Lecture note 3

Mechanism of muscle contraction and Work Physiology
Mechanism of muscle contraction

- Microscopic anatomy of skeletal muscle cells
- Motor unit and Neuromuscular junction
- Action potential and muscle contraction
- Energy Supply for contraction - stored energy, anaerobic and aerobic combustions of nutrients
- Muscle force development
- Energy consideration and cellular respiration
- Static and Dynamic muscle work
Microscopic anatomy

Each muscle cell is packed with protein fibers called **myofibrils** and is a collection of **sarcomeres** separated by **Z-discs**. Sarcomeres are the smallest contractile unit in a muscle fiber. Sarcomere contains two main types of protein fibers: **Myosin** - the thicker filament and **Actin** – the thinner filament. When activated, the contraction is produced by sliding of the myosin fibers over the actin fibers in each sarcomere, which in turn produces a contraction of the muscle cell. The striation seen in the skeletal muscle tissue under the microscope is due to the orderly arrangement of thick and thin filaments.
Motor Units and Neuromuscular Junction

One motor neuron innervates a number of muscle cells (more than 100) and together they are called one **motor unit**. When the nerve fires (conducts a nerve impulse) all muscle fibers of the motor unit contracts (asynchronously). The number of muscle cells in a motor unit is more for the large muscles (>1000), for finer control in delicate muscles (e.g. eye-lid) this number might be less than 10. The nerve impulse (electrical) changes the permeability of the synaptic vesicle membranes at its axon ends which releases neurotransmitter (acetylcholine). This chemical binds with the muscle cell membrane molecules at the synaptic cleft and opens gates for influx of Na+ ions inside the muscle cell body.
Action potential

• In resting state the muscle cell membrane remains electrically polarized (i.e. outside has more +ion concentration than inside).
• The sudden influx of Na+ ions (due to gate opening by the neurotransmitters) depolarizes the membrane at that spot which in turn sets up an electric current between this depolarized and neighboring polarized regions of the cell membrane.
• This current opens more Na-gate molecules on the cell membrane and causes more Na+ ions influx through the neighboring regions, thus depolarizing those regions. This way the depolarization wave propagates through out the cell membrane and reaches deep inside the cell through the t-tubules.
• Acetylcholin is quickly broken down by enzymes and the +ions are actively (using energy molecules) transported back to the outside of cell membrane and the cell membrane returns to its normal polarized (resting) state.
• The electrical depolarization and re-polarization wave through the muscle membrane, thus generated is called the action potential.
• Action potential triggers muscle contraction. It is an all-or-none phenomena, i.e. if action potential is developed, muscle cells in the motor unit contracts with same force.
• The electrical signals generated by the action potentials can be sensed using skin or needle electrodes placed near the muscle. This is the basis of electromyography.
Muscle contraction

• The action potential changes the permeability of sarcoplasmic reticulum which releases Ca++ ions.
• Ca ions binds with a protein molecule which opens the binding site and actin and myosin binds together.
• Myosin molecule binds with energy molecule and changes shape and thus produces a sliding motion over the actin filament, which contracts the muscle.
• At the end of a contraction, Ca ions are transported back. Actin – myosin filaments detach from each other and muscle relaxes by the passive tension of the connective tissues.

(See animation at McGill university website at: http://www.mmi.mcgill.ca/mmimediasampler2002/)
Isometric contraction and length tension characteristics

Force generation capacity of a muscle decreases as it is stretched. This is because the cross bridging space between actin and myosin filaments decreases as the muscle is stretched.

This is one of the reason why maximum isometric strength varies with posture.
Force regulation in skeletal muscles

CNS sends messages to the motor neurons to change the force generation in muscles. Force generation can be controlled by (1) changing the firing frequency of the motor neurons - called rate coding, and (2) by recruiting more motor units, thus increasing the number of muscle cell contracting simultaneously – known as recruitment.

Recruitment pattern and rate coding varies predictably when the muscle is fatigued. By analyzing the frequency distribution of the EMG data, one can estimate the fatigue level of muscle.

RATE CODING: (a) Set of individual contraction at low frequency. (b) At higher firing frequencies, the muscle fiber don’t get enough time to relax and as a result the contraction force of the subsequent twitch summates. (c) At even higher frequency the individual twitches fuses to each other (titanic contraction) and produces maximum force.
Energy consideration

Energy for all molecular movement necessary for muscle contraction comes from break down of adenosin triphosphate (ATP) molecules to adenosin diphosphate molecules.

\[
\text{ATP} \Leftrightarrow \text{ADP} + \text{Energy}
\]

Muscle stores some ATP, which can sustain contraction for few seconds. To continue contraction, other high energy particles are broken down and the energy liberated are used to re-synthesize ADP back to ATP, which sustains contraction.

An another store of high energy molecules is Creatine Phosphate, which can be readily decomposed to Creatine and phosphate to liberate energy, which then can be used to re-synthesize ATP. In a moderately working muscle this storage also depletes within a minute.
Energy consideration (continued)

The bulk of the energy supply comes through metabolism of glucose molecules. Muscle cells stores glycogen (a polymer of glucose) and can receive glucose from blood supply.

Glucose molecules can be metabolized in two ways:

(1) In the absence of oxygen (anaerobic glycolysis) – glucose molecules are broken down to lactic acid and produces energy equivalent to 2 ATP molecules. Anaerobic glycolysis produces Lactic acid, which may build up in muscle cells causing local fatigue painful sensation.

