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Vitamin D and Post-Exercise Muscle Recovery: Current Evidence on Exercise-Induced Muscle Damage, Inflammation and Regeneration: a narrative review

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Abstract

Background. Vitamin D plays a pleiotropic role in skeletal muscle physiology and may influence regeneration, inflammation, and adaptation to exercise. Suboptimal vitamin D status is frequently reported among athletes.

Aim. To critically synthesize current evidence on the role of vitamin D in post-exercise skeletal muscle recovery, exercise-induced muscle damage (EIMD), and athletic performance.

Material and methods. A literature search of PubMed, Scopus, and Web of Science (2012–2026) identified studies on vitamin D and muscle recovery, EIMD, inflammation, and

performance. Given heterogeneity, findings were synthesized narratively; 32 publications were included.

Results. Skeletal muscle is a direct target of vitamin D signaling via receptors in myofibers and satellite cells. Findings on EIMD biomarkers and inflammation remain heterogeneous; benefits occur mainly with insufficient baseline 25(OH)D, though also reported in sufficient endurance athletes. Status varies with season, latitude, and sport type, and inadequacy is common. Evidence on injury risk is inconsistent overall but more consistent for stress fractures. Meta-analyses show no consistent ergogenic effect without deficiency.

Conclusions. Vitamin D is a supportive nutrient rather than a classical ergogenic aid. Effects depend largely on baseline status, supporting individualized supplementation.

Key words: vitamin D, muscle recovery, exercise-induced muscle damage, skeletal muscle, athletic performance, supplementation.

1. Introduction

Vitamin D is a pleiotropic secosteroid hormone involved in a wide range of physiological processes extending beyond its classical role in calcium and phosphorus metabolism, bone mineralization, and skeletal homeostasis [16,17]. In recent years, increasing attention has been directed toward its extra-skeletal functions, including modulation of immune responses, regulation of inflammation, mitochondrial activity, oxidative balance, cellular differentiation, and tissue repair processes [6,18,21,28]. These biological properties have contributed to growing interest in the potential role of vitamin D in sports medicine, particularly in relation to physiological adaptation and recovery following repeated exercise-induced stress.

Skeletal muscle has been identified as a target tissue for vitamin D action due to the expression of vitamin D receptors (VDR) in mature myofibers and satellite cells [6,21,28]. Vitamin D-dependent signaling pathways participate in processes associated with muscle metabolism, mitochondrial function, oxidative stress regulation, and the activity of myogenic precursor cells involved in muscle remodeling and regeneration [6,21,28]. Therefore, adequate vitamin D

status has been proposed as a potential factor influencing the physiological processes involved in maintaining skeletal muscle function and recovery following mechanical stress.

Efficient post-exercise recovery is a fundamental component of athletic performance, particularly in individuals exposed to high training volumes, repeated mechanical loading, and limited recovery intervals. Exercise-induced muscle damage (EIMD) represents a physiological response to strenuous exercise involving structural disruption of muscle fibers, temporary reductions in force production, delayed onset muscle soreness, and activation of inflammatory and repair pathways [1–3]. Although EIMD contributes to adaptive remodeling of skeletal muscle, excessive or prolonged disturbances in inflammatory regulation and repair processes may impair recovery kinetics and subsequent exercise capacity [1–3]. Consequently, understanding factors that may modulate recovery processes has become an important area of research in sports nutrition and exercise physiology.

Vitamin D status may represent one of the potentially modifiable factors influencing recovery-related mechanisms in athletes. Despite the assumption that physically active individuals, particularly those participating in outdoor sports, maintain adequate vitamin D concentrations, insufficient serum 25-hydroxyvitamin D [25(OH)D] levels remain frequently reported among athletic populations [20,30]. Vitamin D status is influenced by multiple factors, including sport discipline, geographical location, season, ultraviolet B (UVB) exposure, training environment, and dietary intake [20,23,30,32]. Athletes involved in indoor sports, individuals training at higher latitudes, and those exposed to limited sunlight may therefore represent groups at increased risk of inadequate vitamin D status despite high levels of physical activity [20,23,30].

