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Vitamin D Deficiency in Athletes: A Narrative Review of Injury Risk, Recovery, Immune Function, and Physical Performance

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ABSTRACT

Background. Vitamin D plays a key role in musculoskeletal health, immune function, and recovery. In athletes, vitamin D deficiency is relatively common and has been associated with an increased risk of injury, impaired post-exercise recovery, and reduced physical performance.
Aim. To summarize current evidence on the prevalence of vitamin D deficiency in athletes and its associations with injury risk, recovery, immune function, and physical performance.

Material and methods. A narrative review of studies published within the last 10 years was conducted to evaluate the prevalence and risk factors of vitamin D deficiency in athletes and its associations with injury risk, recovery, immune function, and physical performance.

Results. Available evidence indicates that vitamin D deficiency is relatively common in athletes, particularly in those with limited sun exposure. The most consistent findings concern its association with impaired bone health and increased risk of bone stress injuries. Deficiency may also be related to impaired recovery and altered immune function, while evidence regarding its effect on physical performance remains inconclusive.

Conclusions. Vitamin D deficiency may represent an important and modifiable factor related to musculoskeletal health, injury risk, recovery, and physical performance in athletes. Monitoring vitamin D status and individualized supplementation may support athlete health and training outcomes.

Keywords: vitamin D, athletes, deficiency, sports injuries, bone stress injuries, recovery, musculoskeletal health, immune function, physical performance

1. Introduction

Musculoskeletal injuries and overload-related disorders remain among the most important problems in sport, affecting not only athletes' current training and competitive capacity, but also the duration of recovery, the risk of recurrent injuries, and the overall course of a sporting career. In recent years, increasing attention has been paid to the role of nutritional and metabolic factors in the prevention of these disorders, including the importance of vitamin D. Vitamin D plays a significant role not only in maintaining calcium–phosphate homeostasis and bone mineralization, but also in musculoskeletal function, regulation of the immune response, and modulation of inflammatory processes.

Despite their high level of physical activity, athletes are not a population free from the risk of vitamin D deficiency. Evidence indicates that insufficient concentrations of 25-hydroxyvitamin D [25(OH)D], regarded as the primary marker of vitamin D status, occur relatively frequently in this group, particularly during the autumn and winter months, under conditions of limited sun exposure, and among athletes participating in indoor sports. [1–4] This phenomenon is

clinically relevant because reduced 25(OH)D concentrations may adversely affect bone metabolism, muscle function, post-exercise recovery, and adaptation to exercise loads, thereby increasing susceptibility to injuries and overload-related conditions. [1–4]

From a sports medicine perspective, the potential association between vitamin D deficiency and an increased risk of overuse injuries, including stress fractures, as well as impaired post-exercise recovery, is of particular importance. Its significance for physical performance, immune system function, and inflammatory responses is also a subject of ongoing investigation. Although the available evidence does not justify treating vitamin D as a universal ergogenic aid, it suggests that adequate vitamin D concentrations may support the maintenance of optimal musculoskeletal function and the ability to tolerate training loads, especially in individuals with previously identified deficiency. [3,5]

However, the findings of studies conducted to date on the role of vitamin D in sport remain partly inconclusive, and their interpretation is complicated by differences in the populations studied, sports disciplines, criteria used to assess vitamin D status, and supplementation protocols. This justifies the need to organize and critically review the current body of knowledge in this field. [1,3,4]

The aim of this review is to analyze the current state of knowledge regarding the significance of vitamin D deficiency in athletes, with particular emphasis on its relationship with the risk of injuries and overload-related conditions, musculoskeletal health, post-exercise recovery, immune system function, the intensity of inflammatory processes, and selected parameters of physical performance. Achieving this aim may contribute to a better understanding of the role of vitamin D in sport and help define its practical relevance in the prevention of overload-related disorders and the optimization of the training process. [3,6]

2. Vitamin D3: Characteristics, Metabolism, and Biological Functions

Vitamin D3 (cholecalciferol) is a secosteroid compound and, although it has traditionally been classified as a vitamin, it is now regarded as a prohormone. Following appropriate hydroxylation steps, its active metabolites participate in the regulation of calcium–phosphate homeostasis, bone metabolism, and muscle function. Its clinical importance is primarily related to its role in maintaining the integrity of the musculoskeletal system. At the same time, the presence of the vitamin D receptor (VDR) in numerous tissues outside the skeletal system suggests a broader spectrum of biological activity, including modulation of the immune response and regulation of inflammatory processes. [7]

The primary source of vitamin D3 in humans is its cutaneous synthesis induced by UVB radiation. This process involves 7-dehydrocholesterol present in the epidermis, which, under the influence of UVB radiation, is converted into previtamin D3 and subsequently into cholecalciferol. The efficiency of cutaneous synthesis depends on multiple factors, including latitude, season, time of day, cloud cover, the extent of skin exposure, the use of sunscreen, skin pigmentation, and age. For this reason, limited exposure to sunlight may substantially increase the risk of vitamin D deficiency. [8]

Diet constitutes the second source of vitamin D; however, its contribution to meeting the body's requirements is usually limited. The most important natural dietary sources include oily marine fish, fish liver oils, egg yolk, and selected animal-derived foods. Recent reviews further indicate that fortified foods also play an important role, representing an effective strategy for improving vitamin D status. [9]

Current Endocrine Society guidelines emphasize that there are few natural food sources rich in vitamin D; therefore, maintaining an adequate intake generally requires a combination of sun exposure, fortified foods, and supplementation. Dietary sources may help sustain serum 25(OH)D concentrations, but they are generally insufficient to ensure optimal vitamin D status, particularly during periods of limited cutaneous synthesis. [10,11]

Regardless of its source, vitamin D3 requires further metabolic conversion to achieve full biological activity. After cutaneous synthesis or intestinal absorption, vitamin D3 enters the circulation and undergoes the first hydroxylation step in the liver, where it is converted to 25-hydroxyvitamin D [25(OH)D], also referred to as calcidiol. This process occurs mainly through the action of the enzyme CYP2R1, which is considered the principal 25-hydroxylase. [10,12] 25(OH)D is the main circulating form of vitamin D in plasma and reflects input from cutaneous synthesis, diet, and supplementation. The next stage of metabolism is the hydroxylation of 25(OH)D, which takes place primarily in the kidneys via 1α-hydroxylase (CYP27B1), resulting in the formation of 1,25-dihydroxyvitamin D [1,25(OH)2D], or calcitriol — the biologically active form of vitamin D. This process is tightly regulated by parathyroid hormone, calcium and phosphate concentrations, and FGF23.

