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Cortisol as a Blood Biomarker for Monitoring Endurance Training - A Narrative Review

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Abstract

Background. Blood cortisol is a key biomarker of hypothalamic-pituitary-adrenal (HPA) axis activity and is widely used in sports science to assess physiological and psychological stress. However, its interpretation is limited by considerable biological variability and multiple influencing factors.

Aim. To summarize current evidence on the physiological role of blood cortisol in endurance exercise and its usefulness for monitoring training load, recovery, and adaptation.

Material and methods. A narrative review of peer-reviewed studies, systematic reviews, meta-analyses, and guidelines on cortisol physiology, exercise endocrinology, and athlete monitoring was conducted.

Results. Blood cortisol reflects the physiological stress response and supports metabolic and immune regulation during endurance exercise. Acute increases are a normal adaptive response, whereas persistent alterations may indicate excessive training stress when interpreted in context. Due to circadian variation and other confounding factors, single measurements have limited value. Current evidence favors longitudinal within-athlete monitoring combined with physiological, psychometric, hormonal, and performance measures.

Conclusions. Blood cortisol is a useful component of endurance athlete monitoring but should not be used as a stand-alone marker. Its greatest value lies in repeated standardized assessments interpreted within a multimodal monitoring approach.

Key words: cortisol, endurance training, exercise physiology, training monitoring, training load, physiological stress, overtraining syndrome, athlete monitoring, Hypothalamic-Pituitary-Adrenal Axis

1. Introduction

Optimal training adaptation in endurance sports requires a careful balance between training stimulus and recovery. While appropriately prescribed training loads promote physiological

adaptations and performance improvements, excessive or poorly managed training stress may result in maladaptation, excessive fatigue, impaired performance, and, in severe cases, overtraining syndrome (1, 2). Consequently, the monitoring of training load and athlete responses has become an essential component of contemporary sports science and athlete management (2).

Traditionally, athlete monitoring has relied on external and internal load measures, including training volume, exercise intensity, heart rate, perceived exertion, and performance-based assessments (2). However, these approaches may not fully capture the complex physiological processes underlying adaptation to training. Increasing attention has therefore been directed toward biological markers that provide additional physiological information regarding stress, adaptation, recovery status, and athlete health (3). Recent evidence from athletic populations, particularly team-sport athletes, suggests that biomarkers may support the monitoring of chronic fatigue and training-related stress when interpreted alongside physiological and performance measures (4).

Among the various biomarkers investigated in sports science, cortisol has received considerable attention because it represents the primary endocrine effector of HPA-axis activation in response to physiological and psychological stress (5). Cortisol is the primary glucocorticoid hormone released through activation of the hypothalamic-pituitary-adrenal (HPA) axis and contributes to the regulation of energy metabolism, immune function, and adaptation to physical stressors (5). During endurance exercise, elevations in cortisol facilitate glucose availability, mobilization of energy substrates, and modulation of inflammatory processes (6). The relationship between exercise and cortisol regulation has been extensively investigated in both acute and chronic training settings, with responses being heavily influenced by exercise intensity, duration, training status, and recovery conditions (6). In addition, cortisol exhibits a pronounced circadian rhythm that should be considered when interpreting exercise-related hormonal responses (7).

Particular interest has been directed toward the potential role of cortisol in identifying excessive training stress, functional overreaching, and overtraining syndrome. However, no single biomarker currently provides sufficient sensitivity and specificity for the diagnosis of overtraining syndrome (1). Consequently, cortisol should be interpreted within a broader physiological context and in combination with other markers of training adaptation and recovery (1, 3). To this end, cortisol has been assessed using several biological matrices,

including blood, saliva, urine, and hair, each providing different information regarding hypothalamic-pituitary-adrenal (HPA) axis activity and stress exposure (8, 9). Among these methods, blood-based assessment, typically performed using serum or plasma samples, remains widely used in both clinical endocrinology and exercise physiology because it reflects circulating cortisol concentrations and serves as a common reference measure when evaluating alternative biological matrices (3, 9). However, despite the widespread use of cortisol measurements in sports science, the interpretation of blood cortisol concentrations remains challenging. Cortisol responses are influenced by numerous biological and methodological factors, including circadian variation, nutritional status, psychological stress, recovery conditions, analytical methods, and individual variability (3, 7, 9). Consequently, the practical value of blood cortisol as a biomarker for monitoring training load, recovery, and physiological adaptation in endurance athletes remains a subject of ongoing investigation. Therefore, the aim of this narrative review is to examine the physiological role of cortisol in exercise, summarize current evidence regarding acute and chronic cortisol responses to endurance training, discuss methodological considerations related to cortisol assessment, and evaluate the potential utility of blood cortisol as a biomarker for monitoring training load, recovery, and physiological adaptation in endurance athletes.

2. Research materials and methods

This work was carried out as a narrative literature review aimed at synthesizing the current scientific evidence regarding the use of cortisol for monitoring endurance training. A literature research was conducted using PubMed, Scopus, Google Scholar and MEDLINE. The search strategy employed combinations of the following keywords: “cortisol,” “endurance training,” “training load,” “overtraining syndrome,” “exercise physiology” and “Hypothalamic-Pituitary-Adrenal Axis”. In total, 61 articles were included in the analysis. Only English-language studies relevant to the topic were considered. Preference was given to recent review papers, clinical research studies, and international guidelines to ensure the inclusion of up-to-date and evidence-based information.

2.1. AI Statement

AI-assisted tools were used exclusively for linguistic refinement and structural editing of the manuscript. The authors have reviewed and edited the content as needed and take full responsibility for the scientific content, interpretation of the data, and final version of the manuscript.

3. Research results

3.1 Physiological Role of Cortisol in Exercise

3.1.1. Regulation of Cortisol Secretion

Cortisol is the principal glucocorticoid hormone in humans and plays a central role in the physiological response to physical and psychological stress. Its secretion is regulated by the hypothalamic-pituitary-adrenal (HPA) axis, a neuroendocrine system responsible for maintaining homeostasis and coordinating adaptive responses to internal and external stressors (5, 10). Activation of the HPA axis begins with the release of corticotropin-releasing hormone (CRH) from the hypothalamus, which stimulates the anterior pituitary gland to secrete adrenocorticotropic hormone (ACTH). ACTH subsequently promotes cortisol synthesis and release from the adrenal cortex. Circulating cortisol exerts negative feedback on both the hypothalamus and pituitary gland, thereby regulating further hormone secretion and maintaining endocrine balance (9, 10). This feedback is primarily mediated through glucocorticoid and mineralocorticoid receptors located in the hypothalamus, pituitary gland, and other brain regions involved in stress regulation, thereby preventing excessive activation of the HPA axis (10).

Cortisol secretion is characterized by a pronounced circadian rhythm, which represents one of the most important determinants of circulating cortisol concentrations. In addition to this circadian pattern, cortisol is secreted in an ultradian pulsatile manner throughout the day, resulting in short-term fluctuations in circulating concentrations that may affect measured values depending on the timing of sample collection (9). These fluctuations contribute to biological variability and should be considered when interpreting single cortisol measurements. Under normal physiological conditions, cortisol levels rise rapidly during the early morning hours, reaching peak concentrations shortly after awakening, and gradually decline throughout the day to reach their lowest levels during the late evening and early stages of sleep (9, 11). This diurnal variation is closely linked to the body's circadian timing system and plays an important role in regulating metabolism, energy availability, time-dependent immune functions, and physiological readiness for daily activities (11). Consequently, the timing of biological sample collection is a critical consideration when interpreting cortisol measurements in both research and applied sports settings (7, 9).

In addition to circadian regulation, cortisol secretion is highly responsive to physical stress. Exercise represents a potent activator of the HPA axis, particularly when characterized by high intensity, prolonged duration, or substantial metabolic demand (5, 6). During exercise, activation of the HPA axis stimulates cortisol release, contributing to the maintenance of energy homeostasis and facilitating adaptation to the increased metabolic demands imposed by physical activity. The magnitude of the cortisol response depends on multiple factors, including exercise intensity, duration, training status, and individual physiological characteristics (6, 12). Evidence suggests that cortisol concentrations increase substantially once exercise exceeds a certain physiological threshold, often reported at intensities exceeding approximately 60-70% of maximal aerobic capacity (VO_2max) or during prolonged exercise bouts. This threshold phenomenon reflects progressive activation of the HPA axis in response to increasing metabolic and physiological stress (5, 12).

The activation of the HPA axis during exercise is generally considered an adaptive response that facilitates the mobilization of energy substrates and supports recovery processes following physical exertion. However, repeated or prolonged activation associated with excessive training stress may alter normal endocrine regulation and contribute to maladaptation to training if adequate recovery is not achieved (5). Therefore, understanding the physiological mechanisms regulating cortisol secretion is essential for interpreting cortisol responses in the context of endurance training and athlete monitoring.

3.1.2. Metabolic and Immunological Functions of Cortisol During Exercise

Cortisol plays a crucial role in maintaining metabolic homeostasis during exercise by coordinating the mobilization and utilization of energy substrates in response to increased physiological demands. As a catabolic hormone, cortisol promotes the availability of metabolic fuels required to sustain prolonged physical activity, particularly during endurance exercise when energy requirements are substantially elevated (5, 6). The metabolic actions of cortisol become especially important during periods of prolonged exercise, energy deficit, or glycogen depletion, when the maintenance of adequate substrate availability is essential for continued performance.

One of the primary metabolic functions of cortisol is the regulation of carbohydrate metabolism. Cortisol stimulates hepatic gluconeogenesis and inhibits glucose uptake in non-exercising, insulin-sensitive peripheral tissues, thereby preserving blood glucose concentrations during

prolonged exercise (5, 13). By increasing hepatic glucose production and maintaining circulating glucose availability, cortisol helps preserve substrate supply for exercising skeletal muscles and supports central nervous system function during prolonged physical activity (5, 6). Elevated cortisol concentrations during endurance exercise are therefore considered an important component of the hormonal response aimed at maintaining glucose homeostasis (6).

In addition to its effects on carbohydrate metabolism, cortisol facilitates lipolysis and the mobilization of free fatty acids from adipose tissue. Although catecholamines constitute the primary acute stimulators of exercise-induced lipolysis, cortisol exerts a permissive effect by enhancing adipose tissue responsiveness to lipolytic stimuli (5, 14). The increased availability of circulating fatty acids provides an alternative energy source for skeletal muscles and may contribute to a reduced reliance on carbohydrate oxidation during prolonged exercise (5, 6). Cortisol also promotes protein catabolism, particularly within skeletal muscle, thereby increasing the release of amino acids that can serve as precursors for hepatic gluconeogenesis and other metabolic pathways involved in maintaining energy balance (5, 14).

Cortisol secretion typically increases as exercise duration extends and glycogen availability declines, highlighting its role in maintaining metabolic homeostasis during prolonged physical activity (5, 6). Together, these actions help maintain substrate availability and energy homeostasis during prolonged endurance exercise. Through the coordinated regulation of carbohydrate, lipid, and protein metabolism, cortisol supports the organism's ability to meet the energetic demands associated with prolonged physical activity. Consequently, exercise-induced elevations in cortisol should not be viewed solely as indicators of physiological stress but also as important adaptive mechanisms that facilitate metabolic regulation and performance maintenance during exercise (5, 6).

Beyond its metabolic functions, cortisol exerts profound effects on the immune system. Glucocorticoids are recognized as key regulators of immune and inflammatory processes, acting through glucocorticoid receptors expressed in numerous immune cell populations (15). Cortisol modulates both innate and adaptive immune responses by influencing leukocyte trafficking, cytokine production, and immune cell activation. These actions contribute to the regulation of inflammation and help prevent excessive immune activation following physiological stressors such as exercise (11, 15).

Acute increases in cortisol occurring during and immediately after exercise are fundamentally adaptive, serving to resolve exercise-induced microtrauma and subsequent inflammation while supporting tissue recovery processes (16). However, prolonged or repeated elevations in cortisol associated with excessive training stress, insufficient recovery, or chronic energy deficiency can adversely affect immune function. Sustained exposure to elevated glucocorticoid concentrations has been associated with impaired immune surveillance, altered cytokine responses, and an increased susceptibility to illness, particularly in athletes exposed to high training loads (15, 17, 18).

The interaction between the endocrine and immune systems is therefore essential for understanding the physiological significance of cortisol during exercise. While acute cortisol responses represent an adaptive mechanism that supports both metabolic regulation and immune control, chronic disturbances in cortisol regulation play a role in maladaptation, impaired recovery, and increased health risks in athletes. These considerations are particularly relevant when evaluating cortisol as a potential biomarker of training stress and physiological adaptation in endurance sports. Because cortisol integrates metabolic, endocrine, and immunological responses to exercise stress, alterations in circulating cortisol concentrations have been proposed as a potential indicator of training load, recovery status, and physiological adaptation in endurance athletes.

3.2 Acute and Chronic Cortisol Responses to Endurance Exercise

3.2.1 Acute Cortisol Responses to Single Exercise Sessions

During endurance exercise, activation of the hypothalamic-pituitary-adrenal (HPA) axis increases cortisol secretion to support energy metabolism and maintain homeostasis (19).

Exercise intensity and duration are major determinants of acute cortisol responses. Short-duration, low-intensity exercise produces minimal hormonal changes, whereas exercise exceeding approximately 60-80% of VO_2max or lasting longer than 60 minutes significantly elevates cortisol concentrations (12, 19). Prolonged events such as marathons and ultramarathons induce particularly large increases due to high metabolic demands (19).

Continuous moderate-intensity exercise generally results in a gradual rise in cortisol levels (20). In contrast, high-intensity interval training (HIIT) often produces a more rapid and pronounced

response because of greater metabolic and physiological stress despite shorter exercise duration (21).

Cortisol concentrations typically peak immediately after exercise or during the early recovery period and gradually return to baseline levels (22). Delayed normalization may indicate insufficient recovery, excessive training stress, or inadequate energy intake (23).

3.2.2. Chronic Adaptations of Cortisol to Endurance Training

Repeated exposure to endurance training induces adaptations within the hypothalamic-pituitary-adrenal (HPA) axis that modify cortisol responses to exercise (5, 19, 26). In well-trained athletes, endocrine adaptations generally improve the efficiency of the stress response, allowing similar exercise tasks to be performed with a reduced cortisol response compared with untrained individuals (5, 28). Consequently, trained athletes often exhibit smaller cortisol responses when performing the same absolute exercise workload, reflecting improved metabolic, cardiovascular, and neuromuscular efficiency. However, when exercise is performed at the same relative intensity, cortisol responses are generally more comparable between trained and untrained individuals (19, 28).

The effects of long-term endurance training on resting cortisol concentrations remain inconsistent. While some studies report lower basal cortisol concentrations in well-trained athletes, others demonstrate no significant changes or even modest increases during periods of intensified training (5, 19). These discrepancies are likely explained by differences in training load, recovery status, nutritional factors, and methodological approaches used for cortisol assessment. Consequently, resting cortisol alone appears to have limited value as an isolated marker of training adaptation (1, 3).

Adaptation of the HPA axis should therefore be viewed as a dynamic process rather than a simple reduction in cortisol secretion. Well-trained athletes typically demonstrate more consistent endocrine responses, faster post-exercise recovery, and more efficient regulation of endocrine responses following repeated exercise bouts (5, 19, 28). Conversely, chronically elevated resting cortisol concentrations or persistently exaggerated cortisol responses may indicate excessive training stress, inadequate recovery, or maladaptation to training and should be interpreted alongside physiological, performance, and perceptual monitoring variables rather than in isolation (1-3).

3.2.3 Factors Influencing Cortisol Responses

Cortisol responses to endurance exercise are influenced by numerous biological, environmental, and methodological factors that should be considered when interpreting hormonal measurements. One of the most important determinants is the time of day, as cortisol follows a pronounced circadian rhythm characterized by peak concentrations in the early morning and progressively declining levels throughout the day (7, 24). Consequently, comparisons between studies or repeated assessments within athletes require standardized sampling times.

Recovery status and sleep quality also substantially influence cortisol regulation. Sleep restriction, inadequate recovery, and accumulated training stress have been associated with elevated basal cortisol concentrations, impaired endocrine recovery, and reduced capacity to adapt to subsequent training sessions (25). Similarly, nutritional status plays a critical role in modulating cortisol responses. Low muscle glycogen stores, restricted energy availability, or prolonged fasting augment cortisol secretion during exercise in order to maintain blood glucose concentrations by increasing gluconeogenesis and substrate mobilization (5, 13, 26).

Environmental and psychological stressors further contribute to variability in cortisol responses. Dehydration, particularly during prolonged exercise performed in hot environments, increases physiological strain and may augment cortisol concentrations (27). In addition, psychological stress, competition anxiety, travel, and disturbances in normal daily routines may activate the HPA axis independently of physical exercise, thereby complicating the interpretation of cortisol as a marker of training stress (1, 24). Finally, biological sex and hormonal status should also be considered, as menstrual cycle phase and oral contraceptive use may influence circulating cortisol concentrations and should be accounted for when interpreting hormonal responses in female athletes (29).

Considerable inter-individual variability in cortisol responses exists even among athletes exposed to similar training stimuli, highlighting the importance of longitudinal within-athlete monitoring rather than reliance on population-based reference values (2, 3, 38)

Table 1. Major factors influencing blood cortisol responses and considerations for their interpretation in endurance athletes.

Factor	Effect on Blood Cortisol	Practical Consideration
Circadian rhythm	Highest concentrations occur in the early morning and decline throughout the day	Standardize sampling time for repeated measurements
Exercise intensity	Higher exercise intensity elicits greater cortisol responses	Compare athletes under similar exercise intensities
Exercise duration	Prolonged exercise results in greater cortisol secretion	Consider exercise duration when interpreting results
Recovery status and sleep	Sleep restriction and inadequate recovery may elevate basal cortisol concentrations	Assess sleep quality and recovery before sampling
Nutritional status	Low glycogen availability, fasting, or low energy availability augment cortisol secretion	Standardize nutritional conditions before testing
Psychological stress	Psychological stress independently activates the HPA axis	Consider non-training stressors during interpretation
Hydration status	Dehydration may enhance cortisol responses during prolonged exercise	Ensure consistent hydration status
Sex and hormonal status	Menstrual cycle phase and oral contraceptive use may influence cortisol concentrations	Account for hormonal status in female athletes
Inter-individual variability	Considerable variability exists between athletes	Prefer longitudinal within-athlete monitoring over population reference values

Abbreviations: HPA, hypothalamic-pituitary-adrenal.

3.2.4 Sex-Related Differences in Cortisol Responses

Men often show greater absolute cortisol responses to exercise than women, although relative responses are frequently similar when exercise intensity is standardized (26). Hormonal fluctuations during the menstrual cycle may affect cortisol responses, with some evidence suggesting higher responses during the luteal phase (28). Oral contraceptive use may increase total cortisol concentrations due to elevated corticosteroid-binding globulin levels, which should be considered when interpreting hormonal measurements in female athletes (29).

3.3. Methodological Considerations in Cortisol Assessment

3.3.1. Biological Matrices for Cortisol Measurement

Cortisol can be measured in multiple biological matrices, each reflecting different aspects of hypothalamic-pituitary-adrenal (HPA) axis activity and differing in temporal resolution and physiological interpretation (24).

- **Blood cortisol (serum or plasma)** is considered a reference method for assessing total circulating cortisol and includes both free and protein-bound fractions (14). However, blood sampling is invasive and may itself induce a stress response that can confound measurement of acute exercise-induced hormonal changes (30).
- **Salivary cortisol** reflects the biologically active free fraction of cortisol and is widely used in exercise physiology due to its non-invasive nature and suitability for repeated sampling (29). Nevertheless, salivary measurements may be influenced by oral health status and sample contamination, which should be controlled in experimental protocols (29).
- **Urinary cortisol** provides an integrated measure of cortisol secretion over time and is useful for assessing overall HPA axis activity rather than acute responses (31). However, urinary output is influenced by hydration status and sampling methodology, which limits temporal resolution (31).
- **Hair cortisol** represents long-term systemic cortisol exposure over weeks to months and is increasingly used as a marker of chronic stress and training load. Despite its

utility, hair cortisol is sensitive to cosmetic treatments, hair growth rate, and environmental factors (32).

Table 2. Comparison of biological matrices used for cortisol assessment in athlete monitoring.

Matrix	Physiological relevance	Advantages	Limitations
Blood (Serum/Plasma)	Total circulating cortisol (free + bound)	Reference method, well-established clinical standard	Invasive; venipuncture may itself induce an acute stress response
Saliva	Biologically active free cortisol fraction	Non-invasive, stress-free, easy repeated sampling, reflects free biologically active cortisol	Influenced by oral health and food/drink contamination
Urine	Integrated cortisol secretion over several hours	Reflects long-term HPA activity, no acute spikes	Dependent on hydration status and renal clearance
Hair	Long-term systemic cortisol exposure (weeks to months)	Excellent retrospective marker of training load	Sensitive to cosmetic treatments and hair growth rate

Although cortisol can be measured in saliva, urine, and hair, blood cortisol remains the most widely used and clinically established matrix for assessing acute endocrine responses in exercise settings (14).

3.3.2. Analytical Methods

Several analytical techniques are used for cortisol quantification, differing in sensitivity, specificity, and practical application (33).

- **Immunoassays**, including general antibody-based methods, are widely used due to their accessibility and relatively low cost, but they may be affected by cross-reactivity with structurally similar steroids (33).
- **ELISA (enzyme-linked immunosorbent assay)** is a common immunoassay used in exercise physiology research and allows high-throughput analysis, although its specificity is lower than that of mass spectrometry-based methods (33).

- **Chemiluminescence immunoassays** offer improved sensitivity and automation, making them suitable for clinical laboratory use and routine cortisol assessment (34).
- **LC-MS/MS (liquid chromatography-tandem mass spectrometry)** is considered the gold standard due to its superior specificity and ability to distinguish cortisol from structurally related compounds (35).

Therefore, the analytical method used for cortisol quantification should be carefully considered when comparing findings across different studies, as methodological differences appear to substantially contribute to between-study variability (33, 35).

3.3.3 Sources of Measurement Variability

Cortisol measurements are influenced by multiple biological and methodological factors that must be considered when interpreting results (24).

- Cortisol follows a strong ***circadian rhythm*** characterized by peak concentrations in the early morning and a gradual decline throughout the day (24).
- **Sampling timing** relative to exercise or stress exposure is critical, as cortisol responses are highly time-dependent and dynamic (24).
- **Pre-analytical factors,** including sample handling, storage conditions, and processing protocols, may significantly affect measured cortisol concentrations (33).
- **Intra-individual variability** is also substantial and reflects day-to-day fluctuations influenced by sleep, nutrition, psychological stress, and training load (30).

3.4. Practical Applications of Cortisol Monitoring in Endurance Training

3.4.1. Monitoring Internal Training Load

Exercise activates the hypothalamic-pituitary-adrenal (HPA) axis, leading to increased cortisol secretion, which supports energy mobilization and metabolic homeostasis during prolonged effort (36). The magnitude of the cortisol response depends primarily on exercise intensity and duration, with prolonged and high-intensity sessions generally eliciting the greatest increases (12). Consequently, serial cortisol measurements may help identify the individual physiological cost of training that is not fully reflected by external load metrics such as distance, pace, or power output (19). Because cortisol is strongly influenced by circadian rhythms, nutrition,

sleep, and psychological stress, repeated measurements under standardized conditions are recommended (1).

3.4.2. Assessment of Recovery Status

The return of cortisol concentrations to baseline after exercise reflects recovery of physiological homeostasis. Prolonged alterations in cortisol responses following repeated exercise bouts may reflect inadequate recovery and cumulative physiological stress (37). Chronic elevations in resting cortisol have been associated with fatigue, insufficient recovery, low energy availability, and impaired performance (2). However, single measurements provide limited information, and monitoring trends over time is generally more informative than isolated values. Combining cortisol assessment with measures such as heart rate variability, sleep quality, subjective fatigue, and performance testing provides a more comprehensive evaluation of recovery status (38).

3.4.3 Cortisol Responses in Functional Overreaching and Overtraining

Functional overreaching is characterized by temporary performance decline followed by supercompensation after recovery, whereas non-functional overreaching and overtraining syndrome involve prolonged maladaptation and impaired performance (19). Disturbances in HPA axis activity are considered one of the mechanisms underlying these conditions. However, studies have reported inconsistent findings, including elevated, reduced, or unchanged cortisol concentrations in overtrained athletes (39, 40). Similar discrepancies have been observed in exercise-induced cortisol responses. These inconsistencies limit the diagnostic value of cortisol as an isolated biomarker. Cortisol concentrations are influenced by numerous non-training factors, including psychological stress, sleep disturbances, and nutritional status (1). Therefore, current evidence supports the use of cortisol as part of a multidimensional monitoring strategy rather than as a standalone diagnostic tool. Interpretation alongside hormonal, physiological, performance, and perceptual markers may improve the detection of maladaptation and excessive training stress (38, 40).

