SZYDŁOWSKA, Sara, BŁASZKÓW, Krzysztof, ELIAS, Jagoda, BIESIADA, Wiktor, ZUBIAK, Marlena and KAŹMIERCZAK, Dominika. Regular monitoring of post-training biochemical markers as a tool for injury prevention in professional athletics – review. Quality in Sport. 2025;39:58897. eISSN 2450-3118.
https://doi.org/10.12775/QS.2025.39.58897
https://apcz.umk.pl/QS/article/view/58897

The journal has been 20 points in the Ministry of Higher Education and Science of Poland parametric evaluation. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024. No. 32553.
Has a Journal's Unique Identifier: 201398. Scientific disciplines assigned: Economics and finance (Field of social sciences); Management and Quality Sciences (Field of social sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 r. Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398.
Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 17.02.2025. Revised: 05.03.2025. Accepted: 06.03.2025 Published: 08.03.2025.

REGULAR MONITORING OF POST-TRAINING BIOCHEMICAL MARKERS AS A TOOL FOR INJURY PREVENTION IN PROFESSIONAL ATHLETICS – REVIEW

1. Sara Szydłowska[1] MD, https://orcid.org/0009-0002-7926-5265,
   University Clinical Hospital in Wrocław, Borowska 213, 50-556 Wrocław
   iron14444@op.pl
2. Krzysztof Błaszków, https://orcid.org/0009-0006-0685-1094
   University Clinical Hospital in Wrocław, Borowska 213, 50-556 Wrocław
   k.blaszkow98@icloud.com
3. Jagoda Elias MD, https://orcid.org/0009-0007-6967-6016
   Lower Silesian Oncology Center in Wrocław, Plac Ludwika Hirszfelda 12, 53-413 Wrocław
   jagoda.anna.elias@gmail.com
4. Wiktor Biesiada MD, https://orcid.org/0009-0002-2662-5300
   Gromkowski Regional Specialist Hospital, Koszarowa 5, 51-149 Wrocław
   wiktor122333@gmail.com
5. Marlena Zubiak MD, https://orcid.org/0009-0009-5329-9214
   Independent Public Provincial Hospital named after Pope John Paul II in Zamość, Aleje Jana Pawła II 10, 22-400 Zamość
   zubiakmarlena@gmail.com
6. Dominika Kaźmierczak MD, https://orcid.org/0009-0001-5384-9273
   Medical University of Silesia: Katowice, Poniatowskiego 15, 40-005 Katowice
   dominika.kazmierczakk@gmail.com

[1] Corresponding author: Sara Szydłowska, University Clinical Hospital in Wrocław, e-mail: iron14444@op.pl

Abstract

Modern professional sports place increasingly high demands on athletes, necessitating the optimization of training loads and effective injury prevention. One of the key tools supporting these processes is the regular monitoring of biochemical markers, which allows for the assessment of the body's response to physical exertion and the detection of overtraining states. This paper discusses the significance of selected biochemical indicators, including creatine kinase (CK), lactate dehydrogenase (LDH), acute-phase proteins (CRP, IL-6, IL-8, IL-10, haptoglobin), metallothionein (MT), electrolytes, and hormones (testosterone and cortisol), in the context of monitoring fatigue, recovery, and injury risk.

Analysis of available studies has shown that the integration of various biomarkers enables a more precise assessment of the body's adaptation to training loads and the early detection of overtraining symptoms. At the same time, attention has been drawn to individual physiological differences affecting the interpretation of results, as well as the need for further research into the standardization of measurement methods.

Regular monitoring of biochemical markers can serve as an effective tool for optimizing the training process, provided it is integrated with an individualized approach to the athlete and considers a broad spectrum of factors influencing the body's response. The implementation of such an approach can contribute to minimizing injury risk, improving performance, and enhancing recovery efficiency, which is crucial for the long-term professional development of athletes.

Aim of the review

The aim of the review was to discuss the role of regular monitoring of biochemical markers in assessing fatigue, recovery, and injury prevention in professional athletes. Key indicators such as creatine kinase (CK), lactate dehydrogenase (LDH), acute-phase proteins, electrolytes, and hormones (testosterone and cortisol) were analyzed.

Results

The analysis of available studies showed that the integration of various biomarkers allows for a precise assessment of the body's adaptation to exercise. Regular monitoring of these indicators enables the detection of overtraining states, optimization of training loads, and minimization of injury risk.

Conclusions

Regular monitoring of biochemical markers is an effective tool in managing the training and recovery process. Its effectiveness depends on individualization of the approach, integration with other diagnostic methods, and further standardization of measurements in future research.

