

Muscles

Muscles provide power for locomotion and other movements.

Two important properties:

- **contractility**
- **excitability**

- Muscles can only **contract** forcefully – they **cannot** elongate forcefully.
- **External** force (stretching) must be applied in order for a muscle to elongate.

Contractility is due to a set of **contractile proteins** – **actins, myosins** – that use ATP to power forceful shortening; evolutionarily conserved (found in nearly all animals), but also very diverse (many variants within and between species).

Excitability is due to same general properties of an axon – distribution of ions across cell membrane, and ability to rapidly change it.

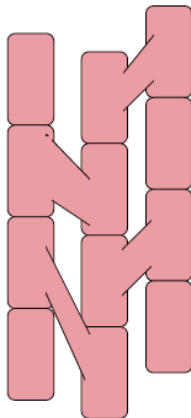
- **action potentials** (all-or-nothing-events)
- **grades responses** (varying intensity of events)

Muscle types

There are three basic types of muscle:

Cardiac muscle: in the heart; highly specialized to maintain heartbeat cycles

- columns of cells directly connected with **gap junctions** (to maintain and coordinate contractions)
- **intrinsic** contractile rhythm; overall heart contractility controlled by specialized cells (Purkinje fibers) that act as neurons
- pacemakers (clusters of electrically active fibers) generate and coordinate heartbeat: sinoatrial node, atrioventricular node
- responsive to workload: extra filling → powerful contraction
- also responds to neural and hormonal signals
- huge blood supply, lots of mitochondria; very resistant to fatigue



Muscle types

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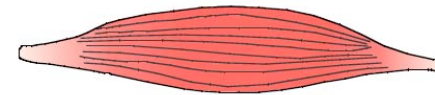
Smooth muscle: primarily in the visceral organs and in the vascular system

- usually exerts pressure on the contents of a space (i.e., peristalsis), or operates as a valve (i.e., vasodilation control)
- not very differentiated; usually consists of sheets of cells containing contractile proteins
- control usually does not involve discrete synapses; instead neurotransmitter (or neurohormone) is released **between** smooth muscle cells
- usually innervated by the **autonomic nervous system** (**sympathetic and parasympathetic**); also responds to hormonal stimulation
- produces a slow, graded contraction; very resistant to fatigue

Muscle types

There are three basic types of muscle:

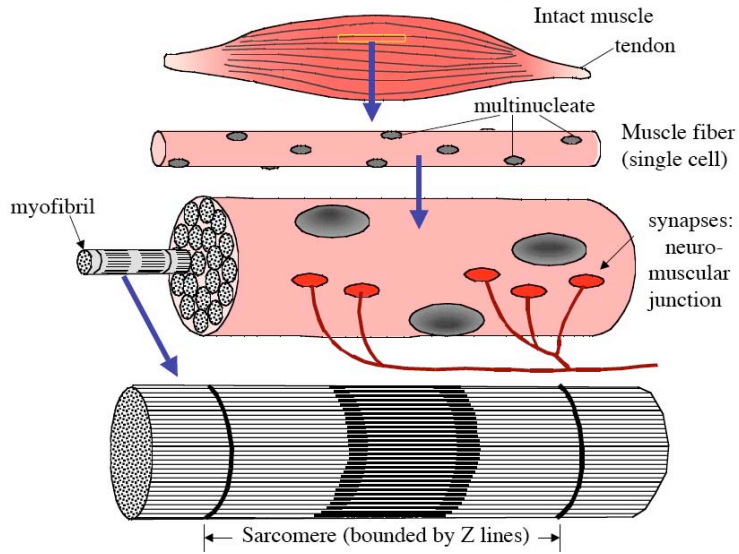
Striated (skeletal) muscle: The muscles that are attached to skeletal elements



