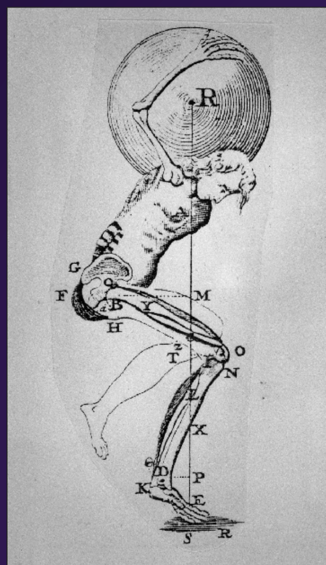


Musculoskeletal Biomechanics

BIOEN 520 | ME 599R

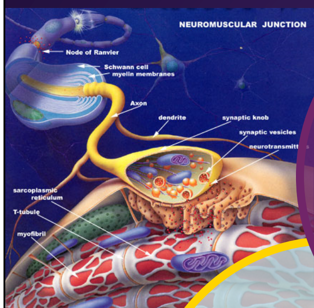
Session 10

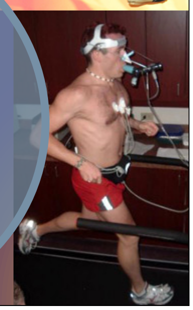
Structure-Function-Properties of Muscle

Plan for Today

- What's cool about muscle?
- Muscle structure and biology
- Basic muscle properties
  - Force-length relationship
  - Force-velocity relationship
- Tools for evaluating muscle function

MUSCLE: The Ultimate Actuator



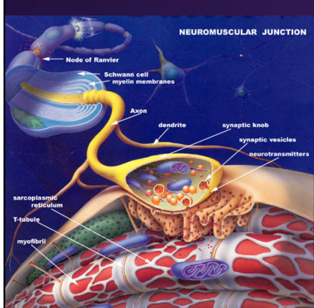


Mechanics
Muscles generate force and motion

Control
Muscles turn on and off

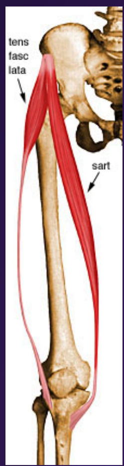
Energetics
Muscles get and use energy

MUSCLE: The Ultimate Actuator

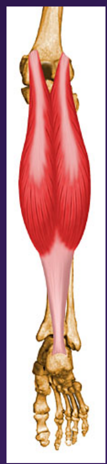


- Muscle links your CNS to the world.
- The structure is fantastic!
  - cross bridges working together
  - fascicle structure and metabolic machinery
  - architecture of whole muscles
- Math represents the biology pretty well.
- Tastes great medium rare.

Basic Rules of Muscle Function



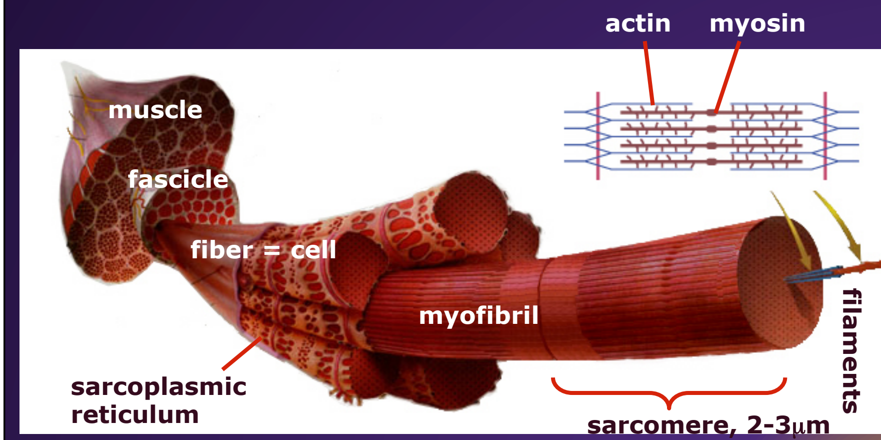
Sartorius



Gastrocnemius

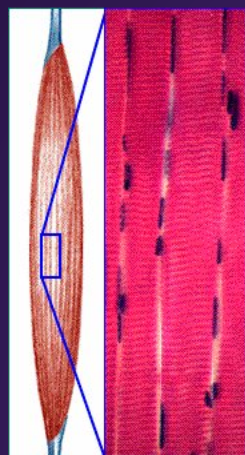
- Muscles **pull**, they don't push.
- Muscles are grouped into antagonist pairs.
- Movement involves coordination of many muscles.
- Multiple muscles act at each joint.
- Muscles with different shapes, sizes, and attachments generate different forces and motions.