Keywords:

Creatine Kinase (CK), C-Reactive Protein (CRP), Electrolytes (potassium, sodium, magnesium, calcium, phosphorus), Hormones (testosterone, cortisol), Fatigue Markers, Muscle Damage, Injury Prevention

Introduction

Over the years, professional sports have begun to place increasingly higher demands on both athletes and the entire interdisciplinary teams that comprehensively support their development. These tasks include the constant adaptation of training, recovery, and adaptation strategies, enabling the systematic pushing of physical performance limits. These teams consist of coaches (responsible for planning and conducting training sessions), physiotherapists (preventing injuries and supporting recovery), sports doctors (diagnosing and treating health issues related to physical exertion), sports nutritionists (ensuring a balanced and individualized diet), sports psychologists (enhancing mental resilience and concentration), biomechanists (analyzing movement and optimizing technique), and strength and conditioning coaches (developing strength, endurance, and speed). One of the main challenges of modern sports training is balancing training intensity with adequate recovery time. Too short a recovery period between training sessions can lead to accumulated fatigue, which in turn increases the risk of injuries and negatively impacts an athlete's performance.

The increase in training intensity and volume, as well as the dynamic nature of modern sports competition, significantly elevate the risk of overload, which can lead to injuries and decreased performance. Therefore, proper monitoring of physiological parameters becomes crucial. A key role in assessing the body's response to physical exertion is played by biochemical markers of fatigue, such as creatine kinase (CK), lactate dehydrogenase (LDH), acute-phase proteins (including CRP, IL-6, IL-8, IL-10 and haptoglobin), metallothionein (MT), electrolytes (with particular emphasis on potassium levels), and hormones (mainly testosterone and cortisol). These markers allow for continuous assessment of the body's reaction to physical effort. Through their analysis, it is possible to detect microdamage in muscles, evaluate inflammatory status, and identify the degree of metabolic overload. Regular monitoring of these indicators enables the appropriate adjustment of training programs, minimizing the risk of injury and optimizing recovery.

This publication provides a detailed discussion on the significance of monitoring fatigue biomarkers in sports practice. By analyzing available scientific data, it presents the benefits of utilizing these indicators in injury prevention, performance optimization, and recovery management. At the same time, it highlights individual differences (such as gender, age, body mass, training level, and genetics) in physiological responses to exercise, emphasizing the necessity of an integrated approach that combines various diagnostic tools and personalized training strategies. Additionally, the publication addresses the limitations associated with result interpretation and explores future research directions in this field.

Characteristics of Biomechanical Markers

Creatine Kinase (CK)

Creatine Kinase (CK) is a key enzyme involved in cellular energy metabolism. It plays a particularly important role in tissues with high energy demand, including striated muscle tissue (both skeletal and cardiac) as well as brain tissue. CK catalyzes reactions in which phosphate groups are transferred from phosphocreatine to ADP, enabling the rapid regeneration of ATP during intense physical exertion. Under conditions of mechanical overload or muscle damage, CK is released into the bloodstream. This makes it a valuable marker in professional sports for assessing muscle status, metabolic fatigue, and the recovery phase [4, 13].

During intense physical exertion, especially activities involving eccentric contractions, structural damage occurs within sarcomeres and the sarcolemma. As a result, CK is released into the bloodstream, indicating the presence of microdamage in the muscles. Its increase is proportional to the intensity and volume of exercise. This characteristic makes CK one of the most sensitive biomarkers for assessing training load and potential muscle damage [3, 4, 17, 29].

By regularly monitoring CK levels, it is possible to precisely track physiological adaptation to training loads and identify the risk of injury. In team sports, where repeated cycles of exertion can lead to the accumulation of fatigue, CK monitoring plays a key role in managing recovery. Additionally, studies show that CK levels may remain elevated for several days after exercise. This allows for appropriate planning of training load levels, continuously updating and modifying them [1, 24, 26].

It is worth noting that there is significant individual variability in response to exercise. Factors such as genetics, fitness level, age, gender, as well as diet, circadian rhythm, nutritional habits, and external influences affect serum CK levels. Additionally, there are no clear reference norms. A partial solution to this issue could be interpreting results based on baseline values for a given athlete, combined with data from other monitoring methods such as CRP, IL-6, hormonal measurements, or subjective fatigue assessment questionnaires. In summary, further research should primarily focus on developing consistent and standardized measurement methods. Equally important is determining individual reference ranges tailored to the specifics of various sports disciplines [12, 13].