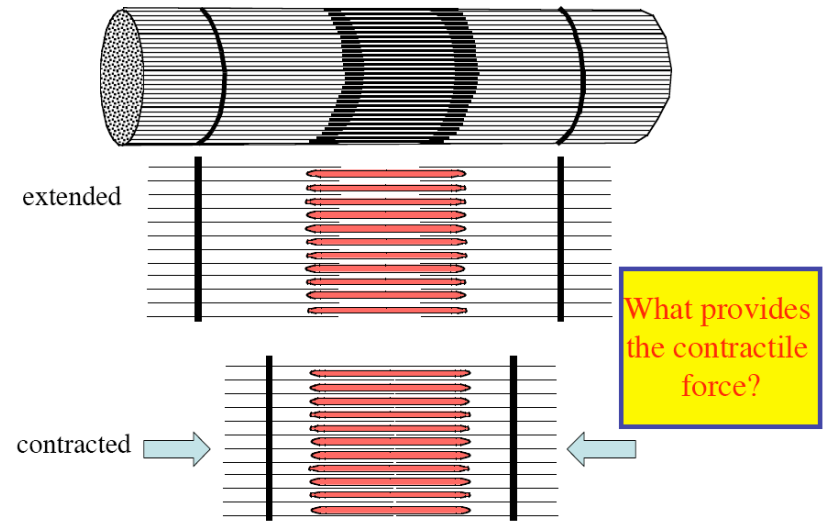
- more highly differentiated than other muscle types
- A muscle consists of large numbers of muscle fibers
- Each fiber (cell) has a single plasma membrane (sarcolemma) but is multinucleate (built from a number of embryonic muscle cells that fuse during development; a syncytium). Various numbers of mitochondria.
- Each fiber is innervated by a motor neuron to cause contraction (a single neuron can innervate many muscle fibers).

Muscles and tendons often **store** energy during **stretching** (elastic properties; like spring or rubber band)