Hierarchical Muscle Structure



adapted from Scientific American, September 2000

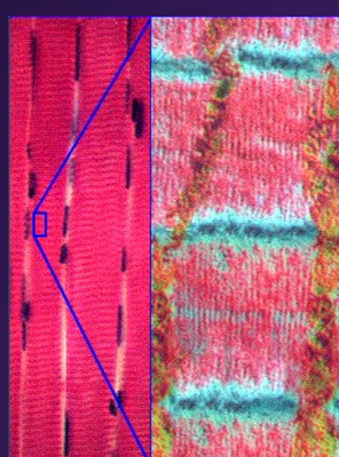
Fascicles are groups of fibers



McNeill Alexander, How Animals Move

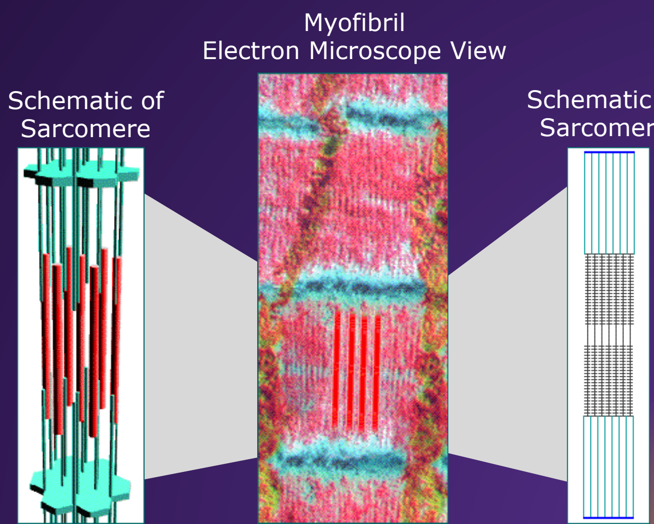
- One can dissect out muscle fascicles.
- Under a light microscope a stripped pattern is seen.
- A muscle cell may be 10-100μm in diameter and 1-30 cm long.

Fascicles are groups of fibers

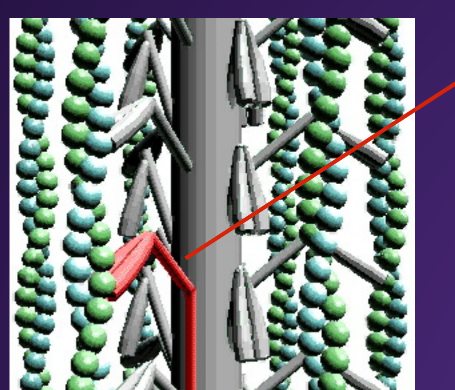


- Under an electron microscope, one can clearly see individual myofibrils
- The source of the stripped pattern (Z-disks) are also seen

Structure of a Sarcomere



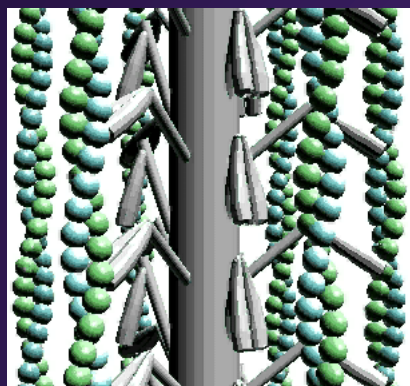
Force is Developed at the Actin-Myosin Cross Bridge.



Thick filament is made of myosin (head and tail)

Actin is the primary component of thin filaments (10nm diameter)

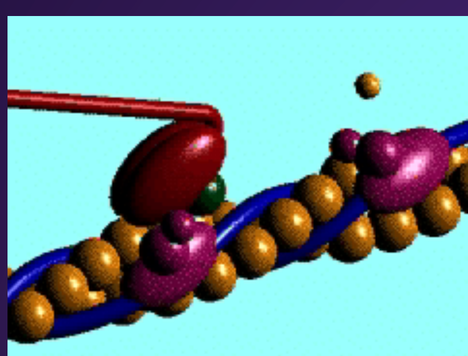
Muscle Shortens as the Proteins Slide Past Each Other.



