REVIEW

Muscle fatigue, muscle recovery and how this knowledge applies to rock climbers

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Abstract

Rock climbers are limited by their metabolic waste products and not by the amount of ATP in the muscle cells. Rock climbing was once a mountaineering sport but is becoming increasingly popular because of competitions and climbing gyms. As the sport becomes more accessible to the public, enthusiasts should learn how to recover their forearms and hands effectively after a difficult climb. Muscle fatigue can be defined as a reversible loss of muscle force. Historically, lactic acid build up was the primary hypothesis for muscle fatigue, but now scientists are looking for other explanations such as inorganic phosphate concentration [Pi], calcium concentration [Ca2+], hydrogen ion concentration [H+], and glucose concentration [Glc]. Fatigue is not correlated with ATP; ATP levels do not show a drop when moderate to intense exercise begins. Active recovery methods are more effective at recovering fatigued muscles than passive recovery methods. Focus 1 of this literature review will discuss metabolic byproducts that show correlations with muscle fatigue; focus 2 of this review will compare active versus passive recovery methods.

INTRODUCTION

Since the conception of rock climbing in the 1950's, the sport has grown dramatically in popularity (Valley Uprising 2014). Rock Climbing is currently being considered as a new sport in the 2020 Olympics (Story 2011). Globally, The Outdoor Industry Association estimates participation to be 4.7 million to 6.9 million people (Story 2011). Rock Climbing was once strictly for mountaineers, but is transitioning to be readily available to the average person. As rock climbing gains popularity, climbing gyms and climbing competitions are appearing all over the U.S. and Europe (Mermier 1997). The health benefits of rock climbing include an increase in muscular endurance and improved cardiorespiratory fitness (Mermier 1997). Rock climbing relies heavily on upper body strength and endurance, but can also requires full body strength, flexibility, and balance.

Two types of climbers that will be discussed in this paper are sport climbers and boulderers. Sport climbers climb with harnesses and are attached to either a permanent anchor or to removable equipment. Boulderers, however, are not attached to a rope and typically their protections are pads on the ground, should they fall. Bouldering routes are shorter while sport climbing routes are typically longer. Both climbing types can improve muscle strength and endurance, but different energy sources are used to fuel the muscle cells during exercise. When muscle cells are no longer able to create a forceful contraction, they are deemed fatigued.

Fatigue is a reversible loss of muscle force, and can last for variable amounts of time (Mika et al. 2016). Muscle force can be created isometrically (no change in length) or isotonically (a change in length)(Silverthorn 2016). Each study mentioned in this literature review that measured muscle force measured isotonic contractions. Scientists used to believe that the cause of muscle fatigue was lactic acid build up, but emerging evidence is suggesting that other metabolic byproducts are the cause of muscle fatigue. The possible causes of muscle fatigue are: increased inorganic phosphate concentration [Pi], decreased calcium concentration [Ca2+], increased hydrogen ion concentration [H+], and decreased glucose concentration [Glc] (Osadjan 2017).

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The causes for muscle fatigue are still being researched, because many metabolic byproducts have shown correlations with fatigue, but may not be the causation for fatigue. Recovery methods for muscle fatigue that are deemed effective can be added to a professional or beginner rock climbers cool down routine. However, these recovery methods can also be applied to any sort of athlete. Therefore, by studying what correlates with climber muscle fatigue, physiologists can continue learn about the causes of muscle fatigue.

Focus 1 of this literature review will discuss metabolic byproducts that show correlations with muscle fatigue; focus 2 of this review will compare active versus passive recovery methods.