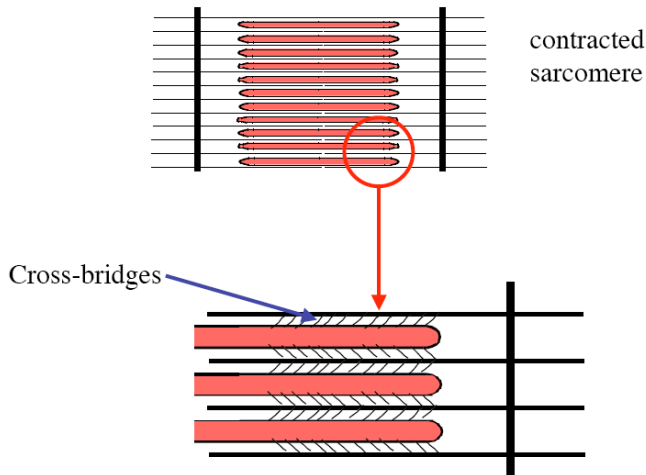
Striated muscle structure



Muscles: sliding filament model

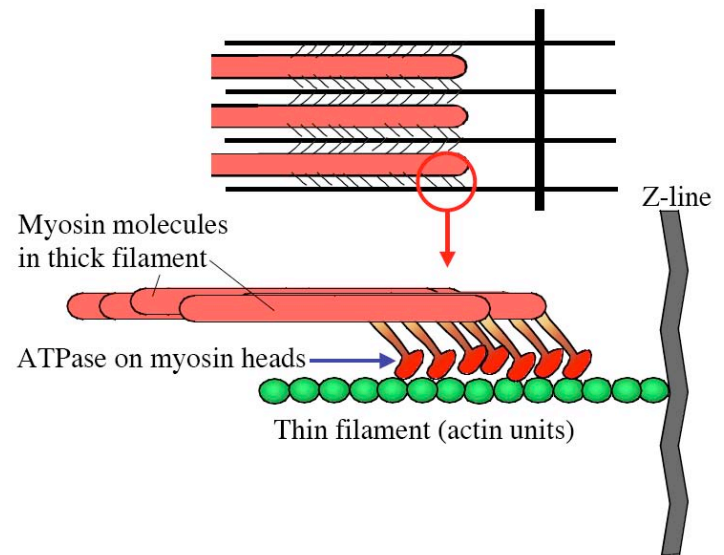


Muscles: sliding filament model

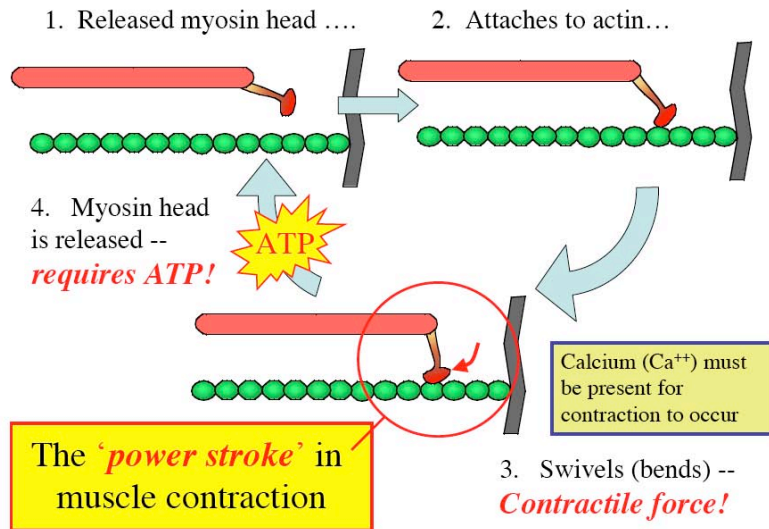


The number of cross-bridges *increases* as the sarcomere shortens.

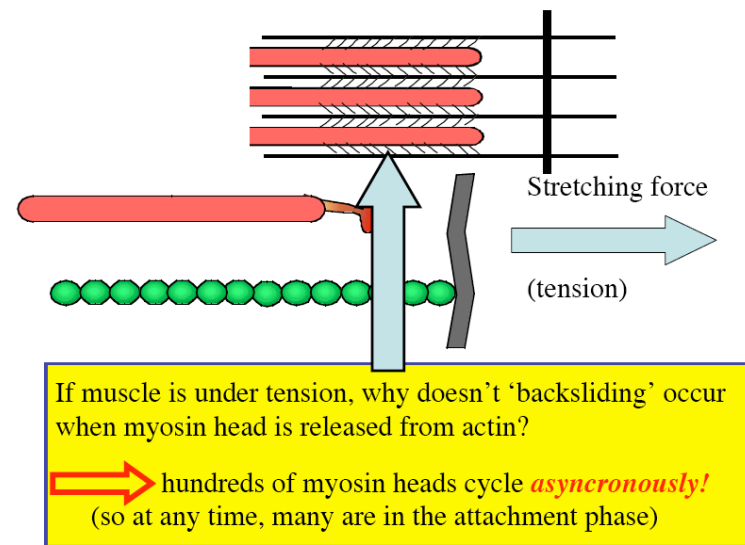
Muscles: details of contraction



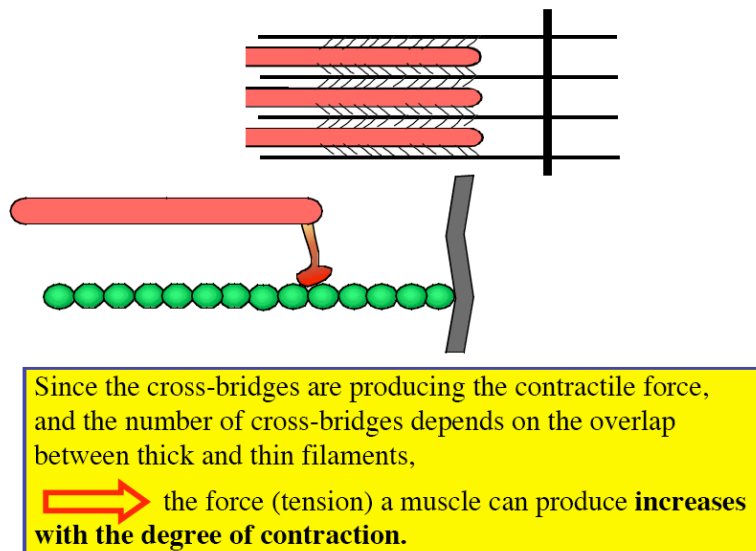
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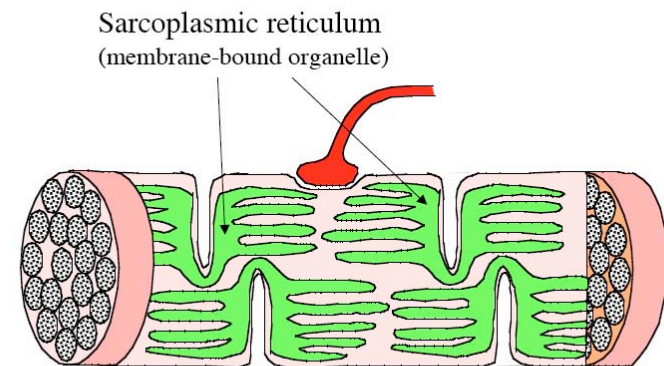
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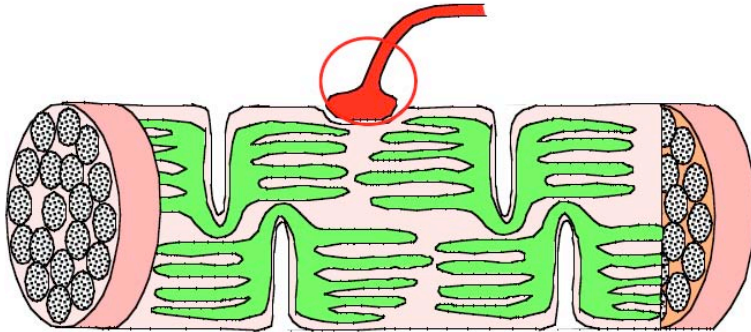
Muscles: control of contraction