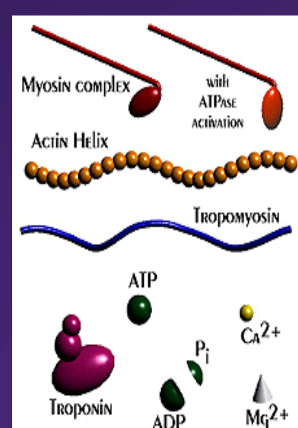
When muscle is activated the myosin heads attach to the thin filaments and form cross bridges

McNeill Alexander, How Animals Move

Muscle Shortens as the Proteins Slide Past Each Other.



SDSU



[http://www.sci.sdsu.edu/movies/actin_myosin_gif.html]

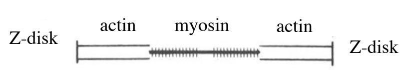
Plan for Today

- What's cool about muscle?
- Muscle structure and biology
- Basic muscle properties
  - Force-length relationship
  - Force-velocity relationship
- Tools for evaluating muscle function

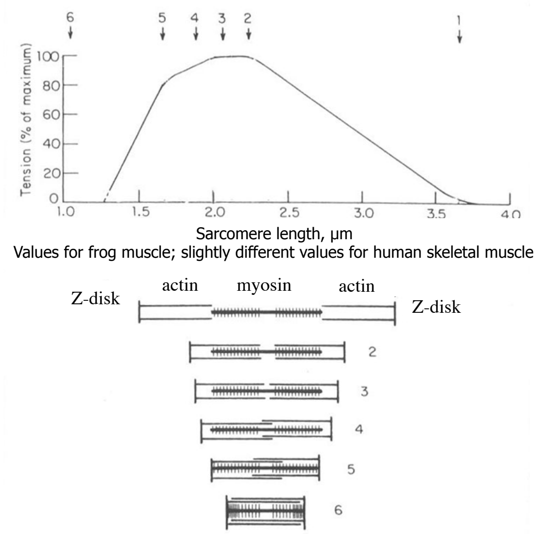
Force-Length Relationship

Length
Velocity
Orientation
Size

SARCOMERE



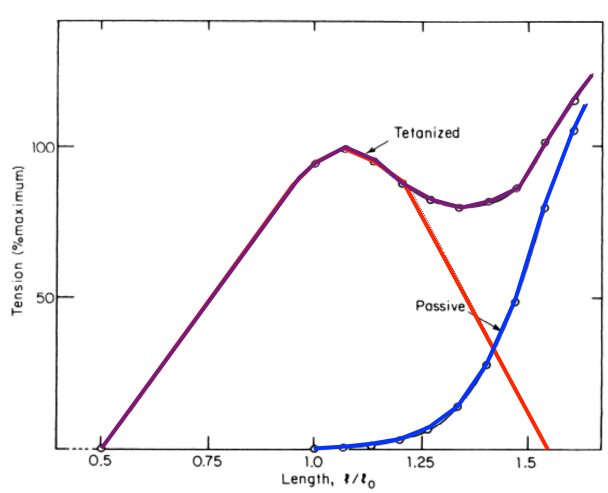