Metabolism overview

The causes of muscle fatigue can be from byproducts of metabolism. Before the byproducts can be discussed, the processes that create the byproducts need to be understood. The following section will describe human metabolism, and where the byproducts causing muscle fatigue arise from. Human metabolism can be simplified into this equation: Nutrients + $O2 \rightarrow CO2 + H2O$ + ATP + heat (McMahon 2002). The energy currency in humans is adenosine triphosphate (ATP); the energy can be utilized by breaking one bond in the molecule ATP, freeing a phosphate, and making adenosine diphosphate (ADP). Muscle fatigue is not caused by the depletion of energy sources, because ATP levels don't decrease substantially. Fatigue can be caused by metabolic byproducts as a way to prevent ATP levels from dropping dangerously low (Levy and Berne 2006).

During rest, ATP is stored and can be used during activity for a very short period of time, so then the stored energy is lost due to exertion (Figure 1,black line). However, the stored energy is used after only a few minutes of exercise. The lost ATP can be regenerated through the creatine phosphate system. The creatine phosphate system can donate one phosphate group to ADP, regenerating the ATP supply (Figure 1, purple line). The creatine phosphate system is also a short-term energy system and only regenerates ATP for 15 seconds during intense exercise (Silverthorn 2016). The byproduct of the creatine phosphate system is inorganic phosphate [Pi]. An increase in [Pi] has shown to correlate with decreased muscle tension (Cooke et al. 1988).

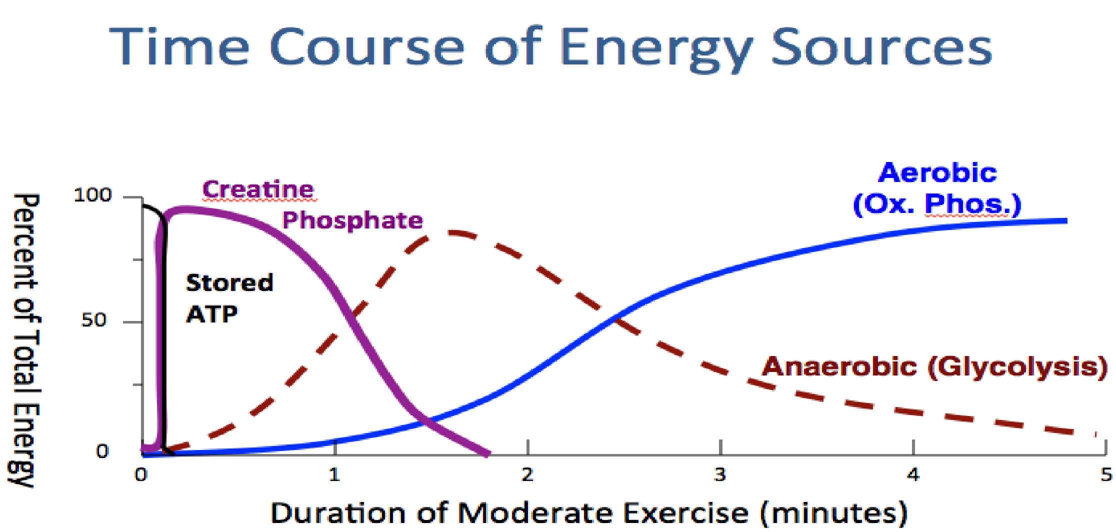

Figure 1. Time Course of Energy Sources. During moderate exercise, stored ATP is the first energy source. The creatine phosphate system restores the lost ATP. After a few minutes of exercise anaerobic exercise is the main energy source. After 2 minutes of moderate exercise, aerobic exercise is the main source of energy.

After the creatine phosphate system is depleted, the body must switch to other methods of converting nutrients into ATP, like anaerobic glycolysis or aerobic oxidative phosphorylation. Anaerobic glycolysis is used immediately after the creatine phosphate system during moderate exercise. Lactic acid is a byproduct of anaerobic glycolysis. Lactic acid readily dissociates, making a lactate molecule and a hydrogen ion (H+). The increase in [H+] during anaerobic glycolysis has been suggested to interfere with metabolic enzymes which leads to a decrease in muscle force. Cells have buffering systems to resist any pH changes. A buffer system means that weak acids and conjugate bases are in the cell so that when a strong acid or a strong base are added to a cell, the buffers can neutralize them. Buffering systems are helpful during anaerobic glycolysis to resist pH change, but can be overwhelmed during high intensity exercise (Dunford and Doyle 2015).

