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Effects of training fatigue on performance

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ABSTRACT

Training exposes athletes to various types of load, often beyond their tolerance threshold. This, without adequate recovery, leads to the accumulation of fatigue. Fatigue can negatively affect the athlete's performance capabilities in terms of force production and motor control. Coaches should have knowledge of the effects of fatigue in order to better plan training avoiding phenomena that qualitatively and quantitatively limit performance or the occurrence of injuries. The aim of the work is to clarify the effects of exercise-induced fatigue, differentiating between central fatigue and peripheral fatigue, in order to provide correct information to develop specific post-exercise and post-workout recovery strategies. The study was carried out through the recognition, by PRISMA method, in the scientific literature of the theories and practices validated and disseminated in the world of sport to optimize training plans. The study reveals a differentiation on the origin of fatigue: in fact, we speak of central fatigue and peripheral fatigue. Both have different effects on the muscle response to training. For this reason, it must be considered differently in the management of loads, in terms of intensity, volume, frequency and density, in order to optimize the programming for reaching the peak performance, without overtraining. The data have been utilized by personal trainer to plan for every type of athlete to reach a better individual performance.
Keywords: Load management; Planning; Overtraining; Performance.

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INTRODUCTION

Training is a medium and long-term process that stimulates the body to morpho-functional adaptations (Calandro et al., 2020). The effectiveness and safety of training necessarily pass through the identification of the specific characteristics of the sport (Eirale et al., 2011) through field tests for monitoring the athletic characteristics of the athlete (Ceruso et al., 2020; D'Isanto, 2020; Esposito et al., 2020; Ceruso et al., 2019; Altavilla, 2019). Monitoring concerns various types of characteristics (D'Elia, 2020; Sannicandro et al. 2015) (anthropometric, technical skills, energy expenditure) and must consider the various periods of athletic training and the level of experience of the athlete (Esposito et al. 2019). For such processes to occur, training programs need to alternate periods of work with periods of recovery. Recovery is seen as a physiological and psychological restorative process related to time (Kellmann et al. 2018). Failure to observe these rules would reduce the ability to adapt by triggering a series of biochemical and neural reactions that lead the athlete to temporary fatigue and chronic fatigue, up to the condition of overtraining. The overtraining condition, known as overtraining, is characterized by the accumulation of stress, which leads to a decrease in both physical and mental performance during the sports season (Budgett, 1990). The condition of intentional overtraining is a training strategy, during certain periods of the season, planned by the coaches in order to enhance physiological adaptations (supercompensation) to obtain the improvement of performance capacity (Issurin, 2010). This condition that develops transient signs and symptoms similar to overtraining syndrome is termed overreaching. However, the recovery of the overreaching condition occurs in a few days through abstention or the reduction of the volume and intensity of training. Recovery from overtraining takes weeks or months and often results in an athlete's career disruption (Ackel-D'Elia et al., 2010).

The training process is different compared to athletes and between individual sports, team sports and sports games. Physiological and technical commitment during a performance differs between athletes and between sports. Skills such as running, for example, have different characteristics in various sports: varied running, typical of team sports, has different biomechanical and bioenergetic characteristics compared to linear running. These numerous requests justify a specific training method (Altavilla, 2020). Therefore, coaches and athletic trainers, in the context of athletic training, must find the right balance in the management of training loads and recoveries, specific for each performance model and for each athlete, also through a study of the phenomena related to human movement with an approach holistic aimed at integrating the various fields of knowledge considering the onset of fatigue a complex phenomenon linked to both peripheral and mental aspects. Properly manipulating the components of athletic training, i.e., intensity, volume and recovery, effectively results in improved performance and a reduction in the risk of developing overtraining, disease or injury (Brink et al. 2010). Finally, additional factors to consider in the management of preparation are nutrition and psychological factors that are often essential for sports results. A clear categorization of recovery based on specific time intervals, however, is not possible due to the high intra-individual and inter-individual variability of the recovery process (Kellmann, 2002). The question of neuromuscular fatigue, therefore, is still wide and not well defined, so even if for several years the research has tried to give a univocal and definitive definition, in practice, a shared vision that discriminates in a way is still lacking. specifies the causes of fatigue and, consequently, provides clear indications so that coaches and athletes can manage the training process safely and effectively. The goal of this review is an in-depth study of the concept of exercise-induced muscle fatigue, understood as a planned, structured and repetitive body movement (Caspersen et al. 1985) with the potential to interrupt homeostasis (Winter & Fowler 2009) and possible consequences attributable to it, through a brief overview of metabolic, structural, neurological and psycho-motivational factors, which may be useful to coaches and athletes in planning and monitoring training plans.

