MUSCULAR SYSTEM

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Functions

The muscular system is composed of specialized cells called **muscle fibers**. Their main characteristic is their ability to **contract**. Muscles, where attached to bones or internal organs and blood vessels, are responsible for movement. Nearly all movements in the body are the result of muscle contraction.

The integrated action of joints, bones, and skeletal muscles produces obvious movements such as walking and running. Skeletal muscles also produce more subtle movements that result in various facial expressions, eye movements, and respiration.

In addition to movement, muscle contraction also fulfills some other important functions in the body, such as **posture, joint stability, and heat production**. Posture, such as sitting and standing, is maintained as a result of force produced by muscle contraction. The skeletal muscles are continually making fine adjustments that hold the body in stationary positions. The **tendons of many muscles extend over joints and in this way contribute to joint stability**. This is particularly evident in the knee and shoulder joints, where muscle tendons are a major factor in stabilizing the joint. Heat production, to maintain body temperature, is an important by-product of muscle metabolism. **Nearly 85 percent of the heat produced in the body is the result of muscle contraction.**

Muscles Types

There are three types of muscles: **skeletal, smooth, and cardiac**.

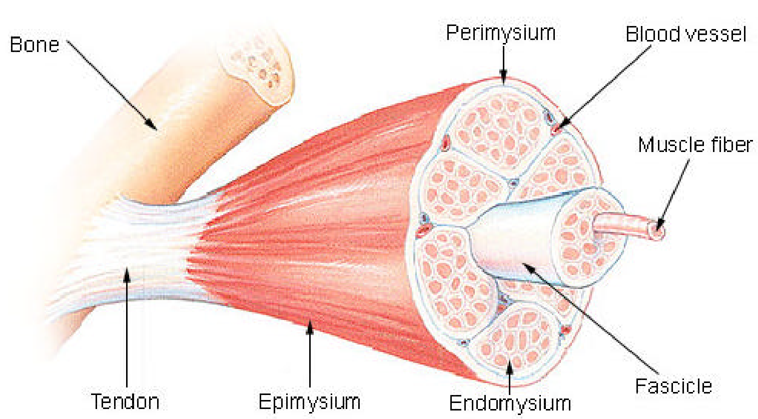
Skeletal muscle, attached to bones, is responsible for skeletal movements. These muscles are under conscious or **voluntary control**. These muscle fibers are **striated** (having transverse streaks when seen under microscope).

Smooth muscle, found in the walls of the hollow internal organs such as blood vessels, the gastrointestinal tract, bladder, and uterus, is under control of the autonomic nervous system. Smooth muscle cannot be controlled consciously and thus acts **involuntarily**. They are microscopically **non-striated (smooth)** and contract slowly and rhythmically.

Cardiac muscle, found in the walls of the heart, is also under control of the autonomic nervous system, **thus involuntary**. **The cardiac muscle cell is striated, like skeletal muscle**. The cardiac muscle cell is rectangular in shape. The contraction of cardiac muscle is involuntary, strong, and rhythmical.

Physical Structure of Skeletal Muscle

Each muscle consists of skeletal muscle tissue, connective tissue, nerve tissue, and blood or vascular tissue. Skeletal muscles vary considerably in size, shape, and arrangement of fibers. They range from extremely tiny strands such as the stapedium muscle of the middle ear to large masses such as the muscles of the thigh.



Each skeletal muscle fiber is a single cylindrical muscle cell. An individual skeletal muscle may be made up of hundreds, or even thousands, of muscle fibers bundled together and wrapped in a connective tissue covering. Each muscle is surrounded by a connective tissue sheath called the epimysium. Fascia, connective tissue outside the epimysium, surrounds and separates the muscles. Portions of the epimysium project inward to divide the muscle into compartments. Each compartment contains a bundle of muscle fibers. Each bundle of muscle fiber is called a fasciculus and is surrounded by a layer of connective tissue called the perimysium. Within the fasciculus, each individual muscle cell, called a muscle fiber, is surrounded by connective tissue called the endomysium.