Lactate dehydrogenase (LDH)

Lactate dehydrogenase (LDH) is an enzyme that, under anaerobic conditions, participates in the final stage of respiration (glycolysis), catalyzing the reversible reaction of converting pyruvate into lactate (pyruvate + NADH + H^+ ↔ lactate + NAD^+). Thus, this process allows for the regeneration of NAD^+, which is essential for continuing glycolysis and further ATP production. Consequently, during intense training, when oxygen deficiency occurs in tissues with particularly high energy demands and high metabolism (e.g., in skeletal muscles), increased LDH activity is observed. It is worth noting that the rise in plasma LDH levels is not due to its synthesis but rather results from cell membrane damage and the release of the enzyme from within cells, especially during eccentric muscle work, which causes microdamage. Additionally, LDH exists in various isoenzyme forms, whose distribution and activity are tissue-specific, making LDH a useful indicator for analyzing physiological load, training adaptation, and recovery processes in athletes [4, 25].

The dynamics of LDH concentration changes depend on the type of physical activity performed. Aerobic exercise, characterized by lower intensity, generates moderate increases in serum LDH. On the other hand, resistance exercises, as mentioned earlier – particularly those of high intensity with a dominant eccentric contraction component – lead to a significant rise in LDH activity, which directly correlates with structural muscle damage [4, 23]. The time it takes for LDH levels to return to baseline after exercise serves as a reliable indicator of the efficiency of recovery processes in muscle tissue. Integrating LDH analysis with other biomarkers can provide a more comprehensive picture of an athlete's physiological state [13, 25].

Elevated resting LDH levels, observed with frequent and prolonged physical overexertion, may indicate insufficient recovery and an increased risk of overtraining and injury. In such cases, regular LDH measurements become a crucial tool in monitoring the body's adaptation to training load and can serve as a basis for making decisions about adjusting training intensity [12, 26].

C-reactive protein (CRP)

C-reactive protein (CRP) is classified as one of the so-called "acute-phase proteins (APPs)". This is a group of proteins present in the blood that are produced in the liver by hepatocytes in response to an ongoing inflammatory process in the body. Their synthesis is induced by pro-inflammatory cytokines, such as interleukin-6 (IL-6). Its serum concentration increases in response to tissue damage, infections, and excessive physical exertion, although in the context of physical exercise, this increase is usually temporary and depends on the intensity and nature of the training. However, regular measurement can be significant in assessing the risk of chronic inflammation in athletes [13, 26]. The use of CRP as an inflammatory marker allows for the early detection of muscle microtraumas resulting from intense physical exertion. Elevated CRP levels reflect the activation of the immune system and the intensification of repair processes [1, 26]. Additionally, CRP can serve as an indicator of overall inflammatory status, pointing to infections or other conditions that may affect an athlete's performance and recovery [13].

The pattern of changes in CRP levels after physical exercise is strongly dependent on the type and intensity of the activity. Endurance exercises, such as marathons, lead to significant increases in CRP, which is attributed to prolonged metabolic and mechanical stress [12, 26]. High-intensity interval training (HIIT) generates moderate CRP elevations, while strength training, although causing smaller CRP increases, still imposes a load on the muscular and immune systems [13, 29]. The return of CRP to baseline levels suggests the resolution of inflammation and the repair of damaged tissues. Regular CRP measurements can support the evaluation of the effectiveness of recovery strategies, such as proper diet and supplementation, as well as physiotherapy [13, 23]. Persistently high CRP levels over an extended period may indicate insufficient recovery or excessive training load, requiring immediate intervention [21, 23]. Chronically elevated CRP levels are often associated with excessive training load, which can lead to overtraining syndrome and increase the risk of injuries. Regular monitoring of this marker enables early detection of an elevated risk of injuries or other serious health complications [12, 26].

Haptoglobin (Hp)

Haptoglobin (Hp), like CRP, is an acute-phase protein. Its primary function is to bind free hemoglobin (Hb) released as a result of hemolysis, thereby protecting tissues from damage caused by reactive oxygen species (ROS) [7, 18]. The increase in its levels in response to physical exercise is due to the stimulation of its synthesis by interleukin-6 (IL-6). Intense exercise, particularly in endurance disciplines, leads to increased hemolysis and the release of free hemoglobin into the bloodstream. This forms an Hp-Hb complex, which is cleared by the reticuloendothelial system. Through this mechanism, the risk of developing chronic inflammatory conditions is reduced [7, 25]. By protecting muscle tissue from oxidative stress, haptoglobin is included in the list of indicators of the body's adaptive processes to physical load. An increase in the level of this protein may reflect the degree of mobilization of the inflammatory response and the effectiveness of repair mechanisms [18].

The characteristics of changes in haptoglobin levels depend on the type, intensity, and duration of exercise. Endurance exercises, which involve intense hemolysis, lead to a significant increase in haptoglobin levels in plasma. Strength and interval exercises cause less pronounced changes, although an increase in the level of this protein is still observed [7, 25]. Intense training, especially with insufficient recovery time, can result in persistently elevated haptoglobin levels, indicating chronic inflammation. Such changes may suggest overtraining and increase the risk of injury. Therefore, monitoring haptoglobin levels can help optimize training load [18, 25]. Stabilization of haptoglobin levels after intense exercise suggests the effectiveness of the body's repair mechanisms.