METHOD

The research was carried out through a careful consultation of the scientific literature: book chapters on sports performance and sports training methodology and scientific articles published between 1923 and 2020. The retrieval of scientific literature took place through the use of specialized web research on: PubMed, GoogleSchoolar, Scopus, PMCfreearticle, CrossRef by PRISMA method. The most recent articles and the most influential authors were considered. The following keywords have been entered into the search engines: *Muscle fatigue*, *sports training*, *physical exercise*. These terms have been combined with each other and with other keywords, namely: *fatigue and nervous system*, *fatigue and sports performance*, *exercise fatigue*, *exercise intensity and fatigue*, *exercise volume and fatigue*.

RESULTS AND DISCUSSION

Table 1. List of sources.

	Authors	Topics	Source
1	Ackel-D'Elia et al. 2010	Overreaching, overtraining	Scientific article
2	Adreani et al. 1997	Muscle afferents group III/IV	Scientific article
3	Amann et al. 2014; 2015	Muscle afferents group III/IV	Scientific articles
4	Bartolomei et al. 2017	Recovery Intensity/Volume	Scientific article
5	Bigland-Ritchie et al. 1978	Central and peripheral fatigue	Scientific article
6	Bompa 1999	Training periodization	Book chapter
7	Brink et al. 2009	Muscle fatigue and injuries	Scientific article
8	Budget 1990	Overtraining	Scientific article
9	Caspersen et al. 1985	Physical exercise	Scientific article
10	Gandevia et al. 2001	Central fatigue	Scientific article
11	Gollnick et Bavly 1986	Training adaptation	Scientific article
12	Harris et al. 1976	Phosphocreatine resynthesis	Scientific article
13	Haevens et al. 2014	High intensity and recovery	Scientific article
14	Hill et Lupton 1923	Muscle fatigue	Scientific article
15	Hultman et Sjoholm 1986	Muscle fatigue	Scientific article
16	Issurin 2010	Training periodization	Scientific article
17	Kellmann 2002	Sport performance and recovery	Scientific article
18	Kellmann et al 2018	Sport performance and recovery	Scientific article
19	Lambert et al. 2012	Muscle fatigue, complex system	Scientific article
20	Mosso 1915	Muscle fatigue	Book chapter
21	Noakes 2012	Role of fatigue in homeostasis	Scientific article
22	Noakes et al. 2001	Central Governor	Scientific article
23	St Clair et al 2003	Muscle fatigue	Scientific article
24	St Clair et Noakes 2004	Muscle fatigue, complex system	Scientific article
25	Tylor et al. 2016	Central fatigue	Scientific article
26	Tucker 2009	Anticipatory regulation and fatigue	Scientific article
27	Tucker et al. 2006	Anticipatory regulation and fatigue	Scientific article
28	Twomey et al. 2009	Muscle fatigue	Scientific article
29	Winter et Fowler 2009	Physical exercise	Scientific article

30 scientific articles and 2 book chapters out of a total of over 100 publications were considered. Publication selection criteria were used: the chapters were extracted from training methodology and training physiology books; the articles are in English, published in scientific journals.

Table 1 lists all the sources included in the review, highlighting, for each author, the subject of the publication and the source.

