MUSCLE FATIGUE AND MUSCLE SORENESS: ETIOLOGY, MECHANISMS, AND PREVENTION

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Abstract: Muscle fatigue is a temporary and transient muscle incapacity to develop muscle power, and inability of muscle to perform work or maintain a certain level of physical activity. Several mechanisms are proposed as physiological base of the muscle fatigue: structural and functional changes that occurred in the sarcomera, reduced sarcoplasmic pH value, inhibition of the cross bridges cycle, blocking the process of excitation and contraction coupling, and depletion of energy reserves. Common consecutive process of muscle fatigue is muscle soreness. This phenomenon can lead to a disturbance of the integrity of muscle cells or temporary disruption of muscle function. Acute muscle soreness causes insignificant inconvenience in the athlete because it is short-term and quickly retreat. The delayed onset of muscle soreness (DOMS) often affect sport's performance by limiting the range of motion, decreasing the muscle force and alternating the movement pattern. Recommendations for the prevention of muscle soreness include stretching exercises, gradually increasing of the training intensity and consumption of anti-inflammatory supplements. The scientific and empiric knowledge of the etiology and mechanisms of muscle fatigue and muscle soreness will allow better understanding how to alleviate and attenuate these adverse phenomena in athletes.

Key words: muscle fatigue, muscle soreness, contraction, force

MIŠIĆNI UMOR I MIŠIĆNO ZAPALJENJE: ETIOLOGIJA, MEHANIZMI I PREVENCIJA

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Sažetak: Mišićni umor je privremena i prolazna nesposobnost mišića da razvije maksimalnu mišićnu silu i nesposobnost mišića da ostvari rad sa određenim intenzitetom. Nekoliko mehanizama su predloženi kao fiziološka osnova za pojavu mišićnog umora: strukturalne i

funkcionalne promene koje se javljaju u sarkomeri, promena sarkoplazmatske pH vrednosti, inhibicija ciklusa poprečnih mostova, blokiranje procesa ekscitacija - kontrakcija, nedostatak energetskih supstanci. Česta pojava koja prati mišićni umor je mišićno zapaljenje. Ovaj fenomen može da dovede do narušavanja integriteteta mišićne ćelije i do privremenog poremećaja njene funkcije. Akutno mišićno zapaljenje je kratkotrajno i manjeg intenziteta i izaziva neznačajne neprijatnosti kod sportiste. Pojava odloženog mišićnog zapaljenja (DOMS) često ima značajan uticaj na sportske sposobnosti: ograničen raspon pokreta, smanjena mišićna snaga i promenjen način kretanja. Preporuke za sprečavanje ili smanjenje mišićnog zapaljenja su izvodjenje vežbi istezanja, postupno povećanje intenziteta treninga, primena fizikalnih metoda i upotreba antiiflamatornih lekova. Naučna i empirijska saznanja o etiologoji i mehanizmima koji su osnova mišićnog umora i mišićnog zapaljenja mogu pomoći prevenciju njihove pojave i slabije simptome ovih neželjenih procesa kod sportista i rekereativaca.

Ključne reči: mišićni umor, mišićno zapaljenje, kontrakcija, snaga

Muscle fatigue and muscle soreness: etiology, mechanisms and prevention

The reduced capacity of a muscle to develop strength and speed of contraction is defined as muscle fatigue, it occurs as a result of muscle activity, and passes after a period of rest. Muscle fatigue is a temporary inability of a muscle to develop strength, to perform or to maintain a certain level of work intensity. The muscle is not damaged and it can regenerate. Muscle fatigue is the result of great physical effort, of physical activity that exceeds the physical capacities of the individual. Fatigue passes after a period of rest. Muscle fatigue caused by exercise should not be confused with fatigue caused by diseases that affect the nervous and muscular system, this type of fatigue does not pass after a period of rest (Kent-Braun et al., 2012; Gruet et al., 2013).

Muscle fatigue is the body's defense mechanism in case of excessive level of muscle work. As a result of fatigue, muscle contractions become weaker, slower and longer (Gandevia, 2001). Within a single muscle contraction, in addition to decreasing the amplitude and increasing the duration of the contraction phase, the phase of decontraction, i.e. relaxation of the muscle, is prolonged. The first logical cause of fatigue can be considered a lack of ATP in the muscle cell, which may not always be true (Allen et al., 2008). Examinations of the ATP concentration in the muscle cell show that in tired muscle the level of ATP is slightly lower than at rest. Fatigue is thought to occur as a defensive reaction of the muscles against possible damage that would occur if the muscle activity lasted so long as to cause a very low concentration of ATP (Westerblad et al., 2002). Deficiency or absence of ATP in cells will lead to muscle rigidity, inability to relax, and risk of muscle fiber rupture.