On the other hand, prolonged elevation of haptoglobin may indicate chronic inflammation and/or overloading of the body [7]. When combined with other biochemical markers, haptoglobin provides a comprehensive picture of an athlete's health status, which is crucial for planning recovery processes and reducing the risk of injury [25]. Haptoglobin can also be used to identify athletes who are particularly susceptible to the development of chronic inflammatory conditions, enabling the implementation of appropriate preventive strategies.

Interleukins (IL-6, IL-8, IL-10)

Cytokines, including interleukins IL-6, IL-8, and IL-10, are key mediators of intercellular communication that regulate immune responses and inflammatory processes [16]. They play a crucial role in cell signaling, influencing the activity of immune cells and modulating the body's response to infection, injury, or physical exertion [19]. These interleukins contribute to balancing pro-inflammatory and anti-inflammatory reactions, supporting metabolic adaptation and muscle tissue repair [12]. In professional sports, their significance as biomarkers for monitoring the physiological state of the body is increasingly recognized, enabling the optimization of training, recovery, and preventive strategies to minimize the risk of injuries and overuse [14].

IL-6 serves both pro-inflammatory and anti-inflammatory functions, making it a crucial regulator of the body's adaptation to physical exertion. Synthesized primarily by skeletal myocytes, IL-6 also acts as a myokine, influencing glucose and lipid metabolism, which allows the body to effectively adjust to increased energy demands [16, 19]. The level of IL-6 can increase up to 100-fold in response to prolonged and intense exercise, particularly in endurance disciplines such as long-distance running or triathlon. The correlation between the rise in IL-6
and the duration and intensity of exercise has been well-documented, and its level is inversely proportional to muscle glycogen stores. For this reason, IL-6 can serve as an indicator of the body's metabolic adaptation to prolonged exertion [13, 19]. Long-term analysis of IL-6 levels not only allows for the assessment of fatigue but also for the prediction of overtraining risk. Chronically elevated IL-6 levels may signal suboptimal recovery processes, and an increased risk of injury associated with chronic inflammation [14].

IL-8 is a potent pro-inflammatory chemokine that plays a role in mobilizing neutrophils to sites of muscle tissue damage. In professional sports, IL-8 serves as a marker of recovery, as it is involved in angiogenesis, stimulation of satellite cell proliferation, and initiation of repair processes [13, 16]. After intense physical exertion, IL-8 levels increase, which is directly associated with repair processes and muscle remodeling. High levels of this cytokine may indicate active regeneration; however, its persistent elevation may signal overtraining, an increased risk of chronic inflammation, and microinjuries [12].

IL-10 is a key anti-inflammatory factor that regulates the balance between inflammation and recovery after physical exertion. Its primary function is to inhibit excessive activity of pro-inflammatory cytokines, such as IL-6 and TNF-α, which helps limit degenerative processes in muscle tissue and accelerate its repair [14, 16].
A high level of IL-10 after exercise indicates the activation of homeostatic and regenerative mechanisms, which is beneficial for athletes subjected to intense training loads. Moreover, the IL-10 to IL-6 ratio is an important marker of inflammatory balance—a high ratio indicates effective recovery and adaptation, whereas a low ratio may suggest an inadequate regenerative response and an increased risk of injury [12].

Metallothionein (MT)

Metallothionein (MT) is a low-molecular-weight, highly conserved protein with a molecular mass of approximately 6–7 kDa, characterized by a high content of cysteine residues. This enables it to bind transition metals such as zinc (Zn), copper (Cu), and cadmium (Cd), playing a crucial role in metal ion homeostasis and detoxification of the body. Additionally, it has a protective function by neutralizing reactive oxygen species (ROS), which can lead to cellular damage and oxidative stress [25, 30, 32].

In the context of physical exertion, MT is a potential biomarker of the body's adaptation to training loads, as its levels increase in response to intense training, suggesting involvement in regenerative processes and modulation of the inflammatory response [25, 30]. However, research on its effectiveness as a biomarker remains limited, and some studies indicate that the increase in MT is not always clearly correlated with improved regenerative capacity [30].

Moreover, MT levels in plasma or urine may be strongly influenced by other factors, such as diet, metabolic stress, and individual genetic predispositions [30]. Some studies also indicate that MT concentration decreases after physical exertion, similar to other markers of muscle catabolism, further complicating its use as a recovery biomarker [25].

Although MT is considered a component of the body's defense mechanisms, its excessive expression may lead to dysregulation of zinc and other trace metal levels, potentially affecting enzyme functions and disrupting metabolic balance [32]. It is also unclear whether higher MT expression in individuals who train regularly is a cause or a consequence of the body's adaptation, and the mechanisms of this relationship require further research [32].