A view 'inside' a muscle fiber

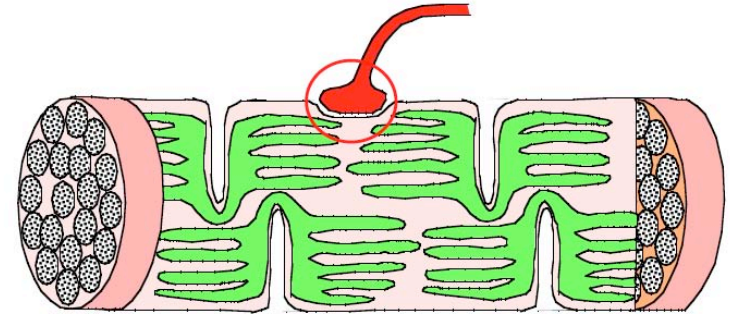
Muscles: control of contraction

1. Action potential arrives at neuromuscular junction



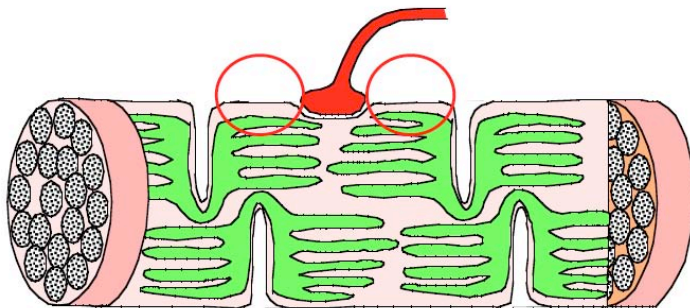
Muscles: control of contraction

1. Action potential arrives at neuromuscular junction
2. Acetylcholine released and binds to receptors



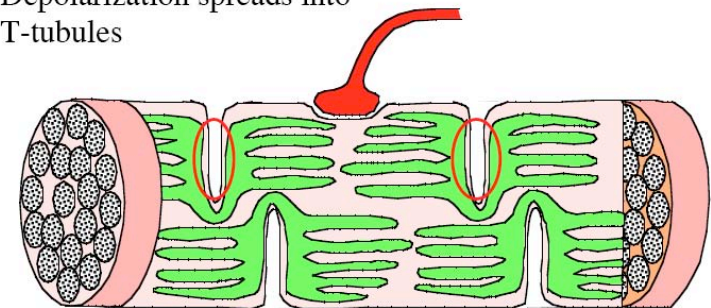
Muscles: control of contraction

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2. Acetylcholine released and binds to receptors
3. Action potential in *muscle* cell membrane