Force-Length Relationship



- **Length**
- Velocity
- Orientation
- Size

Force-Length Relationship

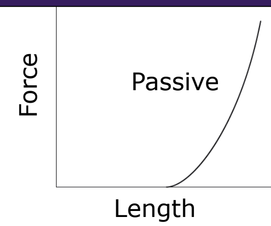
WHOLE MUSCLE

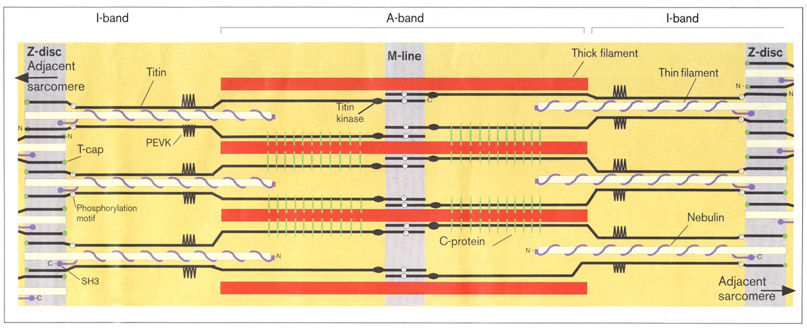


- **Length**
- Velocity
- Orientation
- Size

These curves apply to *ISOMETRIC* muscle

Passive Properties

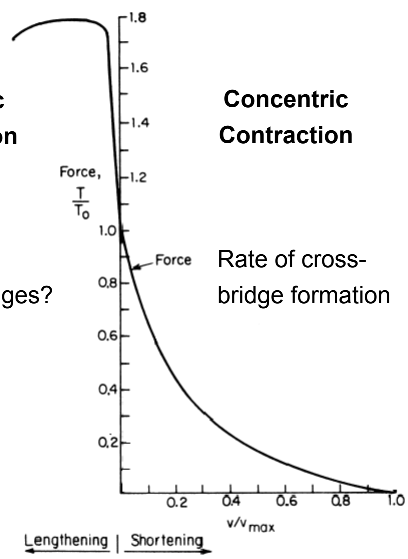




Force-Velocity Relationship

Eccentric Contraction

Breaking cross-bridges?



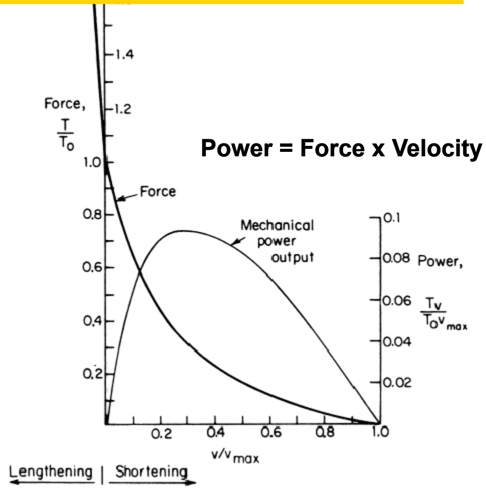
Concentric Contraction

Rate of cross-bridge formation

Length
Velocity
Orientation
Size

Force-Velocity Relationship

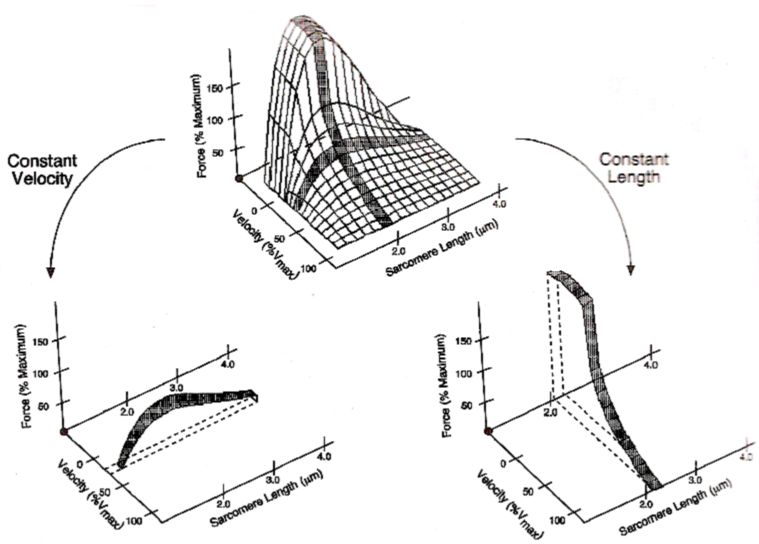
Why does a bike have gears?