An additional limitation is the difficulty in standardizing MT measurements, as different analytical methods may yield varying results, and MT concentrations in urine or plasma can exhibit high interindividual variability. Therefore, further research is needed to establish optimal protocols for MT determination and to assess its actual diagnostic value in professional sports [32].

Electrolytes (potassium, sodium, magnesium, calcium, phosphorus)

Electrolytes such as potassium (K^+), sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and phosphorus (P) are involved in fundamental physiological processes, regulating nerve conduction, muscle contraction function, acid-base balance, and energy metabolism. Their concentrations fluctuate during physical exertion, but interpreting these changes is challenging due to high interindividual variability and interactions with other physiological factors [25, 28].

Potassium plays a crucial role in nerve conduction and muscle contraction. Its plasma concentration (3.5–5.0 mmol/L) is significantly lower than in muscle cells (120–150 mmol/L), due to the activity of the sodium-potassium pump (Na^+/K^+-ATPase). During intense physical exertion, a transient increase in serum K^+ occurs as it is released from muscle cells, which can influence contraction strength and reduce the risk of fatigue [10, 21]. However, excessive accumulation of K^+ in the extracellular space may disrupt muscle membrane depolarization, leading to weakened contraction and an increased risk of exercise-induced cramps [10, 20].

Sodium is the primary extracellular cation responsible for maintaining osmotic pressure and water-electrolyte balance. Its loss through sweat can lead to exercise-associated hyponatremia, the symptoms of which include weakness, muscle cramps, and decreased performance [28]. However, there is controversy regarding the importance of sodium supplementation – some studies suggest that the issue is not always a sodium deficiency, but rather excessive fluid intake leading to dilutional hyponatremia [17, 28].

Magnesium is involved in the regulation of enzyme activity, muscle contraction function, and ATP metabolism. It is essential for the function of antioxidant enzymes and ion transport across cell membranes [6, 20]. Magnesium deficiencies may lead to increased susceptibility to cramps and impaired recovery. Some studies suggest that magnesium supplementation improves muscle function and reduces the risk of cramps, while others do not confirm the unequivocal effectiveness of such an intervention [6, 19].

Calcium is responsible for the proper contractile function of muscles, regulating the release of Ca^{2+} from the sarcoplasmic reticulum. It plays a role in nerve conduction and the activation of enzymes involved in tissue regeneration. Calcium deficiencies can lead to weakened muscle contractions, prolonged recovery time, and an increased risk of stress fractures [11, 20]. However, it is worth noting that serum calcium levels do not always reflect its actual status in the body, as its storage and release are regulated by hormonal mechanisms and bone metabolism [20].

Phosphorus is a key component of ATP and phosphocreatine, making it essential for energy metabolism. Its adequate levels are crucial for maintaining exercise capacity, and a deficiency can lead to reduced ATP synthesis, prolonged fatigue, and decreased physical performance [28]. It is worth noting that excessive dietary intake of phosphorus – particularly in the form of phosphates found in processed foods – can disrupt calcium-phosphate balance and negatively affect bone health [28].

Monitoring electrolyte levels in athletes can provide valuable insights, but interpreting the results requires consideration of individual differences, the timing of sample collection relative to exercise, and methodological limitations of measurement [25]. Some studies suggest that electrolyte measurements may not be sensitive enough to assess fatigue and recovery, and their diagnostic value requires further research [4, 9].

Hormones (testosterone, cortisol)

It should be noted that anabolic and catabolic hormones also play a key role in regulating the adaptive responses of the body to physical exertion. In particular, testosterone (T) and cortisol (C) perform opposing functions in the anabolic-catabolic balance, determining the processes of tissue repair and muscle degradation. The testosterone-to-cortisol ratio (T/C) is widely used in the analysis of training load and its impact on the athlete's homeostasis [22]. Regular monitoring of these hormones enables a precise assessment of the body's adaptive capacity to exercise and the early detection of overtraining and an increased risk of injury [5, 15, 27].

Testosterone is the primary regulator of anabolic processes, influencing muscle protein synthesis, satellite cell proliferation, and tissue regeneration. Its levels increase in response to intense strength training; however, prolonged physical strain, especially under conditions of insufficient recovery, can lead to a gradual decline in its serum concentration [2, 15, 27]. High-intensity resistance exercise induces a temporary increase in testosterone levels, whereas excessive training loads in endurance sports may result in its suppression, thereby weakening regenerative and adaptive capacities [5].

