Chapter 10.5

Muscle Energy and Metabolism

How is ATP created for a skeletal muscle fiber?

Muscle "Energy" Metabolism

- <u>ATP is used to preload myosin heads with energy</u>
- <u>ATP is also required after the contraction cycle to break myosin-actin cross bridges to release cross bridge and allow muscle to relax</u>
- <u>ATP is required to pump calcium back into sarcoplasmic reticulum so muscle may relax</u>
- ATP is constantly being made and is immediately consumed
- ATP is not stored

Muscle “Energy” Metabolism

- *Ability to make small amount of ATP via glycolsis depends on availability of a reduced organic molecule (e.g. glucose)*

- *Ability to make large amounts of ATP depends on availability of a reduced organic molecule (e.g. glucose and/or fatty acids) plus the presence of oxygen*

  – Glycolysis vs Kreb's Cycle + Electron Transport System (note: Kreb's Cycle also called the citric acid cycle)

    - Glcolysis enzymes are in cytosol // anaerobic

    - KC-ETS enzymes are inside mitochondria // areobic

Muscle Metabolism

- Two main pathways for ATP synthesis
  - First metabolic pathway = anaerobic fermentation (glycolysis)
    - enables cells to produce ATP in the absence of oxygen / takes place in cytoplasm
    - yields little ATP // but immediately available
    - by product is toxic lactic acid /// believed to be factor in muscle fatigue

Muscle Metabolism

– Second metabolic pathway: aerobic respiration (Krebs Cycle also called Citrus Acid Cycle with ETS)

- takes place in the mitochondria
- requires oxygen
- produces much more ATP   // glycolysis = 2 vs Kreb's Cycle = 36 to 38
- toxic end product = CO_2
- produces H+ (acid) but use oxygen to make water with H+ (called metabolic water)
- reduces FAD and NAD / these reduced co-enzymes are then oxidized via electron transport system /// reduced co-enzymes transfer protons and electrons to ETS which produces most of the ATP using ATP Synthetase /// two ADP are directly phosphorlated within mitochondria during each "Krebs Cycle"
- Requires a continual supply of oxygen and glucose

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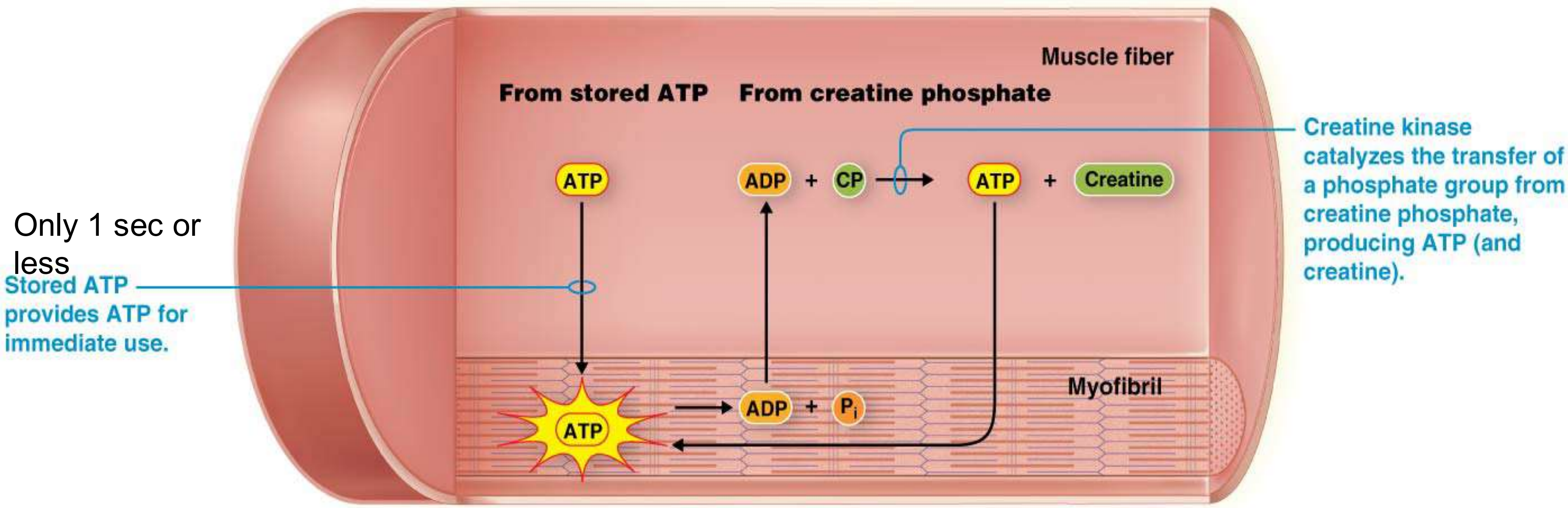
Key Idea: The level of activity (how fast the muscle fiber uses glucose and oxygen) determines the physiologic state of the muscle fibers. To support a high level of muscle contractions you need to increase the blood supply (delivery of glucose and oxygen) to the muscle fiber.

As you move from a resting state to an exercise state, there must occur a "ramping-up process" so the cardiovascular and respiratory systems may increase their function to meet the demands of the now more active muscle organ. This will take several seconds and depends upon the level of muscle activity.