Power = Force x Velocity

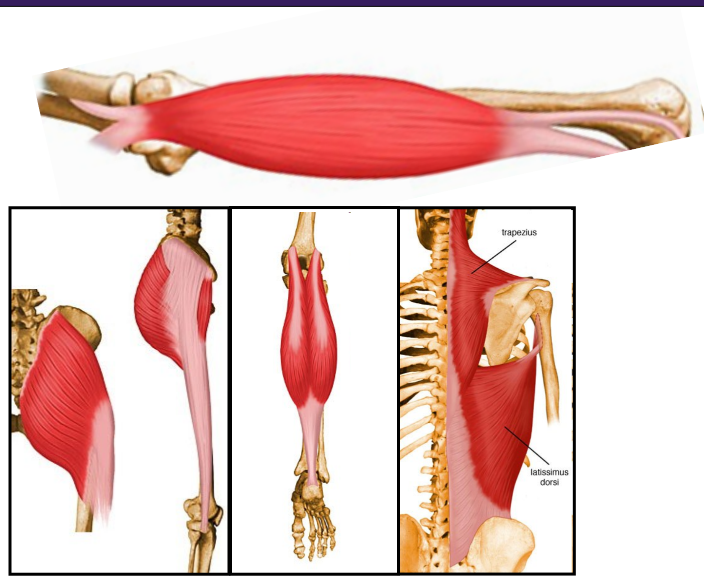
Length
Velocity
Orientation
Size

Force-Length-Velocity Relationship



Length
Velocity
Orientation
Size

Fiber Orientation

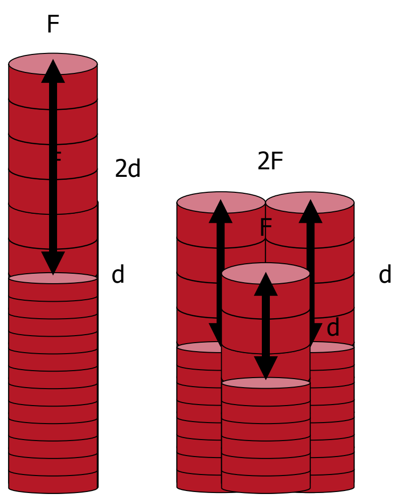


Length
Velocity
Orientation
Size

http://www.rad.washington.edu/academics/academic-sections/msk/muscle-atlas

Effect of number and length of fibers

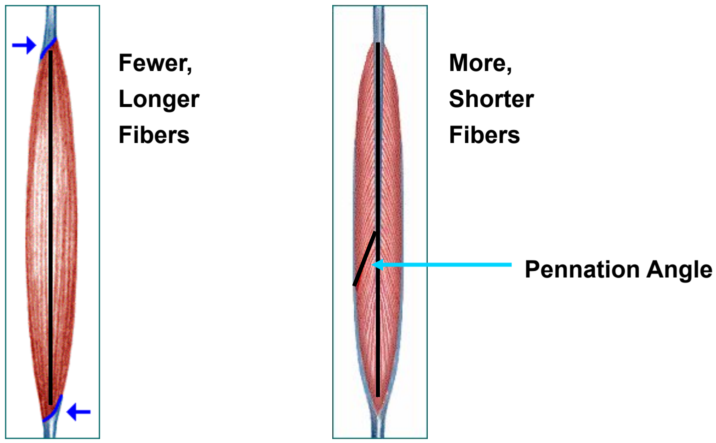
- What happens to muscle force and excursion if there are more sarcomeres in parallel? In series?



Length
Velocity
Orientation
Size

More fibers = More force
Longer fiber = Longer excursion

Fiber Orientation

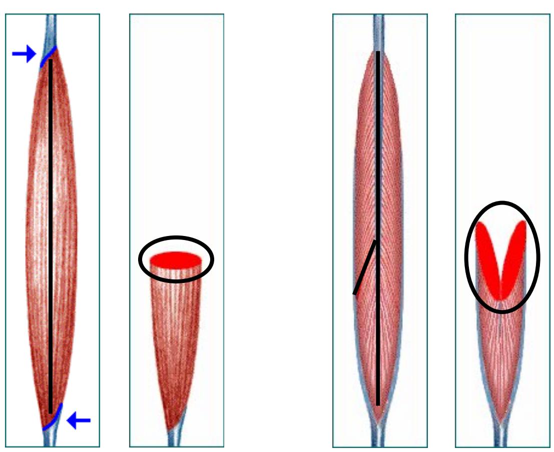


Parallel Fibered

Pennate Muscle

Length
Velocity
Orientation
Size

Physiological Cross-Sectional Area



Length
Velocity
Orientation
Size

Physiological cross-sectional area (PCSA) is proportional to force.