The potential relationship between vitamin D and exercise recovery has been investigated through several biological and clinical approaches. Molecular studies have examined mechanisms involving VDR signaling, mitochondrial regulation, oxidative stress, and skeletal muscle regeneration [6,21,28]. Clinical investigations have evaluated whether vitamin D status or supplementation influences markers of EIMD, inflammatory responses, muscle function, and performance-related outcomes [1–5,8,9,13]. However, current findings remain heterogeneous due to differences in baseline vitamin D concentrations, supplementation protocols, exercise models, participant characteristics, and evaluated outcomes [1,2,10]. Therefore, the clinical relevance of vitamin D optimization for recovery in athletes remains incompletely established, with potential effects appearing more dependent on vitamin D status, supplementation

characteristics, and specific physiological outcomes rather than demonstrating consistent benefits across all athletic populations [1,2,8,9].

Accordingly, this narrative review aims to critically synthesize current evidence regarding the role of vitamin D in post-exercise muscle recovery in athletic populations. Particular emphasis is placed on the molecular mechanisms underlying vitamin D action, exercise-induced muscle damage biomarkers, inflammatory responses, skeletal muscle regeneration, factors influencing vitamin D status, supplementation strategies, and potential effects on functional performance outcomes.

2. Research Materials and Methods

The present study was conducted as a narrative review of the available literature regarding the role of vitamin D in post-exercise skeletal muscle recovery. A literature search was performed using the PubMed/MEDLINE, Scopus, and Web of Science databases. Publications published between 2012 and 2026 were considered eligible. Additionally, reference lists of relevant systematic reviews, meta-analyses, clinical guidelines, and consensus statements were manually screened to identify additional relevant sources.

The literature search was based on combinations of predefined search terms related to vitamin D and exercise recovery, including: "vitamin D," "cholecalciferol," "25(OH)D," "athletes," "exercise-induced muscle damage," "EIMD," "muscle recovery," "skeletal muscle regeneration," "inflammation," "athletic performance," and "supplementation." Only English-language publications were considered.

Eligible publications included peer-reviewed studies investigating vitamin D status or supplementation in relation to skeletal muscle function, exercise-induced muscle damage, inflammatory responses, recovery processes, musculoskeletal outcomes, or physical performance in athletic or physically active populations. Systematic reviews, meta-analyses, randomized controlled trials, observational studies, and relevant clinical guidelines or consensus statements were considered when they provided clinically or mechanistically relevant information regarding the relationship between vitamin D and exercise recovery.

Studies conducted exclusively in non-athletic clinical populations, conference abstracts, editorials, non-peer-reviewed publications, and studies unrelated to vitamin D status or exercise-related outcomes were excluded. The final narrative synthesis included 32 publications selected based on their scientific relevance, methodological characteristics, and contribution to understanding vitamin D-related mechanisms and clinical outcomes.

Due to substantial heterogeneity among available studies regarding participant characteristics, baseline vitamin D status, supplementation protocols, exercise modalities, and outcome measures, quantitative meta-analysis was not performed. Instead, findings were synthesized narratively to provide an integrated overview of molecular mechanisms, clinical outcomes, and practical considerations related to vitamin D and post-exercise recovery. As this study was designed as a narrative review without primary data collection, formal ethical approval was not required.

3. Results

3.1. Cellular and Molecular Mechanisms in Skeletal Muscle

Several interconnected biological pathways have been proposed to explain how vitamin D signaling may influence skeletal muscle recovery, ranging from direct receptor-mediated gene regulation to indirect effects on mitochondrial, immune, and metabolic function. At the cellular level, this begins with the expression of vitamin D receptors (VDR) in mature myofibers and satellite cells, which positions skeletal muscle as a direct biologically relevant target of vitamin D signaling [6,21,28]. Following muscle injury, VDR expression has been shown to increase markedly in regenerating muscle fibers, centrally located myonuclei, and activated satellite cells, suggesting an important role for vitamin D signaling during skeletal muscle regeneration [6]. Beyond its receptor-mediated actions, skeletal muscle itself constitutes a secondary reservoir of vitamin D metabolites, ranking behind adipose tissue in storage capacity. 25(OH)D is taken up and retained within myocytes through a vitamin D binding protein (DBP)-mediated megalin–cubulin transport mechanism, with intracellular retention facilitated by DBP binding to actin; intense exercise produces an immediate, transient increase in serum 25(OH)D, suggesting that muscle-stored vitamin D may be mobilized into the circulation during physical exertion [20]. This storage-and-release function indicates that skeletal muscle does not merely

respond to circulating vitamin D but may also actively contribute to its systemic availability during and after exercise—a mechanism that plausibly underlies the transient post-exercise fluctuations in serum 25(OH)D discussed in Section 3.3. Upon binding 1,25-dihydroxyvitamin D [1,25(OH)₂D], VDR activation operates through two distinct pathways. The genomic pathway regulates gene transcription promoting muscle cell proliferation and differentiation [19]. Simultaneously, rapid non-genomic pathways have been suggested to influence calcium handling and excitation–contraction coupling, potentially affecting muscle contractile function [19,21].