The best-characterized function of calcitriol remains its role in the regulation of calcium–phosphate homeostasis. Vitamin D enhances intestinal absorption of calcium and phosphorus, affects their renal tubular reabsorption, and contributes to the maintenance of normal parathyroid hormone levels. Under conditions of deficiency, calcium absorption becomes less efficient, secondary elevation of PTH occurs, and bone resorption increases, which may lead to deterioration in bone tissue quality. [10,12,13]

The active form of vitamin D exerts its effects through the vitamin D receptor (VDR), which is present in numerous tissues, including the intestine, bones, kidneys, and skeletal muscles. The wide expression of VDR indicates that the actions of vitamin D extend beyond the classical regulation of calcium–phosphate metabolism and include endocrine as well as autocrine and paracrine effects. Vitamin D has been implicated in skeletal muscle function, cellular proliferation and differentiation, modulation of immune responses, and regulation of inflammatory processes, which confirms its pleiotropic biological significance. Therefore, maintaining an adequate vitamin D status is important not only for musculoskeletal health, but also for the proper functioning of the entire organism. [7,14,15]

3. The Importance of Vitamin D for the Musculoskeletal System in Athletes

The importance of vitamin D for the skeletal system stems primarily from its role in bone mineralization, which is mediated mainly through the regulation of calcium–phosphate homeostasis. Maintaining appropriate concentrations of calcium and phosphate is essential for proper deposition of mineral components in the bone matrix and, consequently, for adequate mechanical strength of bone. Prolonged vitamin D deficiency disrupts these processes, contributing to reduced bone quality and increased susceptibility to microdamage. In the context of sport, this is of particular relevance because repetitive mechanical loading may reveal the consequences of even subclinical disturbances in bone metabolism. [5,12,16]

Vitamin D also plays an important role in bone remodeling. This process is based on a dynamic balance between bone formation and resorption, and vitamin D is involved in its regulation both directly and indirectly through its effects on mineral homeostasis and parathyroid hormone secretion. Adequate vitamin D status supports the maintenance of skeletal homeostasis, whereas deficiency may disturb remodeling balance and limit the ability of bone to adapt to training loads. [12,13]

The importance of vitamin D is not limited to bone tissue alone. Beyond the skeletal system, vitamin D is also highly relevant to the functioning of skeletal muscles. The presence of the VDR in muscle tissue, together with findings from experimental and clinical studies, indicates that vitamin D is involved in the regulation of muscle cell proliferation and differentiation, intracellular metabolism, and muscle fiber contractility. Vitamin D may help preserve the structural integrity of muscle, limit degradative processes, and maintain normal muscle function. From the perspective of exercise physiology, it is particularly important that adequate vitamin D status may support the maintenance of muscle strength, functional performance, and an effective adaptive response to training. [5,16,17]

The role of vitamin D in muscle contraction is closely linked to the regulation of calcium homeostasis. Calcium plays a key role in the excitation–contraction coupling mechanism, and vitamin D, by influencing its systemic availability and transport, indirectly contributes to the normal course of muscle contraction. Disturbances in vitamin D status may therefore be associated with impaired muscle function, poorer exercise tolerance, and a reduced capacity to perform repeated muscular work. [5,12,17]

Vitamin D also affects neuromuscular function, including conduction efficiency, coordination of excitation, and the effectiveness of muscle activation. The literature emphasizes that vitamin D deficiency may be associated with impaired motor control, reduced strength, and poorer functional quality of muscle performance. [5,16,17]

In summary, vitamin D is one of the key regulators of musculoskeletal system integrity. Its importance includes not only the maintenance of proper bone mineralization and remodeling, but also the support of muscular and neuromuscular function through its effects on calcium–phosphate homeostasis and the activity of target tissues. From a sports perspective, this provides a strong rationale for further analysis of the relationship between vitamin D3 deficiency and the risk of overuse injuries, impaired recovery, and reduced exercise capacity. [5,12,16,17]

4. Diagnosis and Prevention of Vitamin D Deficiency in Athletes

Proper diagnosis and prevention of vitamin D deficiency in athletes are important both in the context of musculoskeletal health and in the prevention of overuse injuries. This is because vitamin D deficiency may remain asymptomatic for a long time, and its clinical consequences often become apparent only under conditions of increased training load, bone stress injury, or recurrent injury. For this reason, the contemporary approach to athlete care increasingly includes assessment of vitamin D status as part of a broader evaluation of nutritional status, bone health, and injury risk. [2,18-20]

4.1. Assessment of Vitamin D Status in Athletes

The primary and best-established indicator of vitamin D status remains the measurement of serum 25-hydroxyvitamin D [25(OH)D]. It is the main circulating metabolite of vitamin D, has a relatively long half-life of approximately 2–3 weeks, and reflects cutaneous synthesis, dietary intake, and supplementation. Although the hormonally active form of vitamin D is 1,25-dihydroxyvitamin D [1,25(OH)2D], its concentration is not routinely used to assess vitamin D status, because it is strongly influenced by ongoing hormonal and homeostatic regulation, and its half-life is short, being measured in hours. [12,13] For this reason, 25(OH)D, rather than

1,25(OH)2D, is the recommended laboratory marker for evaluating vitamin D status in both clinical and sports practice. [2,20]

In sports medicine practice, the assessment of 25(OH)D is of particular importance in athletes with bone stress injuries. A recent practical review on bone stress injury indicated that at least a basic diagnostic panel should be considered in all athletes with this diagnosis, including measurement of 25-hydroxyvitamin D, complete blood count, and an iron panel with ferritin. In athletes with signs of low energy availability, recurrent bone injuries, or suspected disorders of bone health, a more extensive diagnostic work-up is recommended, including DXA densitometry and additional laboratory tests depending on the clinical picture. [18]

4.2. Optimal 25(OH)D Concentration in Athletes

One of the most frequently discussed issues remains the definition of the optimal 25(OH)D concentration in athletes. For the general population, the National Institutes of Health considers a concentration of 50 nmol/L, equivalent to 20 ng/mL, or higher to be sufficient for bone health and normal calcium metabolism in most individuals. At the same time, levels above approximately 125–150 nmol/L, or 50–60 ng/mL, are not recommended as a routine target, because prolonged maintenance of high concentrations may be associated with a risk of adverse effects. [20]

In sport, however, the situation is more complex. Some authors emphasize that the sufficiency threshold established for the general population may not be optimal for athletes exposed to high mechanical loads, particularly in the context of bone stress injuries. A review devoted to stress fractures indicated that values of at least 30 ng/mL should be considered a desirable minimum after correction of deficiency, whereas a more recent Sports Health publication on bone stress injury suggests that levels in the range of 40–50 ng/mL may have a protective role in some athletes at risk. It should be emphasized, however, that there is currently no single, universally accepted sport-specific target concentration applicable across all disciplines and athlete groups. [2,18]

From a practical perspective, this means that interpretation of 25(OH)D results should take into account not only the laboratory value itself, but also the clinical context, including the type of sport, geographic latitude, season, history of bone stress injuries, signs of low energy availability, and the current phase of the training season. Such an approach is particularly justified in elite athletes, in whom even moderate metabolic disturbances may translate into a greater risk of injury or impaired recovery. [18,19]

4.3. The Importance of Sun Exposure

Natural cutaneous synthesis under the influence of UVB radiation remains the main physiological source of vitamin D. In sports practice, however, the efficiency of this process is highly variable and depends on many factors, such as geographic latitude, season, time of day, weather conditions, skin type, age, the extent of skin exposure, and the use of protective clothing and sunscreen. This means that the mere fact of training outdoors is not sufficient to predict an adequate vitamin D status. [2,20]

This issue is particularly relevant to athletes who train indoors, individuals living at higher latitudes, and athletes assessed during the autumn and winter months. Reviews devoted to vitamin supplementation in athletes emphasize that vitamin D deficiency occurs most frequently in these groups, and that sun exposure alone does not always allow maintenance of an adequate 25(OH)D concentration throughout the year. From a practical point of view, sun exposure may be an important element of prevention; however, it is difficult to standardize as a clinical management tool. For this reason, it should not replace laboratory assessment of vitamin D status in athletes belonging to risk groups. [2,19]

4.4. Vitamin D Supplementation: Recommendations and Safety

Contemporary reviews emphasize that preventive management of vitamin D status in athletes should be based primarily on individualization. Diet remains the foundation, whereas supplementation should be used as an adjunct when dietary intake and sun exposure are insufficient or when deficiency has been confirmed by laboratory testing. It is worth noting that there is still a lack of clear, high-quality, sport-specific dosing guidelines for all groups of athletes. [19]

Current recommendations indicate that cholecalciferol should be the first-line preparation for the prevention and treatment of vitamin D deficiency, and dosing should be adjusted according to age, body mass, sun exposure, dietary pattern, and the presence of risk factors for deficiency. In selected clinical situations, particularly in cases of malabsorption or specific medical indications, other forms may also be considered; however, in the general population and in most physically active individuals, vitamin D3 (cholecalciferol) remains the basis of supplementation. [12,13]

For the general population, the recommended intake of vitamin D is 600 IU per day between the ages of 14 and 70 years and 800 IU per day after the age of 70, assuming minimal sun exposure. In sport, preventive doses are sometimes higher, particularly during the autumn and winter period or in individuals with confirmed deficiency, but they should be selected on the

basis of 25(OH)D monitoring. As an example, a study of world-class British swimmers showed that standardized supplementation at a dose of 4000 IU/day from October to March increased the mean 25(OH)D concentration from 76.4 ± 28.4 nmol/L in 2018 to 115.0 ± 36.6 nmol/L in 2020, while the prevalence of deficiency decreased from 10% to 0%. At the same time, in September 2020, 35% of the athletes had concentrations exceeding 125 nmol/L, which demonstrates that even effective supplementation requires laboratory monitoring and cautious interpretation. [20,21]

In terms of safety, the key issue is avoidance of chronic excessive intake. According to the NIH, the tolerable upper intake level for adolescents aged 9 years and older and for adults is 4000 IU per day. Vitamin D toxicity is almost exclusively related to excessive supplementation and primarily leads to hypercalcemia, hypercalciuria, and high 25(OH)D concentrations, usually exceeding 150 ng/mL. Clinically, this may manifest as nausea, muscle weakness, polyuria, dehydration, nephrolithiasis, and, in severe cases, even renal failure and soft tissue calcification. For this reason, vitamin D supplementation in athletes should be monitored, especially when higher doses, calcium-containing combined preparations, or long-term seasonal regimens are used. [20,21]

In summary, the diagnosis of vitamin D deficiency in athletes should be based primarily on measurement of 25(OH)D concentration, and in high-risk groups—particularly in the presence of bone stress injuries—also on a broader assessment of bone health and nutritional status. Prevention should include diet, reasonable sun exposure, and individually tailored supplementation. The most clinically justified approach appears to be one based on laboratory monitoring and adjustment of interventions to the actual degree of deficiency, rather than the routine use of high doses in all athletes. [2,18-21]

5. Prevalence and Determinants of Vitamin D Deficiency in the Athlete Population

Vitamin D deficiency is also an important health concern in the athlete population, despite the fact that these individuals are highly physically active and often remain under regular medical or dietary supervision. Current systematic reviews indicate that a high level of physical activity does not protect against insufficient 25-hydroxyvitamin D [25(OH)D] concentrations, and the prevalence of reduced levels of this marker remains substantial across different groups of athletes. This issue has practical relevance because vitamin D status may affect musculoskeletal health, the ability to adapt to exercise, and the risk of limited training availability. [22–25]

5.1. Prevalence of Deficiency Among Athletes

Available meta-analyses and systematic reviews indicate that insufficient 25(OH)D concentrations are relatively common in athletes, although the exact prevalence depends on the cut-off values applied, the season in which biological samples are collected, geographic location, and the characteristics of the studied population. In the systematic review and meta-analysis by Harju et al., the prevalence of insufficient vitamin D concentrations in elite athletes was shown to be high, and the available estimates may even be underestimated because relatively fewer studies have been conducted during the winter months, when the risk of deficiency is often greatest. Insufficient vitamin D concentrations were identified in 30% of adult athletes (95% CI, 22%–39%) and 39% of adolescent athletes (95% CI, 25%–55%), indicating that this issue affects a substantial proportion of the physically active population. [22] In practice, this means that vitamin D deficiency should not be regarded as a marginal problem or one confined to the general population. In the sports setting, it occurs both in elite athletes and in individuals who train regularly, although its severity varies seasonally. From a sports medicine perspective, it is also important that vitamin D status may fluctuate considerably throughout the training year, which makes one-time assessment less informative and supports a more deliberate monitoring strategy in groups at increased risk. [22,25]

The prevalence of deficiency in athletes should therefore be considered a dynamic phenomenon that changes depending on the stage of the training year. A study by Książek et al. conducted in young soccer players demonstrated marked seasonal variation in vitamin D concentrations: the mean total 25(OH)D concentration was 45.25 ± 6.94 ng/mL in summer and 38.08 ± 6.34 ng/mL in winter ($p < 0.001$). The authors also found a significant seasonal rhythm for total 25(OH)D, the protein-bound fraction, and other vitamin D metabolites, confirming that vitamin D status in athletes is not constant and may decline substantially during periods of reduced UVB exposure. [25]

5.2. Groups at Particular Risk

Athletes participating in indoor sports are among the groups most frequently identified as being at particular risk. The meta-analysis by Bârsan et al. confirmed that the training environment influences vitamin D concentrations, and that athletes training primarily indoors more often exhibit lower 25(OH)D levels than those engaged in outdoor sports. [23] In the overall analysis, the mean vitamin D concentration was 31.4 ng/mL in outdoor athletes and 27.67 ng/mL in indoor athletes, corresponding to a difference of 3.73 ng/mL in favor of the outdoor group, although this did not reach conventional statistical significance ($p = 0.052$). [23] This difference

should not be interpreted solely as an effect of reduced sun exposure, but rather as the result of multiple interacting factors, including training schedule, place of residence, season, and athletes' lifestyle.

Subgroup analyses also provide interesting findings. In studies conducted exclusively in Asian athletes, the difference between outdoor and indoor athletes was clear and statistically significant: the mean vitamin D concentration was 34.91 ng/mL in the outdoor group and 25.06 ng/mL in the indoor group, corresponding to a difference of 9.85 ng/mL ($p < 0.01$). This suggests that the impact of the training environment may be particularly pronounced in certain populations and should not be assessed independently of other factors such as ethnic background, geographic latitude, or the season in which biological samples are collected. [23]

Season and geographic latitude are also of major importance. In countries located farther from the equator, cutaneous vitamin D synthesis is limited during the autumn and winter months, which translates into lower 25(OH)D concentrations also in athlete populations. Reports concerning seasonal changes in vitamin D concentrations in athletes indicate that these values fluctuate significantly throughout the year and may decline during periods of restricted UVB exposure. Thus, athletes living and training at temperate and northern latitudes represent a group requiring particular attention in the prevention of deficiency. [22,25]

In recent years, para-athletes have also been recognized as a population particularly vulnerable to low vitamin D status. In a systematic review, Langley et al. demonstrated that insufficient and low vitamin D concentrations occur frequently in para-athletes throughout the year, both in summer and winter, with particularly high risk observed in wheelchair athletes and those participating in indoor sports. It was found that 43.2% of samples met the criteria for vitamin D insufficiency and 28.1% for deficiency. A particularly unfavorable pattern was observed in winter, when the prevalence of insufficient concentrations reached 74.1%, compared with 57.1% in summer. [24] This highlights the need for individualized management and for consideration of the specific functional and environmental determinants affecting this group.

Other factors associated with an increased risk of deficiency include limited sun exposure resulting from training hours, the use of clothing covering a large body surface area, darker skin pigmentation, and inadequate dietary intake of vitamin D. Some studies also point to the potential importance of age and stage of athletic career, although the available data in this respect are not always consistent. Nevertheless, current reviews consistently suggest that identification of high-risk groups is a key component of prevention and should precede decisions regarding 25(OH)D testing and implementation of supplementation. [22–24]

In summary, current evidence indicates that vitamin D3 deficiency in the athlete population is common, varies seasonally, and depends on a range of environmental, training-related, and individual factors. Athletes participating in indoor sports, those living or training under conditions of limited cutaneous synthesis, and para-athletes appear to be particularly vulnerable. In this context, particular importance should be attached to identifying athletes at increased risk of musculoskeletal health disturbances and to considering the broader clinical and training context, including dietary habits, sun exposure, type of sport, and history of injuries or overload. [22-25]

6. Vitamin D Deficiency and the Risk of Sports Injuries and Overuse Conditions

The importance of vitamin D for musculoskeletal function is reflected in clinical observations concerning injury risk in athletes. Current literature indicates that vitamin D3 deficiency may represent one of the modifiable risk factors for selected sports injuries, particularly bone stress injuries. In the case of muscle, tendon, and ligament injuries, such an association has also been suggested; however, the available evidence remains less conclusive. For this reason, the relationship between vitamin D status and injury risk should be interpreted within a multifactorial model that also takes into account training load, energy availability, nutritional status, hormonal factors, movement biomechanics, and a history of previous overload-related problems. [6,26-28]

One of the most important recent studies addressing overall sports injury risk is the 2026 analysis by Frank et al., conducted in a group of 284 collegiate athletes. The study showed that 47.2% of the athletes had insufficient vitamin D concentrations, while 17.6% were deficient. Importantly, every 5 ng/mL decrease in 25(OH)D concentration was associated with a 13% increase in the odds of sustaining a musculoskeletal injury (OR 1.13; 95% CI 1.00–1.27; $p = 0.05$). This provides an important argument for the clinical relevance of vitamin D, as it demonstrates not only a qualitative association but also a graded one—a decline in concentration translated into a higher probability of injury. [27] In the same study, however, no significant associations were found between vitamin D status and time to return to sport, suggesting that the role of this vitamin may be more evident in the context of injury risk itself than in the later course of recovery. Owing to the retrospective design of the study and its borderline statistical significance, these findings should nevertheless be interpreted with caution.

6.1. Vitamin D Deficiency and Bone Stress Injuries

The most convincing evidence concerns the association between low 25-hydroxyvitamin D [25(OH)D] concentrations and an increased risk of stress fractures and other bone stress injuries. In the athlete population, vitamin D3 deficiency is currently recognized as one of the modifiable risk factors for bone stress injuries, particularly in sports involving high loads on the lower limbs. [26,29]

One of the key studies in this area remains the analysis by Millward et al., which included 802 NCAA collegiate athletes. Among athletes whose 25(OH)D concentrations remained below 40 ng/mL, the incidence of stress fractures was 13.0%, whereas in athletes who improved their concentrations to at least 40 ng/mL, the incidence was 0.6%, and in the group that consistently maintained normal levels, it was 1.4%. When stress reactions and stress fractures were combined, the differences were similarly pronounced. Although the regression analysis for stress fractures alone did not unequivocally demonstrate a statistically significant protective effect, the analysis combining stress reactions and fractures showed a significant protective effect in men. These findings suggest that persistently low vitamin D concentrations may be associated with greater susceptibility to bone stress injuries. [29]

Interventional data are less conclusive, but they also suggest a potential protective effect. In the 2025 study by Williams et al., a lower incidence of bone stress injuries was observed during the season with vitamin D supplementation than during seasons without supplementation; however, this difference did not reach statistical significance. This means that supplementation may be a promising preventive strategy, but at present it does not yet constitute definitive evidence for a reduction in bone injury risk across all athletes. [30]

In clinical practice, expert recommendations concerning the diagnosis of bone stress injury are also important. These emphasize that reduced 25(OH)D concentration is one component of the metabolic assessment of an athlete with a bone stress injury, and values of at least 30 ng/mL are generally considered sufficient, whereas levels in the range of 40–50 ng/mL may have a protective role in some athletes at risk. [18]

In summary, among all analyzed types of sports injuries, the association between vitamin D deficiency and bone stress injuries is currently the best documented. Nevertheless, vitamin D deficiency should be regarded as one element of a multifactorial risk model rather than as an independent cause of injury. [18,26,29,30]

6.2. Vitamin D Deficiency and Soft Tissue Injuries

The relationship between vitamin D deficiency and soft tissue injuries is less well documented than in the case of the skeletal system. Contemporary literature suggests that low vitamin D status is more frequently observed in individuals with musculoskeletal symptoms and injuries; however, this relationship is not equally strong across all endpoints, and the results of intervention studies remain heterogeneous. [6,27] The 2025 systematic review by Maai et al. indicated that low vitamin D concentrations were common among individuals with musculoskeletal injuries or symptoms, but the effect of supplementation on muscle function and injury outcomes was not consistent. [6]

With regard to tendons, the 2024 review by Tarantino et al. emphasized the biological importance of vitamin D for tendon tissue physiology and the possible association of deficiency with tendinopathy and poorer healing, although the authors noted the limited quality of the available clinical data. [31]

From a practical point of view, this means that vitamin D deficiency should be viewed more as a potential factor modifying the susceptibility of soft tissues to overload than as a direct cause of injury. [6,31,32]

6.3. Vitamin D Deficiency, Ligament Injuries, and Recovery After Injury

In recent years, interest has grown in the possible role of vitamin D in ligament injuries, especially those involving the anterior cruciate ligament (ACL). A 2025 systematic review by Pasquini et al., including five studies and 656,243 participants, indicated that most available studies suggest an association between low vitamin D concentration and a higher risk of ACL injury as well as poorer recovery of muscle strength after reconstruction. However, the authors clearly emphasized the marked heterogeneity of the studies and the limited quality of part of the evidence. [28]

Observational data further support this relationship. In the 2023 study by Albright et al., a prior diagnosis of hypovitaminosis D was associated with a significantly higher incidence of both primary ACL injuries and revision ACL reconstruction. Within 2 years of diagnosis of deficiency, the risk of primary ACL rupture was 81% higher, and the risk of revision ACLR was 28% higher. [33] These findings suggest that low vitamin D status may be associated not only with greater susceptibility to injury itself, but also with a less favorable course of surgical treatment and return to full function.

Observational and mechanistic studies also support this hypothesis. The study by Wen et al. demonstrated that patients with 25(OH)D concentrations <30 ng/mL experienced greater

quadriceps muscle atrophy after ACL reconstruction than those with higher vitamin D concentrations. [34] In turn, Qiu et al. described a correlation between insufficient vitamin D concentration and poorer quadriceps neuromuscular function in patients with ACL injury. [32] These findings suggest that low vitamin D status may influence not only injury risk, but also the quality of recovery after injury and surgical treatment, and thus may potentially be associated with a more difficult return to full function. In sports involving frequent jumping, landing, and sudden changes of direction—where the risk of ACL injury is high—even moderate impairment of muscle function and regenerative response may be of practical importance. Given the limited sample sizes and the preliminary nature of the available studies, these observations should be interpreted with caution and treated as a rationale for further investigation rather than as definitive clinical evidence. [28,34]

6.4. Clinical and Practical Implications

Taken together, the available evidence indicates that vitamin D deficiency should be regarded as a potentially modifiable risk factor for sports injuries, primarily bone stress injuries. In the case of muscle, tendon, and ligament injuries, such a relationship is also suggested, but it is based on evidence that is less consistent and methodologically weaker. Therefore, low 25(OH)D concentration should not be interpreted as an independent cause of injury, but rather as one element of the athlete's broader clinical picture. [6,28,31,32]

From a practical perspective, an individualized approach appears to be the most justified, including assessment of 25(OH)D concentration in athletes at increased risk, especially those with a history of bone stress injuries, features of RED-S, limited exposure to UVB radiation, or those returning to full training loads after severe musculoskeletal injuries. Such an approach is more consistent with the current state of knowledge than a routine, uniform strategy applied to all athletes. [18,30,34]

7. Vitamin D Deficiency, Muscle Function, and Post-Exercise Recovery

Post-exercise recovery is a complex process involving the repair of microdamage to muscle tissue, restoration of energy stores, resolution of excessive inflammation, and recovery of normal neuromuscular function. Available evidence indicates that vitamin D3 may participate in the repair processes occurring after exercise and injury, including by reducing oxidative stress and excessive inflammation, supporting satellite cell proliferation and activation, and stimulating regenerative processes within muscle fibers. Accordingly, adequate vitamin D

status is increasingly regarded as one of the potential factors supporting recovery in athletes. [35-37]

In the 2023 systematic review by Rojano-Ortega et al., it was suggested that an adequate vitamin D level may support muscle function during exercise and accelerate recovery, partly through the reduction of selected pro-inflammatory cytokines. At the same time, the authors emphasized that the results of intervention studies remain heterogeneous and do not yet allow for clear recommendations regarding the effects of supplementation on all recovery-related parameters. They also pointed out that the anti-inflammatory effects of vitamin D may become apparent earlier than the structural restoration of muscle tissue, meaning that classical biochemical markers do not always fully capture the recovery process. [36]

Similar conclusions were drawn from the 2021 meta-analysis by Bello et al. The authors indicated that although vitamin D appears to be biologically relevant for muscle recovery after exercise, pooled analysis did not allow unequivocal confirmation of a significant effect of supplementation on all classical markers of muscle damage. This suggests that the potential role of vitamin D in tissue repair is plausible, but at present it is best interpreted as a supportive factor rather than an independent determinant of recovery. [35]

Most of the available data on vitamin D and recovery after exercise concern markers of muscle damage, such as creatine kinase (CK), lactate dehydrogenase (LDH), myoglobin, and inflammatory cytokines. In the 2020 study by Żebrowska et al., conducted in trained runners, 3 weeks of vitamin D supplementation increased 25(OH)D concentrations and was associated with reductions in selected markers of muscle damage after eccentric exercise, including troponin immediately after exercise and after 1 hour ($p = 0.004$ and $p = 0.03$), myoglobin after 1 hour ($p = 0.01$), TNF-α ($p < 0.03$), and CK activity after 24 hours ($p < 0.05$). [38]

Comparable findings were reported in the 2020 randomized study by Pilch et al. involving young men subjected to eccentric exercise. The authors showed that after 3 months of individually tailored supplementation, the group with initially suboptimal 25(OH)D concentrations demonstrated a more favorable inflammatory response and less pronounced muscle damage; the change in IL-1β concentration 1 hour after exercise differed significantly between the first and second tests ($p = 0.047$), and 25(OH)D concentrations increased significantly in the supplemented group ($p = 0.005$). [39] At the same time, the authors noted that CK activity did not clearly differentiate all study groups, and the results should therefore be interpreted with caution.

Important findings were also provided by the 2023 study by Liu et al. In this double-blind trial in healthy men, 4 weeks of supplementation with 5000 IU of vitamin D3 daily led to an increase

in 25(OH)D concentration and, after intense endurance exercise, was associated with lower levels of IL-6, CK, and LDH compared with placebo. These results support the hypothesis that vitamin D3 may attenuate post-exercise muscle damage and promote a faster return to homeostasis following heavy physical exertion. [37]

Interesting data were also reported in the 2021 study by Mieszkowski et al. in ultramarathon runners. The authors demonstrated that a single high dose of vitamin D (150,000 IU) administered before the race was associated with attenuation of post-ultramarathon changes in interleukin concentrations, which was interpreted as evidence of the anti-inflammatory effect of vitamin D in response to extreme endurance exercise. Although this finding does not yet provide definitive evidence regarding its impact on overall functional recovery, it strengthens the argument that vitamin D may modulate key biological processes taking place after exercise. [40]

Vitamin D3 deficiency may contribute to delayed recovery primarily through amplification of the inflammatory response, poorer regulation of repair processes, and impaired skeletal muscle function. From a practical perspective, this may translate into more persistent post-exercise symptoms, slower restoration of muscle strength, and lower tolerance to subsequent training sessions. Although not all studies demonstrate this effect to the same extent, current reviews indicate that the risk of impaired recovery is particularly likely in individuals with low baseline 25(OH)D concentrations. [5,35,36]

It is also worth emphasizing that the effects of vitamin D on recovery may not be identical in all athletes. In the 2024 review by Wyatt et al., it was noted that the benefits of supplementation are more likely when athletes present with deficiency or insufficiency before the intervention begins. In individuals with adequate 25(OH)D status, the effect may be smaller or more difficult to demonstrate, which partly explains the discrepancies between studies. In sports practice, this means that vitamin D3 may be most relevant not as a universal recovery-enhancing agent for every athlete, but rather as a factor supporting return to training in those with deficiency or insufficient 25(OH)D concentrations. [3]

In summary, current evidence suggests that vitamin D may be one of the factors supporting post-exercise recovery, particularly under conditions of deficiency or insufficient 25(OH)D concentration. The most likely mechanisms include reduction of excessive inflammation, attenuation of muscle damage, and support of neuromuscular functional recovery. At the same time, it should be emphasized that supplementation does not replace other fundamental components of recovery, such as adequate energy and protein intake, sleep, and appropriate training periodization. [3,35-37,40]

8. Vitamin D Deficiency and Physical Performance in Athletes

The effect of vitamin D3 on physical performance and athletic outcomes remains one of the more frequently discussed, yet also more equivocal, issues in sports medicine. On the one hand, vitamin D is involved in the regulation of skeletal muscle function, calcium–phosphate homeostasis, and exercise-related adaptive processes, which suggests a potential influence on exercise capacity. On the other hand, current reviews indicate that any effect on sports performance is not universal and is not observed consistently across all studies. In practice, this means that vitamin D3 should not be regarded as a classical ergogenic aid, but rather as a factor supporting optimal physiological function, particularly in athletes with initially low 25(OH)D concentrations. [3,5,41,42]

In the 2024 systematic review by Wyatt et al., which included 13 placebo-controlled randomized trials conducted in elite athletes, it was indicated that the greatest potential benefits of vitamin D supplementation may concern aerobic capacity, anaerobic power, and strength. Particular attention was given to aerobic performance, usually assessed on the basis of maximal oxygen uptake or endurance tests, which, among the analyzed fitness components, appeared to be the area with the most promising effects of supplementation. In six of the eight studies evaluating aerobic capacity, improvement in at least one parameter was observed after supplementation, suggesting that aerobic performance may be one of the components most responsive to this intervention. [3]

These findings should, however, be interpreted with caution. The review by Wyatt et al. does not indicate that vitamin D supplementation improves aerobic capacity in all athletes, but rather that beneficial effects were observed in selected studies under specific experimental conditions. [3] It may therefore be assumed that the most likely effect of vitamin D3 on aerobic performance is indirect, through improvement of muscle function, maintenance of proper calcium homeostasis, and mitigation of the consequences of deficiency, rather than through a direct and strong ergogenic action. Such an interpretation appears to be most consistent with the current state of knowledge. [3,5]

In addition to aerobic performance, another important area of research concerns the effect of vitamin D3 on muscle strength, power, and anaerobic performance parameters. Beyond the previously mentioned meta-analysis by Han et al., earlier meta-analyses have also indicated that the effect of supplementation on maximal strength and power is usually small and dependent on baseline vitamin D status. In the review by Wyatt et al., four of the six studies assessing sprint ability found no significant differences between the supplemented and control groups, suggesting that the effect of vitamin D on speed and short-duration explosive

performance may be limited or inconsistent. [3] At the same time, the authors noted that supplementation may confer some benefits with regard to anaerobic power and strength, especially in individuals with inadequate baseline vitamin D status. [3]

These conclusions are consistent with the 2023 meta-analysis by Sist et al., which included 11 randomized controlled trials involving 436 athletes. The authors did not demonstrate a statistically significant effect of vitamin D supplementation on improvements in maximal strength and power, emphasizing that the overall effect remains small and inconsistent. [41] In subgroup analyses, when baseline 25(OH)D concentration was below 75 nmol/L, the effect of supplementation on upper- and lower-body strength was small, although not statistically significant, whereas when baseline concentration was ≥75 nmol/L, the effect on muscle power was negligible. [41]

These findings reinforce the view that vitamin D3 supplementation is more relevant as an intervention aimed at correcting deficiency than as a method of enhancing performance in individuals with adequate vitamin D status. The most rational interpretation, therefore, is that vitamin D deficiency may indirectly limit athletic performance through impaired muscle function, greater susceptibility to microdamage, and reduced tolerance to training loads, whereas correction of the deficiency improves the biological conditions for training but does not automatically guarantee improvement in sports performance. From a practical perspective, this means that vitamin D3 deficiency may represent one of the factors limiting the development of muscle strength and power, but its role should be considered in conjunction with the overall training context, including the quality of strength training, energy availability, sleep, and the status of other nutrients. Vitamin D does not replace these elements, but it may influence the biological conditions necessary for their effective use. [3,41]

In summary, the current literature does not clearly confirm that vitamin D3 acts as a universal ergogenic factor. Its role in physical performance most likely becomes evident primarily through maintenance of normal musculoskeletal function and correction of existing deficiency. Potential benefits may concern selected parameters of aerobic capacity, strength, and power; however, their magnitude is variable and depends on the characteristics of the studied population, baseline 25(OH)D concentration, and the conditions under which the intervention is conducted. [3,5,41,42] For this reason, any benefits of supplementation should be interpreted with caution and always in relation to these determinants.

9. Vitamin D Deficiency and Immune Function in Athletes

Vitamin D3 plays an important immunomodulatory role, affecting both innate and adaptive immunity. This action is related, among other factors, to the presence of vitamin D receptors in immune cells such as lymphocytes, monocytes, and macrophages, as well as to its ability to regulate the expression of pro-inflammatory and anti-inflammatory mediators and the synthesis of antimicrobial peptides, including cathelicidin. In the context of sport, this is of particular importance because intense or prolonged exercise, especially when accompanied by insufficient recovery, may temporarily weaken immune surveillance and increase susceptibility to infection. [37,43]

The relationship between physical exercise, immunity, and vitamin D status is complex. Moderate physical activity may support an appropriate immune response, whereas chronically high training loads, particularly in the setting of inadequate recovery, may promote transient immunosuppression and increase susceptibility to infection. In the 2022 review by Crescioli, it was noted that the coexistence of hypovitaminosis D and excessive training load may result in the overlap of two factors that impair immune function, thereby increasing the risk of illness in physically active individuals. [43] In this context, maintaining adequate vitamin D status may have a supportive role in immune function in athletes, particularly during periods of high training load.

Interventional data suggest that vitamin D may favorably affect selected parameters of the immune response after exercise. In the 2023 study by Liu et al., it was shown that 4 weeks of vitamin D3 supplementation at a dose of 5000 IU per day in healthy men performing intense endurance exercise led to an increase in 25(OH)D concentration and was associated with a more favorable immunological profile, including changes in the CD4+/CD8+ ratio, as well as lower concentrations of IL-6, CK, and LDH after exercise. These findings suggest that adequate vitamin D status may help maintain immune balance and attenuate some of the adverse changes induced by very high exercise loads. However, this study does not directly address the incidence of infections in athletes; therefore, its significance should be interpreted primarily in relation to immunological mechanisms and post-exercise responses. [37]

One of the most frequently discussed practical aspects of the immunological action of vitamin D is its relationship with susceptibility to infections, especially acute respiratory infections. From a sports perspective, this issue is highly relevant because even short-term illness may disrupt training plans, limit participation in competition, and prolong the time needed to return to full readiness. Although the number of randomized studies conducted exclusively in athlete populations remains limited, available reviews concerning both athletes and the general

population suggest that low vitamin D status may be one of the factors increasing susceptibility to respiratory tract infections. [3,43,44,45]

In the 2024 systematic review by Wyatt et al., it was emphasized that although earlier studies suggested that vitamin D supplementation might safely reduce the risk of acute respiratory infections, the number of studies in elite sport remains too limited to support strong conclusions. At the same time, the authors noted that vitamin D deficiency remains common in athlete groups particularly exposed to limited UVB radiation, which strengthens the rationale for monitoring this factor in sports practice. [3]

Findings from meta-analyses conducted in the general population indicate that the potential protective effect of vitamin D supplementation against acute respiratory infections exists, but is probably modest and dependent on the clinical context. The 2021 meta-analysis by Jolliffe et al. demonstrated a small but statistically significant reduction in the risk of acute respiratory infection with vitamin D supplementation, with more favorable results observed particularly with daily dosing in the range of 400–1000 IU and in individuals with lower baseline vitamin D status. [44] In turn, the 2024 meta-analysis by Wang et al. suggested that the most promising protective potential may be associated with daily supplementation at doses of 400–1200 IU/day, especially during periods of limited cutaneous vitamin D synthesis, whereas bolus regimens did not show equally convincing effects. [46] At the same time, the 2025 update of the meta-analysis by Jolliffe et al., which included new studies, including large randomized trials, did not confirm a statistically significant protective effect in the overall analysis. [45] This suggests that any immunoprotective effect of vitamin D is more likely to be moderate and dependent on baseline status, supplementation regimen, season, and the characteristics of the study population, rather than strong and universal. [45,46]

At a more mechanistic level, data concerning cathelicidin are also of interest. In a randomized study published in 2024, the effect of vitamin D supplementation on acute respiratory infections and cathelicidin concentration was analyzed; the authors indicated that a possible protective effect of vitamin D may be mediated in part precisely through the induction of antimicrobial peptides. However, the clinical effect remained modest and dependent on baseline status. [47] From the perspective of athletes, this means that vitamin D may represent one of the factors supporting mucosal immunity and antimicrobial response, particularly under conditions of deficiency. [43,47]

In summary, maintaining adequate vitamin D status should be regarded as one of the factors supporting immune function in athletes, especially during periods of high training load and in groups at increased risk of deficiency. From a practical perspective, the greatest importance lies

in correcting existing deficiencies, which may contribute to a more favorable immune response and potentially reduce susceptibility to selected infections, including respiratory tract infections. However, this does not justify the routine use of supplementation as a universal method of "boosting immunity" in all athletes. It should also be emphasized that vitamin D supplementation does not replace the fundamental pillars of immune health, such as adequate energy availability, recovery, sleep, and appropriate management of training loads. [3,43]

10. Vitamin D Deficiency, Inflammatory Processes, and Exercise-Induced Stress

An important area of analysis regarding the role of vitamin D in athletes concerns its relationship with inflammatory processes activated in response to intense physical exercise. Under physiological conditions, the transient inflammatory response after training is part of the body's adaptation to exercise load; however, when this response is excessive or prolonged, it may disrupt post-exercise homeostasis, impair recovery, increase the extent of muscle microdamage, and reduce readiness for subsequent training sessions. For this reason, vitamin D is considered a potential modulator of the balance between pro-inflammatory and anti-inflammatory responses. [4,43]

A potential mechanism underlying this effect is related to the presence of the vitamin D receptor (VDR) in immune cells and muscle tissue, as well as to the influence of vitamin D on the expression of inflammatory mediators. Studies indicate that vitamin D may modulate markers such as interleukin 6 (IL-6) and tumor necrosis factor alpha (TNF-α), although the magnitude of this effect is not consistent across all populations. [3,4] Baseline 25(OH)D status may also be important, as more favorable effects are more often observed in individuals with deficiency. [4]

More recent experimental studies also point to the involvement of local mechanisms. A 2023 study demonstrated that physical exercise increases VDR expression in muscle, which may contribute to inhibition of IL-6 expression and STAT3 phosphorylation. This suggests that adequate vitamin D status may also help attenuate excessive post-exercise inflammatory responses through a direct effect on muscle tissue. [48]

Available data suggest that vitamin D deficiency may contribute to a less favorable inflammatory profile after exercise. In the 2022 study by Savolainen et al., 12 weeks of supplementation in young men with vitamin D deficiency improved the IL-10/TNF-α ratio, despite no improvement in cardiorespiratory fitness. [49] Similarly, Liu et al. showed in 2023 that vitamin D supplementation in healthy men performing intense endurance exercise was associated with lower post-exercise IL-6 concentrations, as well as lower creatine kinase and

lactate dehydrogenase values, which may indicate a relationship between vitamin D status, the magnitude of the inflammatory response, and the extent of muscle damage. [37] Findings from studies conducted in ultramarathon runners have been interpreted in a similar way, in which a single high dose of vitamin D administered before competition attenuated post-exercise changes in interleukin concentrations. [40]

At the same time, the current literature does not allow for a definitive conclusion that vitamin D exerts a strong and universal anti-inflammatory effect in athletes. A 2024 systematic review of randomized controlled trials showed that only some analyses reported significant changes in IL-6 and TNF-α concentrations after supplementation, whereas others found no clear effect. [4] Likewise, a review focused on post-exercise recovery indicated that the beneficial effects of supplementation more often relate to reducing muscle damage and improving recovery conditions than to a clear reduction in all inflammatory markers. [35,36]

From a practical perspective, low 25(OH)D status may impair the regulation of the post-exercise inflammatory response, particularly under conditions of high training load and in the presence of other stressors, such as insufficient recovery, high training volume, or low energy availability. This issue is highly relevant in sports practice, because an excessive or prolonged inflammatory response may aggravate muscle damage, lengthen recovery time, and reduce the ability to maintain high training quality. Available studies suggest that correction of vitamin D deficiency may help limit these unfavorable consequences, especially in individuals with low baseline 25(OH)D concentrations and those exposed to substantial exercise loads. [35,36] With regard to exercise-induced stress, vitamin D therefore appears to act as a factor supporting a more balanced biological response to training load, rather than as a specific anti-inflammatory agent. Its role should be interpreted as part of a broader strategy supporting recovery and exercise adaptation, including proper nutrition, adequate energy intake, sleep, recovery interventions, and rational management of training loads.

In summary, current evidence supports the view that vitamin D participates in the modulation of inflammatory processes in athletes, and that its deficiency may contribute to a stronger or more prolonged pro-inflammatory response after exercise. The most consistent data concern its influence on IL-6, and to some extent also TNF-α, although the magnitude of the effect depends on the population studied, the type of exercise, the supplementation dose, and baseline 25(OH)D status. The most justified conclusion at present is therefore a cautious one: adequate vitamin D status appears to support a more favorable post-exercise inflammatory response, but higher-quality intervention studies conducted directly in athlete populations are still needed. [4]

11. Discussion

Analysis of the available literature indicates that vitamin D plays an important role in maintaining athletes' health; however, its significance should be considered within a multifactorial framework. Vitamin D deficiency is also a common phenomenon in physically active populations, particularly among indoor athletes, those living or training at higher latitudes, during the autumn and winter months, and in groups at increased clinical risk, such as para-athletes. This shows that regular physical activity alone does not protect against inadequate vitamin D status.

The most convincing data concern the relationship between vitamin D and skeletal health. It is specifically in relation to bone overload injuries and bone stress injuries that the role of low 25(OH)D concentration appears to be best documented. From a practical perspective, this suggests that vitamin D deficiency should be regarded as one of the modifiable risk factors for injury, particularly in athletes burdened by additional factors such as high training loads, low energy availability, features of RED-S, or a previous history of bone injuries. At the same time, reduced 25(OH)D concentration should not be interpreted as an independent cause of injury, but rather as one element of a broader clinical picture.

With regard to the influence of vitamin D on muscle function, post-exercise recovery, immunity, and athletic performance, the findings remain less conclusive. Some authors point to potential benefits associated with adequate 25(OH)D concentration, particularly in the context of inflammatory response, muscle damage, and adaptation to exercise. However, the available evidence does not allow firm conclusions to be drawn, especially with respect to a direct effect on improving sports performance. It therefore appears more justified to regard vitamin D as a factor supporting health maintenance and appropriate adaptation to exercise rather than as an independent ergogenic factor.

Interpretation of the available findings is complicated by the substantial heterogeneity of the studies. This concerns both the populations and sports disciplines investigated, as well as the season of sample collection, the cut-off points adopted for deficiency, and the supplementation protocols used. Consequently, some of the associations reported in the literature should be considered more probable than definitively confirmed, and their clinical relevance should be assessed cautiously, with attention to the individual context of the athlete.

In light of current knowledge, the most justified approach appears to be an individualized one, based on assessment of 25(OH)D concentration in athletes belonging to risk groups and on the implementation of targeted prevention and supplementation. Such a strategy is more consistent

with the current state of knowledge than routinely treating vitamin D as a universal aid for performance, recovery, or immunity in all athletes.

12. Conclusions

Based on the literature reviewed, it can be concluded that vitamin D plays an important role in maintaining athletes' health, particularly in the context of proper musculoskeletal function. Deficiency of this vitamin is also common in physically active populations and may increase the risk of selected health problems and injuries, especially bone stress injuries.

The best-documented association remains that between low 25(OH)D concentration and impaired bone health, together with increased susceptibility to bone stress injuries. With regard to the effects of vitamin D on recovery, immunity, muscle function, and athletic performance, the findings are less conclusive, although they suggest that adequate vitamin D status may be important for maintaining exercise capacity and an appropriate physiological response to training loads.

Monitoring 25(OH)D concentration is of considerable practical importance, especially in athletes belonging to groups at increased risk of deficiency. Such an approach allows earlier identification of abnormalities and more rational planning of preventive and supplementation strategies.

Vitamin D should not be regarded as a universal agent for improving sports performance, but rather as an important factor supporting health, adaptation to exercise, and the prevention of selected injuries.

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The authors report no disclosures.

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