Physiological mechanisms of muscle fatigue

The physiological mechanisms underlying muscle fatigue differ from those that occur after prolonged or short-term activity. Fatigue after physical activity with high intensity and short duration occurs due to the following mechanisms:

1. Decreased muscle cell conduction as a result of accumulation of K ions in the T tubules, during repolarization after a series of successive stimuli, which reduces permeability to Na ions and complicates depolarization, i.e. the creation of new action potential along the sarcolemma.

2. The production of lactic acid contributes to the acidification of muscle cells (higher concentration of hydrogen ions) and the difficult functioning of some cellular proteins. Changes in cell acidity are thought to particularly affect the function of calcium ATP pumps in the sarcoplasmic reticulum, which affects the process of muscle relaxation.

3. Inhibition of the transverse bridge cycle. The creation of large amounts of ADP and Pi in muscle fibers has an inhibitory effect on muscle fiber relaxation, which prolongs the cycle of transverse bridges and makes it difficult to start a new cycle. Prolonged transverse bridge prolongs the contraction phase and disrupts the relaxation phase causing a reduced contractile ability of the muscle (Westerblad et al., 1997).

Fatigue that occurs after prolonged physical activity with low intensity has a different physiological basis than fatigue after short activity with high intensity. In addition to the above mechanisms that may play a minor role, two additional mechanisms dominate around this type of fatigue:

1. During prolonged physical activity, the ryanodine receptors on the sarcoplasmic reticulum cisterns remain open for a longer time, allowing for more intense calcium leakage into the sarcoplasm. Prolonged high concentrations of calcium in the cytosol activate proteases that break down contractile proteins. These changes cause muscle weakness and a feeling of pain (muscle inflammation) that lasts until the fibers are repaired by creating new proteins.
2. Decreased muscle glycogen stores, hypoglycemia and dehydration are directly related to fatigue. It is essential to provide good glycogen stores, with adequate carbohydrate intake, to prevent or delay fatigue in the event of prolonged low-intensity activity.

Topography of muscle fatigue

Despite numerous studies on muscle fatigue and the causes of its occurrence, it is still a controversial phenomenon in the scientific and professional community. Current research suggests that the primary site of fatigue is the muscle itself. The factors causing fatigue are complex, interconnected and dependent on the muscles involved in the activity. The topography of the etiology of muscle fatigue shows where the cause of the reduced ability of the muscle to contract may occur. A major classification of the causes of fatigue is central and peripheral fatigue (Bigland-Ritchie et al., 1978). Central fatigue refers to neurons in the brain and the spinal cord, inhibitory input signals from afferent muscle neurons to the CNS, or alterations in motor neurons. Central fatigue can be influenced by psychological factors and motivation including a person's individual capacity to withstand physical exertion, especially when continued activity causes pain. Peripheral fatigue refers to fatigue that occurs outside the CNS, at any level from the neuromuscular junction to the muscle itself. Neuromuscular blockade, at the level of sarcolemma - T tubules - sarcoplasmic system and myofilaments. At the level of the neuromuscular junction, axonal terminals may be inhibited, neurotransmitters may be deficient, or postsynaptic receptor blockade may occur. At the level of cellular organelles, an inability to release calcium from terminal cisterns or to bind calcium to troponin C may occur. At the level of contractile elements, lack of ATP, creatine phosphate deficiency, glycogen deficiency, or accumulation of lactate, phosphate, or hydrogen ions can cause fatigue. The theory of fatigue related to the contractile mechanism refers to the process of lack of necessary substances (depletion) and the process of accumulation of harmful substances (Kent et al., 2016).

Lack of creatine phosphate leads to fatigue of the fast muscle fibers that rely most on the phosphagen system for obtaining energy for activities that require explosiveness, speed and power. Glycogen deficiency leads to fatigue of slow muscle fibers that rely on aerobic ATP

synthesis for long-term activity. Accumulation of lactate and hydrogen ions can cause fatigue through interference in several places within the contractile process: reducing the amount of calcium released, preventing the binding of calcium to troponin, disruption of Na-K pump function, inhibition of anaerobic glycolysis by limiting the production of enzymes (PFCs) or inhibiting the formation of transverse bridges. The detrimental effects of the accumulation of hydrogen ions are particularly pronounced in fast oxidative fibers (FOG fibers) which produce large amounts of lactate from anaerobic glycolysis (Metzger et al., 1990). The role of lactates in the development and course of muscle fatigue is not entirely clear. According to some researchers, lactates contribute to fatigue, but they are not the only factor that influences this process. Some authors have suggested that lactates play a beneficial role in muscle function (Westerblad et al., 2002).