Satellite cells play a central role in skeletal muscle regeneration following exercise-induced damage through activation, proliferation, and differentiation into mature muscle fibers [6,28]. Current evidence indicates that vitamin D signaling may regulate satellite cell activity through modulation of myogenic regulatory factors, including MyoD and myogenin, which are essential for muscle repair processes [28]. More broadly, vitamin D receptor (VDR) signaling is strongly upregulated in satellite cells and central myonuclei during muscle regeneration, supporting a role for vitamin D in coordinating the myogenic repair program [6].

Vitamin D signaling has also been associated with mitochondrial function, oxidative metabolism, and cellular energy regulation [6,21]. Experimental evidence indicates that VDR deficiency impairs mitochondrial ATP production and maximal oxidative capacity independently of mitochondrial density, highlighting the importance of vitamin D for maintaining skeletal muscle bioenergetics [21]. Furthermore, vitamin D contributes to the regulation of antioxidant defense systems by reducing reactive oxygen species (ROS) production and limiting oxidative stress, processes considered relevant for recovery following exercise-induced muscle damage [21]. Notably, vitamin D deficiency disrupts mitochondrial function and exacerbates oxidative stress, activating proteolytic pathways involving muscle-specific E3 ligases such as Atrogin-1 and MuRF1 through the Src-ERK1/2-Akt-FOXO signaling cascade, ultimately contributing to skeletal muscle atrophy [21]. Conversely, experimental studies suggest that vitamin D signaling may attenuate these degradation pathways by reducing the expression of muscle-specific ubiquitin ligases involved in proteolysis [21,28].

Vitamin D may also contribute to recovery processes through immunomodulatory effects, as VDR-mediated signaling participates in the regulation of immune responses under physiological stress conditions [14,15].

Collectively, mechanistic evidence indicates that vitamin D is involved in several processes relevant to skeletal muscle recovery, including satellite cell-mediated regeneration, mitochondrial regulation, oxidative balance, and immune modulation [6,14,15,21,28]. However, the clinical relevance of these mechanisms depends on findings from human intervention studies and may vary according to baseline vitamin D status and exercise-related factors.

3.2. Biomarkers of Exercise-Induced Muscle Damage (EIMD)

Meta-analytical evidence indicates that the effects of vitamin D supplementation on EIMD biomarkers remain variable. Bello et al. concluded that current evidence is insufficient to confirm a universal beneficial effect of vitamin D supplementation on post-exercise muscle recovery. The authors suggested that the anti-inflammatory effects of vitamin D may occur earlier than measurable structural and functional muscle regeneration, while emphasizing that baseline serum 25(OH)D concentration appears to be a key determinant of the physiological response to supplementation [1]. Although several studies reported reductions in selected biomarkers of muscle damage, substantial heterogeneity in supplementation protocols, participant characteristics, exercise models, and baseline vitamin D status prevented definitive conclusions [1].

Similarly, Rojano-Ortega et al. reported that supplementation protocols providing at least 2000 IU/day for longer than one week were more likely to reduce exercise-induced muscle damage and inflammatory responses, although evidence supporting improvements in functional recovery remained limited [2].

Randomized controlled trials provide additional evidence supporting a potential association between vitamin D optimization and reduced EIMD responses. Pilch et al. demonstrated that in young men with suboptimal baseline 25(OH)D concentrations (<30 ng/mL), three months of individualized vitamin D supplementation was associated with significantly lower LDH activity one hour after downhill running (60% VO_2peak) compared with the non-supplemented suboptimal-status group. Myoglobin concentrations one hour post-exercise were also

numerically lower following supplementation; however, this reduction was not statistically significant between groups and was similarly observed in the non-supplemented suboptimal-status group, suggesting it may partly reflect the seasonal rise in vitamin D status common to both groups rather than a supplementation-specific effect. Likewise, the reduction in interleukin-1 β did not reach statistical significance in the between-group comparison. No significant between-group differences were observed for creatine kinase (CK) activity at any post-exercise time point [3].