Lactic acid and hydrogen ions do not always inhibit muscle function. Lactate, from lactic acid, can be converted back into an energy source (glucose); this process is called the Cori Cycle. During the Cori Cycle, blood lactate that builds up after anaerobic glycolysis can be converted into blood glucose and used for cellular energy, in a process called Gluconeogenesis (Figure 2)(Osadjan 2016). The new glucose generated can be used during glycolysis and therefore more ATP can be created for muscle contraction. Rock Climber's muscle cells are most likely taking advantage of the Cori Cycle when lactate is present by converting it back to Glucose (Figure 2).

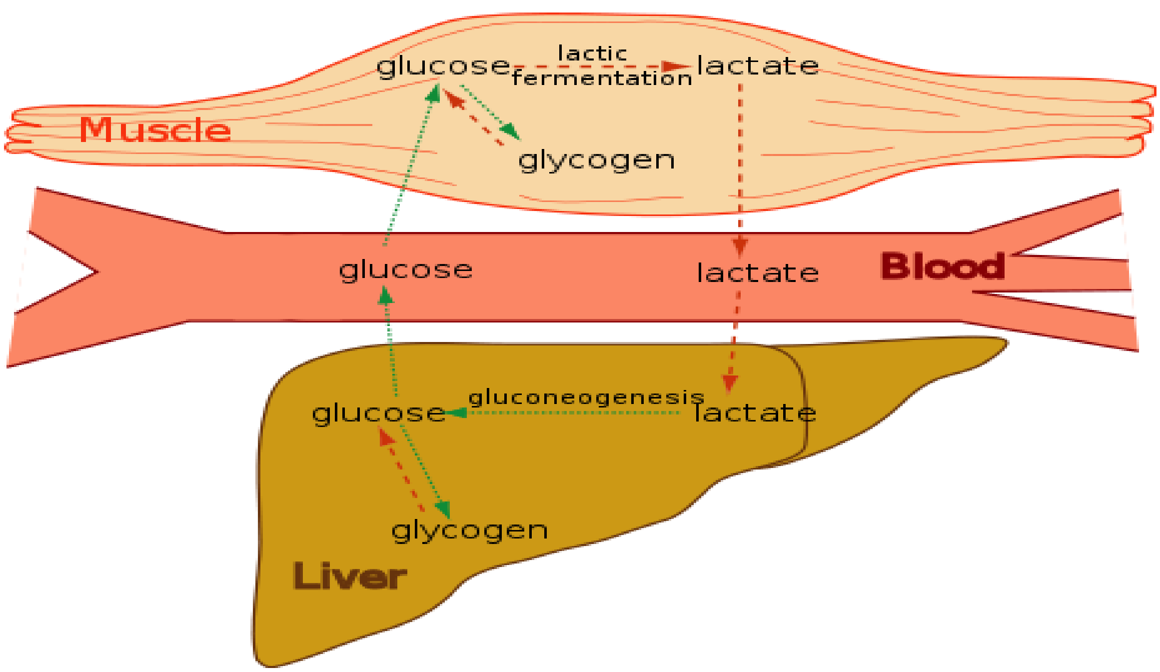

Figure 2. Pathway of Glycolysis and Gluconeogenesis. The Cori Cycle is part of Gluconeogenesis because "new glucose" is created from lactic acid. (Figure from Wikimedia.org, free access)

The final energy source to discuss is aerobic metabolism, which is the pathway that a vast majority of ATP in the body is created. Aerobic metabolism creates much more energy than anaerobic metabolism, but anaerobic metabolism is faster at producing energy (Silverthorn 2016). Aerobic metabolism is mostly responsible for regenerating the ATP lost during anaerobic metabolism (Osadjan 2017). A few factors that are not byproducts of anaerobic metabolism,like [Ca2+] and [Glc], show a positive correlation with muscle fatigue. Calcium and glucose and their role in muscle fatigue will be discussed in the next section.