Skeletal muscle cells (fibers), like other body cells, are soft and fragile. The connective tissue covering furnish support and protection for the delicate cells and **allow them to withstand the forces of contraction. The coverings also provide pathways for the passage of blood vessels and nerves.**

Tendon: Commonly, the epimysium, perimysium, and endomysium extend beyond the fleshy part of the muscle to form a thick ropelike **tendon** or a broad, flat sheet-like **aponeurosis**. The tendon form attachments from muscles to the bones and aponeurosis forms connection to the connective tissue of other muscles. **Typically a muscle spans a joint and is attached to bones by tendons at both ends.** One of the bones remains relatively fixed or stable while the other end moves as a result of muscle contraction. **Ligaments are fibrous tissues that connect bone to bone.**

Skeletal muscles have an abundant supply of blood vessels and nerves. This is directly related to the primary function of skeletal muscle, contraction. Before a skeletal muscle fiber can contract, it has to receive an impulse from a nerve cell. Generally, an artery and at least one vein accompany each nerve that penetrates the epimysium of a skeletal muscle.

The Nervous System

It is the major controlling, regulatory, and communicating system in the body. It is the center of all mental activity including thought, learning, and memory. Together with the **endocrine system** (producing hormones), the nervous system is responsible for regulating and maintaining **homeostasis (regulates internal environment so as to maintain a stable, constant condition)**. Through its receptors, the nervous system keeps us in touch with our environment, both external and internal.

The nervous system is composed of organs, principally the brain, spinal cord, nerves, and ganglia (a mass of nerve tissue containing nerve cells external to the brain or spinal cord). These, in turn, consist of various tissues, including nerve, blood, and connective tissue.

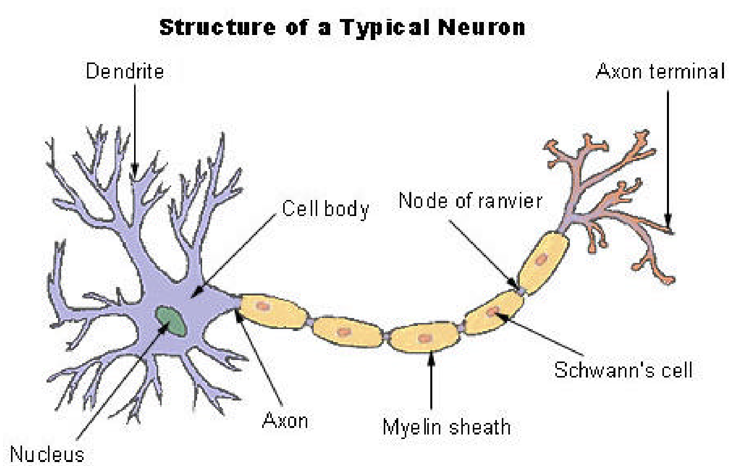
The various activities of the nervous system can be grouped together as three general, overlapping functions: **Sensory, Integrative, and Motor**.

Millions of sensory receptors detect changes, called stimuli, which occur inside and outside the body. They monitor such things as temperature, light, and sound from the external environment. Inside the body, the internal environment, receptors detect variations in pressure, pH, carbon dioxide concentration, and the levels of various electrolytes. All of this gathered information is called sensory input.

Sensory input is converted into electrical signals called **nerve impulses** that are transmitted to the brain. There the signals are brought together to create sensations, to produce thoughts, or to add to memory; Decisions are made each moment based on the sensory input. This is integration.

Based on the sensory input and integration, the nervous system responds by sending signals to muscles, causing them to contract, or to glands, causing them to produce secretions.

Neurons, or nerve cells, carry out the functions of the nervous system by conducting nerve impulses. They are highly specialized and **amitotic**. This means that if a neuron is destroyed, it cannot be replaced because neurons do not go through mitosis (cell division). The image below illustrates the structure of a typical neuron.