Muscle fatigue, historical evolution of the concept

Already at the end of the nineteenth century some scholars, such as the Italian Angelo Mosso, argued that the causes of fatigue following exercise were to be attributed to both structural and biochemical factors, that is, referred to the ability of energy systems to support a certain performance up to the accumulation of metabolites, and to central factors, which concern the ability of the nervous system to keep the speed of impulse conduction and the individual's volitional capacity constantly high (Mosso, 1915).

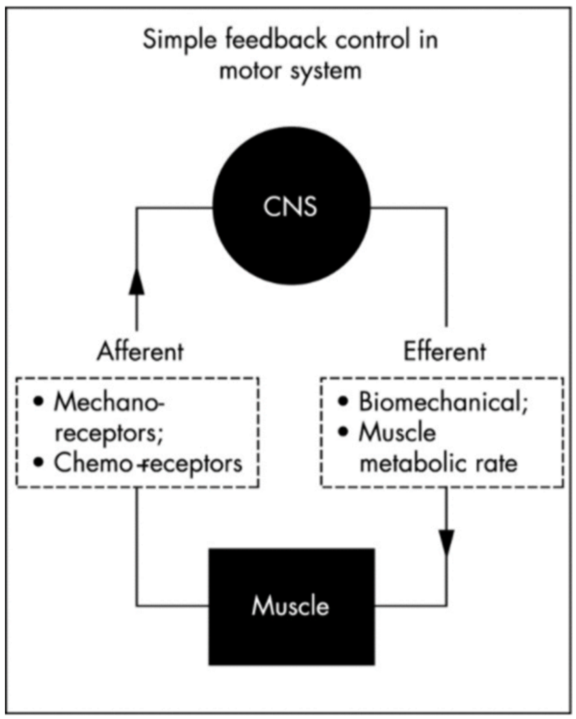

Figure 1. Central Governor Model (Lambert et al., 2005).

However, this interpretation was not taken into consideration by the majority of scholars of the time, who, instead, supported the intuitions, of a more reductionist nature, of Archibald Vivian Hill. Hill claimed that exercise-induced fatigue arises from the accumulation of muscle lactate secondary to inadequate oxygen supply due to limited cardiac output (Hill, Lupton, 1923). Performance, according to this model defined as cardiovascular / anaerobic / catastrophic, would be compromised only by the state of energy exhaustion and accumulation of metabolites that limits the functionality of the heart and muscles. To prevent heart damage during maximal exercise, Hill proposed the existence of a "*governor*" in the heart or brain to limit cardiac work when myocardial ischemia developed. This hypothesis, however, was soon abandoned perhaps due to a lack of supporting scientific evidence. This interpretation takes into consideration only the physiological aspect of neuromuscular fatigue caused by physical exercise, excluding the role of psychological factors such as motivation and self-confidence in the ability to perform.

The need to face biological phenomena with a holistic approach has led other authors, in contrast with Hill's thought and in line with Mosso's thought, to hypothesize the existence of a sort of central control involved in the mechanisms of onset of fatigue. Many scholars, including Noakes, revisited Hill's hypothesis of the existence of a Central Governor who, through anticipatory control mechanisms, would regulate the ability to generate force and power in response to a given task to make organs never reach maximum exhaustion and, therefore, are protected from damage during high intensity exercises (Noakes et al., 2001).

The Central Governor model defines fatigue no longer a physical event but rather an emotion (St Clair Gibson et al., 2003; Noakes, 2012) useful for the brain to regulate exercise performance (Tucker, 2009).

Physiological fatigue

In physiology, the term fatigue is generally used to define the transient loss or decrease of the voluntary capacity to produce force during exercise (Bigland-Ritchie et al., 1978) and is considered a deficit originating from the integration of mechanisms and functions regulatory at multiple biological levels (Twomey et al. 2017). The nature of muscle fatigue depends on the characteristics of the exercise, i.e., its intensity and duration.