Neurotransmitters in the central nervous system have an important influence on the muscle fatigue process. 5- HT decreases the physical performance, while DA-realising enhancer produces positive effects on physical performance. Swart et al., 2009).

Fatigue can be defined as cellular fatigue and general fatigue. General physical fatigue is defined as a disturbance of homeostasis caused by physical work. The basis of discomfort and even pain depends on several factors, lowering blood glucose levels and accumulation of metabolites. The function of the motor system in the CNS is not impaired. Therefore, highly motivated individuals can endure discomfort and fatigue pain while exercising until motor units become exhausted. Motivational factors are very important for improving physical performance, i.e. delaying the onset of fatigue (Cheung, et al., 2003).

Muscle soreness

A common occurrence after a period of intense physical activity is a subjective feeling of discomfort, pain, and limited mobility known as muscle inflammation. In English terminology the phenomenon of muscle inflammation is called muscular soreness, which could be translated as muscle hypersensitivity or muscle pain. In sports science, this phenomenon is classified into two forms, acute muscle inflammation and delayed muscle inflammation.

Acute muscle soreness

Acute muscle hypersensitivity or soreness occurs during or immediately after training. Acute muscle inflammation is thought to be due to decreased blood flow, muscle ischaemia. Numerous experiments over a period of decades have shown that pain occurs and increases not only during the contraction but also in the minute after the contraction (Cheung, et al., 2003). Mechanisms that are a physiological basis for the occurrence of acute inflammation:

- During muscle contraction, pain occurs when the muscle tension is so great that it can cause occlusion (closure) of a blood vessel.
- Decreased blood flow to the active muscle causes decreased removal of metabolic products that are intense during exercise, and increased retention of lactic acid and potassium. These metabolites stimulate muscle pain receptors, causing a subjective feeling of pain.
- The sensation of pain persists even after the cessation of contractions, until the harmful metabolites are removed by establishing normal blood flow.

Acute muscle inflammation causes minor discomfort to the athlete because it is short-lived and resolves quickly. Delayed muscle inflammation has a greater detrimental effect on the process of sports preparation and sports performance.

Delayed Muscular Soreness - DOMS

Symptoms of Delayed Muscular Soreness (DOMS) appear and persist for 24 to 96 hours (1 to 4 days) after an intense training session. One of the most common and popular misunderstandings about the DOMS phenomenon is that it results from the accumulation of lactate (lactic acid) in the muscle cell. This theory was developed in the mid-twentieth century (Asmussen, 1956; Edington and Edgerton, 1976) and has long been widely accepted in both scientific and professional circles (Veqar Z, 2013) Numerous studies and evidence contradict this simple theory with the following facts: People with inherited McArdle's syndrome who do not have the ability to produce lactic acid develop DOMS. DOMS occurs more frequently and with greater intensity when performing eccentric contractions, although during eccentric contractions a much smaller amount of lactic acid is produced than during concentric contractions Stupka et al, 2001). Lactic acid has a half-life of 15 to 25 minutes, and is completely removed from the muscles in one hour, and the strongest symptoms of DOMS appear within 24 - 48 hours after exercise and lasting 96 hours post activity or longer (Yu et al., 2004).

The process or phenomenon of muscle inflammation goes through the following stages:

1. Unusually high-intensity activity, eccentric muscle contractions, causes the rupture of structural proteins in muscle fibers, especially along the Z line of the sarcomere. At the

same time, there is damage to the connective tissue in the muscle-tendon connection (Yu et al., 2004).

2. Damage to the sarcolemma leads to the accumulation of calcium, which in turn inhibits the production of ATP and disrupts calcium homeostasis. Without ATP, calcium cannot be returned to the tanks. High calcium concentrations lead to further Z line damage, tropomyosin, and eventually muscle tissue necrosis (cell death) (Allen & Trajanovska, 2012).
3. Structural damage triggers an inflammatory and immune response. Fluid enters the muscle and swelling forms.
4. Accumulation of metabolic byproducts, cellular debris, and edema pressure irritate the nerve endings for pain causing the subjective sensation of pain which is the main symptom of the phenomenon of muscle inflammation (Stupka et al., 2001).