Testosterone exhibits a circadian rhythm, reaching its highest levels in the morning. Exposure to chronic exercise-induced stress can disrupt this rhythm, leading to long-term impairment of regenerative processes [27]. Testosterone not only stimulates protein synthesis but also plays a key role in regulating neurotransmitters, influencing the central nervous system and the body's ability to adapt to exercise [15, 31]. Additionally, testosterone enhances the synthesis of erythropoietin (EPO), which improves oxygen transport to tissues and the aerobic capacity of athletes [15]. It also acts synergistically with growth hormone (GH) and insulin-like growth factor (IGF-1), supporting muscle mass development and recovery [15]. In this way, testosterone plays a crucial role as an anabolic hormone, influencing many aspects of bodily function, particularly in the context of physical exercise and recovery.

Cortisol is a catabolic hormone whose primary function is the mobilization of energy substrates through protein breakdown and the stimulation of gluconeogenesis. Its excessive concentration can lead to the degradation of muscle structures, reduced regenerative capacity, and weakened immune function [15, 27]. Intense exercise causes a transient increase in cortisol; however, its chronic elevation indicates a state of prolonged exercise-induced stress, which negatively affects training adaptation and recovery [5, 8]. Endurance athletes are particularly susceptible to hypercortisolemia due to cumulative training load, which may result in a catabolic effect and an increased risk of injuries [8].

Cortisol also affects electrolyte balance by influencing sodium-potassium homeostasis through increased sodium retention and promotion of potassium excretion, which has significant implications for muscle function and the risk of cramps and overload-induced tissue injuries [5, 25]. Furthermore, chronic hypercortisolemia leads to a weakened immune system by inhibiting lymphocyte proliferation and antibody synthesis, increasing the risk of infections in athletes [8]. In this way, cortisol plays a key role as the primary catabolic hormone, impacting various aspects of bodily function, particularly in the context of physical exertion and recovery.

The T/C ratio is one of the key biochemical parameters used in monitoring training loads. A decrease in this ratio indicates a dominance of catabolic processes and may serve as a warning sign, suggesting the need for modifications in the training plan [5, 27]. Long-term reduction of the T/C ratio is correlated with overtraining and endocrine imbalance, necessitating the individualization of training loads and the implementation of appropriate recovery strategies [5, 8].

Different training protocols have a significant impact on the T/C ratio – high-intensity interval training (HIIT) and prolonged exercise sessions can cause substantial changes in the anabolic-catabolic balance. Systematic monitoring of this ratio allows for the assessment of the body's adaptation level and the adjustment of training strategies to its current capabilities [15, 29]. In this way, the testosterone-to-cortisol ratio (T/C) serves as a key indicator of the anabolic-catabolic balance, enabling the optimization of the training process and reducing the risk of overloading the body.

Conclusions

Modern professional sports demand not only the maximization of physical performance but also effective injury prevention and the optimization of recovery processes. In this context, regular monitoring of biochemical markers plays a pivotal role in assessing the body's fatigue, identifying overtraining states, and tailoring training loads to the individual capabilities of athletes. This study provides a comprehensive analysis of the significance of markers such as creatine kinase (CK), lactate dehydrogenase (LDH), acute-phase proteins (CRP, IL-6, IL-8, IL-10, haptoglobin), metallothionein (MT), electrolytes, and hormones (testosterone and cortisol) in evaluating the physiological state of the body and minimizing injury risk.

Based on current scientific evidence, the integration of multiple biomarkers enables a more holistic assessment of fatigue and recovery, facilitating precise adjustments to training strategies. At the same time, individual differences – such as training status, genetics, gender, and body composition – must be considered when interpreting results. A personalized approach to monitoring biochemical markers can significantly enhance the management of training loads and recovery processes.

The study also highlights the limitations associated with biomarker analysis, including the absence of standardized reference values and the influence of external factors on marker concentrations. Further research is needed to standardize measurement protocols and identify new indicators that can more accurately assess the body's adaptive capacity to exercise.

In conclusion, regular monitoring of biochemical markers represents a valuable tool for injury prevention and performance optimization in athletes. Its effectiveness, however, relies on a comprehensive approach that integrates biochemical parameters with individual physiological characteristics. The adoption of advanced diagnostic methods and personalized training strategies can significantly improve the efficiency of athletic preparation, reduce the risk of overtraining and injuries, and contribute to the long-term success of elite athletes.

Authors' contribution

All authors contributed to the article. Conceptualization – Sara Szydłowska; methodology – Krzysztof Błaszków, Jagoda Elias; check - Marlena Zubiak, Dominika Kaźmierczak; formal analysis – Wiktor Biesiada; resources – Jagoda Elias; data curation – Wiktor Biesiada; writing - rough preparation – Dominika Kaźmierczak; writing - review and editing - Sara Szydłowska, Wiktor Biesiada; visualization –Dominika Kaźmierczak; supervision – Krzysztof Błaszków; project administration – Sara Szydłowska. All authors have read and agreed with the published version of the manuscript.

