Introduction to Biomedical Engineering

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Biomechanics of skeletal muscle

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Introduction

The most basic property of muscle is its ability to produce force—muscle is the only tissue capable of actively developing force.

The human nervous system + muscular system= neuromuscular system

Despite centuries of research on muscle and its contractile behavior, some aspects of muscular force production have not yet been resolved and need more attention.

For example, the precise mechanism of cross-bridge attachment and cross-bridge movement that are believed to cause relative movements of the myofilaments, and so produce force, are not fully understood—some researchers (e.g., Pollack, 1990) propose mechanisms of force production that do not agree with cross-bridge theory (Huxley, 1957).
**Introduction**

Muscle is the largest tissue mass in the body, up to 40-50% of the body weight.

There are over 700 muscles, which have a variety of mechanical characteristics.

Muscles: skeletal, cardiac, and smooth muscles.

Cardiac and smooth muscles are not under direct voluntary control.

The behavioral properties of muscle: extensibility (the ability to be stretched) and elasticity, irritability (the ability to respond to a stimulus), and the ability to develop tension.
Types of muscle

**Cardiac muscle** - Found only in the heart, very good for endurance, stretch is limited (similar to smooth muscle), not voluntarily controlled by nerves, composes the bulk mass of the heart.

**Smooth muscle** - Found in the digestive system, blood vessels, airways..., Controlled by involuntary nerve function, lines hollow internal organs (blood vessels, urinary tract).

**Skeletal muscle** - Most common group, muscles you can see and feel, attaches to bone via tendons, responsible for locomotion and body motion, contracts voluntarily, two types of contractions (twitch (a sudden quick contraction), and tetanus (prolonged contraction of skeletal muscle fibers), 40-45% of total body weight in adults.
Skeletal muscle

Adaptive soft biological tissue

Material properties:
- Anisotropic
- Viscoelastic
- Nearly incompressible
- Inhomogeneous

Purposes:
- Aid in daily locomotion (done via the connection of muscle to bone (tendon))
- Distribution of load in human motion
- Maintain body posture at rest
Sliding filament model

Also known as the cross bridge model, proposed by H.E. Huxley in 1954. Explains interaction between myofilaments (cross bridges) in sarcomere that cause muscle contraction. Muscle contraction strength is related to the number of cross-bridges formed - it’s also related to the distance between myofilaments (length of the sarcomere).
Skeletal muscle anatomy

The basic and most important **structural element** of muscle is the **muscle fiber**, or **muscle cell** which is about **10 to 100 μm** in diameter, and generally extends along the entire muscle. Within the muscle cell (fiber), there are a large number of parallel smaller **myofibrils**, about 1-2 micrometers in diameter. The repeat unit of myofibrils is called **sarcomere** (Actin (thin, 5-8nm dia.) and Myosin (thick, 12-18nm dia.)). The actin and myosin are arranged in parallel and slightly offset from each other in discrete units called sarcomere.
Skeletal muscle anatomy

Thin filaments (actins) are long rod-like chains of the protein actin (with a small amount of the other proteins troponin and tropomyosin). Thick filaments (myosin) are also rod-shaped proteins, but contain a round head at the end and project away from the main body of the rod - this projection is called a “cross-bridge” and can rotate about a pivot point when the molecule adenosine triphosphate (ATP) attaches to the myosin.

When a muscle fiber is stimulated, the concentration of calcium increases inside the muscle cell. This causes the binding sites on the actin to open, allowing bonds with the myosin to occur in the presence of ATP. Specifically, a calcium ion binds to troponin protein on the thin filament, causing structural changes in the tropomyosin protein, making actin-myosin binding site ready. For muscle contraction, our body needs calcium - if not enough ca intake, ....
Muscle contraction - cross bridge theory

During contraction, the myosin molecule forms a chemical bond with an actin molecule on the thin filament (called a cross-bridge)- ATP allows for the temporary attachment of the cross bridges between myosin and actin

ATP splits into ADP and $\text{PO}_3^{2-}$ upon attachment (ATP= adenosine triphosphate, ADP(adenosine diphosphate) , ATP=ADP+ Phosphate+ Energy)

As soon as the cross-bridge is formed, the myosin head bends, thereby creating force and sliding the actin filament past the myosin- this process is called the power stroke

The myosin then releases the actin molecule- when the actin is released, myosin head is reset to its original position
Sliding filament theory

Contraction consists of 4 steps:

- Actin/myosin binding
- Power stroke
- Crossbridge detachment
- ATP hydrolysis (ATP = ADP + ...)

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Muscle contraction


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Sliding element model

Resting or optimal length of sarcomere: produce a maximum tension - it’s related to the number of cross bridges formed.