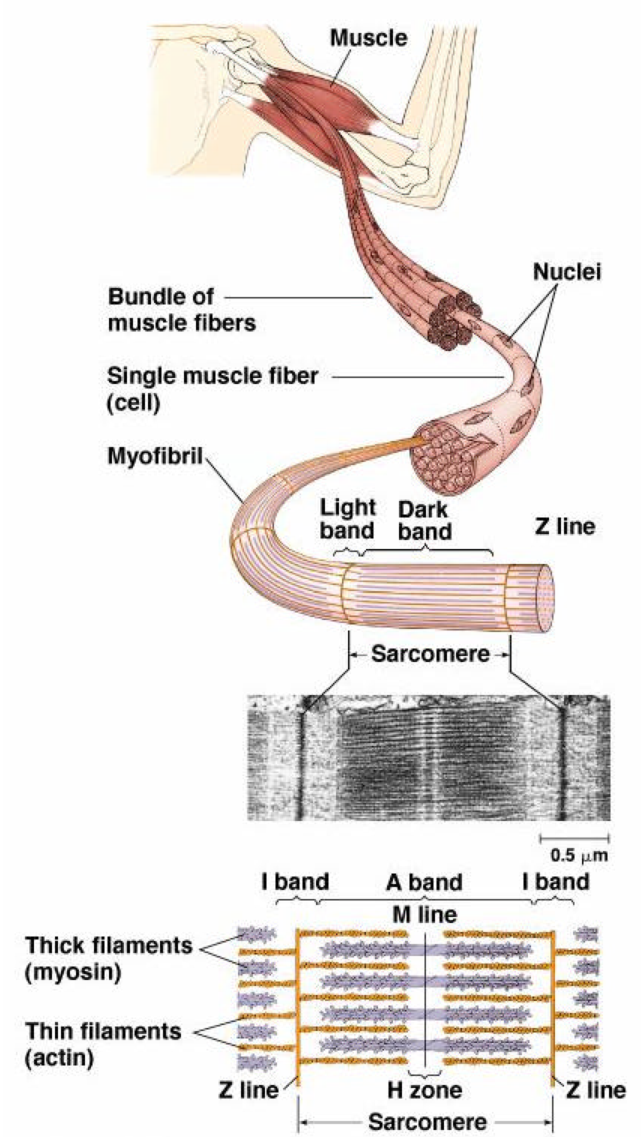
Each neuron has three basic parts: cell body (soma), one or more dendrites, and a single axon.

Dendrites are usually, but not always, short and branching, which increases their surface area to receive signals from other neurons. There is only one axon that projects from each cell body. Axons terminate in many short branches or telodendria. The distal ends of the telodendria are slightly enlarged to form **synaptic bulbs**. **Each of these synaptic bulbs innervates an individual muscle cell.** Many axons are surrounded by a segmented, white, fatty substance called myelin or the myelin sheath. The myelin layer increases the speed at which impulses propagate along the myelinated fiber. Myelinated fibers make up the white matter in the CNS, while cell bodies and unmyelinated fibers make the gray matter.

Functionally, neurons are classified **as afferent, efferent, or interneurons (association neurons) according to the direction in which they transmit impulses relative to the central nervous system.** **Afferent, or sensory**, neurons carry impulses from peripheral sense receptors to the CNS. **Efferent, or motor**, neurons transmit impulses from the CNS to effecter organs such as muscles and glands. **Interneurons, or association neurons**, are located entirely within the CNS in which they form the connecting link between the afferent and efferent neurons.

Mechanism of Muscle Contraction

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.



