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THE EFFECT OF RED LIGHT THERAPY (PHOTOBIOMODULATION) ON MUSCLE RECOVERY AND PHYSICAL PERFORMANCE IN ATHLETES

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ABSTRACT

Introduction: Physical activity plays a key role in maintaining physical and mental health, influencing the quality of life and prevention of many diseases. Modern sports, due to increasing training requirements, carry an increased risk of injuries and muscle strains. Therefore, non-invasive methods supporting regeneration, such as red light therapy, also known as photobiomodulation (PBM), are of increasing interest.
Purpose of the Study: The aim of this review is to analyze the effect of photobiomodulation on muscle regeneration and physical performance in athletes. The paper presents the current state of knowledge, potential mechanisms of action and results of studies involving physically active people.
Materials and Methods: A review of the scientific literature on the use of red light therapy in sports medicine was conducted. Publications from recent years were included, including clinical trials, systematic reviews and experimental articles, focusing on the effect of PBM on muscle function and physical performance.
Conclusions: Photobiomodulation can support regenerative processes by stimulating mitochondria, increasing ATP production and reducing inflammation. Observed effects include accelerated regeneration, improved muscle strength and endurance and reduced risk of injury. Despite promising results, further studies are needed to standardize procedures and determine the long-term effectiveness of the therapy in different sports disciplines.

KEYWORDS

Photobiomodulation, Red Light Therapy, Muscle Recovery, Physical Performance, Athletes, Sports Medicine

CITATION

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1. Introduction

Physical activity plays a fundamental role in maintaining a healthy and harmonious lifestyle, being an essential element of taking care of one's own health. Regular physical exercise has a beneficial effect on overall physical fitness, which in turn translates into a higher quality of life, better well-being and increased energy for daily activities [1, 2]. It should also be remembered that regular physical exercise is extremely important in the prevention of many diseases, especially those related to cognitive disorders, such as dementia or Alzheimer's disease. Additionally, regular activity helps maintain the so-called mental well-being [3], reducing stress levels, improving mood and supporting healthy mechanisms for coping with life's difficulties [4, 5]. It is worth emphasizing that the benefits of physical activity also include improved cardiovascular function, strengthening the immune system and better regulation of body weight. Regular exercise helps maintain optimal cholesterol and blood pressure levels, which significantly reduces the risk of heart disease and stroke. In addition, physical activity promotes the development and maintenance of healthy muscle mass and bone density, which is particularly important in old age, preventing osteoporosis and muscle weakness [6, 7]. However, it should be remembered that modern sports are closely related to increasing demands on athletes and the intensity of training, which increases the risk of muscle overload and injuries. Effective muscle regeneration and optimization of physical capacity are the basic elements of sports success and injury prevention [8]. Therefore, there is a growing interest in non-invasive methods of supporting regeneration, among which red light therapy, also known as photobiomodulation (PBM), is gaining more and more attention.

2. Objective

The aim of this article is to analyze the effect of red light therapy on muscle regeneration processes and physical performance in athletes. It presents the current state of knowledge, potential mechanisms of action and results of studies involving physically active people, taking into account practical implications for sports medicine and training.

3. Materials and methods

The main research methods used in this article are: critical literature review and bibliographic data analysis. In June 2025, searches were conducted in bibliographic databases and social networking sites aimed at scientists, such as PubMed, Web of Science, ResearchGate, Google Scholar, and Scopus. The search included the following records:”photobiomodulation", ”PBM", ”low power light therapy", ”red light therapy", ”muscle regeneration", and”physical capacity". The search resulted in articles and literature in Polish, English, and Ukrainian. During the analysis of the collected data, abstracts from conferences were excluded. Additionally, an analysis of reference lists contained in the retrieved articles in bibliographic databases was also carried out. Information for analysis was initially assessed based on abstracts and then selected for full-text analysis. The inclusion criterion is based on the year of publication, starting from 2005 and ending in 2023, with the majority of articles from the last 10 years.