If length > resting length, force produced ↓: less contact causes reduction in number of cross bridges.

If length < resting length, force produced ↓: thin filaments overlap, interfering with cross bridge formation.

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Length-tension relationship in skeletal muscle

![Graph showing the length-tension relationship in skeletal muscle, with relative tension on the y-axis and percent rest length on the x-axis. The graph illustrates the optimal length for maximal cross-bridge interaction and tension development, with less tension development at suboptimal lengths and no cross-bridge interaction at lengths greater than optimal.]

Actin
Myosin

1.65 μm
Less than optimal length
Fewer cross-bridge interactions = reduced tension development

2.25 μm
Optimal length
Maximal cross-bridge interaction = maximal tension development

3.65 μm
Greater than optimal length
No cross-bridge interaction = no tension development
Parallel and pennate muscles

The angle between the muscle fibers and tendon is called the pennation angle (the angle between the longitudinal axis of the whole muscle and its fibers)

In **parallel muscles**, their muscle fibers are aligned parallel to the overall axis of the muscle (the line of action between tendons)- e.g. biceps brachii

**Pennate muscles** have their fibers oblique to the axis
Parallel and pennate muscles

The pennate muscles are generally more powerful than their weight-matched parallel counterparts, since they allow recruitment of more fibers. Parallel muscles, however, allow for greater contraction, since their fibers are generally longer than those in pennate muscles.
Hill’s three element model

The elastic behaviour of muscle has been described as consisting of the following major elements:

1) Contractile element- force generator (force generated through actin-myosin interaction) and dashpot (frictional dissipation within the muscle) in parallel- CE

2) Series elastic element (elasticity of tendons)- SEE

3) Parallel elastic element (elasticity of connective tissue when at muscle rest- muscle membrane)- provides resistive tension when a muscle is passively stretched- PEE

Both the SEE and PEE have a viscous property
Muscle force: passive and active components.

Passive: viscoelastic mechanical response to deformation displays characteristics similar to passive tissues, such as tendon and ligament.
Force-velocity behavior

For shortening of muscle, the maximum force produced occurs when the muscle is at rest. Power velocity curve for shortening has a parabolic shape, and the local maximum typically occurs at a shortening velocity of about $1/3$ the max. possible velocity.

Force velocity and power velocity relations for muscle

**Force-Velocity Relationship**

![Graph showing force, power, and velocity relationships](image)
Force-velocity behavior

Force-velocity equation:

\[ V = \frac{b(T_0 - T)}{(T + a)} \]

where \( V \) is the velocity of shortening, \( T_0 \) = maximal force at zero velocity and optimum sarcomere length, \( T \) = instantaneous force, \( a \) and \( b \) = constants with units of force and velocity, respectively.

Setting \( T \) equal to zero, one can find the velocity corresponding to the maximum velocity of shortening.
Mechanical behavior

At the organ level, when a muscle receives an electrical stimulus, the response is discrete and highly repeatable (after a latency period of about 15 ms, muscle produces a transient force which rises to a peak and quickly falls off- the duration of the twitch is approx. 100 ms).
Mechanical behavior

The transient force produced is known as the twitch response. The magnitude of the force produced during a twitch depends on the type of muscle and the number of fibers stimulated.

A series of electrical signals, the force-time responses add.

Low frequency of stimuli: unfused tetanus

Frequency about 30 Hz, fused tetanus; F-t response reaches a plateau.
A tetanic contraction occurs when a motor unit has been maximally stimulated by its motor neuron.
Muscle force modeling

The maximum possible stress in most muscles is about 0.2 MPa, regardless of the size and shape of the muscle.

Knowing the muscle cross-sectional area, one can find the relative force producing capacity of different sized muscles.

Using the max. stress method, we can find the max. force capacity of the muscles, when all motor units are active.

It is not possible to determine the tensile force in an active muscle from its size or length, unless we know the percentage of the motor units within the muscle that have been stimulated.
Force-velocity behavior

Force-velocity equation:

\[ V = \frac{b(F_0 - F)}{(F + a)} \]

where \( V \) is the velocity of shortening, \( F_0 \) = maximal force at zero velocity and optimum sarcomere length, \( F \) = instantaneous force, \( a \) and \( b \) = constants with units of force and velocity, respectively.

Setting \( F \) equal to zero, one can find the velocity corresponding to the maximum velocity of shortening.

![Graph showing power output and velocity of movement](image-url)
Suggested texts

- B. Ng and W. Herzog, Biomechanics of the musculo-skeletal system, 3d edition, 2007

- M. Nordin and V.H. Frankel, Basic biomechanics of the musculoskeletal system, 3rd edition, Lippincott Williams & Wilkins, 2001