Żebrowska et al. reported that three weeks of vitamin D₃ supplementation (2000 IU/day) in endurance athletes increased pre-exercise 25(OH)D concentrations (~40.3 ng/mL) and reduced myoglobin concentrations 1 hour after eccentric exercise. Moreover, serum 25(OH)D levels were inversely correlated with myoglobin elevation at 24 hours post-exercise ($r = -0.57$), indicating an association between vitamin D status and the magnitude of muscle damage response [13]. Liu et al. further demonstrated that four weeks of vitamin D₃ supplementation (5000 IU/day in an oil formulation), which increased mean serum 25(OH)D concentrations from 21.89 to 44.67 ng/mL, significantly attenuated CK and LDH responses at 4 and 24 hours following exhaustive cycling compared with placebo [4].

Overall, available evidence suggests that vitamin D optimization may influence selected biomarkers of EIMD, although findings within individual studies are often marker-specific rather than uniform across all measured biomarkers (e.g., LDH but not CK in [3]). While the most pronounced improvements are typically observed in individuals with insufficient baseline 25(OH)D concentrations [1,2,4,22], measurable attenuation of muscle damage markers has also been reported in endurance athletes with sufficient pre-supplementation status following severe eccentric loading [13]. Consequently, the magnitude of these effects ultimately depends on exercise characteristics, supplementation strategy, and initial vitamin D status.

3.3. Inflammatory Response and Immune Health

Strenuous exercise induces a transient inflammatory response involving cytokines such as interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF- α), and other mediators involved in skeletal muscle remodeling and recovery [4,14]. Due to its immunomodulatory properties, vitamin D has been investigated as a potential regulator of exercise-induced inflammatory responses, particularly in athletes exposed to repeated or prolonged physiological stress [4,5,15].

Furthermore, skeletal muscle is increasingly recognized as an endocrine and immunologically active tissue capable of releasing myokines during contraction, including IL-6 and other signaling molecules involved in metabolic regulation and immune communication [15]. Vitamin D may influence these processes through modulation of immune cell activity, inflammatory signaling pathways, and maintenance of physiological immune responses following exercise-induced stress [15]. Therefore, adequate vitamin D status may contribute to the regulation of post-exercise inflammatory adaptation; however, the extent of these effects appears dependent on baseline vitamin D concentrations, exercise characteristics, and individual physiological conditions [4,5,14,15].

Liu et al. demonstrated that four weeks of vitamin D₃ supplementation (5000 IU/day) reduced post-exercise inflammatory responses and attenuated exercise-induced immune perturbations following exhaustive cycling. Compared with placebo, supplemented participants exhibited lower IL-6 concentrations at 2, 4, and 24 hours after exercise together with a better-maintained CD4⁺/CD8⁺ T-cell ratio, suggesting attenuation of transient exercise-induced alterations in immune function [4].

Similar findings were reported by Żebrowska et al. following eccentric exercise in extreme endurance athletes with baseline 25(OH)D concentrations already within the optimal range (>30 ng/mL). Three weeks of vitamin D₃ supplementation (2000 IU/day) resulted in significantly lower maximal and 1-hour post-exercise TNF- α concentrations compared with pre-intervention values, along with a significantly lower 24-hour post-exercise IL-6 concentration compared with the placebo control group. Furthermore, serum 25(OH)D concentrations were negatively correlated with TNF- α levels 24 hours post-exercise ($r = -0.58$; $p < 0.05$), indicating an association between vitamin D status and inflammatory response magnitude, independent of baseline deficiency [13].

The interaction between strenuous exercise, inflammation, and vitamin D metabolism is highly dynamic. Intense eccentric contractions induce a systemic inflammatory response, which may influence transient changes in circulating vitamin D levels. Research has revealed that intense exercise causes immediate but transient fluctuations in serum 25(OH)D concentrations. Specifically, acute post-exercise decreases in 25(OH)D were associated with concurrent increases in pro-inflammatory cytokines, such as interferon-gamma (IFN- γ), whereas increases in circulating albumin were associated with transient elevations in 25(OH)D [29]. This suggests

that exercise-induced muscular weakness and inflammation may temporarily alter vitamin D mobilization and metabolism in athletes, further complicating the assessment of vitamin D status immediately following severe mechanical loading.