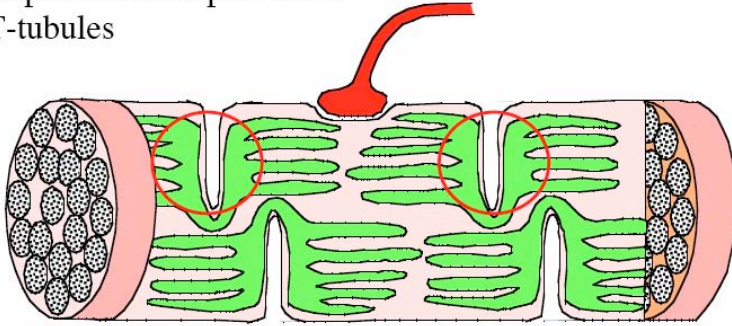
Muscles: control of contraction

1. Action potential arrives at neuromuscular junction
2. Acetylcholine released and binds to receptors
3. Action potential in *muscle* cell membrane
4. Depolarization spreads into T-tubules



Muscles: control of contraction

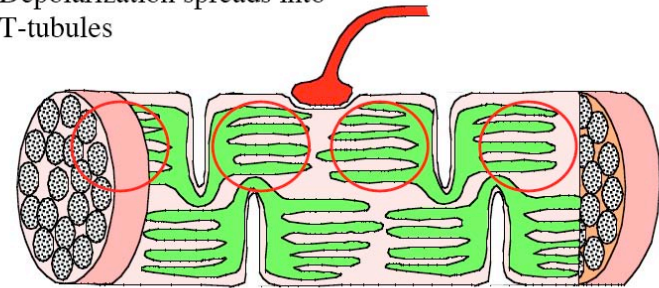
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5. Depolarization spreads to sarcoplasmic reticulum

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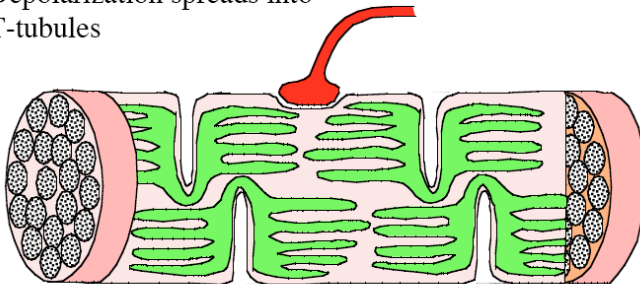
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6. SR releases Ca^{++} , which diffuses to myofibrils

Muscles: control of contraction

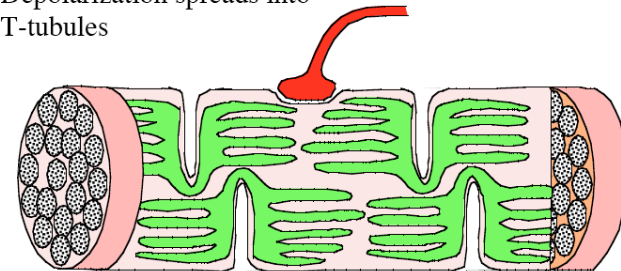
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7. Ca^{++} triggers contraction (allows myosin ATPase to work)

Muscles: control of contraction

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5. Depolarization spreads to sarcoplasmic reticulum
6. SR releases Ca^{++} , which diffuses to myofibrils
7. Ca^{++} triggers contraction (allows myosin ATPase to work)
8. Ca^{++} reabsorbed into SR (active transport) to complete the cycle

Muscles: control over movement

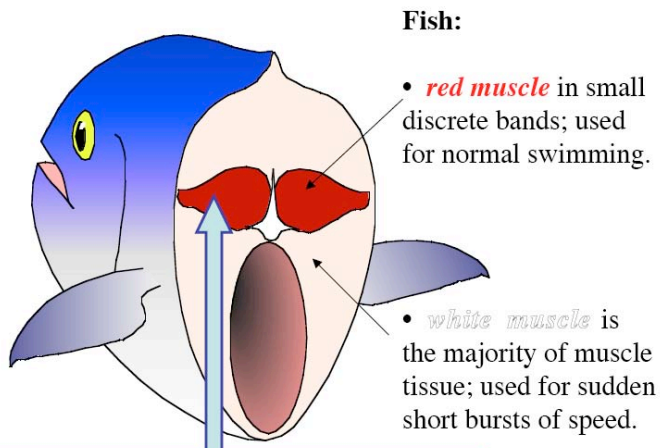
What determines the precision of a movement?