3.4.4 Individualization of Training Programs

Interindividual variability in hormonal responses to exercise has highlighted the potential value of cortisol monitoring for the individualization of endurance training programs. Athletes exposed to identical external training loads may demonstrate markedly different cortisol

responses due to differences in fitness level, training history, recovery capacity, nutritional status, and psychological stress (36, 19). The use of individual hormonal profiles may therefore improve the personalization of training loads by identifying athletes who exhibit excessive physiological strain in response to a given workload. Persistently elevated cortisol concentrations or delayed post-exercise recovery may indicate the need for additional recovery strategies or temporary reductions in training volume or intensity (1). Conversely, stable cortisol profiles accompanied by positive performance adaptations may suggest an adequate balance between training stress and recovery. Monitoring longitudinal trends rather than isolated measurements allows practitioners to establish individual reference ranges and improve the interpretation of endocrine responses over time (2). Nevertheless, cortisol should be considered as one component of a broader athlete monitoring framework. Integrating hormonal data with performance measures, heart rate variability, subjective wellness questionnaires, and training load metrics may provide a more comprehensive basis for individualized training prescription and optimization of endurance performance (1, 38).

Taken together, the available evidence suggests that the greatest practical value of cortisol lies in repeated longitudinal assessments interpreted alongside physiological, performance, and perceptual measures rather than in isolated measurements (1-3, 38).

3.5. Cortisol within a Multimodal Athlete Monitoring Framework

Blood cortisol provides valuable information regarding activation of the hypothalamic-pituitary-adrenal (HPA) axis and the endocrine response to training stress. However, because cortisol is influenced by numerous physiological and psychological factors, its interpretation is limited when considered in isolation (7). Current evidence suggests that cortisol is most informative when incorporated into a multidimensional monitoring strategy combining hormonal, physiological, psychometric, and performance-related measures (2, 41). Such an integrated approach improves the ability to distinguish adaptive responses to endurance training from maladaptation, non-functional overreaching, and overtraining syndrome.

3.5.1 Testosterone-to-Cortisol Ratio

Among endocrine markers, the testosterone-to-cortisol (T/C) ratio has been extensively investigated as an indicator of the balance between anabolic and catabolic processes (4). Whereas testosterone promotes protein synthesis and recovery, cortisol reflects metabolic stress

and substrate mobilization. Consequently, changes in the T/C ratio may provide greater insight into training adaptation than either hormone alone (42).

Longitudinal reductions in the T/C ratio have been associated with accumulated fatigue, non-functional overreaching, and an increased risk of overtraining, although considerable inter-individual variability limits the use of universal threshold values (1). Rather than relying on absolute cut-offs, repeated within-athlete measurements appear to offer greater practical value for monitoring endocrine responses throughout a training season (43).

3.5.2. Integration with Other Monitoring Measures

Although no universally accepted multimodal monitoring model exists, accumulating evidence suggests that combining cortisol with physiological, psychometric, and performance-based measures provides a more comprehensive assessment of training adaptation than endocrine markers alone (2, 38, 44). Heart rate variability (HRV), resting heart rate, session rating of perceived exertion (sRPE), and wellness questionnaires provide complementary information regarding acute training stress and recovery status.

Elevated cortisol occurring together with unfavorable changes in HRV, subjective fatigue and performance may indicate inadequate recovery or excessive training stress (2, 38). Conversely, transient increases in cortisol occurring alongside stable performance and preserved autonomic function are generally considered consistent with normal adaptive responses to intensified training. This multidimensional interpretation reduces the likelihood of misclassifying normal physiological adaptation as maladaptation (1, 45).

3.5.3. Relationship with Performance

Ultimately, the usefulness of cortisol as a biomarker depends on its relationship with functional performance outcomes. Measures such as time-trial performance, running economy, power output, lactate threshold, and neuromuscular performance provide important context for interpreting endocrine responses (1, 2). Elevated cortisol without deterioration in performance may simply reflect an appropriate response to increased training load, whereas persistent elevations accompanied by declining performance are more consistent with maladaptation or insufficient recovery (1).

Despite these potential applications, several limitations restrict the use of cortisol as a stand-alone marker of training adaptation. Baseline concentrations vary substantially between individuals, necessitating longitudinal within-athlete monitoring rather than comparison with population reference values (43). Furthermore, cortisol secretion is influenced by circadian

rhythm, nutritional status, sleep quality, psychological stress, illness, and recent exercise, all of which may confound interpretation. Standardization of blood sampling protocols, including sampling time, fasting status, and recovery from recent exercise, is therefore essential (45).

In addition, no universally accepted cortisol threshold exists for identifying non-functional overreaching or overtraining syndrome (1, 46). Evidence consistently indicates that isolated cortisol measurements have limited diagnostic value, whereas repeated assessments interpreted alongside complementary physiological and performance measures provide substantially greater clinical and practical utility (1, 47).

In contemporary athlete monitoring, blood cortisol is increasingly viewed as one component of an integrated monitoring framework. Rather than serving as a daily readiness marker, periodic cortisol assessment may provide information regarding cumulative endocrine stress, particularly when interpreted alongside autonomic, psychometric, and performance-based indicators (2, 44). This multidimensional approach acknowledges that adaptation to endurance training results from the interaction of biological, mechanical, and psychological stressors rather than any single biomarker (48).

Table 3. Practical interpretation of blood cortisol measurements within a multimodal athlete monitoring framework.

Blood cortisol finding	**Possible interpretation**	**Recommended practical approach**
Acute post-exercise cortisol increase	Normal physiological response to exercise-induced HPA axis activation	No intervention if recovery and performance remain normal
Chronically elevated resting cortisol	Possible accumulated training stress, insufficient recovery, or low energy availability	Evaluate recent training load, recovery, nutrition, and sleep
Delayed return toward baseline following exercise	Possible inadequate recovery or cumulative physiological stress	Consider recovery optimization and temporary training adjustment

Elevated cortisol with stable performance and recovery markers	Likely normal adaptation to increased training load	Continue monitoring using longitudinal measurements
Elevated cortisol accompanied by reduced HRV, increased fatigue, or declining performance	Increased likelihood of maladaptation or excessive training stress	Perform comprehensive multidimensional athlete assessment
Isolated abnormal cortisol measurement	Limited diagnostic value because of biological and methodological variability	Repeat measurement under standardized conditions and interpret together with complementary monitoring measures

3.6. Future Perspectives

3.6.1. Development of Cortisol Monitoring Technologies

Recent technological advances are expanding the possibilities for cortisol monitoring by complementing conventional laboratory-based blood analysis with rapid point-of-care testing and emerging biosensor technologies. (49). Point-of-care testing platforms have the potential to provide rapid cortisol measurements with minimal sample processing, enabling more timely assessment of endocrine responses in both training and competition environments (50). In parallel, the development of minimally invasive biosensors capable of continuous or near-continuous biomarker monitoring represents a promising area of research (49, 51). Although most wearable cortisol sensors currently assess cortisol in alternative biological matrices such as sweat or interstitial fluid and require further validation before widespread implementation in sport, these technologies may ultimately complement conventional blood-based assessments by providing continuous information on physiological stress (51). The integration of hormonal monitoring with wearable technologies could facilitate more frequent data collection and improve the practicality of longitudinal athlete monitoring (51).

3.6.2 Personalized Monitoring of Athletes

Future athlete monitoring is expected to increasingly adopt individualized approaches that prioritize longitudinal within-athlete assessment over comparisons with population-based reference values (52). Considerable inter-individual variability exists in basal cortisol concentrations and endocrine responses to exercise, limiting the usefulness of universal reference values (52, 53). Consequently, establishing individual hormonal profiles and monitoring longitudinal changes over time may provide a more accurate representation of an athlete's adaptation to training (52, 54). Evaluating trends in cortisol concentrations across different training phases, rather than relying on isolated measurements, may improve the early identification of excessive physiological stress, insufficient recovery, or maladaptation (53). Incorporating individualized hormonal data into training prescription may also support more precise adjustment of training loads and recovery strategies according to each athlete's physiological responses (54, 55).

3.6.3. Integration of Cortisol with Multimodal Monitoring Systems

The future of athlete monitoring is likely to move beyond the interpretation of individual biomarkers toward comprehensive, multimodal assessment frameworks (56). Within these systems, cortisol should be interpreted alongside complementary endocrine and biochemical markers, including testosterone and inflammatory biomarkers, as well as physiological and performance variables such as heart rate variability, sleep quality, internal and external training load, neuromuscular function, and endurance performance metrics (57, 58). Integrating these diverse data streams may provide a more comprehensive understanding of an athlete's adaptive state than any single measurement alone (56, 58).

Advances in artificial intelligence and predictive analytics are expected to further enhance the interpretation of complex longitudinal datasets (59). Machine learning algorithms may identify individualized response patterns, detect subtle changes that precede performance decline or non-functional overreaching, and support evidence-based decision-making regarding training and recovery (60). As computational methods continue to develop, athlete monitoring is likely to evolve from reliance on isolated biomarkers toward personalized biomarker panels integrated with physiological, performance, and behavioral data (61).

Within this multidimensional framework, blood cortisol is likely to remain an important indicator of endocrine stress. However, its greatest value will be realized when interpreted

longitudinally and integrated with complementary physiological, biochemical, psychometric, and performance measures to support individualized training and recovery decisions (47, 61).

5. Conclusions

Blood cortisol remains one of the most extensively investigated endocrine biomarkers in exercise physiology and provides valuable insight into activation of the hypothalamic-pituitary-adrenal (HPA) axis during endurance training. The available evidence indicates that acute increases in cortisol represent a normal physiological response that supports energy metabolism, maintenance of homeostasis, and adaptation to the metabolic demands of prolonged exercise. However, chronic alterations in cortisol regulation may reflect excessive training stress, insufficient recovery, or maladaptation when interpreted within the broader physiological context.

Despite its physiological relevance, blood cortisol has important limitations as an isolated biomarker. Its concentration is influenced by numerous biological and methodological factors, including circadian rhythm, nutritional status, sleep quality, psychological stress, recent exercise, and considerable inter-individual variability. Consequently, standardized sampling procedures and longitudinal within-athlete monitoring are essential to improve the reliability and clinical interpretation of cortisol measurements.

Current evidence does not support the use of blood cortisol as a stand-alone diagnostic marker of functional overreaching, non-functional overreaching, or overtraining syndrome. Instead, its greatest practical value lies in repeated assessments interpreted alongside complementary physiological, psychometric, hormonal, and performance-related measures. Integration of cortisol into a multimodal athlete monitoring framework provides a more comprehensive understanding of training adaptation, recovery status, and cumulative physiological stress than any single biomarker alone.

Overall, blood cortisol should be considered a valuable component of individualized athlete monitoring rather than a definitive indicator of training status. When assessed under standardized conditions and interpreted within a multidimensional framework, cortisol may contribute to optimizing training prescription, supporting recovery strategies, and improving the long-term management of endurance athletes.

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Supplementary Materials

Not applicable.

Author Contributions

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Software: AK;

Check: NS, AD and DT;

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Conflicts of Interest

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References:

1. Meeusen R, Duclos M, Foster C, et al. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc*. 2013;45(1):186-205. https://doi.org/10.1249/MSS.0b013e318279a10a

2. Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med*. 2014;44 Suppl 2(Suppl 2):S139-S147.https://doi.org/10.1007/s40279-014-0253-z

3. Lee EC, Fragala MS, Kavouras SA, Queen RM, Pryor JL, Casa DJ. Biomarkers in Sports and Exercise: Tracking Health, Performance, and Recovery in Athletes. *J Strength Cond Res*. 2017;31(10):2920-2937. https://doi.org/10.1519/JSC.0000000000002122

4. 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(21):6862. https://doi.org/10.3390/s24216862

5. Hackney AC, Walz EA. Hormonal adaptation and the stress of exercise training: the role of glucocorticoids. *Trends Sport Sci*. 2013;20(4):165-171. https://pmc.ncbi.nlm.nih.gov/articles/PMC5988244/

6. Popovic B, Popovic D, Macut D, et al. Acute Response to Endurance Exercise Stress: Focus on Catabolic/anabolic Interplay Between Cortisol, Testosterone, and Sex Hormone Binding Globulin in Professional Athletes. *J Med Biochem*. 2019;38(1):6-12. Published 2019 Mar 1. https://doi.org/10.2478/jomb-2018-0016

7. Anderson T, Wideman L. Exercise and the Cortisol Awakening Response: A Systematic Review. *Sports Med Open*. 2017;3(1):37. Published 2017 Oct 10. https://doi.org/10.1186/s40798-017-0102-3

8. Wright KD, Hickman R, Laudenslager ML. Hair Cortisol Analysis: A Promising Biomarker of HPA Activation in Older Adults. *Gerontologist*. 2015;55 Suppl 1(Suppl 1):S140-S145. https://doi.org/10.1093/geront/gnu174

9. Choi MH. Clinical and Technical Aspects in Free Cortisol Measurement. *Endocrinol Metab (Seoul)*. 2022;37(4):599-607. https://doi.org/10.3803/EnM.2022.1549

10. Herman JP, McKlveen JM, Ghosal S, et al. Regulation of the Hypothalamic-Pituitary-Adrenocortical Stress Response. *Compr Physiol*. 2016;6(2):603-621. Published 2016 Mar 15. https://doi.org/10.1002/cphy.c150015

11. Dumbell R, Matveeva O, Oster H. Circadian Clocks, Stress, and Immunity. *Front Endocrinol (Lausanne)*. 2016;7:37. Published 2016 May 2. https://doi.org/10.3389/fendo.2016.00037

12. Hill EE, Zack E, Battaglini C, Viru M, Viru A, Hackney AC. Exercise and circulating cortisol levels: the intensity threshold effect. J Endocrinol Invest. 2008 Jul;31(7):587-91. https://doi.org/10.1007/BF03345606

13. Nicolaides NC, Charmandari E, Kino T, Chrousos GP. Stress-Related and Circadian Secretion and Target Tissue Actions of Glucocorticoids: Impact on Health. Front Endocrinol (Lausanne). 2017 Apr 28;8:70. https://doi.org/10.3389/fendo.2017.00070

14. Sapolsky RM, Romero LM, Munck AU. How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. Endocr Rev. 2000 Feb;21(1):55-89. https://doi.org/10.1210/edrv.21.1.0389

15. Cain DW, Cidlowski JA. Immune regulation by glucocorticoids. Nat Rev Immunol. 2017;17(4):233-247. https://doi.org/10.1038/nri.2017.1

16. Nieman DC, Wentz LM. The compelling link between physical activity and the body's defense system. J Sport Health Sci. 2019;8(3):201-217. https://doi.org/10.1016/j.jshs.2018.09.009

17. Gleeson M. Immune function in sport and exercise. *J Appl Physiol (1985)*. 2007;103(2):693-699. https://doi.org/10.1152/japplphysiol.00008.2007

18. Walsh NP. Recommendations to maintain immune health in athletes. *Eur J Sport Sci*. 2018;18(6):820-831. https://doi.org/10.1080/17461391.2018.1449895

19. Duclos M, Tabarin A. Exercise and the Hypothalamo-Pituitary-Adrenal Axis. *Front Horm Res*. 2016;47:12-26. https://doi.org/10.1159/000445149

20. 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(9):1722-1744. https://doi.org/10.1111/sms.13999

21. Peake JM, Tan SJ, Markworth JF, et al. Metabolic and hormonal responses to isoenergetic high-intensity interval exercise and continuous moderate-intensity exercise. Am J

Physiol Endocrinol Metab. 2015;308(7):E539-E552. https://doi.org/10.1152/ajpendo.00276.2014

22. VanBruggen MD, Hackney AC, McMurray RG, Ondrak KS. The relationship between serum and salivary cortisol levels in response to different intensities of exercise. *Int J Sports Physiol Perform*. 2011;6(3):396-407. https://doi.org/10.1123/ijspp.6.3.396

23. Viru A, Karelson K, Smirnova T. Stability and variability in hormonal responses to prolonged exercise. Int J Sports Med. 1992;13(3):230-235. https://doi.org/10.1055/s-2007-1021259

24. Tsigos C, Chrousos GP. Hypothalamic-pituitary-adrenal axis, neuroendocrine factors and stress. *J Psychosom Res.* 2002;53(4):865-871. https://doi.org/10.1016/S0022-3999(02)00429-4

25. Leproult R, Van Cauter E. Role of sleep and sleep loss in hormonal release and metabolism. *Endocr Dev.* 2010;17:11-21. https://doi.org/10.1159/000262524

26. Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to exercise and training. *Sports Med.* 2005;35(4):339-361. https://doi.org/10.2165/00007256-200535040-00004

27. Logan-Sprenger HM, Heigenhauser GJF, Killian KJ, Spriet LL. Muscle metabolism during exercise with dehydration. *J Appl Physiol.* 2012;112(12):1966-1974. https://doi.org/10.1152/japplphysiol.00062.2012

28. Kajantie E, Phillips DIW. The effects of sex and hormonal status on the physiological response to acute psychosocial stress. Psychoneuroendocrinology. 2006;31(2):151-178. https://doi.org/10.1016/j.psyneuen.2005.07.002

29. Gatti R, De Palo EF. An update: salivary hormones and physical exercise. Scand J Med Sci Sports. 2011;21(2):157-169. https://doi.org/10.1111/j.1600-0838.2010.01252.x

30. Kirschbaum C, Hellhammer DH. Salivary cortisol in psychoneuroendocrine research. Psychoneuroendocrinology. 1994;19(4):313-333. https://doi.org/10.1016/0306-4530(94)90013-2

31. Vining RF, McGinley RA, Maksvytis JJ, Ho KY. Salivary cortisol: a better measure of adrenal cortical function than serum cortisol. Clin Chem. 1983;29(10):1850-1853. https://doi.org/10.1177/000456328302000601

32. Russell E, Koren G, Rieder M, et al. Hair cortisol as a biological marker of chronic stress. Curr Opin Psychiatry. 2012;25(1):63-69. https://doi.org/10.1097/YCO.0b013e32834c87ea

33. Wood P. Steroid assays-why do they vary so much? J Endocrinol. 2013;216(1):T1-T10. https://doi.org/10.1530/JOE-12-0449

34. Raff H. Utility of salivary cortisol measurements in Cushing's syndrome and adrenal insufficiency. J Clin Endocrinol Metab. 2009;94(10):3647-3655. https://doi.org/10.1210/jc.2009-1166

35. Taylor RL, Machacek D, Singh RJ. Validation of a high-throughput liquid chromatography-tandem mass spectrometry method for urinary cortisol and cortisone. Clin Chem. 2002;48(9):1511-1519. https://doi.org/10.1093/clinchem/48.9.1511

36. Hackney AC. Stress and the neuroendocrine system: the role of exercise as a stressor and modifier of stress. *Expert Rev Endocrinol Metab.* 2006;1(6):783-792. https://doi.org/10.1586/17446651.1.6.783

37. Athanasiou N, Bogdanis GC, Mastorakos G. Endocrine responses of the stress system to different types of exercise. Rev Endocr Metab Disord. 2023;24(2):251-266. https://doi.org/doi:10.1007/s11154-022-09758-1

38. Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures. *Br J Sports Med.* 2016;50(5):281-291. https://doi.org/10.1136/bjsports-2015-094758

39. Cadegiani FA, Kater CE. Hormonal aspects of overtraining syndrome: a systematic review. *BMC Sports Sci Med Rehabil.* 2017;9:14. https://doi.org/10.1186/s13102-017-0079-8

40. Kreher JB, Schwartz JB. Overtraining syndrome: a practical guide. *Sports Health.* 2012;4(2):128-138. https://doi.org/10.1177/1941738111434406

41. Rebelo A, Bishop C, Thorpe RT, Turner AN, Gabbett TJ. Monitoring Training Effects in Athletes: A Multidimensional Framework for Decision-Making. *Sports Med*. 2026 Mar 13. https://doi.org/10.1007/s40279-026-02417-4

42. Mondal S, Hathi DK, Bhattacharya S, Kalra S. The Testosterone: Cortisol Ratio - A Tool with Practical Use and Research Potential in Endocrinology. *Indian J Endocrinol Metab*. 2025;29(5):510-516. https://doi.org/10.4103/ijem.ijem_85_25

43. Pedlar CR, Newell J, Lewis NA. Blood Biomarker Profiling and Monitoring for High-Performance Physiology and Nutrition: Current Perspectives, Limitations and Recommendations. *Sports Med*. 2019 Dec;49(Suppl 2):185-198. https://doi.org/10.1007/s40279-019-01158-x

44. Souza RA, Beltran OAB, Zapata DM, Silva E, Freitas WZ, Junior RV, da Silva FF, Higino WP. Heart rate variability, salivary cortisol and competitive state anxiety responses

during pre-competition and pre-training moments. *Biol Sport*. 2019 Mar;36(1):39-46. https://doi.org/10.5114/biolsport.2018.78905

45. Mănescu DC, Plăstoi CD, Pîrvan A, Pașcan CD, Păun L, Sersea IE, Niculescu B, Popescu VE, Voinea A, Popescu A. Biomarkers as Temporal Signals: A Decision-Linked Multi-Layer Framework for Exercise Recovery, Overload, and Adaptation. *Int J Mol Sci*. 2026; 27(8):3675. https://doi.org/10.3390/ijms27083675

46. Urhausen A, Kindermann W. Diagnosis of overtraining: what tools do we have? *Sports Med*. 2002;32(2):95-102. https://doi.org/10.2165/00007256-200232020-00002

47. Hecksteden A, Skorski S, Schwindling S, Hammes D, Pfeiffer M, Kellmann M, Ferrauti A, Meyer T. Blood-Borne Markers of Fatigue in Competitive Athletes - Results from Simulated Training Camps. *PLoS One*. 2016 Feb 18;11(2):e0148810. https://doi.org/10.1371/journal.pone.0148810

48. Armstrong LE, Bergeron MF, Lee EC, Mershon JE, Armstrong EM. Overtraining Syndrome as a Complex Systems Phenomenon. *Front Netw Physiol*. 2022 Jan 18;1:794392. https://doi.org/10.3389/fnetp.2021.794392

49. Vignesh V, Castro-Dominguez B, James TD, Gamble-Turner JM, Lightman S, Reis NM. Advancements in Cortisol Detection: From Conventional Methods to Next-Generation Technologies for Enhanced Hormone Monitoring. *ACS Sens*. 2024 Apr 26;9(4):1666-1681. https://doi.org/10.1021/acssensors.3c01912

50. Dunbar J, Hazell G, Jehanli A. Evaluation of a new point of care quantitative cube reader for salivary analysis in the English Premier League soccer environment. *Br J Sports Med*. 2015;49(suppl 2):A2-A3. https://doi.org/10.1136/bjsports-2015-095576.7

51. Assalve G, Lunetti P, Di Cagno A, De Luca EW, Aldegheri S, Zara V, Ferramosca A. Advanced Wearable Devices for Monitoring Sweat Biochemical Markers in Athletic Performance: A Comprehensive Review. Biosensors (Basel). 2024 Nov 26;14(12):574. doi: 10.3390/bios14120574 https://doi.org/10.3390/bios14120574

52. Rist B, Pearce AJ. Tiered Levels of Resting Cortisol in an Athletic Population. A Potential Role for Interpretation in Biopsychosocial Assessment? J *Funct Morphol Kinesiol*. 2019 Jan 21;4(1):8. https://doi.org/10.3390/jfmk4010008

53. Minetto MA, Lanfranco F, Tibaudi A, Baldi M, Termine A, Ghigo E. Changes in awakening cortisol response and midnight salivary cortisol are sensitive markers of strenuous training-induced fatigue. *J Endocrinol Invest*. 2008 Jan;31(1):16-24. https://doi.org/10.1007/BF03345561

54. Kallen VL, Stubbe JH, Zwolle HJ, Valk P. Capturing effort and recovery: reactive and recuperative cortisol responses to competition in well-trained rowers. *BMJ Open Sport Exerc Med*. 2017 Jul 6;3(1):e000235. https://doi.org/10.1136/bmjsem-2017-000235

55. Nuuttila OP, Nummela A, Korhonen E, Häkkinen K, Kyröläinen H. Individualized Endurance Training Based on Recovery and Training Status in Recreational Runners. *Med Sci Sports Exerc*. 2022 Oct 1;54(10):1690-1701. https://doi.org/10.1249/MSS.0000000000002968

56. Bourdon PC, Cardinale M, Murray A, et al. Monitoring Athlete Training Loads: Consensus Statement. *Int J Sports Physiol Perform*. 2017;12(s2):S2-161. https://doi.org/10.1123/ijspp.2017-0208

57. Hecksteden A, Kraushaar J, Scharhag-Rosenberger F, Theisen D, Senn S, Meyer T. Individual response to exercise training - a statistical perspective. *J Appl Physiol*. 2015;118(12):1450-1459. https://doi.org/10.1152/japplphysiol.00714.2014

58. 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 Dec 14;2023:6614990. https://doi.org/10.1155/2023/6614990

59. Claudino JG, Capanema DO, de Souza TV, Serrão JC, Machado Pereira AC, Nassis GP. Current Approaches to the Use of Artificial Intelligence for Injury Risk Assessment and Performance Prediction in Team Sports: a Systematic Review. *Sports Med Open*. 2019 Jul 3;5(1):28. https://doi.org/10.1186/s40798-019-0202-3

60. Van Eetvelde H, Mendonça LD, Ley C, Seil R, Tischer T. Machine learning methods in sport injury prediction and prevention: a systematic review. *J Exp Orthop*. 2021 Apr 14;8(1):27. https://doi.org/10.1186/s40634-021-00346-x

61. Haller N, Behringer M, Reichel T, Wahl P, Simon P, Krüger K, Zimmer P, Stöggl T. Blood-Based Biomarkers for Managing Workload in Athletes: Considerations and Recommendations for Evidence-Based Use of Established Biomarkers. *Sports Med*. 2023 Jul;53(7):1315-1333. https://doi.org/10.1007/s40279-023-01836-x