Muscle Force Variation

1. Tension Developed by Each Fiber
   a. Action potential frequency
   b. Fiber length at onset of activation
   c. Fiber Diameter
   d. Fatigue

2. Number of Active Fibers
   a. Number of fibers per motor unit
   b. Number of active motor units

3. Muscle Action
4. Speed of Contraction

Frequency of Stimulation Alters Force Production

- Motor Neuron Conduction Frequency
  - Length of absolute refractory period indicates Somatic Efferent Motor Neuron could reach threshold >200 times per second
  - In vivo estimates are about 100/second
    - Each action potential causes enough Ca++ to produce a twitch
    - When Ca++ is rapidly added by successive action potentials, not all is removed prior to arrival of next “batch”
    - Amount of Ca++ in area of contractile proteins remains elevated
    - Cross bridge cycling occurs for longer time period ➔ more shortening ➔ more force developed by contractile machinery
Frequency of Stimulation Alters Force Production

- Motor Neuron Conduction Frequency
  - Length of absolute refractory period indicates Somatic Efferent Motor Neuron could reach threshold >200 times per second
  - In vivo estimates are about 100/second
  - In addition to Ca** effects, developed also increases due to:
    - Increased heat in area (waste heat)
    - Increased acidity in area
    » Within physiologic limits, increase enzyme activity increase force development

<table>
<thead>
<tr>
<th>4 parts of a Muscle twitch</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1) latent period - 5 msec</td>
<td>time between application of AP &amp; initiation of contraction</td>
</tr>
<tr>
<td>2) contraction time - 40 msec</td>
<td>muscle shortens &amp; does its work</td>
</tr>
<tr>
<td>3) relaxation time - 50 msec</td>
<td>muscle elongates &amp; returns to original position</td>
</tr>
</tbody>
</table>

SINGLE TWITCH: 1 STIMULUS, 1 RESPONSE
**Muscle Twitch Physiology**

3 major phases of the twitch contraction:

- **Latent Period**
  - This is the period of time from the action potential to the onset of contraction. The time delay is due to the excitation-contraction coupling. Action potential leads to release of Ca\(^{++}\) from storage in SR.

- **Contraction Phase**
  - This is the time that tension is developing due to the cross-bridge cycling. Ca\(^{++}\) allowing cross bridge cycling, sarcomere shortens, peak tension for effective Ca\(^{++}\) reached.

- **Relaxation Phase**
  - This is the time that the tension is decreasing (i.e., relaxing) and is longer than the contraction phase. This is due to the amount of time it takes to get all the Ca\(^{++}\) pumped back to SR storage.

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**Increased Rate of stimulation: increase force**

YC Fung, *Biomech, 1993*
Increase Frequency of Stimulation → Increase Force Produced

Duration of contraction differs according to dominant fiber type; frequency for “tetanus” varies across motor units
**Muscle Force Variation**

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**Length-tension relationship (sarcomeres)**

A. Optimum overlap
B. Few available binding sites
C. No available binding sites
D. Fewer binding sites due to overlap
Isometric length-tension curve

- Not continuous \( F-L \) curve
- Isometric forces at max stim at various lengths
- Unique for each muscle due to:
  - Fiber types
  - Pennation
  - PCSA
  - Fiber length

Idealized force versus length

Determined by numerous isometric \( F \) measurements
Muscle Force Variation

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Muscle Fiber Diameter (cross sectional area)
Pennation

Pennation produces different:
• Working range $R$
• Optimal length $L_0$
• Maximal force $F_0$

Overload induces muscle hypertrophy (increased cross sectional area)

• Load-induced hypertrophy occurs as a result of protein synthesis that is induced by the insulin-growth factor 1 (IGF1) and calcineurin–nuclear factor of activated T cells (NFAT) signalling pathways.
• Calcium could couple a mechanical stimulus to the IGF1 pathway and lead to increased gene transcription by activating the calcium-dependent phosphatase calcineurin, which dephosphorylates and activates transcription factors such as NFAT.
Hypertrophy requires PROTEIN SYNTHESIS

Nature Reviews | Molecular Cell Biology

Computer tomography images taken from the midthigh region of a female subject in the strength training (ST) group before and after training.