The effects of vitamin D supplementation have also been evaluated during prolonged endurance exercise. Mieszkowski et al. reported that a single acute oral dose of 150,000 IU vitamin D₃ administered 24 hours before a 240-km ultramarathon significantly attenuated post-race increases in inflammatory and immune-related markers, including IL-6, IL-10, and resistin, compared with placebo [5]. Additionally, a systematic review by Saedmocheshi et al., which included six RCTs conducted exclusively in athletes with sufficient baseline vitamin D status, found that only two of the six trials reported significant reductions in IL-6 and TNF- α following supplementation, while the remaining four studies showed no significant change in these cytokines; the authors attributed this inconsistency primarily to differences in vitamin D dosage, participant age, and intervention duration, rather than to baseline vitamin D status, since none of the included cohorts were vitamin D-deficient [14].

Overall, current evidence suggests that vitamin D supplementation may modulate selected inflammatory and immune markers following strenuous exercise, particularly in individuals with suboptimal vitamin D status [4,5,13]. However, the magnitude of these effects remains inconsistent even among athletes with sufficient baseline vitamin D status, and appears to depend on supplementation dose, duration, and exercise type rather than baseline status alone [14].

3.4. Vitamin D Status: Seasonal and Environmental Variations

Vitamin D insufficiency is frequently reported among athletes and is influenced by environmental conditions, seasonal variation, and sport-specific characteristics [20,30]. Endogenous vitamin D synthesis depends primarily on ultraviolet B (UVB) exposure, which is affected by latitude, atmospheric conditions, season, and time spent outdoors [18]. Interestingly, inadequate exposure and dietary intake alone may not fully explain the high prevalence of deficiency in athletes [20]. Recent evidence suggests that high training loads may contribute to alterations in vitamin D metabolism and increased risk of insufficient status among athletes [20].

Farrokhyar et al. reported a high prevalence of vitamin D inadequacy among athletes, with increased risk observed in populations exposed to limited sunlight availability, including athletes participating in predominantly indoor sports [30]. Seasonal fluctuations further contribute to variability in serum 25(OH)D concentrations, with athletes generally exhibiting higher concentrations during periods of greater sunlight availability and lower concentrations during winter months, as discussed by Owens et al. [23].

Giustina et al. emphasized that limited UVB exposure, higher latitude, and restricted outdoor activity increase the risk of vitamin D insufficiency [18]. Similarly, Ip et al. highlighted that geographical location, training environment, and sport-specific demands contribute to differences in serum 25(OH)D concentrations, indicating that some athletic populations may require closer monitoring of vitamin D status throughout the year [20].

Overall, available evidence indicates that vitamin D status in athletes is highly dependent on environmental, seasonal, and physiological factors. Reduced UVB exposure during winter periods, participation in predominantly indoor sports, and training-induced storage depletion represent important determinants of suboptimal 25(OH)D concentrations in athletic populations [18,20]. These observations are further supported by a recent systematic review, which highlighted seasonal fluctuations in serum 25(OH)D concentrations as an important factor influencing both vitamin D status and the effectiveness of supplementation strategies in athletes [23,26].

3.5. Vitamin D Status, Musculoskeletal Injury Risk, and Recovery Outcomes

Clinical guidelines differ significantly in their approach to defining and managing vitamin D status. The 2023 Polish guidelines define vitamin D deficiency as serum 25(OH)D concentrations ≤ 20 ng/mL (≤ 50 nmol/L), concentrations of >20 – 30 ng/mL (50 – 75 nmol/L) as suboptimal, and values between 30 and 50 ng/mL (75 – 125 nmol/L) as optimal [16]. In contrast, the 2024 Endocrine Society Clinical Practice Guideline no longer endorses specific 25(OH)D levels to define vitamin D sufficiency, insufficiency, or deficiency. Furthermore, the Endocrine Society explicitly suggests against routine 25(OH)D testing in generally healthy populations, recommending a risk-based approach rather than universal target-driven screening [17].

Inadequate vitamin D status has also been associated with impaired muscle function and altered musculoskeletal health, factors that may indirectly influence injury susceptibility and athletic

performance [20,24]. Vitamin D contributes to calcium homeostasis, bone metabolism, and skeletal muscle function, which are relevant for maintaining musculoskeletal integrity during intensive training [20,24]. Ip et al. reported differences in vitamin D status between sporting disciplines, with higher prevalence of inadequacy observed particularly among athletes participating in power and water sports compared with some other athletic populations [20]. These findings highlight that vitamin D status varies according to sport-specific characteristics, training environment, and lifestyle factors rather than following a uniform pattern across all athletic disciplines.