Therefore, the muscle fiber must have a mechanism to "bridge" the metabolic demands from resting state to active state. This dynamic transition will occur over different periods of time from resting state to walking or running.

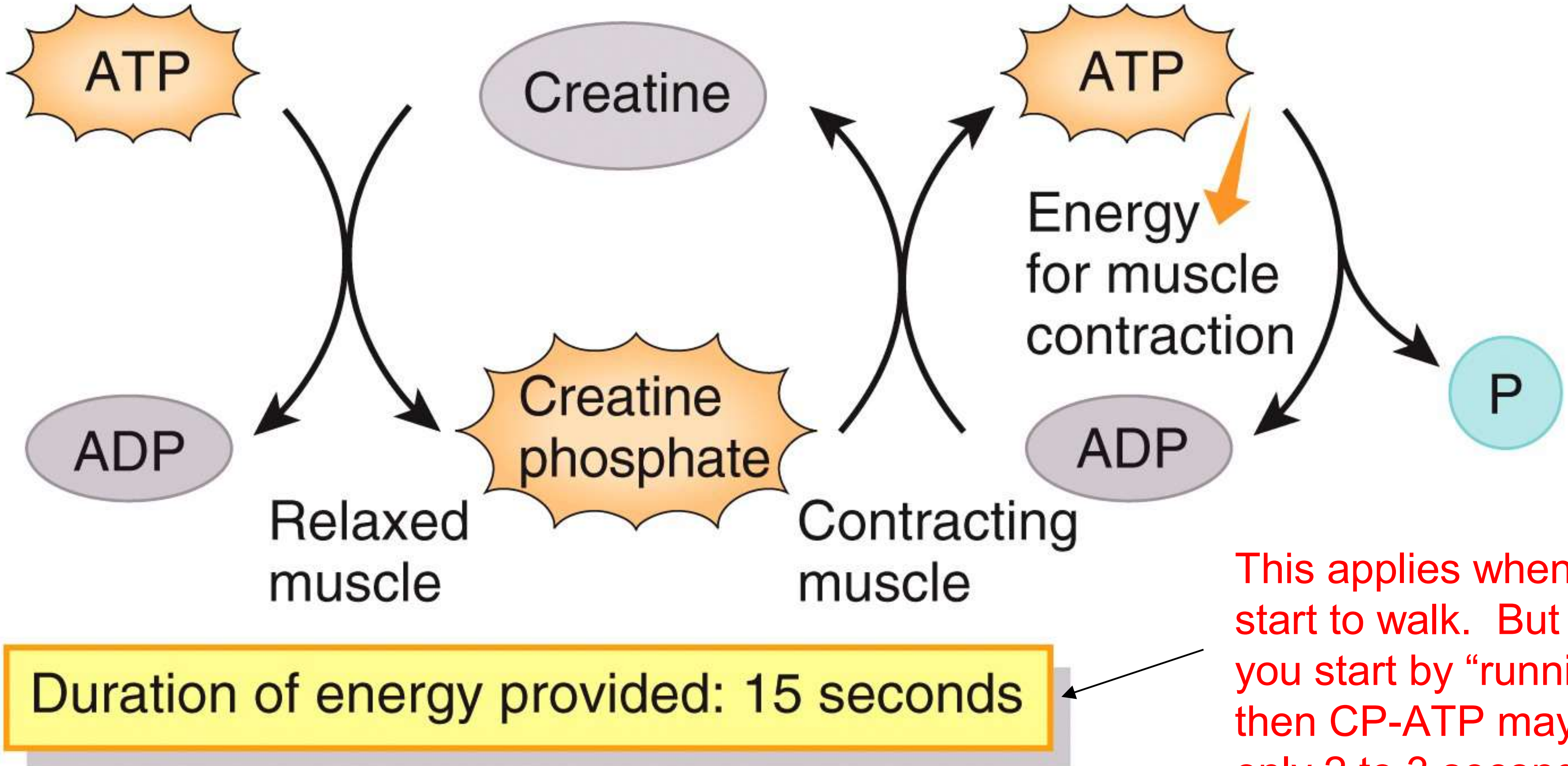
Sources of energy for muscle fibers.

Only 1 sec or less



(a) Immediate energy sources

ATP is always being made within cytosol but when you start to exercise this small amount of ATP is consumed within a second. ADP can be "reenergized" by borrowing a phosphate from creatine phosphate (i.e. like getting a jump start to a battery).

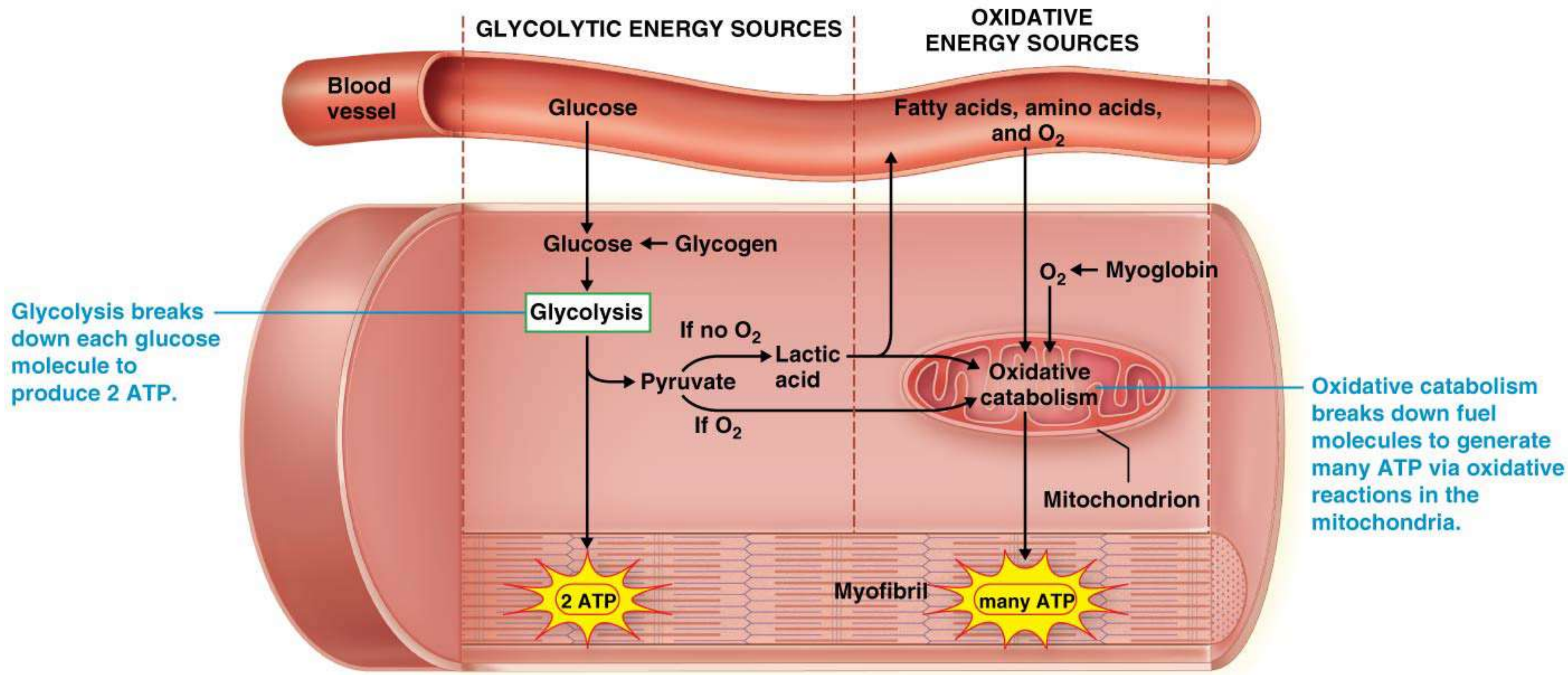


(a) ATP from creatine phosphate

This applies when you start to walk. But if you start by "running" then CP-ATP may last only 2 to 3 seconds

Note: myoglobin is stored inside muscle fiber // releases oxygen so mitochondria can use this small amount of oxygen to produce limited amount of ATP. This is only enough to support Krebs Cycle for one to two seconds. Now the creatine phosphate and phosphogen systems may supplement ATP production after myoglobin depleted of oxygen .

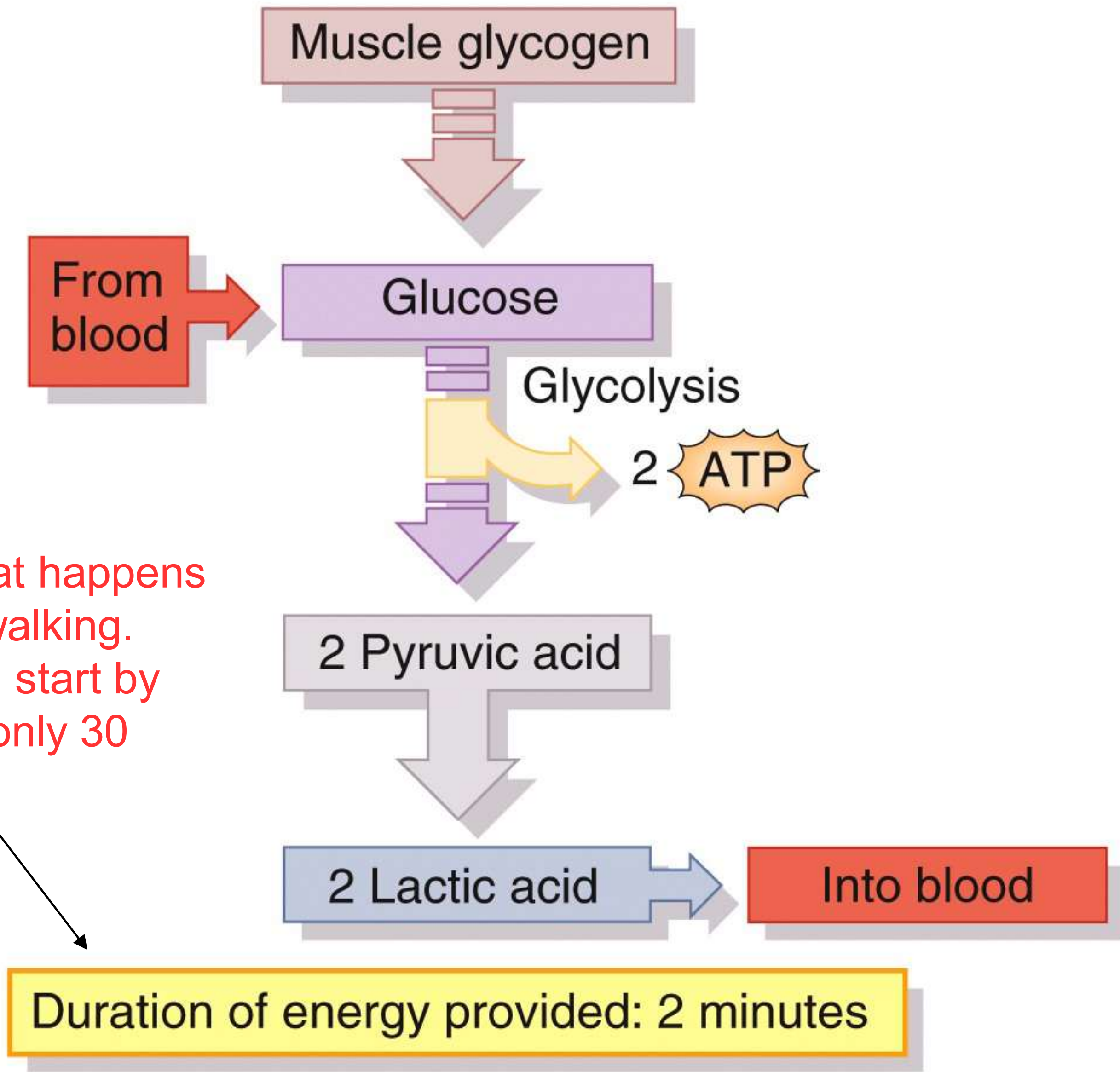
Sources of energy for muscle fibers.



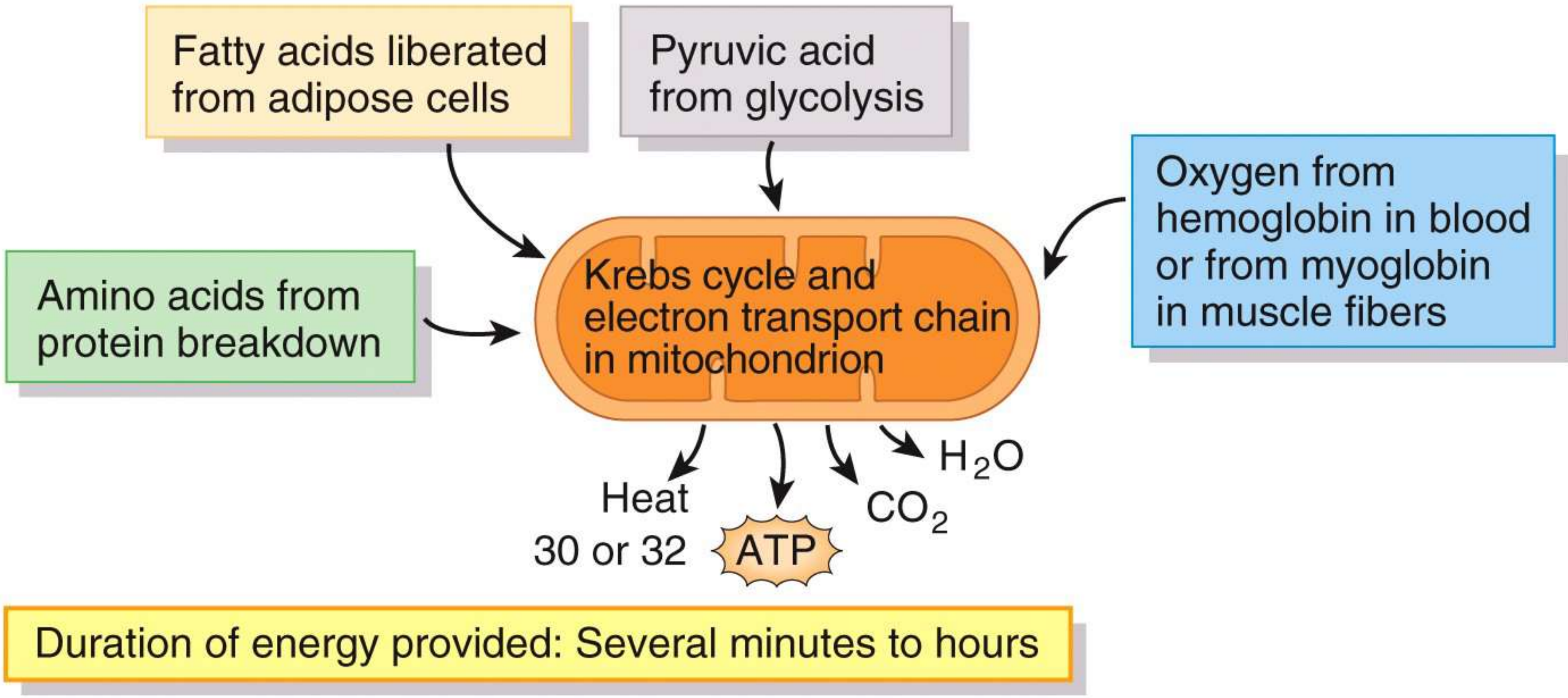
(b) Glycolytic and oxidative energy sources

Muscle fibers do store a small amount of oxygen bound to myoglobin. So at the start of exercise, oxidative catabolism starts but stored oxygen depleted rapidly and more oxygen from lungs must be delivered. This process takes time. How is ATP produced during this “lag period”?

This shows what happens when you are walking. However, if you start by “running” then only 30 seconds +/-



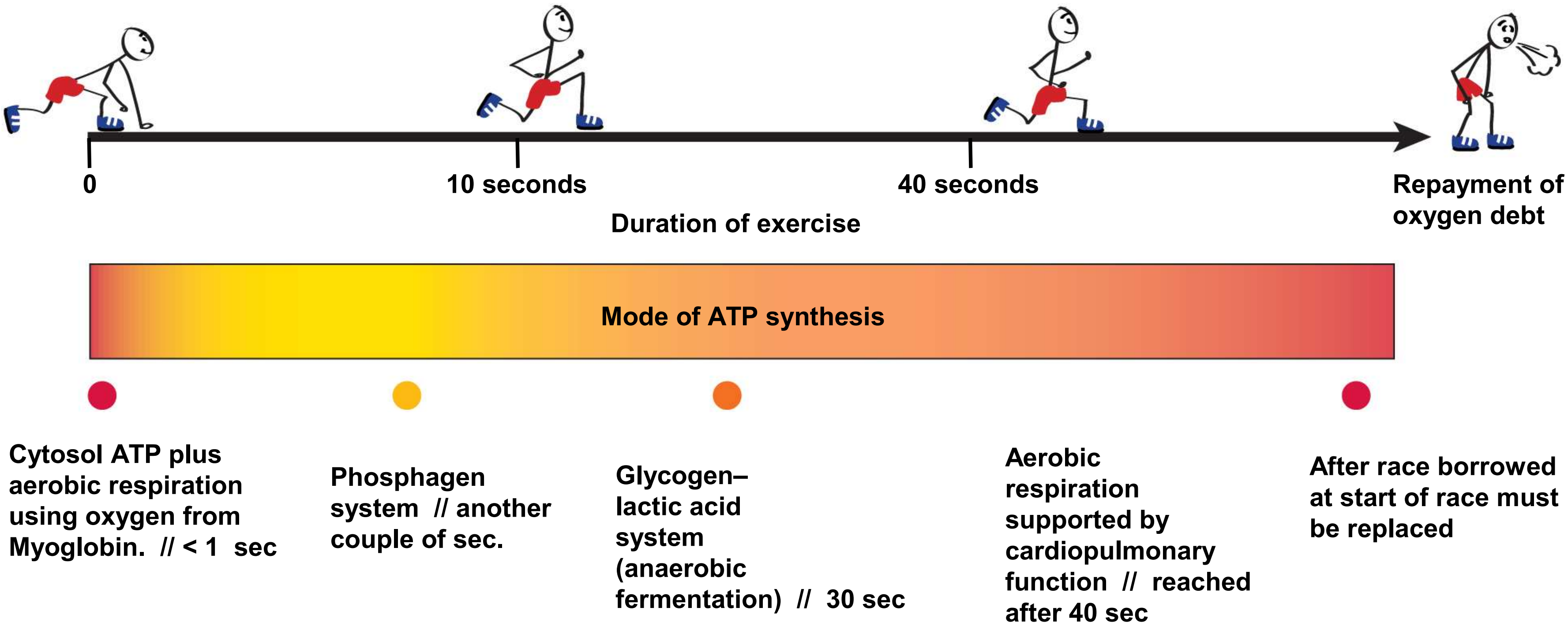
(b) ATP from anaerobic glycolysis



(c) ATP from aerobic respiration

Note: How is skeletal muscle ATP managed if you want to run a long race? The next slides will outline the steps.

Modes of ATP Synthesis During Extreme Exercise



At rest we oxidize fatty acids to supply energy for our skeletal muscles (note: our brains continue to oxidize glucose / brain cells and RBCs only ferment glucose)

As level of activity increases, skeletal muscles will shift from fat to glucose as an energy source.

Only after glucose reserves are exhausted will we shift back to fat metabolism

Immediate Energy Needs

- During short, intense exercise like 100 m dash
- Skeletal muscles start to contract before blood supply to muscle organ increases to meet metabolic needs (e.g. blood brings oxygen, glucose, and removes waste products)
- Skeletal muscles contain only limited amount of myoglobin / stores small amount of oxygen inside muscle fibers
  - Maybe used to accommodate some aerobic respiration – 1 second
  - Myoglobin's oxygen rapidly depleted

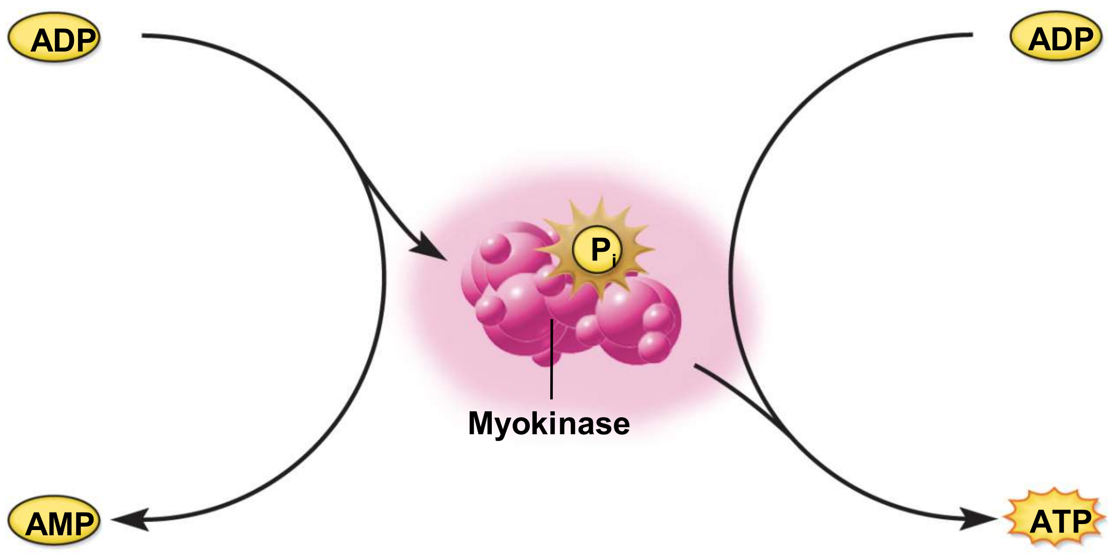
Immediate Energy Needs

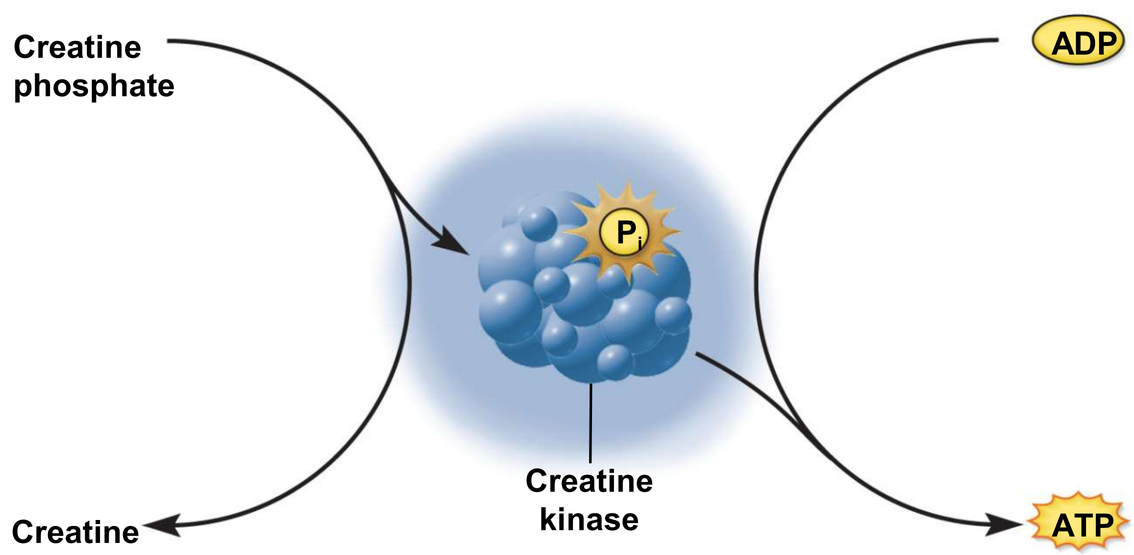
- After myoglobin gone / muscles meets ATP demand by borrowing phosphate groups (P_i) from other molecules and transferring the P_i to ADP (makes ATP!) = Phosphogen System
  - two enzyme systems control these phosphate transfers
    - myokinase – transfers P_i from one ADP to another converting the latter to ATP
    - creatine kinase – obtains P_i from a phosphate-storage molecule creatine phosphate (CP)
    - fast-acting system that helps maintain the ATP level while other ATP-generating mechanisms are being activated

Immediate Energy Needs

- Phosphagen system
  - provides nearly all energy used for short bursts of intense activity
    - <u>one minute of brisk walking</u>
    - <u>6 seconds of sprinting or fast swimming</u>
    - important in activities requiring brief but maximum effort // football, baseball, and weight lifting