Parallel Fibered
Less Force
More Excursion

Pennate Muscle
More Force
Less Excursion

Compare muscles

Sartorius

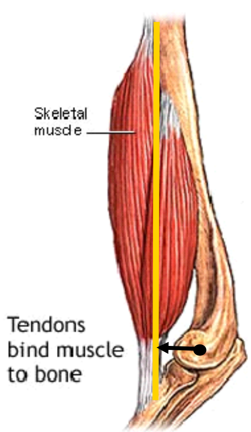
Gastrocnemius

Which muscle can generate more force?

More excursion?

Muscle Moment Arms

Muscles pull on bones to create a moment about a joint.



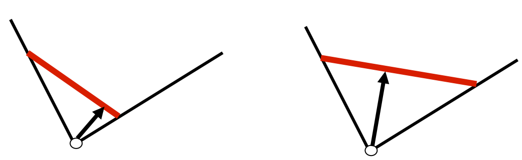
Moment Arm

- Perpendicular distance between muscle's line of action and joint center
- Muscle length change required for joint angle change
- Changes with joint angle

Length
Velocity
Orientation
Size
Moment Arm

Moment = Force x Moment Arm

Which muscle would generate greater moment?

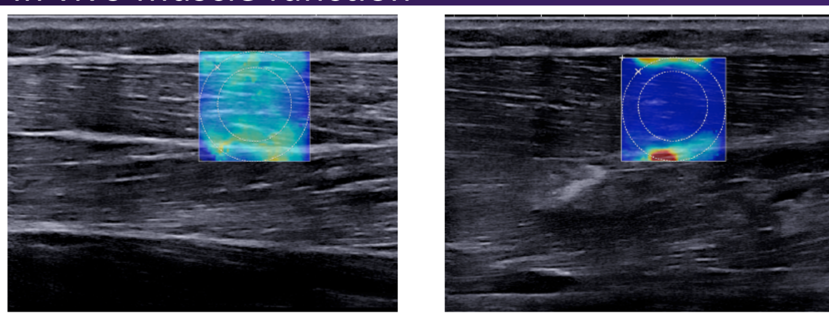


Plan for Today

- What’s cool about muscle?
- Muscle structure and biology
- Basic muscle properties
  - Force-length relationship
  - Force-velocity relationship
- Tools for evaluating muscle function