Interpretation of vitamin D status in athletes may also be complicated by individual biological variability, including genetic differences affecting vitamin D transport and metabolism. Variations in vitamin D-binding protein (VDBP) concentrations and binding affinity may influence the relationship between total serum 25(OH)D concentrations and biologically available vitamin D [23]. This may be particularly relevant when comparing populations with different genetic backgrounds, as differences in total 25(OH)D concentrations do not always correspond to differences in functional vitamin D availability. Therefore, reliance solely on total serum 25(OH)D concentrations may not fully capture individual differences in vitamin D physiology and musculoskeletal risk [23,24].

Vitamin D insufficiency has also been investigated as a potential risk factor for musculoskeletal injuries in athletic populations. Evidence regarding general injury risk and muscle function remains inconsistent, with the association appearing to be influenced by multiple factors, including training load, sport type, and calcium availability [20,24]. Notably, evidence specifically concerning stress fractures has been more consistent, with several studies indicating that vitamin D supplementation may reduce their incidence in at-risk athletic populations [24].

Vitamin D status has also been investigated in relation to recovery following muscle damage. Barker et al. reported that higher serum 25(OH)D concentrations were associated with faster recovery of skeletal muscle strength after exercise-induced muscle injury, suggesting a potential relationship between vitamin D status and recovery kinetics [29]. However, current evidence remains heterogeneous due to differences in participant characteristics, baseline vitamin D status, injury models, and evaluated recovery outcomes [24,29].

Overall, available evidence indicates that vitamin D status may influence musculoskeletal health and recovery processes in athletes, although the strength of these associations depends

on population characteristics and clinical context. Accordingly, current evidence supports individualized interpretation of vitamin D status rather than universal threshold-based approaches [16–18].

3.6. Functional Performance Outcomes Following Vitamin D Optimization

Vitamin D status has been extensively investigated as a potential determinant of functional performance in athletes, particularly with respect to muscular strength, power production, and exercise capacity. Due to the expression of vitamin D receptors in skeletal muscle, vitamin D availability has been proposed to influence neuromuscular function and physical performance outcomes [7,19]. Consequently, inadequate vitamin D status has been associated with impaired muscle function and reduced physical performance outcomes [7,9,19].

Several meta-analyses have evaluated whether vitamin D supplementation influences strength-related outcomes in athletes. Dahlquist et al. proposed biologically plausible ergogenic mechanisms, suggesting that optimization of vitamin D status may enhance force production by increasing calcium sensitivity within the sarcoplasmic reticulum and thereby improving excitation-contraction coupling and cross-bridge cycling [7]. However, the authors also emphasized that clinical evidence supporting these mechanisms remains limited. Zhang et al. reported that vitamin D supplementation was associated with improvements in lower-limb muscle strength among athletes; however, no significant effects were observed for upper-limb strength or muscle power outcomes [9].

Evidence regarding endurance performance remains limited and inconsistent. Knechtle and Nikolaidis discussed vitamin D as a factor potentially associated with sport performance, including endurance-related outcomes; however, their editorial did not provide evidence from intervention studies demonstrating improvements in endurance capacity following supplementation [12]. Current clinical evidence does not support a consistent ergogenic effect of vitamin D supplementation on endurance performance, particularly among athletes without baseline vitamin D insufficiency [9,26].

Overall, available evidence does not support a consistent ergogenic effect of vitamin D supplementation in athletes. Benefits appear most likely among individuals with low baseline 25(OH)D concentrations and are influenced by supplementation dose, duration, exercise modality, and individual athlete characteristics [8–12,19,26].

3.7. Supplementation Protocols and Safety

Vitamin D supplementation studies in athletic populations demonstrate considerable variability regarding dosage, formulation, duration, and monitoring strategies. The response to supplementation depends on baseline serum 25(OH)D concentrations, environmental factors, training conditions, and individual characteristics, as emphasized in vitamin D-specific and broader sports nutrition literature [10,25,31,32].

Regarding vitamin D formulation, evidence indicates that cholecalciferol (vitamin D₃) is more effective than ergocalciferol (vitamin D₂) in increasing and maintaining circulating 25(OH)D concentrations. Tripkovic et al. demonstrated that this difference was particularly evident during intermittent high-dose supplementation protocols, supporting the greater efficacy of vitamin D₃ in improving vitamin D status [31].

Supplementation protocols used in athletes include both daily maintenance regimens and intermittent high-dose approaches; however, no single strategy has been consistently demonstrated to be superior across all athletic populations [10,25]. Wyatt et al. reported substantial heterogeneity in supplementation protocols investigated among elite athletes, including differences in dosage, duration, and monitoring strategies [10]. The increase in serum 25(OH)D concentrations appears to be influenced by baseline status, with individuals presenting lower initial concentrations generally showing greater responses to supplementation [23,25].

Although vitamin D supplementation is generally considered safe, indiscriminate use of high-dose regimens is discouraged. Emerging evidence indicates that excessive dosing can trigger unintended compensatory physiological mechanisms [23]. For example, administering extremely high doses of vitamin D₃ (e.g., 70,000 IU/week) to elite athletes effectively raises both 25(OH)D and 1,25(OH)₂D, but it simultaneously triggers a significant increase in the catabolic product 24,25(OH)₂D. Notably, this catabolic metabolite can remain elevated even after supplementation ceases, potentially reducing the availability of 25(OH)D for conversion to its active form through enhanced catabolic activity. Additionally, high-dose supplementation has been shown to induce compensatory decreases in parathyroid hormone (PTH) [23]. Therefore, current guidelines emphasize that supplementation strategies should be highly individualized, prioritizing the correction of measured deficiencies rather than employing very

high-dose supplementation in an attempt to optimize already sufficient vitamin D levels [16–18,23].

4. Discussion

4.1. From Molecular Mechanisms to Clinical Outcomes: Bridging the Translational Gap

Molecular and experimental studies provide a strong biological rationale for the involvement of vitamin D in skeletal muscle physiology and recovery. The expression of vitamin D receptors (VDR) in mature myofibers and satellite cells indicates that skeletal muscle is a direct target of vitamin D signaling [6,28]. Through VDR-mediated pathways, vitamin D may influence processes relevant to recovery, including regulation of myogenic factors such as MyoD and myogenin [28], as well as satellite cell activity, mitochondrial function, and oxidative stress responses [6,21,28]. However, translating these mechanistic findings into clinically meaningful improvements remains challenging. Skeletal muscle recovery is a complex process influenced by the magnitude of exercise-induced muscle damage (EIMD), inflammatory responses, training status, and individual biological variability [22,29]. Current evidence suggests that the effects of vitamin D on muscle recovery are largely status-dependent, with measurable responses appearing more likely in individuals with insufficient baseline 25(OH)D concentrations, whereas additional supplementation in vitamin D-sufficient individuals generally provides more limited measurable effects [1,2]. Furthermore, the potential role of vitamin D may vary depending on the type of tissue stress or injury. Although associations have been observed between vitamin D status, eccentric exercise-induced muscle damage markers, and selected musculoskeletal outcomes, evidence from other injury models remains inconsistent, highlighting the complexity of translating molecular mechanisms into clinical outcomes [24,28,29]. Therefore, vitamin D should be considered as one component of a broader physiological network regulating recovery rather than as an independent determinant of muscle regeneration.

4.2. Heterogeneity of Findings Regarding EIMD and Inflammatory Responses

The current evidence regarding vitamin D and exercise-induced muscle damage (EIMD) remains heterogeneous. Although mechanistic studies and intervention trials indicate that

vitamin D may influence inflammatory mediators and biochemical markers of muscle damage, including IL-6, TNF- α , CK, LDH, and myoglobin, the magnitude and clinical relevance of these effects remain inconsistent [1,3,5,13].

Several factors may contribute to these discrepancies. Baseline vitamin D status appears to be one of the most important determinants of response, as individuals with insufficient 25(OH)D concentrations appear more likely to demonstrate measurable responses following supplementation compared with vitamin D-sufficient individuals [1,2]. Additionally, individual variability in vitamin D receptor (VDR) genotype has been proposed as a potential source of heterogeneity in physiological responses to supplementation, although this factor remains insufficiently explored in athletic populations [9]. However, recent evidence suggests that short-term supplementation may still attenuate muscle damage and inflammatory responses in extreme endurance athletes even when baseline 25(OH)D levels are already sufficient, indicating that specific training demands might temporarily increase physiological requirements [13]. In addition, differences in exercise protocols, including eccentric damage models and prolonged endurance activities, may generate distinct mechanical and inflammatory responses that influence the observed outcomes [3,5,13].