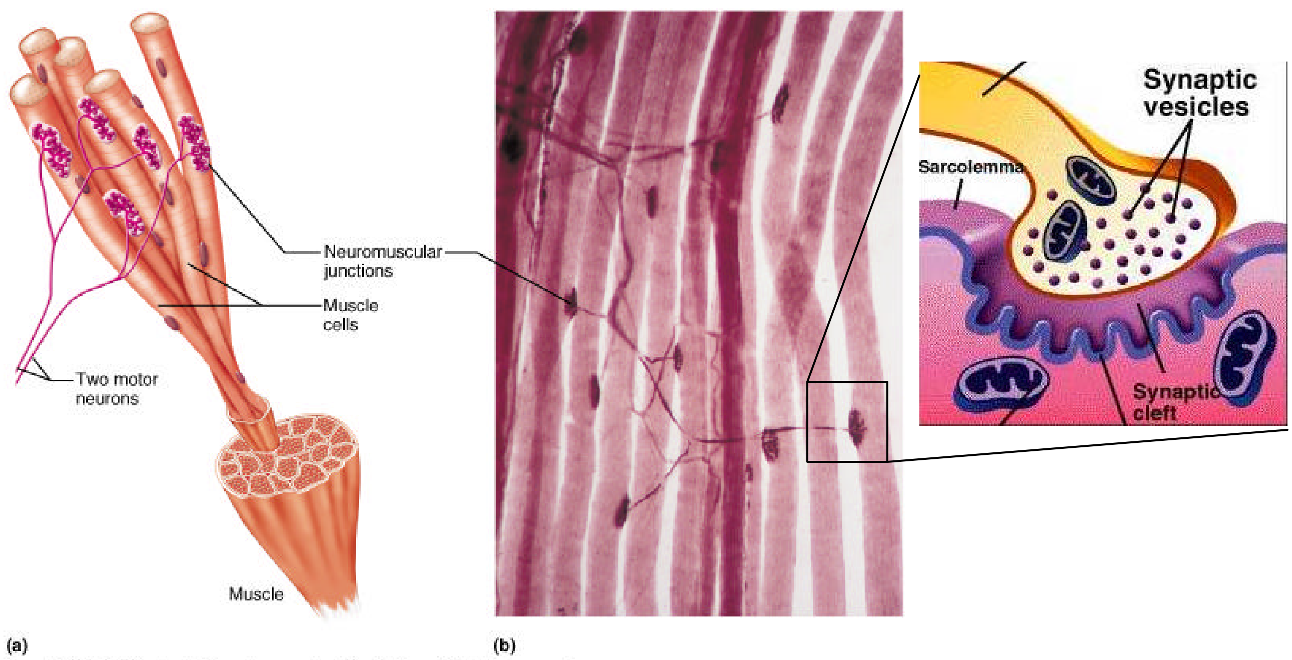
Motor Unit

Synaptic bulbs of one motor neuron's (nerve cell) innervate a number of muscle cells that are dispersed randomly in the overall muscle mass. **The muscle cells and the motor neuron that**

innervates them are called one motor unit. When the neuron of a motor unit sends a nerve impulse, all the muscle cells (fibers) of the motor unit contract together.

Even though one nerve cell innervates all muscle cells in the motor unit, the individual muscle cells contracts slightly asynchronously. This is because, the telodendrias from the axon differ in length and the impulse reaches the muscle cells asynchronously. This asynchronous contraction, spread though out the muscle bulk, produces an overall smooth contraction of the muscle. 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 (known as **motor end plate**) and opens gates for Na+ ions inside the muscle cell body.

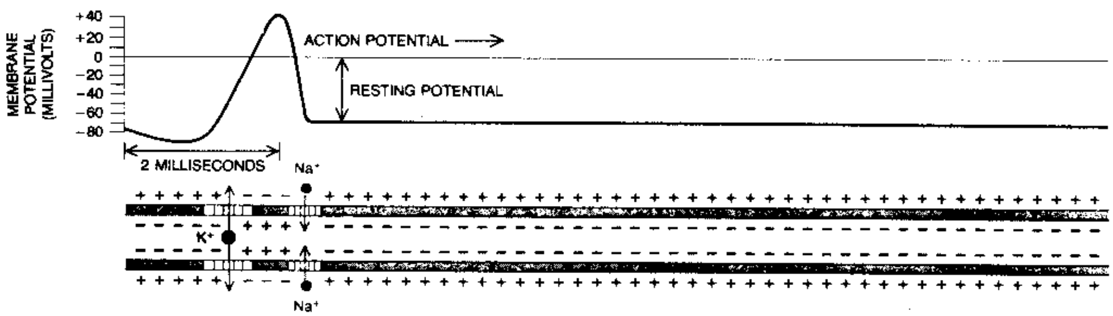


Action Potential & Muscle Contraction

- In a resting muscle, there is a higher concentration of Na+ ions in the extra-cellular space and a higher concentration of K+ ions in the intracellular space (inside the muscle cell membrane). **In resting state the muscle cell membrane remains electrically polarized (i.e.**

outside has higher positive ion concentration than inside). This is due to the fact that K+ ions are small and can freely defuse across the cell membrane but larger Na+ ions cannot, which makes the cell membrane polarized.

- Neurotransmitter (acetylcholine) released by the neuron binds with specific molecules at the motor end plate of the muscle fiber, opening gates for Na+ ions. This causes an influx of Na+ ions to move inside the muscle cell membrane, and thereby depolarizing the membrane at that region.
- When this depolarization reaches a threshold level, a local electric current sets up between the depolarized region and neighboring polarized regions of the cell membrane. This electric current again opens more voltage sensitive Na-gates on the cell membrane and causes Na+ ions influx through the adjacent regions, thus depolarizing those regions. This way the depolarization wave propagates in outward direction from the motor end plate and travels the entire length of the cell. The wave also reaches the deep inside of the cell trough the t-tubules.