- a single motor neuron, and all the muscle fibers it innervates is a **motor unit**
- some motor units have graded contractions (related to action potential frequency)
- in other muscle types, each motor unit is 'all or nothing', so when the neuron transmits an action potential, all the muscle fibers attached to it will contract **fully**.
- muscles control the degree of contraction by recruiting different *numbers of motor units*:
 - More motor units active = greater contraction
- so the **total number of motor units** – *not* the size of the muscle – determines the precision of the contraction

- leg muscles: big, powerful, but not very precise
- finger or lip muscles: small, weak, but extremely precise

Muscles: red vs. white fibers

Sometimes in discrete clusters:



This is what ectothermic fish (tuna, white sharks) keep warm with countercurrent systems

Specialized muscles for different jobs

Vertebrate striated muscle comes in a wide variety of types. Two basic forms are:

• 'fast-twitch' muscle (white muscle)

• 'slow-twitch aerobic' muscle (red muscle)

Specialized for burst activity:

Specialized for endurance activity:

- fast, all-or-nothing
- few mitochondria
- sparse blood supply

- slow, graded contractions
- rich in mitochondria
- myoglobin (hence, red), large blood supply

-- fatigues quickly

-- more resistant to fatigue

Striated muscle is usually very responsive to conditioning

Muscles: red vs. white fibers

In mammals and birds, most muscles have both red and white fibers, but proportions vary:

- muscles used repeatedly and constantly have lots of red fibers (i.e. chicken leg muscle)
- muscles used mainly for burst exercise have lots of white fibers (i.e., chicken breast muscle)

→ To some extent, there has to be a **trade-off** between **speed** (white muscle) and **endurance** (red muscle) – hard to do both!!

- can see this in human athletes (*within* a species)
- can also see it in animal athletes (*between* species):

A natural sprinter: cheetah



- world's fastest runner: can hit **65-70 mph** (~100 kph), and can reach that speed in **2-3 seconds!**
- not much endurance: can only run at top speed for 20-40 seconds (~ 1/2 -1 km); then must stop and rest.
- muscle physiology is highly specialized for brief, intense exercise.

Wolves: natural endurance runners



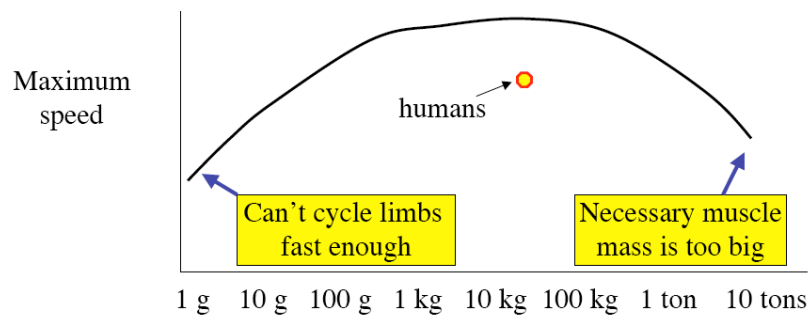
- Same size as cheetahs, but not nearly as fast (maybe 40 mph)
- **much** greater endurance than cheetahs: they catch prey animals by running them down over very long distances (also use teamwork).
- all wild canids (dogs) have lots of physiological specialization for high endurance capacity.

Muscles: how fast can animals run?

Muscle tension (force): proportional to cross-sectional area -- changes as the *square* of body length

Body mass: proportional to the *cube* of body length

→ so big animals need to have proportionally more muscle to have the same performance as small animals



Muscles: how fast can animals run?

T. rex weighed about 7 tons (as much as a big elephant). It almost certainly had the same basic muscle and bone characteristics as living animals.

- Elephants only get up to about 20 mph (35 kph)
- Recent calculations show that to run at 40 mph, **T. rex** would have needed to be about 90% leg muscle by weight!

So instead of looking like this...



... it would have to look more like **this**:

