

Muscle Energy and Metabolism



How is ATP created when at rest? If walking? Or running?

What is the big picture?

Skeletal muscle contracts using the sliding filament theory. It requires a lot of ATP. The amount of ATP is different when you are awake, and the muscle is at rest. This is the muscle tone which allows you to sit in your chair for example. It's called your posture.

If you get up and start to walk, then the muscle needs more ATP. If you start to run, then the muscle will need even more ATP. So, the resources required to make ATP between the resting state, the walking state, and the running state must increase to meet the energy demand of the skeletal muscle.

ATP is made from glucose (or fat when all available stored glucose is depleted). Glucose is the preferred molecule to use for making ATP. Blood glucose level is adequate for ATP production in the resting state. But when you start to walk or run then the pancreas will need to release glucagon to signal the liver to release glucose from glycogen. More oxygen will also be needed so the respiratory system will need to increase respiration.

You can see both the endocrine system and respiratory system both need to increase their activity to meet the energy requirement of the skeletal muscle when it shifts from resting, to walking, or to running. This is further complicated because there is a delay in the process for the endocrine and respiratory systems to meet the muscles increase energy needs from the resting state. So, how do skeletal muscles bridge this gap?

Review How ATP Is Made

Two metabolic pathways synthesize ATP

1) Anaerobic fermentation (glycolysis)

Enables cells to produce 2 ATP // no oxygen required // fast // occurs in cytoplasm and myoplasm // Called fast glycolytic metabolism

Glucose (6 carbons) metabolized to two pyruvate molecules (3 carbon each) // when oxygen is not available then two lactic acid molecules (3 carbon) is produced instead of the pyruvate. // The anaerobic end product is toxic lactic acid /// believed to be factor in muscle fatigue

If oxygen is available, then a carbon is removed from pyruvate to make acetyl and it is attached to Co-A. Acetyl-CoA then enters the mitochondria. // This then starts the Krebs' Cycle which is followed by the Electron Transport Chain.

Review How ATP Is Made

2) Aerobic respiration (Krebs Cycle also called Citrus Acid Cycle) and the Electron Transport System (ETS)

Takes place in the mitochondria // makes a lot of ATP // requires oxygen // also makes metabolic water and toxic CO_2

At the end of the ETS free protons (H^+ = acid) are produced // oxygen combines with H^+ (called metabolic water) // this is why we breath in oxygen!

Glycolysis = 2 vs Kreb's Cycle = 36 to 38

Kreb's cycle reduces FAD and NAD / these reduced co-enzymes (hydrogen atom attached) are then oxidized via electron transport system

Reduced co-enzymes transfer electrons to ETS /// the protons are placed in a separate region to be later reunited with its proton and attached to oxygen // electrons produce most of the ATP as the electrons pass through ATP Synthetase

Two ADP are directly phosphorylated within mitochondria during each "Krebs Cycle"



How is ATP created throughout a race?

A muscle fiber will use different amounts of oxygen and glucose when at rest vs walking vs running.

When you exercise you need more ATP and will need more oxygen and glucose to produce this extra ATP.

The respiratory system, endocrine system, and cardiovascular system all must increase their functions to deliver the glucose and oxygen to the more active muscle fibers.



How is ATP created throughout a race?

As soon as you start to run, the demand for more oxygen and glucose increases immediately, however.

The respiratory, endocrine, and cardiovascular systems responds slower.

Time is required before the necessary amount of oxygen and glucose is delivered to the muscle fiber.

What mechanisms compensate for this gap in energy to support muscle function?



How is ATP created throughout a race?

How are muscle fibers able to “bridge” this time between the amount of ATP used before the start of the race and the amount of ATP needed when running?

This dynamic problem also occurs between the resting state and the walking state.

Similar events occur but the duration of the events differ between rest and the walking or running states.

ATP Metabolism



ATP is made “on demand” to power muscle fiber contractions. **ATP is not stored. // once made it last less than one second (our benchmark)**

At the start of exercise.....

The cardiovascular system needs to increase cardiac output after you start to exercise.

The respiratory system needs to increase ventilation rate.

The endocrine system needs to release glucagon to signal liver to release glucose into the blood.

These three events will take several seconds.

How do muscle fibers “bridge the ATP demand” when you start to walk or run?



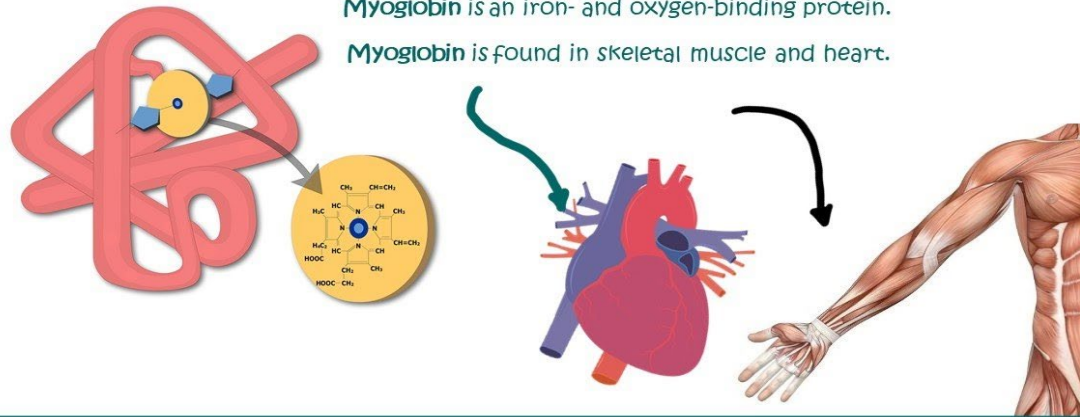
1) Myoglobin stores oxygen in the sarcoplasm. This source of oxygen is used to support aerobic respiration in the mitochondria when blood oxygen levels drops rapidly, like when you start to exercise. But only a couple seconds of energy.

2) Muscle fibers store a small amount of glycogen in the sarcoplasm. This is used when blood glucose levels drop. Used by glycolysis which does not require oxygen, however. Again, only a few seconds.

Myoglobin

Myoglobin is an iron- and oxygen-binding protein.

Myoglobin is found in skeletal muscle and heart.



Hemoglobin transports oxygen in RBC to the skeletal muscle

Oxygen diffuses from blood to muscle fiber's mitochondria where ATP is made

Any extra oxygen not needed to produce ATP maybe stored in the sarcoplasm attached to myoglobin // very small amount of oxygen

When oxygen levels in blood do not meet the MF oxygen requirement for ATP production, MF will use the oxygen attached to myoglobin so mitochondria may prolong ATP production. // Myoglobin's oxygen provides only a second or two of function

How do muscle fibers make “more ATP” when you start to walk or run?

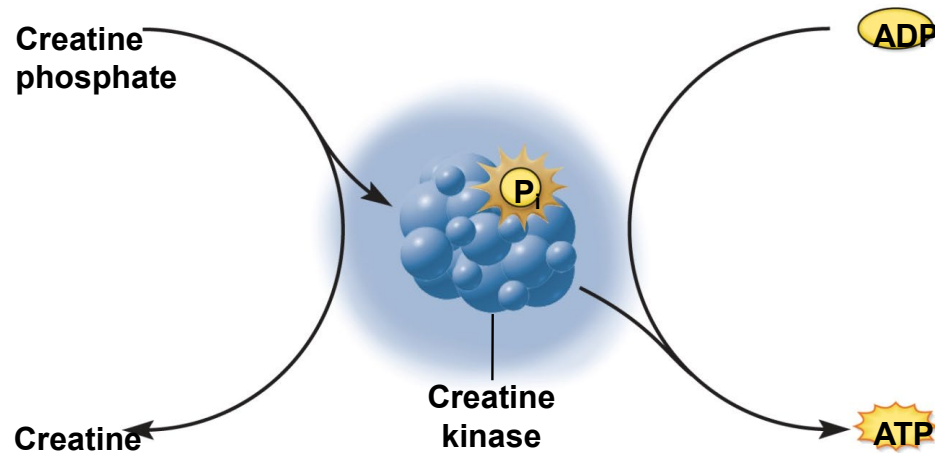


3) ATP is constantly being made in the sarcoplasm by glycolysis. Glycolysis requires no oxygen and produces a small amount of ATP (only 2ATP). This ATP must be used immediately and last for less than a second. Another problem with anaerobic fermentation (glycolysis) is the accumulation of lactic acid. This will become a limiting factor for muscle contraction.

4) The phosphoguan system evolved to store ATP's energy in muscle cells. This system transfers ATP's high energy third phosphate to creatin to form creatin phosphate and ADP.

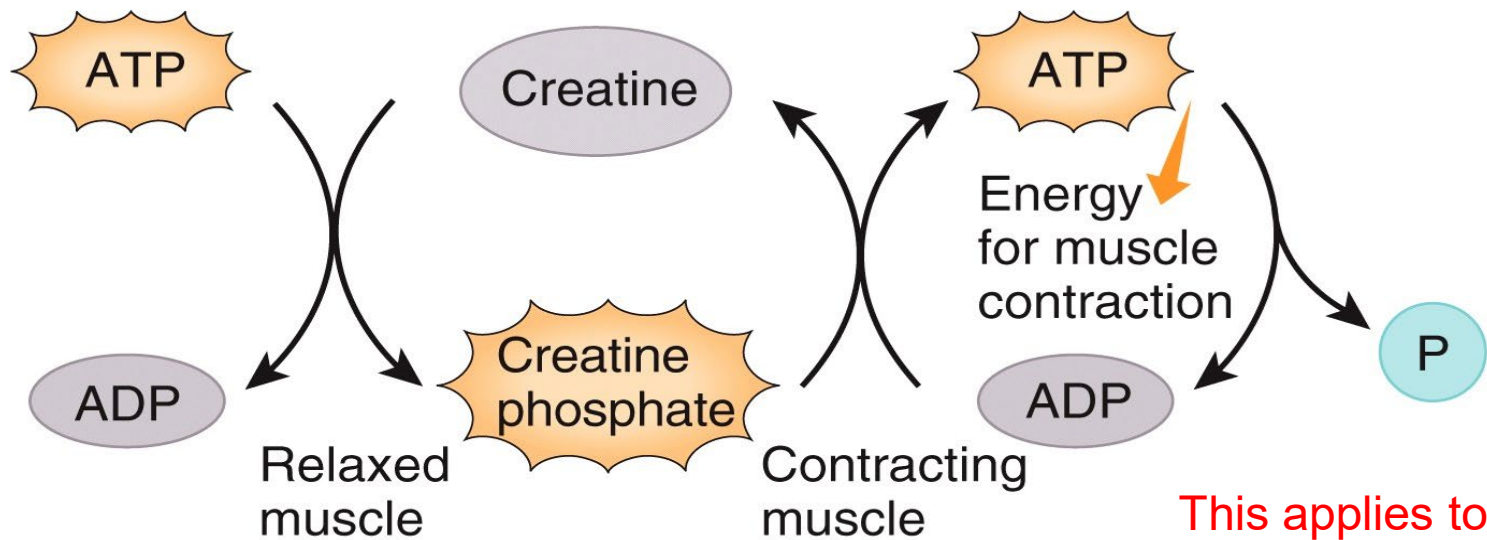
When a muscle fiber needs ATP, creatin phosphate may re-phosphorylate ADP to ATP. (how muscle fiber may store energy) Muscle fibers store about six seconds worth of energy in the form of creatin phosphate.

Creatine Phosphate



In the resting state, excess ATP can not be stored. However, if the muscle fiber has ATP not required for immediate use, the muscle fiber may transfer ATP's high energy phosphate to another molecule, creatine phosphate.

At a later time, when muscle fiber needs more ATP, creatine phosphate maybe used to phosphorylate ADP back to ATP.



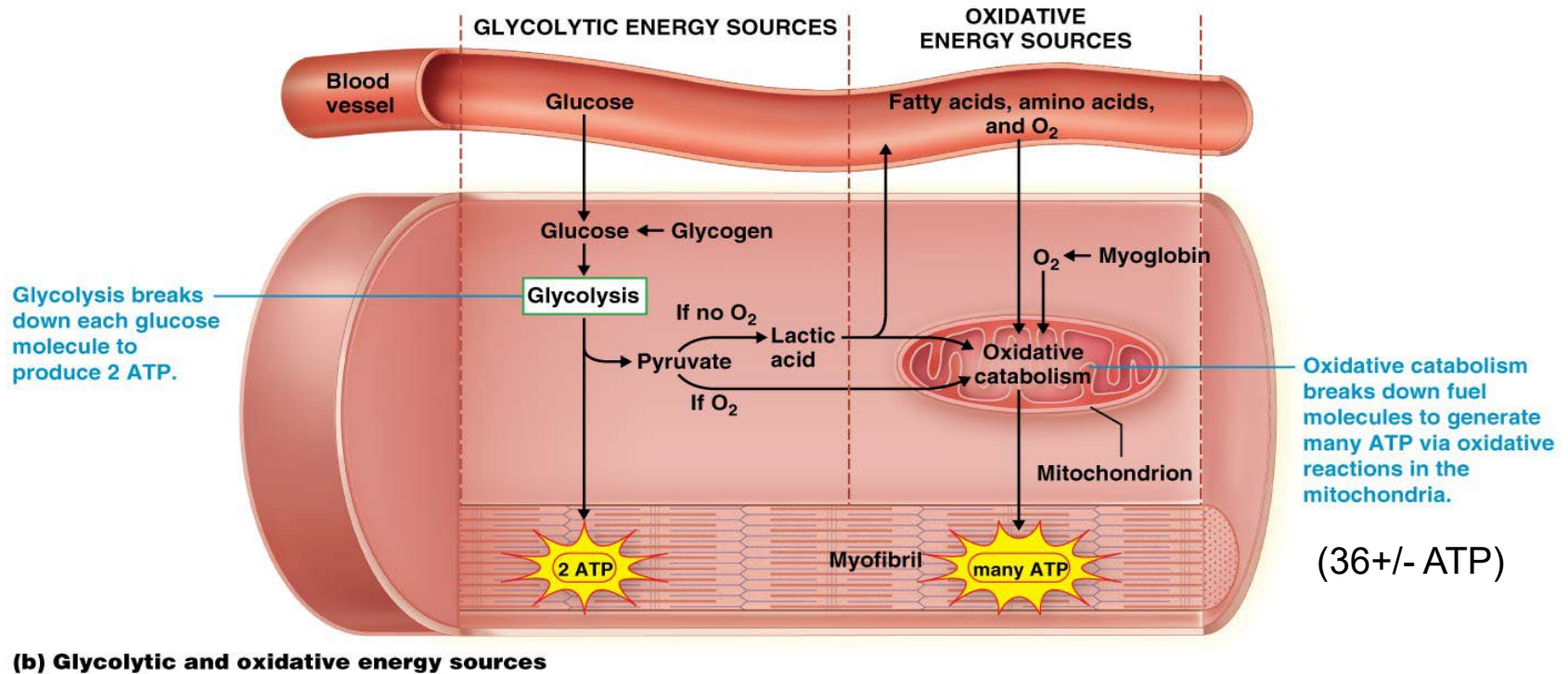
Duration of energy provided: 15 seconds

(a) ATP from creatine phosphate

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

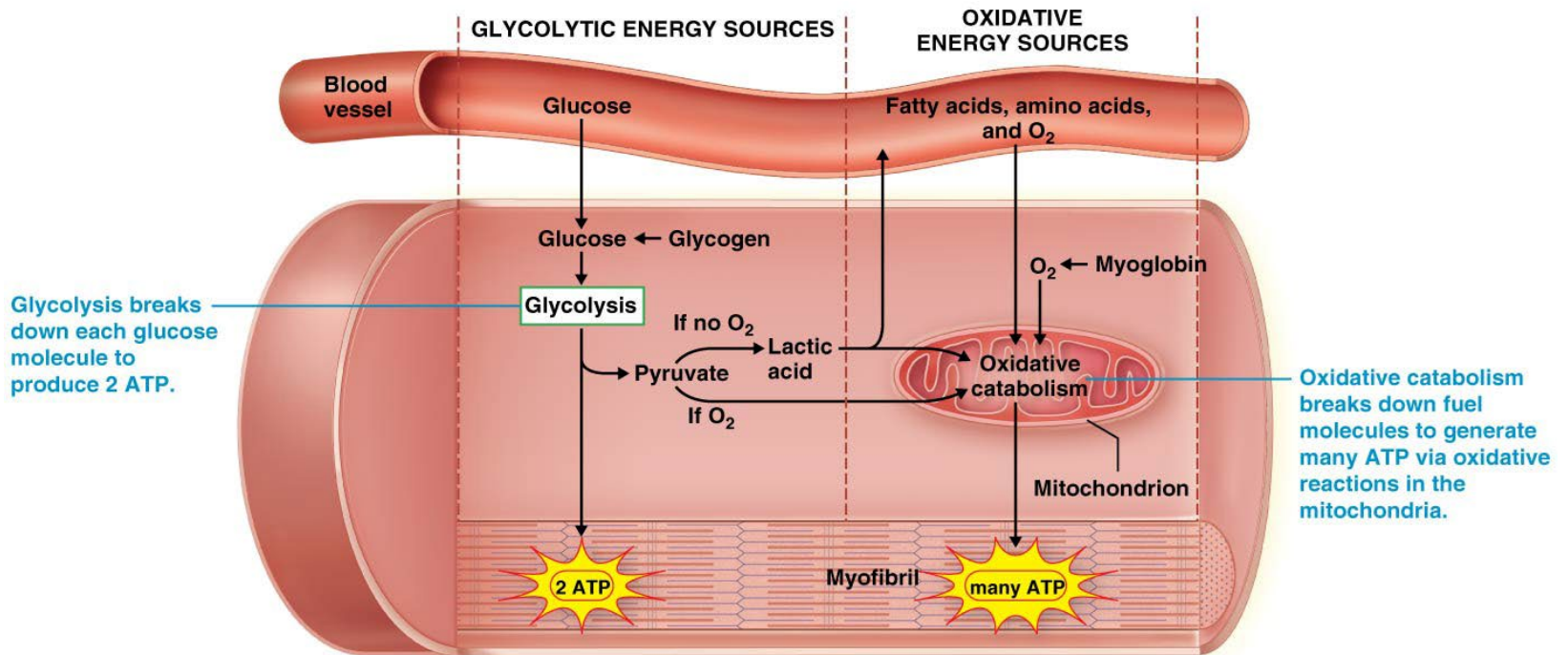
Now the creatine phosphate (phosphogen system) may supplement ATP production after myoglobin is depleted of oxygen .

Sources of energy for muscle fibers.



When at rest, the blood supplies enough oxygen and glucose to meet the muscle fiber's ATP requirements. This requires a coordinated effort by the endocrine (glucose), respiratory (oxygen), and cardiovascular (transport) systems .

When you start to walk or exercise, MF demand for glucose/oxygen increases. There is not enough glucose/oxygen in the blood. Endocrine, respiratory, and cardiac functions will all need to increase. This will take time. How will MF bridge the energy gap between the resting state and when you start to walk or run?



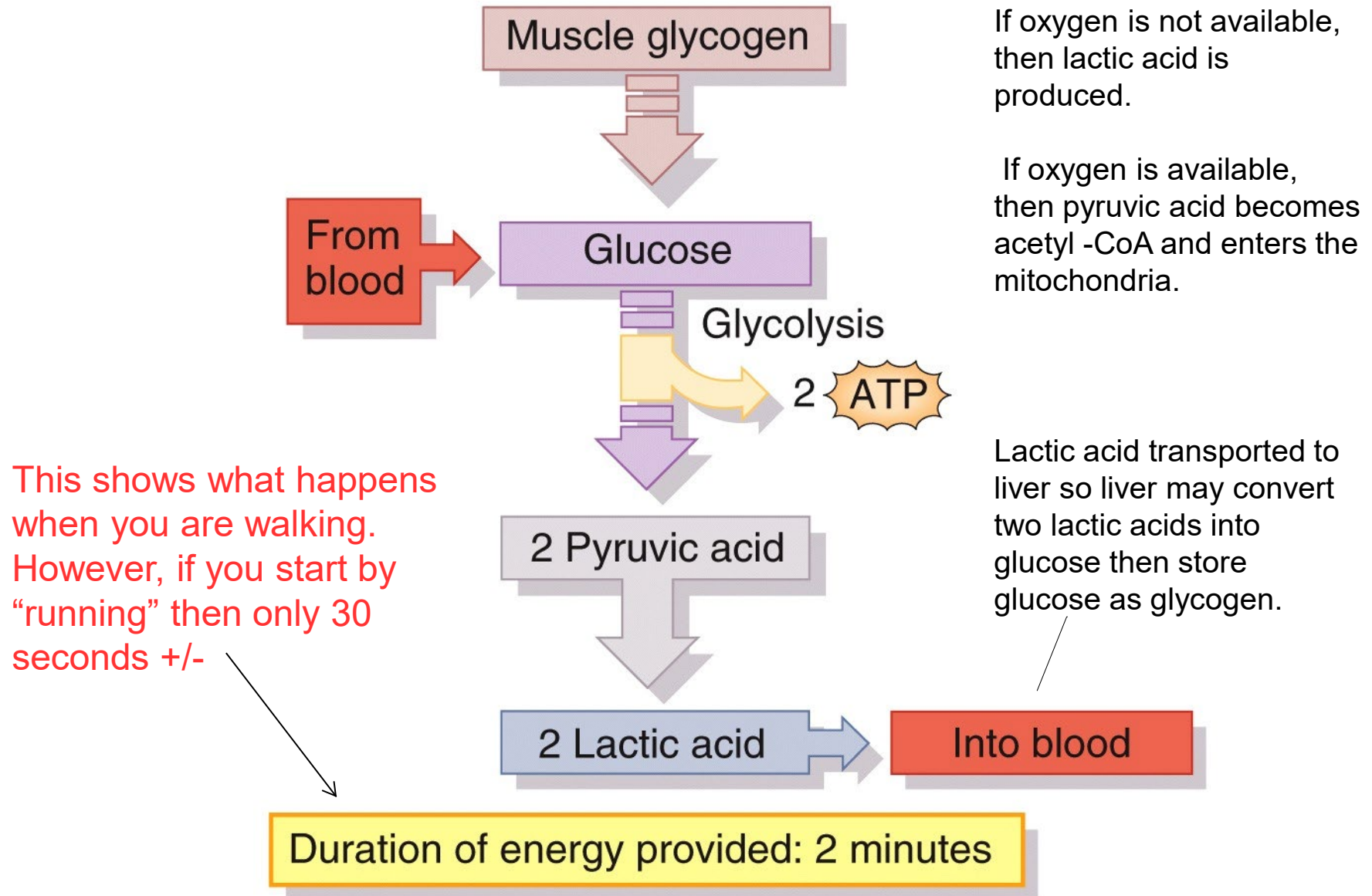
(b) Glycolytic and oxidative energy sources

Anaerobic fermentation produces lactic acid

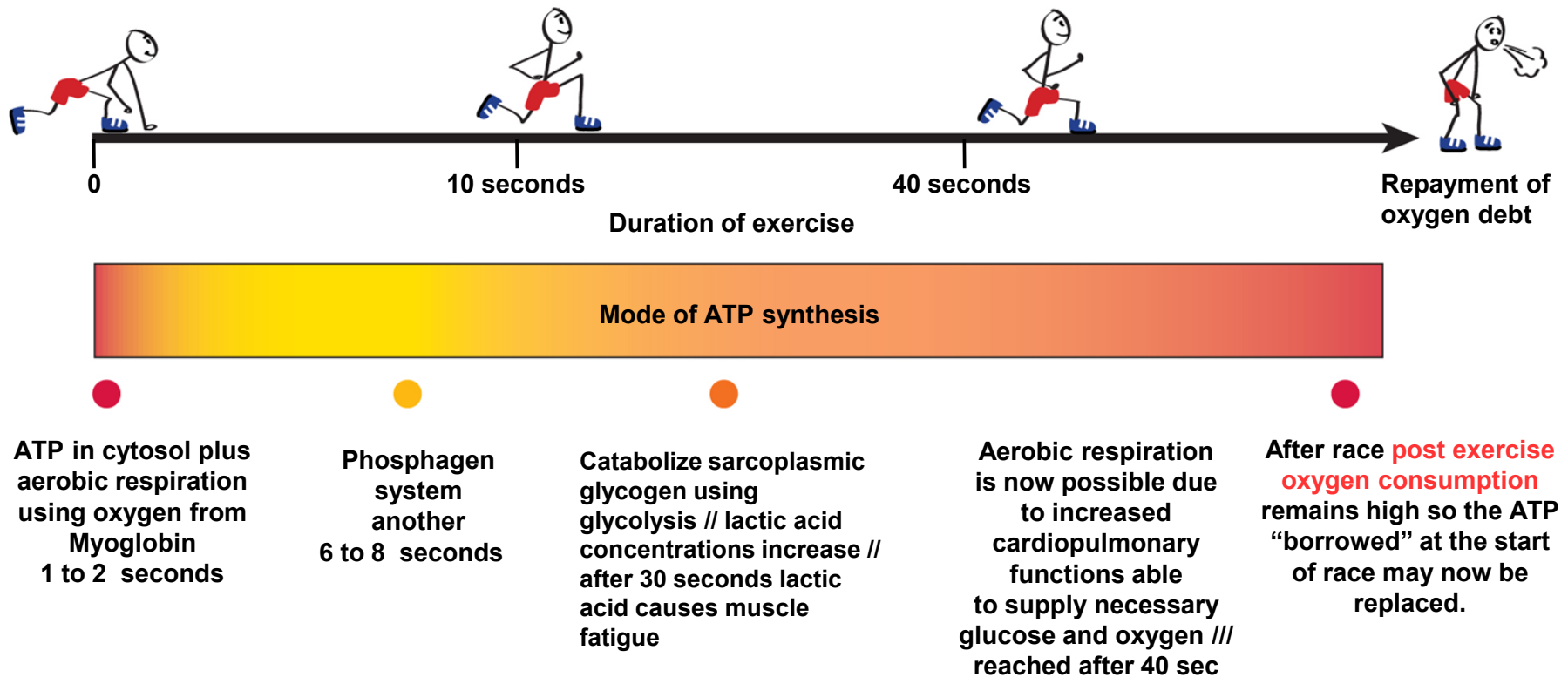
Lactic acid becomes a limiting factor for glycolysis as an energy source.

As lactic acid concentration increases in the sarcoplasm, muscle fatigue reduces ability of the muscle fiber to contract.

Anaerobic Glycolysis



Modes of ATP Synthesis During Extreme Exercise

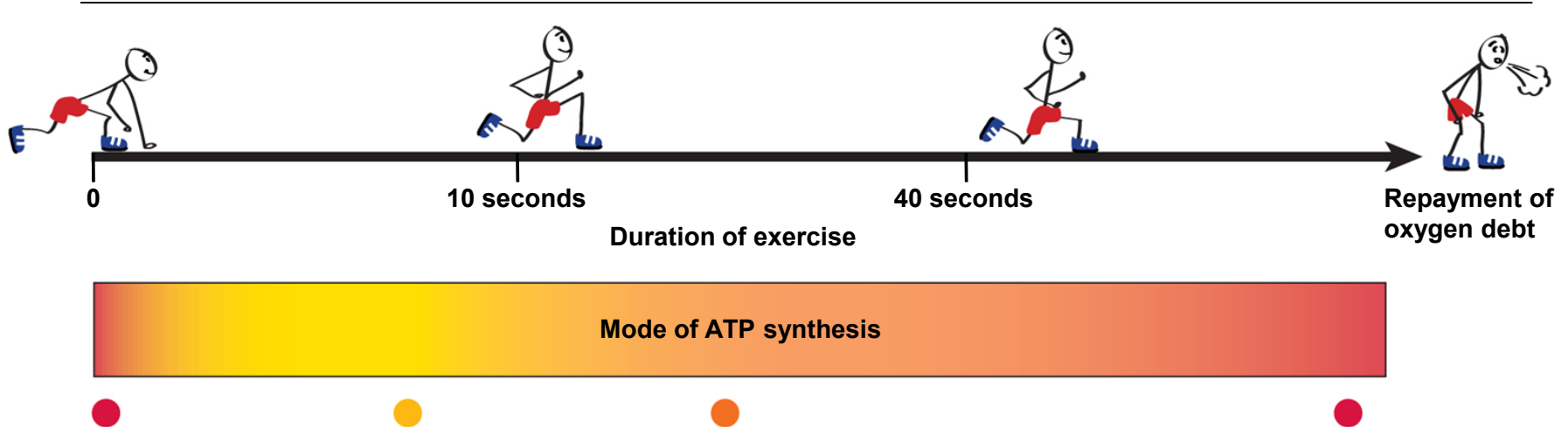


At rest we oxidize fatty acids to supply energy for our skeletal muscles (note: our brains continue to oxidize glucose / brain cells and RBCs only ferment glucose)

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

Long-Term Energy Needs



After you start the race, after 40 seconds of running

Respiratory and cardiovascular systems “catches up” to the energy demands of skeletal muscles

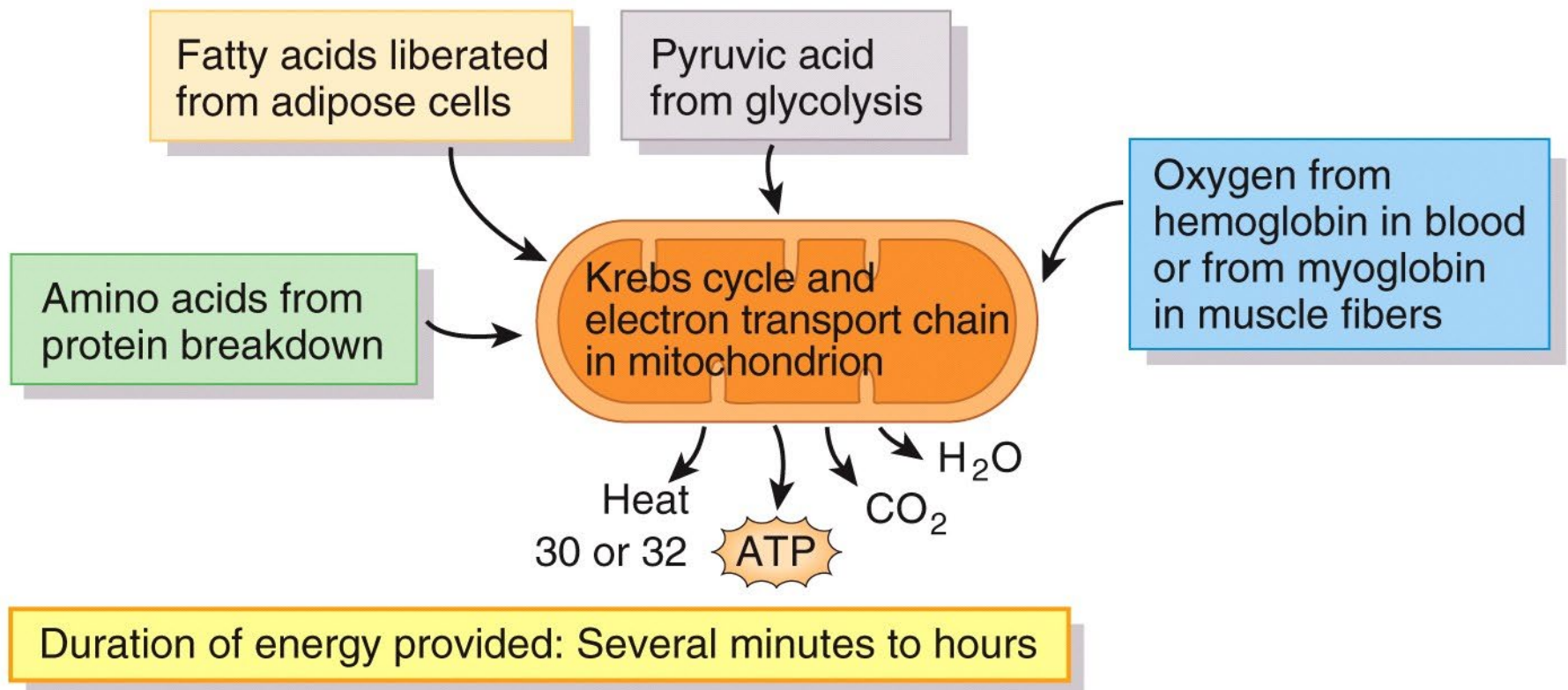
But muscle fibers have accumulated large amount of lactic acid

Now cardiorespiratory system is able to deliver enough oxygen to meet the muscle's oxygen requirement for aerobic respiration /// mitochondria able to make enough ATP to sustain muscle contractions.

Limiting factor now becomes conditioning and amount of stored glycogen and fat.

Aerobic Respiration

Reduced molecules are modified so they may enter the Krebs cycle at different entry points. This allows for alternative fuel sources when glucose is not available.



What is Oxygen Debt?

Why do you continue to breathe rapidly after you stop strenuous exercise?

Called **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 is needed more than current muscle activity for the following reasons:

Replace oxygen to the myoglobin // 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

- Synthesize extra ATP to replace phosphate “borrowed” from creatine-phosphate at the start of the race
- Oxygen debt also called post exercise oxygen consumption.

Oxygen Debt

Furthermore, additional oxygen needed for

Metabolize 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
- can be twice as great in trained endurance athletes as in untrained person
- May result 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 textbook 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

athletes feel sense of heaviness outweighs
benefits of extra available glycogen