Focus 1: The Hypothesis of Fatigue

Muscle fatigue can be defined as a reversible loss of muscle force, which can last from a few minutes up to few days (Mika et al. 2016). The cause for muscle fatigue is still being researched, but new evidence shows a number of measurable things in the blood that tend to correlate with muscle fatigue. Some of these measurable things are lactate/lactic acid, pH, intracellular calcium, and glucose/glycogen concentration (Osadjan 2017).

Early on, lactic acid build up was argued as the cause of muscle fatigue (Allen 2006), but is now only used to measure exercise intensity (Dunford and Doyle 2015). The argument that lactic acid causes muscle fatigue is not supported (Bond 1991) because lactic acid can diffuse over the cell membrane and thus could not be the cause of muscle fatigue (Poso 2002). Moreover, lactate flow is determined by concentration gradients, or the relatively amount of a substance from one side of a membrane to the other. Since lactate is high in the muscles and low in the plasma, lactate will flow out of the muscle cell (Poso 2002).

pH, or [H+], were another major hypothesis for muscle fatigue, but evidence supporting that hypothesis is not consistent. Westerblad (2016) states that pH does not change very much during exercise. He argues that if muscle fatigue is caused by acidosis, it does so indirectly by inhibition of enzymes used in glycolysis and glycogenolysis. However, Cooke et al. (1988) argues otherwise, stating that pH does have an effect on muscle tension and it has an additive effect with [Pi].When rabbit muscles were tested under low pH concentrations and a high [Pi], there was a 20% decrease in muscle tension (Cooke et al. 1988).

Assuming pH does have an effect on muscle fatigue, some studies have shown that resistance training in rock climbing can improve the buffering system in cells and thus resist pH changes better than in untrained muscles (Robergs et al. 2005). Pi causes muscle fatigue by binding to Ca2+ causing it be an insoluble precipitate, if Ca2+ is insoluble cross bridge cycling is inhibited (Figure 3) (Cooke et al. 1988, Fitts 2016). However, pH does not consistently show correlation with muscle fatigue. In cases when stimulation or exercise is ceased, muscle force recovers much faster than pH (Allen 2006). Consequently, scientists are looking into other factors such as a decrease in glycogen concentration (Allen 2006).

Glycogen is the stored form of glucose and is the primary energy used in muscles (Allen 2008). As discussed in the previous section, glucose is the first molecule in the beginning of metabolism. If glucose is not available, glycolysis does not occur and, therefore ATP is not made (Silverthorn 2016). The link between glycogen/glucose concentration and fatigue is still unclear, but when muscles were recovered in the absence of glucose, glycogen did not recover and the muscle fibers fatigued quicker in subsequent tests (Allen 2008). An additional theory in how glycogen plays part in muscle fatigue is that it assists in the release of Ca2+ from the sarcoplasmic reticulum (Allen 2008) which then can be used in crossbridge cycling.

[Ca2+] is also considered as a possible cause of muscle fatigue (Allen 2008; Williams and Klug 1995). Calcium plays a part in muscle contraction because it removes a small filament complex called troponin/tropomyosin. When this complex moves out of the way of another protein called myosin, it can bind with actin (Figure 3). When myosin binds to actin, it causes a head on myosin to cock backward, and this repeated ratcheting motion is how muscles contract. If you sum up all of the microscopic ratcheting motions, you get a muscle contraction on the macroscopic level. Therefore, if Ca2+ is not present in high enough concentrations to remove the troponin/tropomyosin complex out of the way for myosin to attach, there is a decrease in muscle contraction. Experimentally Allen (2008) showed that tetanic contractions decreased with a decrease in [Ca2+]. Although more research is needed to understand the cause of muscle fatigue, there is strong evidence that active recovery is an effective way to recover fatigued muscles.