Tools for evaluating muscle function

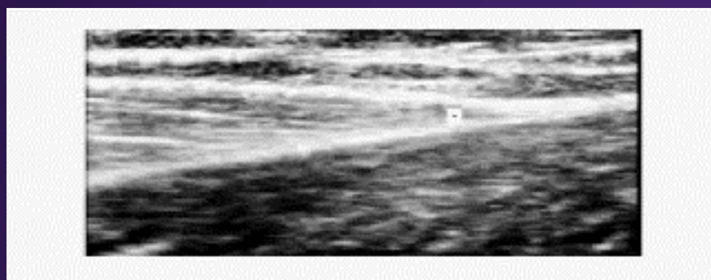
- *In vivo* muscle function



SW vel = 4.6 m/s   SW vel = 2.5 m/s

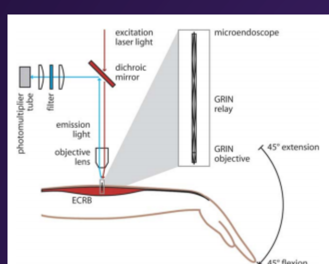
Tools for evaluating muscle function

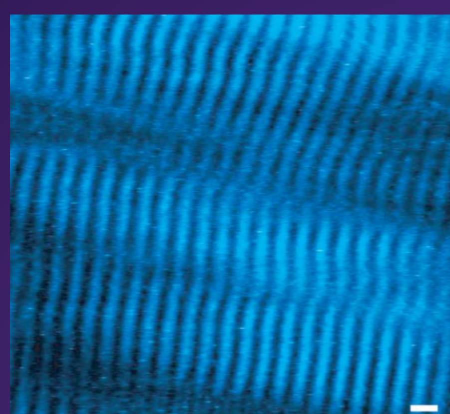
- *In vivo* muscle function



Tools for evaluating muscle function

- *In vivo* muscle function



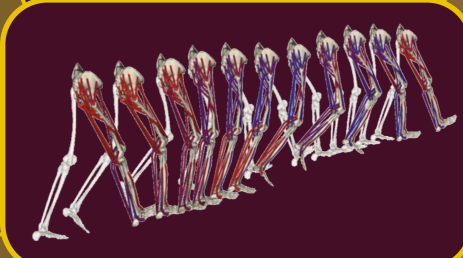


Tools for evaluating muscle function

- *In silico* muscle function

Visualize complex movement patterns

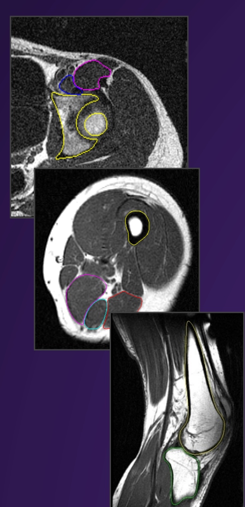
Probe parameters that are difficult to measure



Perform "what if" studies

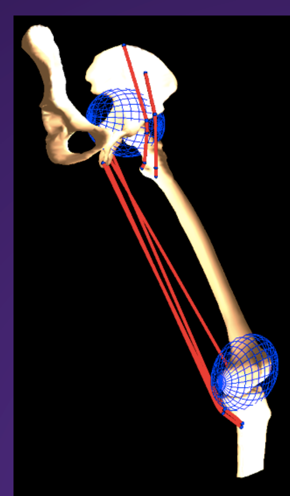
Identify cause-effect relationships

Musculoskeletal Models



MR images

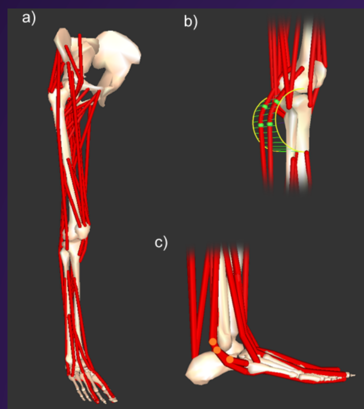
3D reconstruction

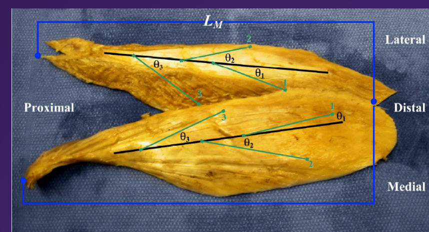


line muscles combined with geometric assumptions

Arnold et al., 2000

Musculoskeletal Model

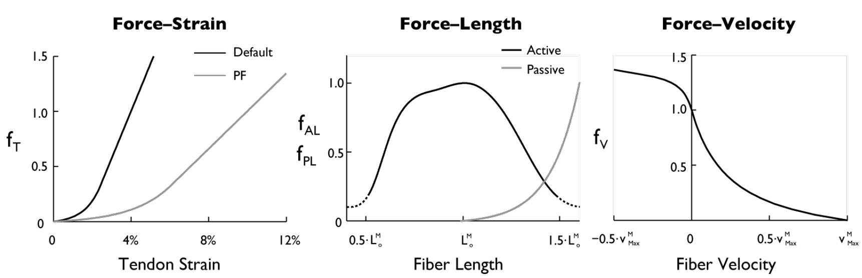


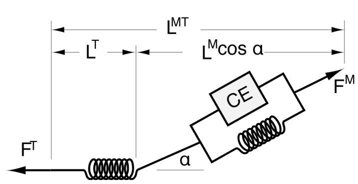


21 Cadavers
82.5 ± 9.42 years

Arnold, et al., Clin Orthop Relat Res 467, 1074-1082, 200
Ward, S.R., et al., Clin Orthop Relat Res 467, 1074-1082, 2009.