Immediate Energy Needs





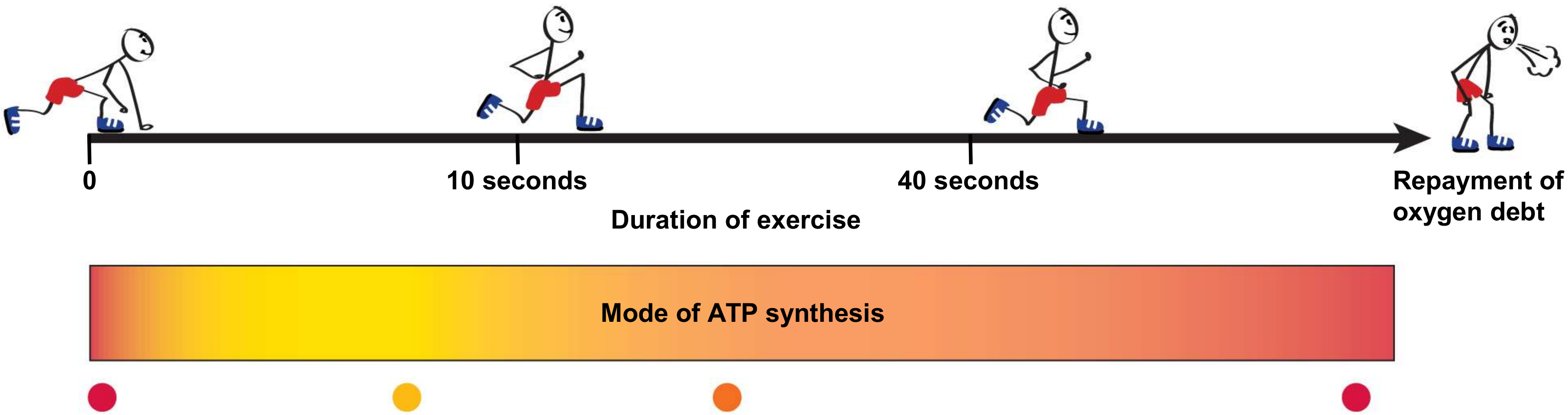
Short-Term Energy Needs

- as the phosphagen system is exhausted
- muscles shift to anaerobic fermentation
  - muscles obtain glucose from blood or muscle fiber’s stored glycogen deposits
  - in the absence of oxygen
    - glycolysis can generate a net gain of 2 ATP for every glucose molecule consumed
  - converts glucose to lactic acid / L.A. leaves cell and transported to liver

Short-Term Energy Needs

- <u>Glycogen (glucose) lactic acid system</u> // the pathway from glycogen to lactic acid
- Produces enough ATP for <u>30 – 40 seconds of maximum activity</u>