Disclosures: No disclosures.

Financial support: No financial support was received.

Conflict of interest: The authors declare no conflict of interest.

References:

1. **Bestwick-Stevenson T, Toone R, Neupert E, Edwards K, Kluzek S.** Assessment of fatigue and recovery in sport: Narrative review. *Int J Sports Med.* 2022;43(11):1151–1162. doi:10.1055/a-1834-7177.
2. **Borucka-Konopka AM.** Efekt placebo u mężczyzn aktywnych fizycznie w aspekcie badań fizjologicznych i biochemicznych [rozprawa doktorska]. *Poznań: Akademia Wychowania Fizycznego im. Eugeniusza Piaseckiego w Poznaniu*; 2020.
3. **Byrne C, Twist C, Eston R.** Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. *Sports Med.* 2004;34(1):49–69. PMID:14715039.
4. **Callegari GA, Novaes JS, Neto GR, Dias I, Garrido ND, Dani C.** Creatine kinase and lactate dehydrogenase responses after different resistance and aerobic exercise protocols. *J Hum Kinet.* 2017;58:65–72. doi:10.1515/hukin-2017-0071.
5. **Cofré-Bolados C, Reuquen-López P, Herrera-Valenzuela T, Orihuela-Diaz P, Garcia-Hermoso A, Hackney AC.**Testosterone and cortisol responses to HIIT and continuous aerobic exercise in active young men. *Sustainability.*2019;11(21):6069. doi:10.3390/su11216069.
6. **Córdova A, Mielgo-Ayuso J, Bonilla L.** Serum magnesium behavior in professional cyclists after a multi-stage competition. *Eur J Sports Exerc Sci.* 2015;4(3):8–14.
7. **de la Rubia Ortí JE, Platero JL, Benlloch M, Franco-Martinez L, Tvarijonaviciute A, Escribá-Alepuz J, Sancho-Castillo S.** Role of haptoglobin as a marker of muscular improvement in patients with multiple sclerosis after administration of epigallocatechin gallate and increase of beta-hydroxybutyrate in the blood: A pilot study. *Biomolecules.*2021;11(5):617. doi:10.3390/biom11050617.

8. **Dote-Montero M, Carneiro-Barrera A, Martinez-Vizcaino V, Ruiz JR, Amaro-Gahete FJ.** Acute effect of HIIT on testosterone and cortisol levels in healthy individuals: a systematic review and meta-analysis. *Scand J Med Sci Sports.*2021;31:1722-1744. doi:10.1111/sms.13999.

9. **Gagnon DD, Dorman S, Ritchie S, Mutt SJ, Stenbäck V, Walkowiak J, Herzig K-H.** Multi-day prolonged low- to moderate-intensity endurance exercise mimics training improvements in metabolic and oxidative profiles without concurrent chromosomal changes in healthy adults. *Front Physiol.* 2019;10:1123. doi:10.3389/fphys.2019.01123.

10. **Gast LV, Baier L-M, Meixner CR, Chaudry O, Engelke K, Uder M, Nagel AM, Heiss R.** MRI of potassium and sodium enables comprehensive analysis of ion perturbations in skeletal muscle tissue after eccentric exercise. *Invest Radiol.* 2023;58(4):265–272. doi:10.1097/RLI.0000000000000931.

11. **Gejl KD, Andersson EP, Nielsen J, Holmberg H-C, Ørtenblad N.** Effects of acute exercise and training on the sarcoplasmic reticulum Ca2+ release and uptake rates in highly trained endurance athletes. *Front Physiol.* 2020;11:810. doi:10.3389/fphys.2020.00810.

12. **Hacker S, Keck J, Reichel T, Eder K, Ringseis R, Krüger K, Krüger B.** Biomarkers in endurance exercise: Individualized regulation and predictive value. *Transl Sports Med.* 2023;Article ID 6614990. doi:10.1155/2023/6614990.

13. **Haller N, Behringer M, Reichel T, Wahl P, Simon P, Krüger K, et al.** Blood-based biomarkers for managing workload in athletes: Considerations and recommendations for evidence-based use of established biomarkers. *Sports Med.*2023;53(10):1315–1333. doi:10.1007/s40279-023-01836-x.

14. **Haller N, Reichel T, Zimmer P, Behringer M, Wahl P, Stöggl T, Krüger K, Simon P.** Blood-based biomarkers for managing workload in athletes: perspectives for research on emerging biomarkers. *Sports Med.* 2023;53:2039–2053. doi:10.1007/s40279-023-01866-5.

15. **Luebbers PE, Kriley LM, Eserhaut DA, Andre MJ, Butler MS, Fry AC.** Salivary testosterone and cortisol responses to seven weeks of practical blood flow restriction training in collegiate American football players. *Front Physiol.* 2025;15:1507445. doi:10.3389/fphys.2024.1507445.