(2) In the presence of oxygen (aerobic glycolysis) glucose molecules break down to more simpler molecules (CO$_2$, H$_2$O) and thus produces more energy, equivalent to 36 ATP molecules. O$_2$ is brought in and CO$_2$ are expelled from the muscle cell through cellular respiration. This process of energy production can continue as long as enough O$_2$ is available through cellular respiration.
Cellular respiration

At the start of a dynamic muscular work, energy is supplied primarily from stored high energy particles and from anaerobic glycolysis. This is because circulatory system takes some time to catch up with the higher O₂ demand at the muscle site. CO₂, and Lactic acid build up (causing change in Ph level) in the muscle site triggers the CNS to initiates actions to increase cellular respiration (CO₂ and O₂ movement in and out of the cells). This is done by two ways (1) by dilating the arteries near the muscle site and constricting arteries in skin and other organs (redistribution of blood supply), and (2) by increasing cardiac output and ventilation at lungs to maintain the O₂ at the working muscle site. Heart rate, stroke volume, blood pressure and respiratory rate increase according to the intensity of the muscular work.

Cellular respiration is also effected by constriction of the nearby arteries by the mechanical force developed by the muscle itself. The blood supply starts decreasing at an intensity of 15% of the muscles max. voluntary contraction (MVC) capacity and blood supply is completely restricted above 60% of MVC.
Static work

An activity which requires muscle to maintain contraction continuously it is called static work. Muscles that are maintaining a static work postures, or during holding a hand tool are example of this kind of work. As blood supply is impeded in this kind of muscle contraction, majority of the energy is produced through anaerobic pathway. As a result, metabolite (Lactic acid) accumulates in the muscle cells and local fatigue of the muscles ensues quickly.

<table>
<thead>
<tr>
<th>% MVC</th>
<th>Endurance time</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>6 seconds</td>
</tr>
<tr>
<td>75</td>
<td>21 seconds</td>
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<tr>
<td>50</td>
<td>1 minute</td>
</tr>
<tr>
<td>25</td>
<td>3.4 minute</td>
</tr>
<tr>
<td>15</td>
<td>&gt; 4 minute</td>
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Dynamic Work

In this kind of work muscle contraction is followed by a muscle relaxation. Work with rhythmic movement, such as walking are example of this kind. During relaxation phase, the metabolite generated during work can be washed away and thus this kind of muscle work can be continued for long time without fatigue.

The rhythmic movement also helps venous return of blood and thus is less taxing on heart performance.

In pure dynamic work, maximum intensity of work is determined by the circulatory systems capacity to supply O₂ which is determined by the Max heart rate capacity, or by Maximum O₂ (Max VO₂ in L/min).

Fatigue in this kind of work is primarily from the central fatigue from CNS, less blood glucose level, etc.
Cardiovascular Anatomy

**Pulmonary and Systemic circulation**

Respiratory System

Venous pooling

Cardiac output = HR * SV  liters/min

- Basal CO = varies with age and surface area
- Activity CO = varies with metabolic load, can increase by 18 times the basal CO.
- Skin CO is about 0.4 liters/min but can go up to 1.6 liters/min with vasodilation, give rise to increase in HR.

Blood pressure: DBP/SBP
Metabolism

Cardiovascular system responds to change in metabolic rate. Metabolic rate can be estimated by (1) Formulas, (2) Oxygen consumption, (3) Approximately from HR for low to medium intensity work.

Total Metabolism = Basal + Activity + Digestion.

Metabolic rate is given in

\[
\text{Watts (W)} = 1 \text{ Jules/Sec} = 0.85885 \text{ Kcal/hr (Kcal = Cal)} = 0.00134 \text{ HP}
\]

Basal (W) = 1.28*Weight (Kg) for male

= 1.16 * Weight (kg) for female

Calorie intake can be calculated based on metabolic demand.
Cardio vascular responses to exercise or work intensity

Heart Rate – increases with work intensity for light to medium intensity work. Cost of work in terms of HR: (1) Peak HR – Basal, (2) area under the HR curve during work, but more accurate is (3) area under the work and recovery HR, (4) %HR capacity utilized.

Confounding variables – emotional stress, heavy exercise, digestion, or vasodilation.

Other responses are Stroke Volume, A-V differential of O$_2$ content, blood redistribution and aerobic/anaerobic proportion.
Cardiovascular Capacity is determined by Maximum O₂ uptake (VO₂):

\[ \text{VO}_2 = \text{ventilation rate (mL/min)} \times (\text{diff. in concentration of O}_2 \text{ in inspiration and expiration}) / \text{body weight (mL/kg-min)} \] at a maximum intensity of work.

Decreases with age: 25 – 51.6 mL/kg-min, VO₂max can be determined by various laboratory test. It gives a measure of fitness level.

Proportion of Capacity is important because it determines the amount of physical stress. Guidelines have been developed for different kind of tasks what maximum proportion to capacity one can sustain without localized or systemic fatigue during a work day. Static and dynamic work is a consideration. For purely dynamic work see Figure 4.27 in textbook.

Gender, Age and Training effect should be considered.

The fact that people can work hard, does not mean that they should. High metabolic rate jobs are prime candidate for mechanization.