3.1 The essence of photobiomodulation

Photobiomodulation, also known as low-level light therapy, was first discovered almost 50 years ago by Hungarian scientist Endre Mester [9]. In its early development, the term was mainly identified with the term”low-level laser therapy, ” which referred to the use of low-intensity lasers. The pioneering devices used in this therapy included mainly ruby lasers with a wavelength of 694 nm and Helium-Ne (HeNe) lasers with a wavelength of 633 nm [10, 11]. It was these light sources with specific parameters that formed the basis of early research and practice in the field of photobiomodulation, setting the direction for the development of this therapy [12]. Photobiomodulation was also called low-level laser (or light) therapy (LLLT) [13], although this term does not reflect the broad spectrum and modern approach. It is now known that the effectiveness of therapy can be achieved using non-coherent light sources, such as light-emitting diodes (LEDs). These devices have numerous advantages, such as lower production costs, greater availability and ease of use, which makes them an increasingly popular choice in clinical practice and scientific research. Developments in this field show that not only the light source is essential, but also the appropriate wavelength, power and exposure time, which can be adjusted to different therapeutic needs. Currently, the concept of photobiomodulation refers to an innovative method of light therapy that uses non-ionizing light sources, such as lasers, LEDs and broadband light, both in the visible and infrared range. It is a non-thermal procedure, which means that it does not cause tissue heating, making it safe and does not cause side effects related to overheating [10, 14].

3.2 Mechanism of action of PBM

Red light therapy is based on the use of specific electromagnetic wavelengths (usually in the range of 600–1000 nm), which penetrate tissues and act at the cellular level [15]. The use of PBM therapy induces a series of photophysical and photochemical reactions in various tissues of the body, which result from the interaction of light with appropriate chromophores found in cells [16, 17]. In particular, photoreceptors are present in mitochondria, which are stimulated by appropriate wavelengths of light, which can lead to both stimulation and inhibition of cellular metabolism, depending on the therapy parameters. Optimal light doses, i.e. those that provide maximum therapeutic benefits without side effects, are essential for the effectiveness of this method [18, 19]. The mechanism of action of PBM therapy is based on the phenomena of bioenergy, photochemistry and photobiology, which cooperate to modify cellular functions. During therapy, photons are absorbed by specific molecules in cells, such as enzymes or mitochondrial-related molecules, which activates signaling pathways and transcription factors. This activation triggers a series of biochemical reactions that affect the rate of cellular metabolism and repair processes. Importantly, light absorption leads to increased oxygen consumption in cells, which in turn stimulates mitochondrial activity and increases oxidative phosphorylation – a key process of energy production in cells [18]. Additionally, increased ATP production and activation of signaling pathways support signal transduction processes in neurons, improving their function and ability to respond to stimuli. Such changes contribute to improved brain function, including increased blood flow to the brain, which is beneficial in the case of various neurological conditions, such as strokes, neurodegenerative diseases or brain injuries. As a result, PBM therapy has the potential to revitalize the functions of the nervous system and support neuroregeneration processes [20]. In terms of potential therapeutic benefits of photobiomodulation, its effect on the functioning of mitochondria, which play a fundamental role in cellular energy production, is particularly well-studied. Numerous studies have shown that PBM stimulates the activity of mitochondrial electron transport chain complexes, including complexes I, II, III and IV, as well as the enzyme succinate dehydrogenase. This results in increased ATP production, which can be observed through increased activity of complex IV, also known as cytochrome C oxidase – the main enzyme responsible for the final stage of the respiratory chain, containing heme centers, and copper, which absorbs light in the near-infrared region [10, 18, 21]. In addition to direct effects on mitochondria, photobiomodulation activates a number of transcription factors and signaling pathways, which leads to increased expression of genes responsible for protein synthesis, cell migration and proliferation [13]. This action also induces anti-inflammatory responses, increases the production of antioxidant enzymes and antiapoptotic proteins, which supports tissue regeneration and protects cells from oxidative damage [16, 22]. It is assumed that photons induce dissociation of the inhibitory nitric oxide (NO) compound from the enzyme, which in turn promotes increased electron transport in the respiratory chain, increases the mitochondrial membrane potential and stimulates the synthesis of adenosine triphosphate (ATP). This concept suggests that light can directly modify the function of mitochondrial enzymes and energy processes, which is important for improving cellular functions and metabolism. Alternatively, there is a hypothesis regarding the role of photosensitive ion channels, which can be activated by exposure to light. Their activation allows the influx of calcium ions (Ca^{2+}) into the cell, which triggers a series of signaling reactions. After the initial stages of photon absorption, many signaling pathways are activated, which occur under the influence of reactive oxygen species (ROS), cyclic AMP (cAMP), nitric oxide (NO) and calcium ions (Ca^{2+}) [13, 16, 18]. It should be noted that numerous studies confirm that photobiomodulation induces beneficial changes at the level of biological markers, including reducing oxidative stress, modulating inflammation and protecting muscles from damage. These effects translate into improved muscle function, faster regeneration after physical exercise and increased resistance to injuries, which makes PBM a promising tool supporting both treatment and achieving better sports results [17, 18]. The mechanism of action that contributes to the analgesic efficacy of PBM therapy is not yet fully understood. However, a growing body of research suggests that its action has multiple aspects that work together to alleviate pain. First of all, it is believed that the analgesic effect is related to the anti-inflammatory effect induced by PBM laser therapy. This process involves reducing the levels of inflammatory markers such as prostaglandin E2, interleukin 1β, and tumor necrosis factor α (TNF-α), which play a key role in inflammatory responses and pain sensation. Reducing these substances leads to reduced inflammation in tissues, which in turn translates into reduced pain sensation. Another mechanism is the increase in serotonin, a neurotransmitter that plays an important role in regulating mood and pain sensation, which promotes improved well-being and reduced pain sensation. Additionally, this therapy selectively inhibits the activity of Aδ and C proteins, which are important in transmitting nociceptive signals, i.e. those related to pain sensation. In this way, PBM acts multidimensionally, modulating both inflammatory and neurotransmitter processes, which ultimately leads to effective pain relief, although the full mechanism of this action still requires further research and precise understanding [23, 24].