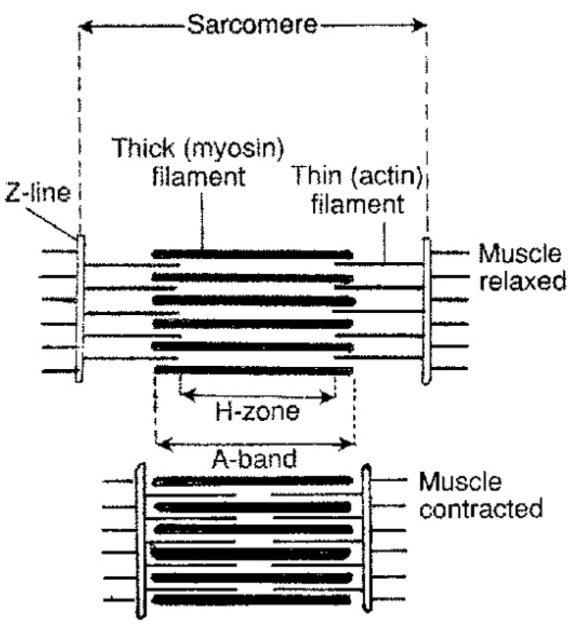


- Right after the depolarization, acetylcholine is broken down by enzymes and Na+ ions are actively (using energy molecules) transported back to the outside of cell membrane and the cell membrane returns to its normal polarized state. The electrical depolarization and re-polarization wave through the 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 intensity of the action potential does not change the contraction force (twitch 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.
- The action potential changes the permeability of sarcoplasmic reticulum which releases Ca++ ions.

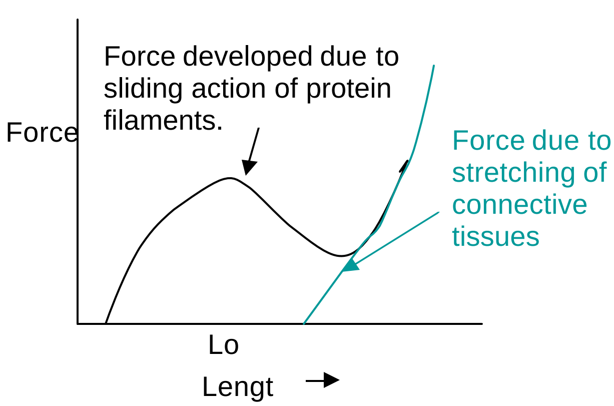
- Ca++ ions bind with a protein molecule, changes its shape, which causes opening of the binding site of actin molecule. In the presence of the binding site, the myosin protein molecule binds with actin molecule and changes its shape. This change of shape produces a molecular force and which tends to slide the myosin molecule over the actin molecule.
- The sliding action of all myosin and actin molecules cross bridges contracts the muscle cell.
- 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. Thus for one action potential on muscle twitch with a constant force is developed.

(See animation at McGill university website at :
http://www.mmi.mcgill.ca/mmimediasampler/

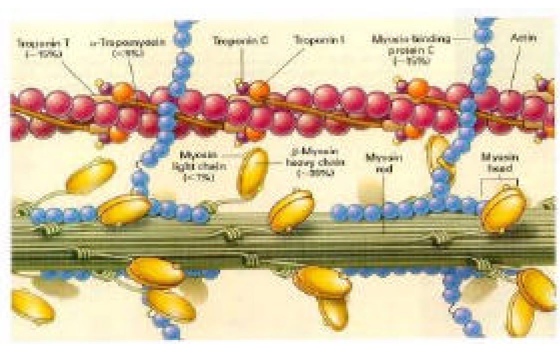
Length Tension Characteristics of Muscle Fibers



Muscle fibers along with its connective tissues are elastic, i.e., muscle fibers can be elastically stretched by the action of external forces. For example, as we flex our elbow, the length of the biceps muscle fibers shortens. Opposite happens when the elbow is extended. With the change of length of muscle fiber from its resting or optimum length, the number of cross bridges between actin and myosin filaments decreases. As a result of this, the force developed for an action potential decreases as it is stretched or shortened from its normal resting length.