Pre-training

Post-training

(op-leg) increased 32% in this subject; the nonoperated side (con-leg) did not change from pretraining to posttraining.


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**Muscle Force Variation**

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**Muscle Fatigue**

- **Decline in muscle power output**
  - Decrease in force generation
  - Decrease in shortening velocity
  - Failure to relax at proper rate

- **High-intensity exercise (~60 seconds)**
  - Accumulation
    - H⁺, ADP, Pi, and free radicals (naturally produced during mitochondrial oxidative phosphorylation)
    - Diminishes cross bridges bound to actin
  - Alteration in Membrane Excitability
  - Inhibition at SEMN cell body
    - Protective afferent input from peripheral afferents (GTO)

- **Long-duration exercise (2–4 hours)**
  - Muscle factors
    - Accumulation of free radicals
    - Electrolyte imbalance
    - Glycogen depletion
Muscle Fatigue Causes

• Many factors can contribute to the fatigue of skeletal muscle. Fatigue from high-intensity, short-duration exercise is thought to involve at least three different mechanisms:

1. Conduction Failure

   – The muscle action potential can fail to be conducted into the fiber along the T-tubules, which halts the release of Ca\(^{2+}\) from the sarcoplasmic reticulum.

   • This conduction failure results from the buildup of potassium ions in the small volume of the T-tubule during the repolarization of repetitive action potentials. Elevated external potassium ion concentration leads to a persistent depolarization of the membrane potential, and eventually causes a failure to produce action potentials in the T-tubular membrane.

2. Lactic Acid Buildup

   – Elevated hydrogen ion concentration alters protein conformation and activity.

   – Thus, the acidification of muscle by lactic acid may alter a number of muscle proteins, including the proteins involved in Ca\(^{2+}\) release.

   – The function of the Ca\(^{2+}\)-ATPase pumps of the sarcoplasmic reticulum is also affected, which may in part explain the impaired relaxation of fatigued muscle.
Muscle Fatigue Causes

3. Inhibition of Cross-Bridge Cycling

- The buildup of ADP and P_i within muscle fibers during intense activity may directly inhibit cross-bridge.

- Slowing the rate of this step delays cross-bridge detachment from actin, and thus slows the overall rate of cross-bridge cycling.

- These changes contribute to the reduced shortening velocity and impaired relaxation observed in muscle fatigue resulting from high-intensity exercise.

Muscle Fatigue

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Fig. 9-23
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Effect of motor unit recruitment

Size Principle: smallest units with fewest fibers have lowest threshold and are recruited first and deactivated last

YC Fung, Biomech, 1993
**Whole-muscle Contraction**

- Motor unit 1: slow-oxidative fibers
- Motor unit 2: fast-oxidative-glycolytic fibers
- Motor unit 3: fast-glycolytic fibers

**Muscle contraction**

- To increase strength of contraction
  - Recruit more motor units
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Muscle Actions

- Static (Isometric)
  - Muscle exerts force without changing length
  - Pulling against immovable object
  - Postural muscles

- Dynamic (isotonic)
  - Concentric
    - Muscle shortens during force production
  - Eccentric
    - Muscle produces force but length increases
    - Associated with muscle fiber injury and soreness
<table>
<thead>
<tr>
<th>Type of Exercise</th>
<th>Muscle Action</th>
<th>Muscle Length Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>Concentric</td>
<td>Overcome Gravity (lift) Decreases</td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td>Resist Gravity (controlled lowering, deceleration) Increases</td>
</tr>
<tr>
<td>Static</td>
<td>Isometric</td>
<td>No change</td>
</tr>
</tbody>
</table>

**Muscle Actions**

(a) ISOMETRIC

LIFT - LEAST
HOLD - MORE
RESIST - MOST

(b) DYNAMIC - CONCENTRIC

(c) DYNAMIC - ECCENTRIC
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Load-shortening Relationship

Slope = shortening velocity

Light load
Intermediate load
Heavy load

Distance shortened (mm)

Time (msec)

Single action potential
Load-velocity Relationship

Maximum shortening velocity (zero load)

Maximum isometric tension (zero velocity)

Load

Isotonic shortening

Lengthening contraction

Shortening velocity

Lengthening velocity