This decline in the ability to generate force or power can come from various levels of the neural axis, from the motor cortex, from the spinal cord to the neuromuscular junction, from the muscle membrane and from metabolism. Fatigue, therefore, can have a peripheral or central origin. The term peripheral fatigue indicates the reduction in strength due to processes distal to the neuromuscular junction, while those due to processes within the motor neurons and central nervous system are commonly known as central fatigue.

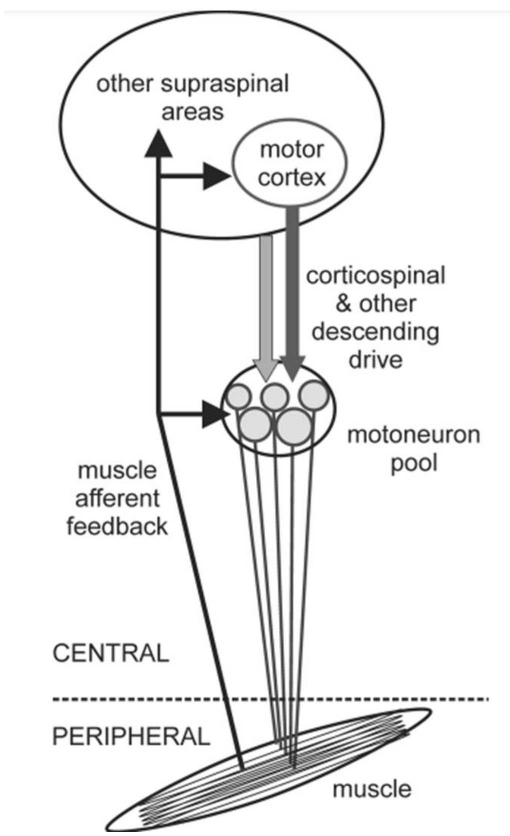

Figure 2. Schematic of neural contributions to muscle fatigue in single joint exercise (Taylor et al., 2016).

At the peripheral level, the decrease in force generated during contractions is mainly related to the change in the levels of energy substrates and intracellular ions which exert a negative effect on contractile force as they lead to an attenuated response to neural excitation. The molecules involved in energy sustenance are phosphages, glucose, glycogen, fatty acids and amino acids. Peripheral fatigue is generally associated with depletion of phosphages (Gollnick, 1986) and glycogen.

The phosphagen concentrations are exhausted very quickly until exhaustion in high-intensity anaerobic activities. The ATP, on the other hand, is not completely depleted. During the recovery phases, the aerobic energy system restores the PC and ATP stores: the complete resynthesis of ATP occurs in 3-5 minutes, while the PC resynthesis occurs in about 8 minutes (Harris et al. 1976). Some research has shown that an increase in resting CP concentrations results in a decrease in their rate of exhaustion at a given high intensity. The selective muscle hypertrophy of fibres II allows the increase of PC concentrations.

The depletion of glycogen stores is another mechanism that leads to the onset of peripheral fatigue experienced during or after training. Also, in this case, an increase in glycogen stores in the muscles at rest helps to delay the onset of fatigue. Aerobic and anaerobic training and nutrition can increase the concentration of glycogen at rest.

At high intensities, the use of glycogen to produce ATP in the absence of oxygen leads to the accumulation of lactate. Consumption of PC and concomitant accumulation of lactate generates musculoskeletal fatigue.

The structural and composition characteristics of the muscles also affect the development of the state of fatigue. However, skeletal muscle is a highly plastic tissue with a particularly remarkable ability to adapt to effort, modifying its structure and composition through structured physical exercise.

Central fatigue, i.e., the decrease in the voluntary activation of the muscle by the nervous system, is a concept that has attracted the attention of research in recent years. A number of factors contribute to the onset of central fatigue, including the decrease in the efference of the upper motor centres towards the motor neurons, the increase in synaptic inhibition directed to the motor neurons and the intrinsic adaptations in the motor neurons that make them progressively less reactive to synaptic excitation during sustained activity (Gandevia 2001, Taylor et al., 2016).