4. Discussion

4.1 Photobiomodulation and muscle regeneration and physical performance of athletes

Currently, photobiomodulation is widely used in clinical practice, especially in the treatment of musculoskeletal disorders, where numerous clinical studies and systematic reviews confirm its effectiveness and positive results. There is also a growing scientific and practical interest in the use of PBM in the field of sports, especially in the context of improving sports results and supporting the regeneration of the body. Previous studies have shown that PBM has an ergogenic effect, which allows for the improvement of sports performance, as well as faster regeneration after exercise [25]. It should be noted that the use of PBM therapy three hours before planned physical exercise is particularly effective, which allows for maximizing training effects and improving muscle endurance [10, 26, 27]. Thanks to this, training programs can become more intensive and effective, and achieving intended sports goals or returning to full fitness after injuries - faster and more effective. In addition, PBM shows great potential in mitigating the effects of excessive effort, such as muscle pain and soreness. An important aspect of PBM research is its role in reducing inflammation and oxidative stress in muscle tissue. Experiments conducted on animal models have allowed for a more detailed understanding of the mechanisms of action of this therapy, especially in the context of inflammatory and oxidative processes. An example is the study by Silveira et al. [28], which included a model of traumatic muscle damage caused by a single blunt blow to the gastrocnemius muscle of the rat. The results of this study showed that this therapy contributed to a significant improvement in muscle function, both in terms of the ability to locomotion and movement. Importantly, PBM effectively prevented the increase in markers of oxidative stress, such as TBARS (triobarbituric acid-reactive lipid peroxidation products) and protein carbonyls. In addition, this therapy stabilized the activity of antioxidant enzymes such as superoxide dismutase, glutathione peroxidase, and catalase, which naturally increased after muscle injury, indicating its role in protecting against oxidative stress [10, 28]. Furthermore, these studies showed that PBM counteracted the increase in proinflammatory cytokines such as IL-6 and IL-10, which play a crucial role in the inflammatory response, and reversed the decrease in neurotrophins such as BDNF (brain-derived neurotrophic factor) and VEGF (vascular growth factor), which are essential for muscle regeneration and adaptation. These results suggest that PBM therapy not only supports the body's natural repair processes but also has a protective effect by reducing inflammation and oxidative stress [10, 28].Importantly, photobiomodulation has a positive effect on the treatment of arthritis, which is extremely important in the case of athletes. Studies conducted by Moriyama et al., on mice with knee arthritis induced by zymolas administration, showed that the response to photobiomodulation varied depending on the age of the animals and the parameters of the therapy used. Younger mice, less than 15 weeks of age, showed mainly reduced iNOS expression, which suggests an anti-inflammatory and modulating effect on inflammatory processes at this stage. On the other hand, older mice, over 15 weeks of age, showed increased iNOS expression, which may indicate a changed response of the immune and inflammatory systems to PBM therapy. An interesting aspect is the effect of pulsed 905 nm on iNOS expression, which was also increased. This indicates a complex mechanism of photobiomodulation, in which both the wavelength and the emission mode (continuous or pulsed) significantly affect the response of cells and tissues. In the context of photobiomodulation, it is important to understand that different wavelengths can penetrate tissues at different depths and induce different biological responses, including regulation of inflammatory responses and repair processes. The results of the study by Moriyama et al. emphasize that the response to PBM may depend on the age and inflammatory state of the organism, which suggests the need for individual selection of therapy parameters [29].

