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 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

- 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

- 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.

McNeill Alexander, How Animals Move

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

Myofibril Electron Microscope View

Schematic of Sarcomere

Schematic of 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

[http://www.sci.sdsu.edu/movies/actin_myosin_gif.html]
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Force-Length Relationship

![Diagram of a sarcomere with Z-disk, actin, myosin, and actin in different positions for different lengths.](Image)
Force-Length Relationship

Values for frog muscle; slightly different values for human skeletal muscle

Z-disk
actin
myosin
actin
Z-disk

Whole Muscle

These curves apply to ISOMETRIC muscle

Length
Velocity
Orientation
Size
Passive Properties

Force-Velocity Relationship

Eccentric Contraction
Concentric Contraction
Breaking cross-bridges?
Rate of cross-bridge formation

Lengthening | Shortening
Force-Velocity Relationship

Why does a bike have gears?

Power = Force x Velocity

Force-Length-Velocity Relationship
Fiber Orientation

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?

More fibers = More force
Longer fiber = Longer excursion
### Fiber Orientation

<table>
<thead>
<tr>
<th></th>
<th>Fewer, Longer Fibers</th>
<th>More, Shorter Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibered</td>
<td><img src="image" alt="Parallel Fibered" /></td>
<td><img src="image" alt="Pennate Muscle" /></td>
</tr>
</tbody>
</table>

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

- Pennation Angle

### Physiological Cross-Sectional Area

<table>
<thead>
<tr>
<th></th>
<th>Less Force</th>
<th>More Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excursion</td>
<td>More</td>
<td>Less</td>
</tr>
</tbody>
</table>

|             | ![Parallel Fibered](image) | ![Pennate Muscle](image) |

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

Which muscle can generate more force?

More excursion?

Sartorius  Gastrocnemius

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

Moment = Force $\times$ Moment Arm

Which muscle would generate greater moment?
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Tools for evaluating muscle function

• In vivo muscle function

![Images showing SW vel]
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


Models Muscle Contraction Dynamics

\[ F_T = f_T \cdot F_{\text{Max}} \]

\[ F^M = (a \cdot f_{AL} + f_v + f_{PL}) \cdot F_{\text{Max}} \]

Musculoskeletal Simulations

OpenSim

http://opensim.stanford.edu
Musculoskeletal Model

- 23 body segments
- 92 muscle-tendon actuators

OpenSim Repository

- Lower-extremity: Arnold et al, 2010
- Lumbar-spine: Christophy et al, 2011
- Running: Hamner et al, 2010
- Shoulder: Mattas et al, in prep.
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

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THE END