The onset of fatigue can be understood as a mechanism for protecting the integrity of the human body tissues that occurs before the condition of total exhaustion. The brain, in subconscious mode, modulates the number and frequency of activation of motor units through a stimulation strategy that will allow the completion of the task in the most efficient way while maintaining internal homeostasis (St Clair Gibson & Noakes 2004). This mechanism is realized through a sensory feedback system that informs the CNS about the condition of peripheral structures. Both components of fatigue are related to group III and IV muscle afferent feedback. The mechanical and chemical stimuli induced by muscle contraction in physical exercises activate the molecular receptors located at the terminal end of group III and group IV nerve fibres. Exercise-induced activation of these receptors increases the spontaneous discharge of muscle afferents (Adreani et al., 1997) which project through the spinal cord to various spinal and supraspinal sites within the CNS.

The role of group III / IV muscle afferents on the development of peripheral fatigue is manifested through their contribution to cardiovascular, haemodynamic and ventilatory adjustments that occur during exercise (Amann et al. 2014).

The involvement of muscle afferents of group III / IV in the development of central fatigue during exercise, on the other hand, is mediated by their inhibitory effect on the output of spinal motor neurons which causes a reduction in muscle activation and consequently in physical performance (Gandevia et al, 1996; Amann et al., 2014).

According to this model, the brain determines in advance the intensity of the exercise that can be sustained for the expected duration of the exercise itself. Consequently, all forms of exercise are submaximal as there is always a reserve of motor units in the limbs being exercised (Amann et al., 2014) which is never fully utilized even during maximal exercise. The intensity of the intensity will be determined by a number of factors including, the emotional state, the state of recovery from a previous exercise, the level of motivation and previous experience, the degree of self-esteem.

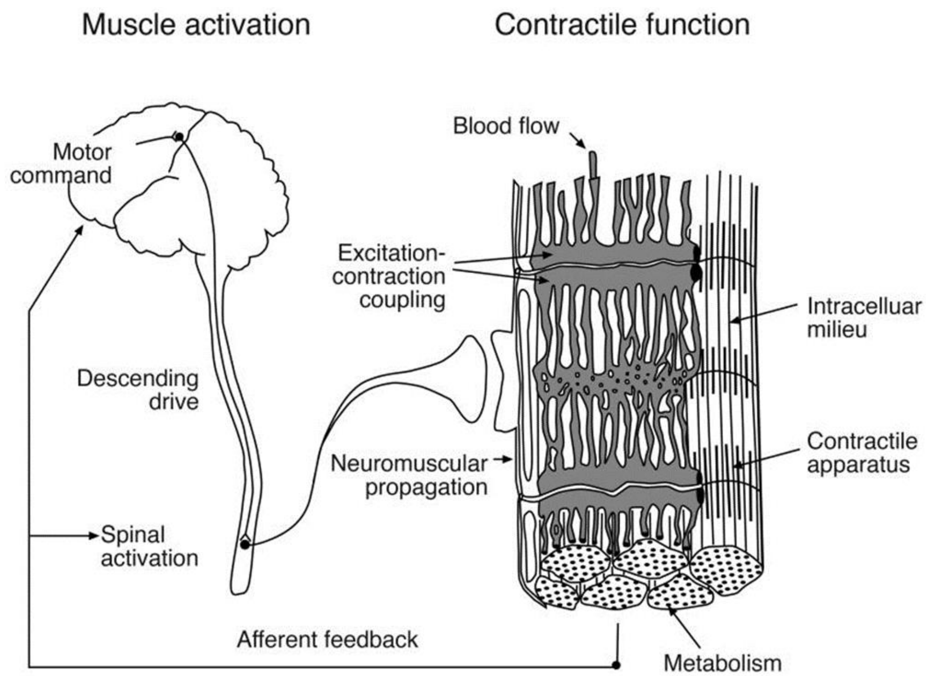

Figure 3. Potential Fatigue Mechanisms (Enoka & Duchateau, 2017).