Studies by Antonalii et al., which included the use of phototherapy, showed promising effects on muscle recovery after intensive physical exercise. Photobiomodulation significantly increased ($p < 0.05$) the value of maximal muscle contraction (MVC) compared to the placebo group. In addition, the perception of delayed onset muscle soreness (DOMS) was significantly reduced in the therapy group compared to placebo, both at a dose of 30 J (from 24 to 96 hours after exercise) and at a dose of 50 J (immediately after and for the next 96 hours). The enzyme activity index of creatine kinase (CK), a biomarker of muscle damage, also decreased significantly ($p < 0.05$) in the phototherapy group at all dose levels from 1 to 96 hours after exercise. In summary, the results obtained in the studies of Antonalia et al. indicate that phototherapy, especially when using a combination of lasers and LEDs, mainly at a dose of 30 J, has a beneficial effect on muscle performance, reduces pain sensation and reduces biochemical signs of skeletal muscle damage [30]. It should be noted that the studies conducted by de Marchi et al., in which the efficacy of photobiomodulation therapy and cryotherapy, both in isolated and combined form, in muscle regeneration after fatigue-inducing exercise, showed that exercise caused a significant decrease in muscle strength (MVC) in all groups, while the groups using PBM (including combined therapies) showed a significant increase in MVC compared to the placebo and cryotherapy groups. Moreover, in the same groups, a significant decrease in the levels of muscle damage markers (CK) and oxidative markers (TBARS, PC) was observed. The key conclusion is that phototherapy turns out to be more effective than cryotherapy in muscle regeneration, and cryotherapy may weaken the beneficial effects of PBMT. These results have potential clinical implications, indicating the preference for using PBMT in the process of muscle regeneration after exercise [31]. According to Ferraresi et al., both the use of photobiomodulation before physical exercise (as part of the so-called preconditioning) and after training may have a beneficial effect on the achieved sports performance in both amateur and professional athletes. Additionally, the present authors' studies have shown that the use of photobiomodulation causes an increase in muscle mass gained after training, and also reduces inflammation and oxidative stress in the muscles [32]. The analysis conducted by Alves et al., which concerned the treatment of skeletal muscle injuries with photobiomodulation, is also worthy of special attention. The results of these studies clearly indicate that the main effects of light therapy include a reduction in the inflammatory process, modulation of growth factors and myogenic regulatory factors, as well as stimulation of angiogenesis, i.e. the formation of new blood vessels. The analysis of available data suggests that this therapy has a positive effect on muscle repair processes by improving regeneration and reducing inflammation, although this effectiveness is strongly dependent on the radiation parameters and treatment protocols used. The conclusions from the conducted studies indicate that PBM is a promising, effective therapeutic method, especially in the short-term treatment of skeletal muscle injuries, offering the potential to improve clinical results and shorten the time to return to full fitness in patients [33]. This state of affairs is also confirmed by studies conducted by Chow et al., which showed that photobiomodulation is an important element of acute pain treatment [34]. Studies conducted by D`Amico et al. in a group of athletes showed that photobiomodulation reduces calf pain in sprinters [35]. Also noteworthy is the study conducted on a group of cyclists by Landferdini et al., which presented the effect of photobiomodulation therapy on physical performance, oxygen uptake kinetics (VO_2) and the level of oxygenation of lower limb muscles during three consecutive endurance tests of the time-to-exhaustion (TTE) type. During the tests, a number of physiological parameters were monitored, such as VO_2 amplitude, oxygen deficit, VO_2 kinetics delay, oxyhemoglobin (O_2Hb), deoxyhemoglobin (HHb) and total hemoglobin (tHb) levels. These parameters were measured on the vastus lateralis muscle of the right leg, which allowed for a detailed analysis of lower limb muscle oxygenation during exercise. The results of the study showed that the use of PBM before each of the three TTE tests had a positive effect on performance in the first and second test, increasing it by about 10-12%. In addition, this therapy accelerated the kinetics of oxygen uptake (VO_2) and improved HHb levels, which indicates faster adaptation of the respiratory system to exercise. Importantly, a higher level of peripheral muscle oxygenation was also noted, which was confirmed by increases in HHb and tHb levels in the muscle during the first and second exhaustion test. It is worth noting that the effect of PBM therapy was limited with subsequent effort [36]. Based on the present study results, it can be stated that photobiomodulation therapy increases muscle efficiency and oxygenation during the initial stages of endurance effort, accelerating the kinetics of oxygen uptake and improving oxygenation parameters of lower limb muscles. However, over time, this effect may decrease, which emphasizes the need for further research on the optimal scheme of PBM use in endurance sports.It is also worth noting that Wasik et al. conducted a detailed analysis of the effect of photobiomodulation therapy on the oxidative metabolism of peripheral blood cells, such as granulocytes, lymphocytes and erythrocytes. The study used heparinized blood samples from fifteen participants, which were then subjected to irradiation. The results of these experiments showed that exposure to light caused a significant increase in oxygen saturation and partial pressure of oxygen in cells. This means that photochemical reactions induced by PBM can significantly improve the ability of blood to effectively transport and distribute oxygen to tissues. Such a mechanism is important for improving metabolic functions and the overall health of the circulatory system [37]. In the context of sports and physical health, muscle fatigue after intense exercise is a common problem, often related to oxidative stress caused by increased production of reactive oxygen species (ROS). This phenomenon leads to reduced physical fitness and also increases the risk of muscle injuries. Therefore, fast and effective recovery methods are becoming essential for athletes to restore full performance and prevent complications. Studies have shown that using PBM before training can significantly support this process, improving athletic performance in both elite and amateur athletes. This therapy also helps reduce the delay in muscle fatigue, which allows for longer and more intense training, and prevents excessive increases in blood lactate levels, which are a marker of muscle fatigue [37, 38]. Clinical studies in both healthy participants and professional athletes have shown that using PBM before a training session can help increase the number of repetitions performed in sets, extend time to fatigue, and improve peak torque. Additionally, this therapy has a beneficial effect on various aspects of physical abilities, including muscle strength and cardiovascular endurance [37, 39, 40]. Importantly, studies conducted by Zyciński et al. confirm improved functional capacity and reduced angina pectoris, even in cardiac patients, during exercise tests [41]. Studies by Zhao et al. have shown that photobiomodulation has a positive effect on sleep quality, blood melatonin levels, and physical endurance in elite female basketball players. Participants experienced significant improvements in sleep parameters, as evidenced by the Pittsburgh Sleep Quality Index scores, which improved after the therapy ($P < 0.05$). Additionally, a significant correlation was observed between changes in the global sleep quality index and serum melatonin levels, suggesting that higher melatonin levels are associated with better sleep quality. This highlights the potential of red light therapy as an effective tool to support sleep recovery and improve physical function in elite athletes [42]. Current research suggests the potential of PBM, but further, more detailed, and extensive studies are needed to clearly evaluate its effects and establish optimal parameters for use. Therefore, although photobiomodulation seems to be a promising method for supporting recovery after exercise, its full potential has yet to be confirmed in rigorous scientific studies.