Focus 2: Rock Climbers Recovery

Active versus passive recovery methods have been tested to see which will improve muscle endurance and strength. Active recovery can be defined as many things such as ice water immersion, easy climbing, biking etc. Passive recovery would be sitting or relaxing until the subsequent climb. To measure if a recovery method was effective, things like muscle re-oxygenation, lactate concentration, and hand-grip strength were measured and the results were compared pre- and post-climb.

Arm Shaking

When Balas (2015) measured climber's re-oxygenation of muscles post-climb, arm shaking is more effective (32%) at returning oxygen faster to the muscles than hand over hold condition. Oxygen is the final electron acceptor in the electron transport chain, so it is necessary for aerobic metabolism. Sport climbers have the best re-oxygenation of their muscles compared to beginner climbers, which suggests that sport climbers have aerobic muscular adaptations (Balas 2015). Green and Stannard's (2010) results disagreed with these findings that shaking improves forearm muscle re-oxygenation. Their results showed that shaking had no effect on isometric hand-grip. Although the difference in Green and Balas results are interesting, these two studies differed in methodology and what they measured as effective recovery so the two cannot be equally compared.

Easy Climbing and Walking

When measuring hand grip force after ascents, and practicing two different recovery methods (easy climbing or walking), Valenzuela et al. (2015) found that there was no difference between the recovery methods and regaining hand grip force. Even though easy climbing and walking did not make a significant difference in hand-grip force, easy climbing was a significant way to recover because climbers were able to ascend more meters with this recovery method (Valenzuela et al. 2015).

Cold Water Immersion, Electromyostimulation, Biking, and Passive Rest:

Other recovery methods tested for the removal of blood lactate are cold water immersion, electromyostimulation, biking, and passive rest. Results indicate that all recovery methods were effective at removing blood lactate from muscles (Heyman 2009). Crowe's (2007) results also supported that blood lactate decreased significantly following cold water immersion. Biking was the most effective recovery method overall because during and after the recovery period blood lactate was the lowest. As an interesting note, Watts et al. (1996) measured blood lactate levels after climbing and found it took 20 minutes of resting recovery before blood lactate levels decreased to beginning levels.

CONCLUSION

Muscle fatigue is a complex process and the causes are still being researched. Rock climbers use both anaerobic and aerobic processes to fuel their cells (Bertuzzi 2007), but sometimes the byproducts created from anaerobic glycolysis can inhibit muscle function. Muscle fatigue is not caused by a decrease in ATP so researchers are exploring pH, [Pi], [Ca2+]

and [Glc] as possible causes. Studies suggest that increased [Pi] and decrease pH seem to have an additive effect at decreasing muscle tension. Also, decreased [Ca2+] can decrease muscle tension by inhibiting cross bridge cycling. A decrease in [Glc] can inhibit glycolysis and therefore a decline in ATP. Scientists are unsure whether pH, [Pi], [Ca2+] and [Glc] are directly or indirectly inhibiting muscles.

Recovery methods that have been shown to be effective is arm shaking because it re-oxygenates fatigued muscles. Easy climbing or walking as recovery methods did not have significant results when trying to regain hand-grip force. Cold water immersion, electromyostimulation, biking, and passive rest all followed similar trends and decreased blood lactate levels, though biking was the most effective at decreasing blood lactate. Overall, active recovery is more effective at regaining lost muscle strength than passive rest. Moreover, climbers are advised to perform a sport-specific exercise during their active recovery (Valenzuela 2015).

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Biography Shannon is a senior at the University of Minnesota Duluth who is graduating with a Bachelor of Science in biology and a minor in chemistry. She decided to write about this topic because she loves to rock climb and she found the exercise portion of her human physiology class fascinating. Her plans after graduation are to take a year off then she wants to return to school for her masters. Shannon's hobbies are running, mountain biking, and sailing.

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