Fatigue monitoring in sports training

Field methods for assessing muscle fatigue caused by exercise mostly include quantitative measurements of the drop in peak strength, torque, or power of muscle contraction, expressed as a "*fatigue index*", which is the percentage or rate of decrease. performance over time, through stress resistance tests and the use of ergometers or dynamometers. An example of a test frequently used to identify the fatigue index is the cycling maximum sprint test, the Wingate test, which measures the difference between maximum and minimum power, and the Anaerobic Fatigue / Fatigue Index, i.e., percentage of power lost from start to finish of Wingate. Another example of evaluating fatigue strength can be the measurement of the number of repetitions against a submaximal load.

It is useful to know the intensity, speed and volume of exercise in which the two types of exercise fatigue occur. There are various studies that clarify these aspects. In particular, Thomas et al. (2015; 2016) have shown that peripheral fatigue is higher in short duration and high intensity tests. Conversely, in the longer time trials the peripheral fatigue is lower, and the central fatigue is higher.

Recovery from neuromuscular fatigue after exertion differs according to the level of onset and the intensity and duration of the effort. Recovery times must consider various aspects, including muscle damage, metabolic responses, and inflammation. Practice shows that the recovery phases between training sessions can improve the quality of subsequent training, as well as reduce the risk of injury. This aspect suggests that, in the training process, the extent of recovery, on a par with the external loads, must be well defined considering several variables: structural and metabolic characteristics of the athlete, objectives of the micro cycle, emotional state of the athlete, etc.

Different responses in fatigue based on the type of training

Below are the responses in terms of central and peripheral fatigue and the related recovery times in relation to the mode, duration and intensity of exercise.

With reference to the mode of exercise, maximal efforts produce an accumulation of metabolites in the muscles causing fatigue. Recovery from this condition occurs in the 30 seconds following the effort also thanks to an adequate blood reperfusion; centrally, the fatigue caused by maximal efforts is mainly due to the effects of the afferents of groups III and IV which prevent a complete depletion of energy substrates and excessive accumulation of metabolites by lowering the level of voluntary activation; recovery from this condition is achieved in about 90 seconds. Exercises in an eccentric and isometric regime cause an excessive accumulation of metabolites and, often also muscle damage, which generate a high rate of peripheral fatigue that can last several minutes or hours up to a few days in the case of damage to the muscle fibres; at the central level, however, the fatigue related to the efforts in isometric and eccentric conditions are always due to the inhibitory mechanisms triggered by the afferents of groups III and IV which generate a lowering of voluntary activation to protect the tissues from excessive damage. Recovery from this condition takes anywhere from 1 to 30 minutes.

Table 2. Mode of exercise and fatigue (from Carroll et al., 2017, modified).

Peripheral fatigue	**Central fatigue**
Maximum efforts: - Accumulation of metabolites - Fast recovery with blood reperfusion (<30 sec)	Maximum efforts: - Effects of afferents of groups III and IV - Reduction of Voluntary activation - Recovery time about 90 sec
Isometric-eccentric exercises: - Accumulation of metabolites - Muscle damage - Recovery from a few hours to days	Isometric-eccentric exercises: - Effects of afferents groups III and IV - Reduction of Voluntary Activation - Recovery from 1 minute to 30 minutes

In relation to the duration of the exercise, the fatigue that develops at the peripheral level is mainly caused by the depletion of energy substrates and the accumulation of metabolites. Recovery times range from 1-3 minutes for short-term efforts to over 6 minutes for long-lasting efforts. As for the central component, short-term efforts cause a lowering of voluntary activation and reduced conduction between motor neurons; recovery takes 2-3 minutes; central fatigue induced by long-lasting efforts lasts up to 30 minutes.

Intensity, understood as the level of physical effort required by the neuromuscular system to perform a certain exercise, has a decisive influence on the onset of fatigue. The high intensity causes high fatigue, especially at the peripheral level, which requires recovery ranging from 2 to 5 minutes (Bompa, 2001) to allow the disposal of metabolites and the restoration of energy supplies. The low intensity of exercise, mainly referred to endurance activities, causes effects depending on the duration of the exercise. At the central level, high intensity activities generate fatigue that lasts for a few minutes, while activities at lower intensity and of longer duration strain the nervous system more.