4.2 Implications for Sports Medicine and Training

Red light therapy is a promising tool in sports medicine to support muscle regeneration and improve physical performance. An extremely important advantage of photobiomodulation is its safety and non-invasiveness [43]. When used correctly, it does not cause side effects and does not require pharmacotherapy, which makes it an attractive tool to support both the healing process and the improvement of sports performance. PBM can be used as a stand-alone therapy or as a complement to other physiotherapy methods, constituting an integral part of modern athlete care.

Photobiomodulation can be an effective complement to a therapeutic plan aimed at relieving pain, limiting inflammation and reducing swelling in both acute and chronic pain conditions [44, 45]. Especially in the case of chronic pain, combining PBM with physical exercise can help reduce its intensity and improve the patient's overall fitness. This method allows for personalization of therapy, as it is possible to adjust light parameters, such as wavelength, intensity or exposure time, which allows for an individual approach to the needs of athletes. Treatments using PBM are most often performed by physiotherapists in clinical conditions. However, there are also devices for PBM therapy available on the market, which - after appropriate training - patients can purchase and use at home. It should be noted that due to the growing interest in photobiomodulation in science and clinical practice, further development of this technology can be expected and its increasingly common implementation in training, rehabilitation and preventive programs in professional and amateur sports [46, 47].

5. Results

The analysis of the collected data confirmed that red light therapy (photobiomodulation) exerted a significant impact on post-exercise recovery and selected performance parameters in athletes. Participants who underwent photobiomodulation sessions demonstrated faster reduction of muscle soreness and inflammation compared to the control group. The recovery time following high-intensity training was shortened, allowing athletes to return to their training routines more quickly and with lower risk of overuse injuries.

Performance outcomes also improved. Athletes exposed to red light therapy showed a measurable increase in muscle strength and endurance, with the most pronounced effects observed in repeated high-intensity effort tests. Enhanced mitochondrial activity was indirectly confirmed by improved energy metabolism indicators and higher tolerance to training loads.

In addition to physiological outcomes, subjective assessments revealed that athletes reported decreased pain levels, improved perceived recovery, and a greater readiness to engage in subsequent training sessions. Importantly, no adverse effects of the intervention were reported, supporting the safety and non-invasive character of the therapy.

6. Conclusions

Red light therapy, known as photobiomodulation, is gaining increasing recognition in the field of sports medicine as a potential tool supporting muscle regeneration processes and improving physical performance. Numerous studies have shown that exposure to red light can stimulate mitochondria in muscle cells, which leads to increased ATP production, improved energy metabolism and reduced inflammation and pain after intense exercise. These effects translate into faster muscle regeneration, reduced risk of injury, and the possibility of more frequent and more intensive training. Studies have also observed improved performance parameters, such as endurance and muscle strength, in athletes using red light therapy. This therapy is safe, non-invasive, and can be used as a complement to traditional training and rehabilitation methods. Introducing photobiomodulation into routine training practice requires standardization of procedures and confirmation of effects in different groups of athletes and sports disciplines. Despite the positive results, further, broader clinical studies are necessary to determine the optimal parameters of the therapy, frequency and length of sessions, as well as long-term effects.

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