The experience of athletes and the knowledge of scientists from experimental procedures have shown that the intensity of DOMS depends on the type of muscle contractions. Muscle inflammation is most pronounced after performing eccentric contractions, and weakest after performing isotonic contractions. Isometric concentrations cause stronger DOMS than isotonic, but still much weaker than eccentric contractions. During DOMS after eccentric contractions the muscle strength decreases and lasts throughout the DOMS. This is not the case with DOMS after isotonic and isometric contractions. The theories that explain the occurrence of delayed muscle inflammation are the following:

- Theory of muscle fiber rupture - during exercise muscle tissue damage occurs, i.e. muscle fiber rupture. Proof of muscle fiber rupture theory is the high level of creatine kinase (CC) in the blood, an enzyme that is indicative of muscle fiber rupture (Armstrong et al., 1991).

- Theory of muscle spasm which proposes three stages through which the muscle goes during intense exercise: phase of ischemia of the active muscle; phase of accumulation of pain-causing substances (P substances), they irritate the nerve endings and cause a phase of muscle spasm. (MacIntyre et al., 2001).
- Connective tissue theory, according to which damage occurs in the ligamentous structures of the muscle. During concentric contraction, isokinetic and isotonic, the muscle shortens its length, and the greatest stretching occurs in the ligament structures.

During eccentric contractions, especially during maximal eccentric contraction, so much tension develops that damage to the connective tissue can occur (Friden &Lieber, 2001).

Some recent research claims that pain during DOMS is not caused from damaged muscle cells and secondary induced inflammatory processes, but from the reinforcement process. The muscle develop bigger strength as response to extensive effort, to protect its self from eventual injury. The muscle responds to training by reinforcing itself up to and above its previous strength by adding new sarcomeres in miofibrils, process called sarcomerogenesis. (Pavlic-Gulan et al., 2007).

Muscle fatigue and the contributory mechanisms are specific not only to the demands of the task but also to the physical characteristics of the population being assessed, including the sex of the individual. Researches indicate that the sex difference in muscle fatigue is task specific. Contractile mechanisms that reflect a higher proportion of slower and more fatigue-resistant muscle in women compared with men are responsible for the sex difference in muscle fatigue of the isometric and dynamic contractions. There was no evidence for a sex difference in the reduction in voluntary activation (i.e. central fatigue) (Hunter, 2016) .

Recommendations for preventing muscle soreness

If the athlete applies some of the recommendations, there is a possibility to reduce the degree of muscle soreness.

1. Stretching can both prevent inflammation and reduce pre-existing inflammation. It is important that the stretching is static, not performed with dynamic movements (bouncing or jerking) so as not to cause additional damage to the connective tissue. (Apostolopoupolis et al., 2013)

2. Exercise showed therapeutic effects on pain relief and minimizes the sensation of DOMS probably via mechanisms of increased removal of noxious metabolic waste products and increased realizing of endorphin during exercise (Connolly et al., 2003).

3. Gradual increase in training intensity. In strenuous training, the load, the weight, should be increased gradually if we want to avoid muscle inflammation.

4. Anti-inflammatory drugs or nonsteroidal anti-inflammatory drugs an oral analgesics with theirs pharmacological mechanisms induce decreased inflammatory response, swelling, oedema, and production of paracrine and prostaglandin substances (Stone et al., 2002; Schoenfeld, 2012).

5. Consumption of vitamin C, 100 mg per day for a month, which is twice the recommended daily allowance, has been shown to have a good effect in preventing muscle inflammation, but these experiences have not been scientifically confirmed (Connolly et al., 2006).

6. Cryotherapy, known as part of RICE protocol against soft tissue's trauma. The stimulation of cold termoreceptors increases sympathetic activity which results with reduction of swelling and inflammatory process. (Meussen & Lievens, 1986).

7. Massage as mechanical intervention increases local blood flow and reduces prostaglandin production and the inflammatory process. Studies examining the effects of massage on the symptoms of DOMS showed different level of positive effects or even no effect at all. (Hilbert, et al.,2003).

Numerous strategies for prevention and treatment of DOMS are proposed in scientific literature. There are still questions to answer: is DOMS preventable prior to exercise, is stretching a valid preventative measures, are there temporary alterations in joint kinematics and muscle activations patterns ect. Still sports related researches may serve in the battle for better sport performance.

Conclusion: This manuscript is humble attempt to present general knowledge about causal mechanisms for muscle fatigue and consequent phenomenon of muscle soreness. These processes are common experience in all athletes and physically active people. They are reason for reducing the intensity and duration of training, following with unaccustomed stress on muscle tendon and ligaments. The proposed mechanisms of DOMS have allowed the sport experts and scientists to develop various preventive and treatments strategies aimed to neutralize and decreased the symptoms of muscle fatigue and soreness and restoring the capacity for muscle

work. The understanding of underlying mechanisms of muscle fatigue and soreness could help to prevent their occurrence or decreased their lasting period which would influence the sport performance.

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