Table 3. Duration of exercise and fatigue (from Carroll et al., 2017, modified).

Peripheral fatigue	**Central fatigue**
Short duration exercises: - Depletion of energy substrate - Accumulation of metabolites - Recovery with reperfusion in 1-3 minutes	Short duration exercises: - Reduction of Voluntary Activation - Inhibition of communication between motor neurons - Recovery time greater than 2-3 minutes
Long duration exercises: - Depletion of energy substrates - Accumulation of metabolites - Recovery in 6 minutes or more	Long duration exercises: - Reduction of Voluntary Activation - Inhibition of communication between motor neurons - Recovery time greater than 6 minutes

The literature therefore argues that high-volume workouts favour the onset of a higher rate of fatigue, especially at the central level, whose recovery is slower than sessions with low volumes and high intensity (Bartolomei et al., 2017, Heavens et al., 2014). A recent study by Bartolomei et al. He compared the physiological responses of a high-volume versus high-intensity exercise protocol. It emerged, in fact, that subjects subjected to a high-volume training load presented a state of greater fatigue than other subjects subjected to high-intensity training, with high levels already in the first 30 minutes post exercise.

Table 4. Exercise intensity and fatigue (from Carroll et al., 2017, modified).

Peripheral fatigue	**Central fatigue**
High Intensity: - Accumulation of metabolites - Fast recovery with reperfusion (2-5 minutes) - In some cases, peripheral fatigue lasts for a few days	High Intensity: - Few effects - Recovery within 2 minutes
Low Intensity: - Effects depending on the duration of the work	Low Intensity: - Long-lasting low-intensity exercises strain greater central fatigue, which can last a few days

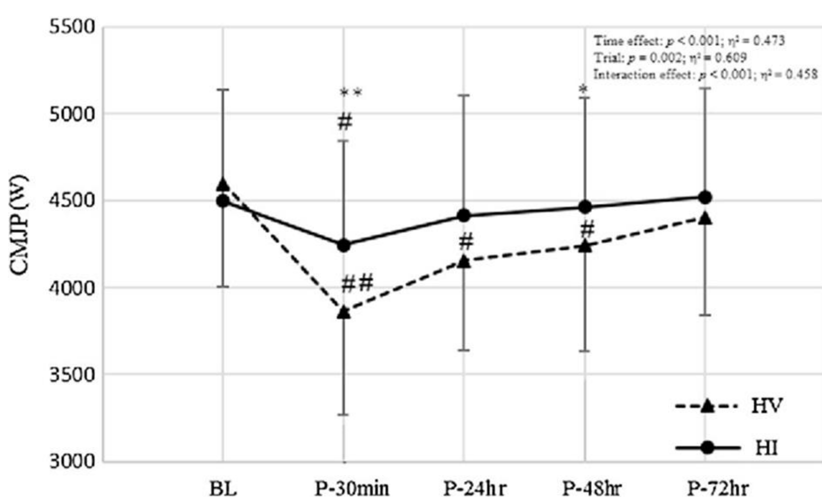

Figure 4. Fatigue: intensity vs volume (Bartolomei et al. 2015).

CONCLUSIONS

The purpose of the review was mainly to list the characteristics of muscle fatigue caused by exercise, highlighting the levels of onset, the consequences and mechanisms of recovery from such situations to avoid overtraining conditions and consequent injuries.

From what has been learned, through the scientific literature, fatigue should not be considered exclusively as a factor limiting performance, but rather as a protective mechanism for the neuromuscular system useful for avoiding dangerous exposure to trauma.

In the training process, coaches and athletes must manage loads and recoveries in a targeted manner in order to achieve the desired effects of supercompensation. Incorrect programming can establish a state of chronic fatigue, defined overtraining, which has negative effects on the continuation of training as it exposes athletes to injuries, as well as being one of the causes of abandoning sports practice.

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