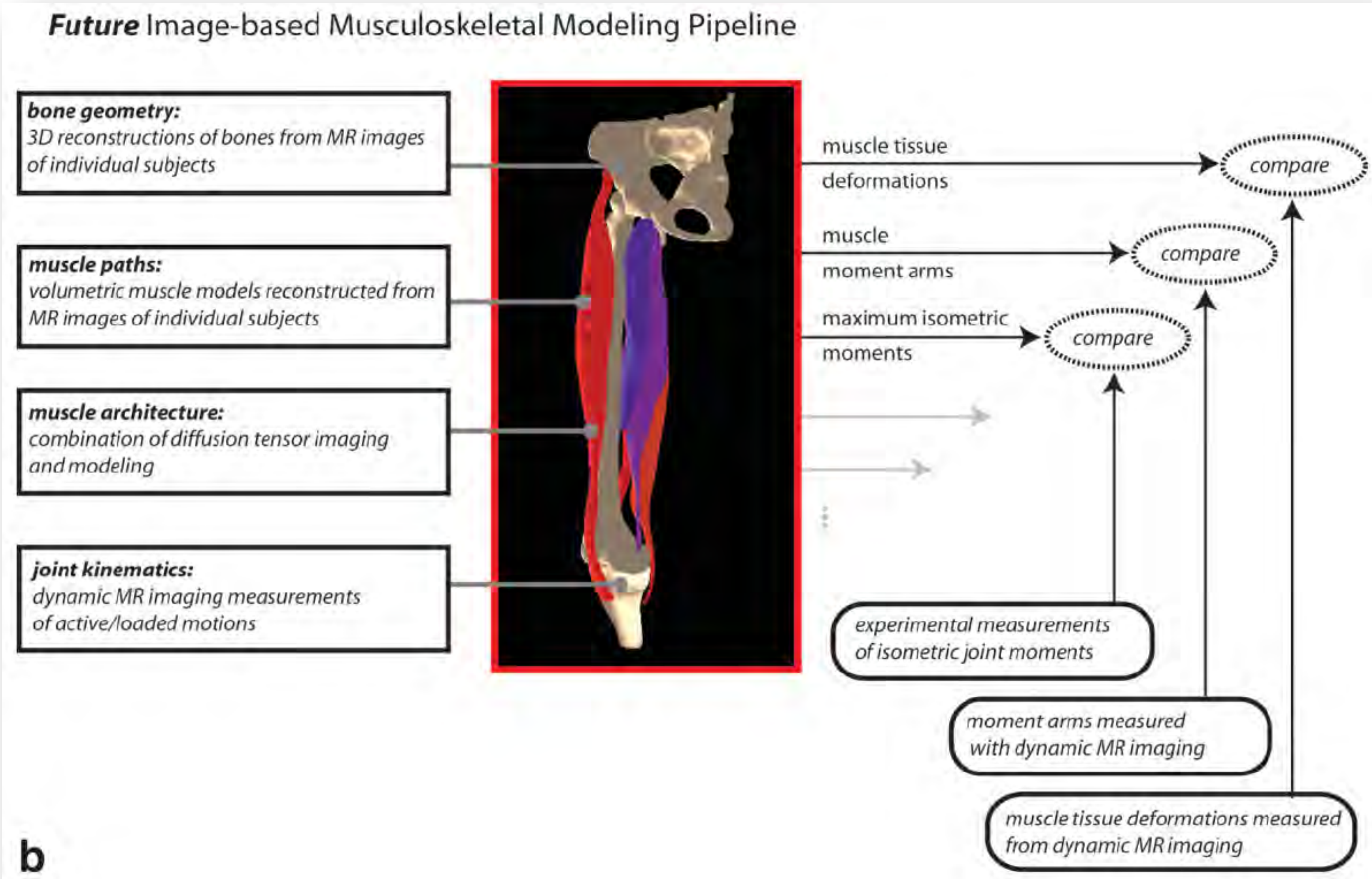
Blemker et al., 2007

Traditional MS Modeling Pipeline



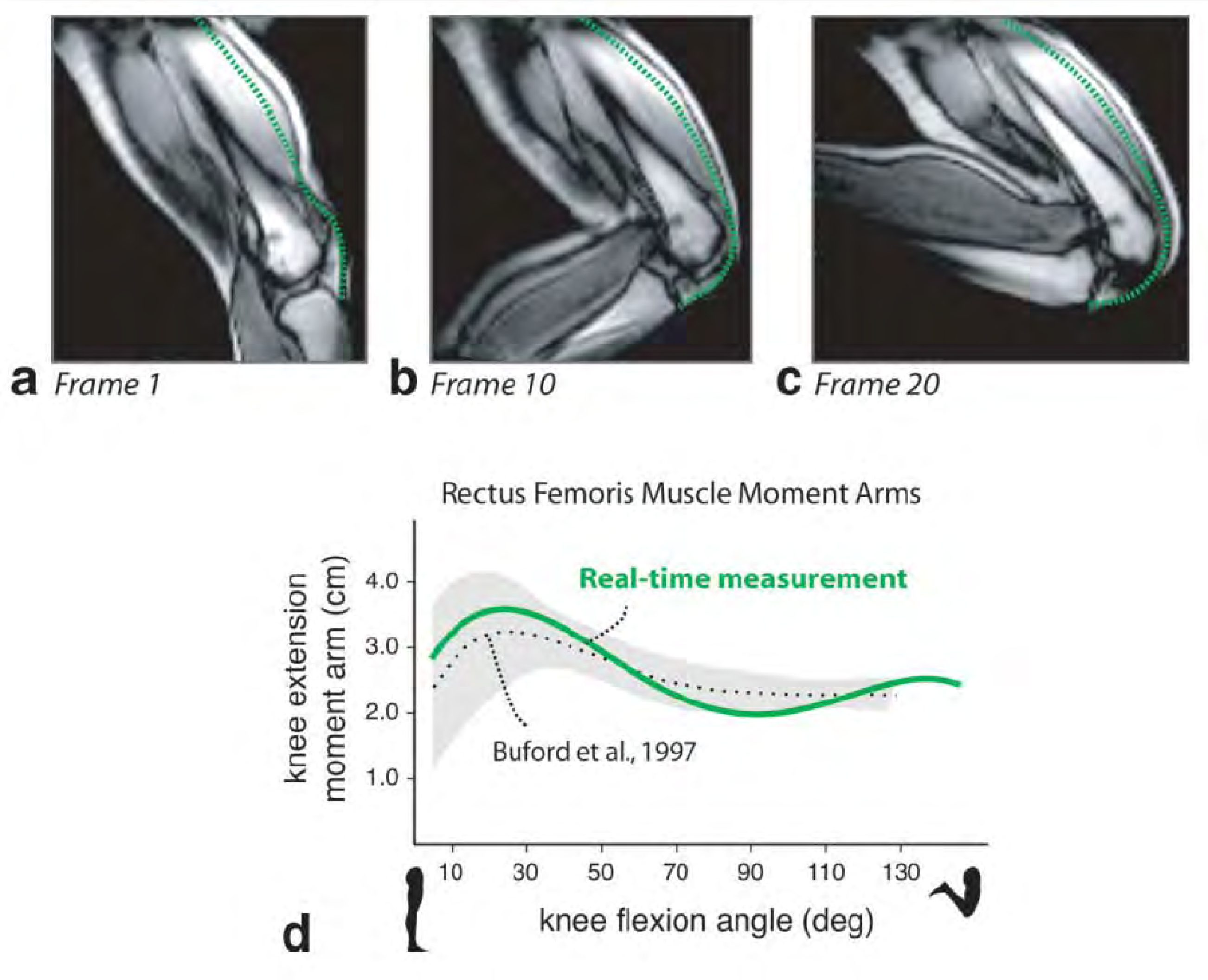
Blemker et al., 2007

Future MS Modeling Pipeline



Blemker et al., 2007

Imaging Muscle Moment Arms



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For Next Time…

- Read ***articles*** #9 & #10 of the Course Reader
  - ***Lu & O'Connor, 1999*** ***(reviewed by Katie)***
  - ***De Groote et al., 2008*** ***(reviewed by Nicholas)***
- Continue to think about topics for your ***individual research project (proposal due the week of Feb 6)***
- Continue working on ***Simulation Lab #1***! ***Due Jan 31***