Models Muscle Contraction Dynamics



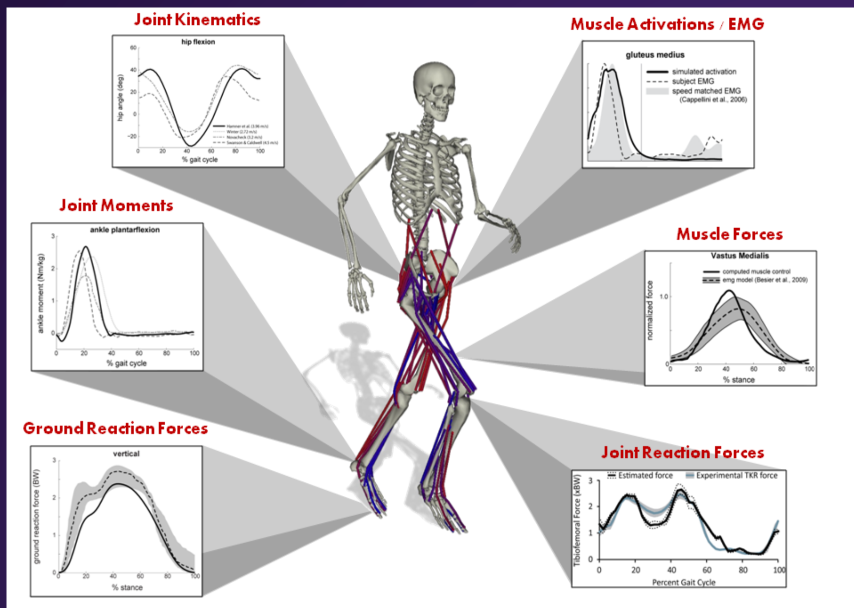


$$F^M = \left(a \cdot f_{AL} \cdot f_V + f_{PL}\right) \cdot F_{Max}^M$$

$$F^T = f_T \cdot F_{Max}^M$$

1. Thelen, D.G., Anderson, F.C., Delp, S.L., J Biomech 36, 321-328, 20
2. Zajac, F.E. Crit. Rev. Biomed. Eng. 17, 359–411, 1989.

Musculoskeletal Simulations



OpenSim

http://opensim.stanford.edu

Musculoskeletal Model

- 23 body segments
- 92 muscle-tendon actuators


Dynamic Optimization of Human Walking

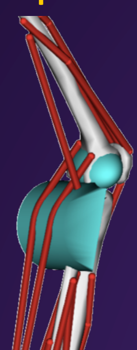
Frank C. Anderson
Marcus G. Pandy

A PLANAR MODEL OF THE KNEE JOINT TO CHARACTERIZE THE KNEE EXTENSOR MECHANISM

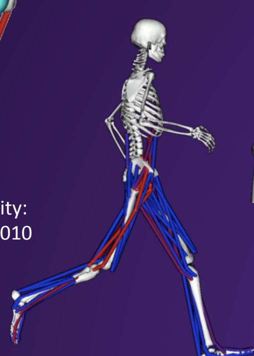
An Interactive Graphics-Based Model of the Lower Extremity to Study Orthopaedic Surgical Procedures

SCOTT L. DELP, J. PETER LOAN, MELISSA G. HOY, FELIX E. ZAJAC, MEMBER, IEEE, ERIC L. TOPP, AND JOSEPH M. ROSEN

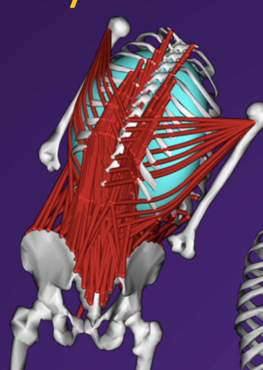
OpenSim Repository



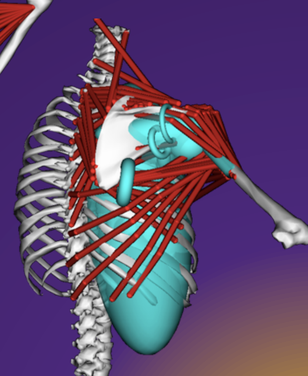
Lower-extremity:
Arnold et al, 2010



Running:
Hamner et al, 2010



Lumbar-spine:
Christophy et al, 2011



Shoulder:
Matias et al, in prep.

Download and try the tutorials!

http://opensim.stanford.edu

ME412/512: Biomechanics of Movement

Course Objectives

After completing this course, you will be able to:

1) Describe the biological, mechanical, and neurological mechanisms by which muscles produce movement
2) Identify and use engineering tools that are used to study movement
3) Write and solve equations of motion for simple models of human movement
4) Apply biomechanics principles to "real-world" clinical and biomechanical research.

Tuesday/Thursday Winter 2017

Prerequisites: Statics, Dynamics, Differential Equations

A Quick Intro to Muscle

- What's cool about muscle?
- Muscle structure and biology
- Basic muscle properties
  - Force-length relationship
  - Force-velocity relationship
- Tools for evaluating muscle function

THE END