Lo = Normal resting length of the

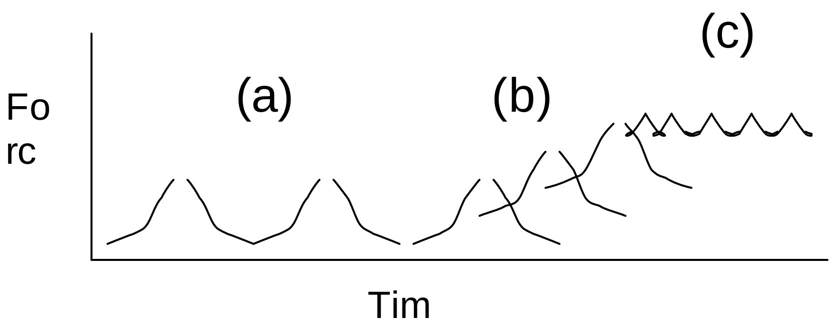


The graph shows the force developed in a muscle fiber for a single twitch, when it is kept at various lengths. L_o is the normal resting length of the muscle fiber. The black line shows the contractile force generated by the action of myosin sliding over actin filaments. After sufficient stretch, the elastic contractile force from the connective tissues adds a passive tension.

This is one of the factors why maximum isometric strength varies with posture and joint angles. The other factor comes from the biomechanical advantage realized from the joint angle (which we will study later).

Force Regulation in Skeletal Muscles

Force generation in a muscle is controlled by two processes: **rate coding and recruitment**.



RATE CODING is changing the firing frequency of firing of a motor neuron. In the figure above, section (a) denotes a set of individual contraction at low frequency of nerve impulses. (b) At higher firing frequencies, the muscle fiber doesn't get enough time to relax and as a result the contraction force of the subsequent twitch summates. (c) At even higher frequency of impulses, the individual twitches fuses to each other (titanic contraction) and produces maximum force. Thus by increasing the firing frequency of a motor unit, more force can be generated.

RECRUITMENT: Force production can also be increased by recruiting more motor units, thus increasing the number of muscle cells contracting simultaneously. This is known as **recruitment**. CNS uses both rate coding and recruitment to regulate muscle force.

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.

Energy Consideration of Muscle Contraction

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

ATP ⇔ ADP + Energy

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

Muscle cells store a high energy molecule, **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.

The bulk of the energy supply comes through **metabolism of glucose molecules**. Fat and protein molecules are also metabolized in some cases. Muscle cells stores glycogen (a polymer of glucose molecules) and can receive glucose from blood supply. Glucose molecules can be metabolized in two ways:

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

In the presence of oxygen (**aerobic glycolysis**), glucose molecules break down to simpler molecules (CO2, H2O) 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 blood capillaries, which is known as **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 O_2 demand at the muscle site.

CO_2, and Lactic acid are built up (causing change in Ph level) in the muscle site triggering the CNS to initiates actions to increase cellular respiration (CO2 and O2 movement in and out of the cells). This is achieved in a combinations of ways (1) Redistribution of blood supply (dilating the arteries near the muscle and constricting arteries in skin and other organs), 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.

Fatigue in Static and Dynamic Muscular Work

Cellular respiration is affected by constriction of the nearby arteries by the mechanical force developed by the muscle itself. The blood supply starts to decrease when the muscle contracts with an intensity of 15% of its maximum voluntary contraction (MVC) capacity and blood supply is completely occluded above 60% of MVC in most of the muscle cells. Reduction of blood supply means reduction of cellular respiration (O_2 supply and CO_2 removal).

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

Typical endurance limits of skeletal muscles in static muscle contraction	
% MVC	Endurance time for static muscle contractions
100	6 seconds
75	21 seconds
50	1 minute
25	3.4 minute
15	> 4 minute

In **dynamic muscular work** muscle contraction is followed by a muscle relaxation. That is static tension interspaced with relaxation. Work with rhythmic movement, such as walking, is an example of this kind. During relaxation phase, the metabolite (waste byproducts) generated during work can be washed away. As a result, 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 O_2 which is determined by the Maximum heart rate capacity, or by Maximum O_2 (Max VO2 in L/min) delivering capacity. Fatigue in this kind of work is primarily from the central fatigue, less blood glucose level, etc.