16. **Małkowska P, Sawczuk M.** Cytokines as biomarkers for evaluating physical exercise in trained and non-trained individuals: A narrative review. *Int J Mol Sci.* 2023;24(13):11156. doi:10.3390/ijms241311156.

17. **Meyer T, Meister S.** Routine blood parameters in elite soccer players. *Int J Sports Med.* 2011;32(11):875–81. doi:10.1055/s-0031-1280776. PMID:22020850.

18. **Michnik A, Sadowska-Krępa E, Domaszewski P, Duch K, Pokora I.** Blood serum DSC analysis of well-trained men response to CrossFit training and green tea extract supplementation. *J Therm Anal Calorim.* 2017;130(3):1253–62. doi:10.1007/s10973-017-6346-9.

19. **Nash D.** The IL-6 signalling pathway: potential biomarkers for training load, performance, and health status in endurance runners? *[Doctoral thesis]. Cardiff Metropolitan University*; 2023.

20. **Nielsen FH, Lukaski HC.** Update on the relationship between magnesium and exercise. *Magnes Res.* 2006;19(3):180–189.

21. **Nieman DC, Zwetsloot KA, Simonson AJ, Hoyle AT, Wang X, Nelson HK, Lefranc-Millot C, Guérin-Deremaux L.**Effects of whey and pea protein supplementation on post-eccentric exercise muscle damage: A randomized trial. *Nutrients.* 2020;12(8):2382. doi:10.3390/nu12082382.
22. **Płoszczyca K.** Wpływ treningu interwałowego o wysokiej intensywności w warunkach hipoksji normobarycznej na poziom wybranych hormonów oraz profil lipidowy u pływaków [rozprawa doktorska]. *Katowice: Akademia Wychowania Fizycznego im. Jerzego Kukuczki w Katowicach*; 2020.
23. **Salem A, Ben Maaoui K, Jahrami H, AlMarzooqi MA, Boukhris O, Messai B, et al.** Attenuating muscle damage biomarkers and muscle soreness after an exercise-induced muscle damage with branched-chain amino acid (BCAA) supplementation: A systematic review and meta-analysis with meta-regression. *Sports Med Open.* 2024;10:42. doi:10.1186/s40798-024-00686-9.
24. **Saw, A.E.; Main, L.C.; Gastin, P.B.** Monitoring the Athlete Training Response: Subjective Self-Reported Measures Trump Commonly Used Objective Measures: A Systematic Review. *Br. J. Sports Med.* 2016;50, 281-291.
25. **Sobiech KA.** Przydatność markerów biochemicznych w ocenie monitoringu wysiłku fizycznego. *Nowa Medycyna.*2000;12:1–7.
26. **Soler-López A, Moreno-Villanueva A, Gómez-Carmona CD, Pino-Ortega J.** The role of biomarkers in monitoring chronic fatigue among male professional team athletes: A systematic review. *Sensors.* 2024;24:6862. doi:10.3390/s24216862.
27. **Tsunekawa K, Shoho Y, Ushiki K, Yanagawa Y, Matsumoto R, Shimoda N, et al.** Assessment of exercise-induced stress via automated measurement of salivary cortisol concentrations and the testosterone-to-cortisol ratio: a preliminary study. *Sci Rep.* 2023;13:14532. doi:10.1038/s41598-023-41620-5.
28. **Ugwuja S, Obeagu EI, Ochei K.** Effect of physical exercises on serum electrolyte. *IOSR J Dent Med. Sci.*2014;13(9):118–121. doi:10.9790/0853-1392118121.
29. **Wiewelhove T, Raeder C, Meyer T, Kellmann M, Pfeiffer M, Ferrauti A.** Markers for routine assessment of fatigue and recovery in male and female team sport athletes during high-intensity interval training. *PLoS One.*2015;10(10):e0139801. doi:10.1371/journal.pone.0139801.
30. **Wochyński Z, Sobiech KA, Milnerowicz H, Nowak P.** Can metallothionein be considered a diagnostic marker in physical exercise? *Adv Clin Exp Med.* 2003;12(5):641–645.
31. **Wojtasik W, Szulc A, Kołodziejczyk M, Szulc A.** Wpływ wysiłku fizycznego na homeostazę i środowisko wewnętrzne organizmu człowieka. *J Educ Health Sport.* 2015;5(9):754-767. doi:10.5281/zenodo.44340.
32. **Yang R, Roshani D, Gao B, Li P, Shang N.** Metallothionein: A comprehensive review of its classification, structure, biological functions, and applications. *Antioxidants.* 2024;13(7):825. doi:10.3390/antiox13070825.