Long-Term Energy Needs

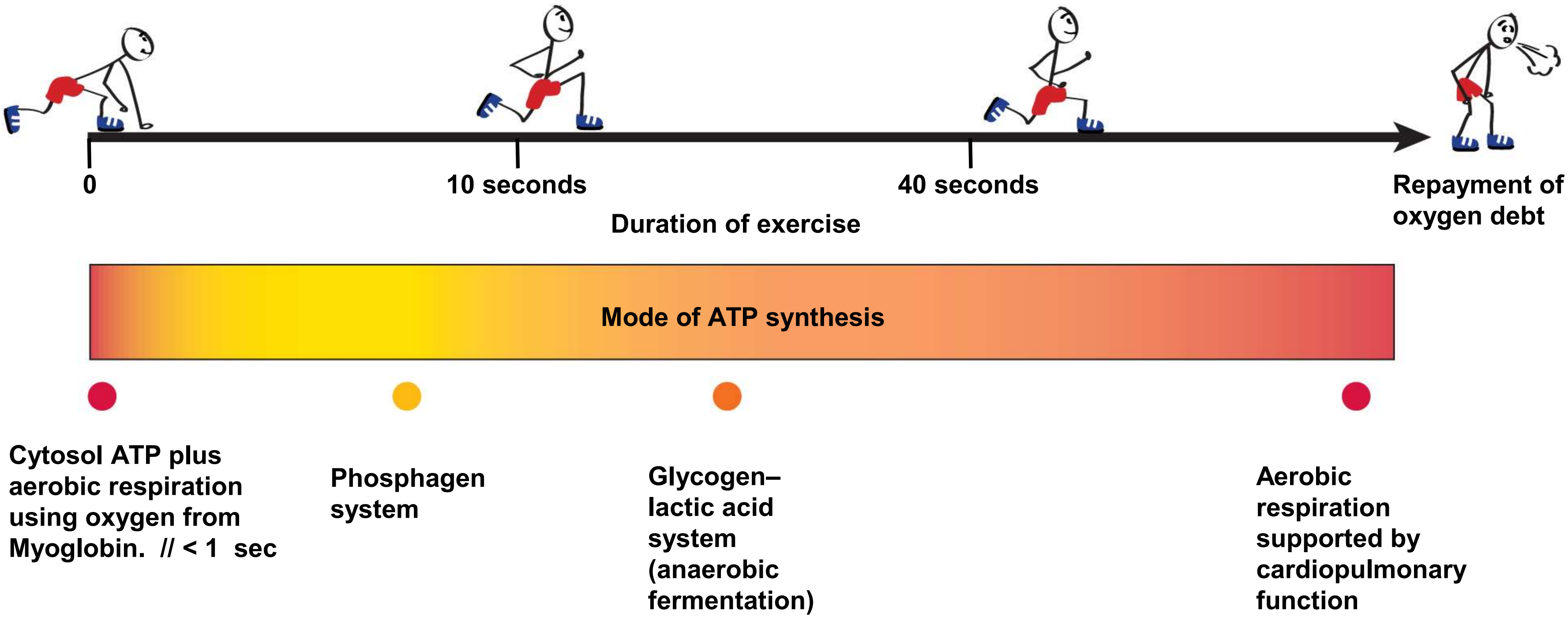


- After 40 seconds or so
  - <u>respiratory and cardiovascular systems "catches up"</u> to demands of skeletal muscles
  - now cardiorespiratory system able to deliver enough oxygen to meet the muscle's oxygen requirement for aerobic respiration /// mitochondria able to make enough ATP to sustain muscle contrations.

Long-Term Energy Needs

- Aerobic respiration produces 36-38 ATP per glucose
  - efficient means of meeting the ATP demands of prolonged exercise
  - one's rate of oxygen consumption rises for 3 to 4 minutes and levels off to a steady state in which aerobic ATP production keeps pace with demand
  - <u>little lactic acid accumulates</u> under steady state conditions
  - *depletion of glycogen and blood glucose, <u>together with the loss of fluid and electrolytes through sweating</u>, set limits on endurance and performance even when lactic acid does not*

Modes of ATP Synthesis During Extreme Exercise



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What is Oxygen Debt?

- Why does heavy breathing continues after strenuous exercise?
  - excess post-exercise oxygen consumption (EPOC) – the difference between the resting rate of oxygen consumption and the elevated rate following exercise.
  - typically about 11 liters extra is needed after strenuous exercise
  - oxygen debt occurs because we need to replace the ATP consumed to restore myoglobin and replenish CP

Oxygen Debt

- Oxygen need in excess of current muscle activity for the following reasons:
  - **replace oxygen reserves** depleted in the first minute of exercise
    - oxygen bound to myoglobin and blood hemoglobin
    - oxygen dissolved in blood plasma and other extracellular fluid
    - oxygen in the air in the lungs
  - **replenishing the phosphagen system**
    - synthesizing ATP and using some of it to donate the phosphate groups back to creatine until <u>resting levels of ATP and CP are restored</u>

Oxygen Debt

- Oxygen need in excess of current muscle activity for the following reasons:
  - **lactic acid**
    - 80% of lactic acid produced by muscles enter bloodstream
    - much of this lactic acid ends up in liver
    - converted back to pyruvic acid in the kidneys, cardiac muscle, and especially the liver
    - liver converts most of the pyruvic acid back to glucose to replenish the glycogen stored in the skeletal muscles or liver.
    - This requires ATP and explains continued demand for oxygen even after strenuous exercise stops!
  - **serving the elevated metabolic rate**
    - occurs while the body temperature remains elevated by exercise and consumes more oxygen

Endurance

- endurance – the ability to maintain high-intensity exercise for more than 4 to 5 minutes
  - determined in large part by one's maximum oxygen uptake (VO_2max)
  - maximum oxygen uptake – the point at which the rate of oxygen consumption reaches a plateau and does not increase further with an added workload
    - proportional to body size
    - peaks at around age 20
    - usually greater in males than females
    - <u>can be twice as great in trained endurance athletes as in untrained person</u>
      - results in twice the ATP production

Muscle Fatigue

- Characterized by progressive weakness and loss of contractility from prolonged use of the muscles
  - To experience muscle fatigue try this:
    - repeated squeezing of rubber ball
    - rapidly opening and closing your hand as if making a fist (one minute)
    - holding text book out level to the floor

Fatigue

- Causes of muscle fatigue
  - ATP synthesis declines as glycogen is consumed
  - ATP shortage slows down the Na^+ - K^+ pumps
    - compromises their ability to maintain the resting membrane potential and excitability of the muscle fibers
  - Lactic acid lowers pH of sarcoplasm
    - inhibits enzymes involved in contraction, ATP synthesis, and other aspects of muscle function

Fatigue

- Causes of muscle fatigue (cont)
  - release of K^+ with each action potential causes the accumulation of extracellular K^+ /// hyperpolarizes the cell and makes the muscle fiber less excitable
  - motor nerve fibers use up their Ach /// less capable of stimulating muscle fibers – junctional fatigue
  - central nervous system, where all motor commands originate, fatigues by unknown processes, so there is less signal output to the skeletal muscles

Beating Muscle Fatigue

- Taking **oral creatine** increases level of creatine phosphate in muscle tissue and increases speed of ATP regeneration
  - useful in burst type exercises – weight-lifting
  - risks are not well known
    - muscle cramping, electrolyte imbalances, dehydration, water retention, stroke
    - kidney disease from overloading kidney with metabolite creatinine

Beating Muscle Fatigue

- carbohydrate loading – a form of dietary regimen
  - Loads maximum amount of glycogen into muscle cells
  - extra glycogen is hydrophilic and adds 2.7 g water/ g glycogen
    - athletes feel sense of heaviness outweighs benefits of extra available glycogen