Interpretation of EIMD biomarkers also requires caution, as reductions in CK, LDH, or myoglobin reflect aspects of muscle damage but do not fully represent the complex processes underlying structural regeneration and functional recovery [3,5,13]. Future studies should therefore combine biochemical markers with functional outcomes and apply standardized exercise protocols while stratifying participants according to baseline vitamin D status [1–5,13,14].

4.3. Vitamin D Management: A Risk-Based, Individualized Approach

Vitamin D management in athletes should reconcile differing regional recommendations with a consistent, practical principle: assessment and supplementation should be individualized rather than applied uniformly. The 2023 Polish guidelines recommend assessing serum 25(OH)D in individuals at increased risk of deficiency and adjusting supplementation to baseline status and clinical circumstances [16]. In contrast, the 2024 Endocrine Society guideline advises against routine population-wide 25(OH)D testing and does not define universal thresholds for optimal status in healthy adults, citing insufficient evidence for universal targets and concerns about unnecessary testing [17,18]. Despite this divergence, both

frameworks converge on a risk-based approach: targeted assessment remains clinically relevant for athletes exposed to recognized risk factors — limited UVB exposure, indoor training environments, high latitude, or other sport-specific conditions [16–18,20].

Current evidence does not support a universally optimal 25(OH)D concentration for athletic performance, nor does it justify targeting supraphysiological concentrations in vitamin D-sufficient individuals; such practice offers no proven benefit and may introduce unnecessary risk [9,16,17,18,26,32]. From a practical standpoint, vitamin D management should therefore focus on identifying and correcting insufficiency, and be integrated into a broader athlete support framework encompassing nutrition, training-load management, and recovery monitoring — rather than used as an independent, universal strategy for enhancing recovery or performance [16,20,32].

4.4. Ergogenic Agent or Correction of Deficiency?

The potential role of vitamin D as an ergogenic aid requires careful interpretation. Observational associations between higher serum 25(OH)D concentrations and better performance outcomes do not establish causality and may be influenced by multiple physiological, behavioral, and environmental factors, including training status, outdoor exposure, and overall health [7,19]. Randomized controlled trials suggest that potential improvements in selected performance-related outcomes are more likely among individuals with insufficient baseline 25(OH)D concentrations; however, meta-analytical evidence has not demonstrated consistent benefits across different domains of athletic performance, including strength and power [8,9,11].

A key distinction should therefore be made between correcting vitamin D insufficiency to restore normal physiological function and attempting to enhance performance beyond normal capacity in vitamin D-sufficient individuals. This principle parallels observations from the skeletal health literature: Abrahamsen and Harvey [27], commenting on musculoskeletal (bone) outcomes, emphasized that further vitamin D trials in populations without confirmed deficiency

are unlikely to be justified, as supplementation provides little benefit once adequate status is achieved. A comparable pattern — limited benefit in the absence of deficiency — appears to hold for muscle-related outcomes in athletes [8,9,11].

4.5. Limitations and Future Research Directions

Current evidence regarding vitamin D and exercise recovery is limited by substantial methodological heterogeneity. Differences in definitions of vitamin D status, supplementation protocols, participant characteristics, and monitoring strategies complicate direct comparisons between studies [10,16–18]. Notably, many intervention studies in this field have been conducted predominantly or exclusively in male athletes [3,4,5], limiting the generalizability of current findings to female athletic populations and highlighting the need for sex-balanced study designs in future research. In particular, variability in baseline 25(OH)D concentrations and the use of different supplementation regimens, including differences in dose, duration, and formulation, may substantially influence observed outcomes [10,25,31].

Many intervention studies are also limited by relatively small sample sizes, short follow-up periods, and the use of isolated exercise models that may not be fully generalizable to real-world athletic settings [3,5,10,13,14]. Furthermore, commonly used biomarkers of exercise-induced muscle damage, such as CK, LDH, and myoglobin, provide valuable information regarding tissue stress but do not independently capture the processes underlying muscle regeneration, remodeling, or functional recovery [3,5,13].

Future research should therefore prioritize well-designed randomized controlled trials with standardized exercise protocols, stratification according to baseline vitamin D status, and longer-term monitoring of functional outcomes. Integrating biochemical markers with direct assessments of strength recovery, performance measures, and injury-related outcomes may help determine the specific conditions under which vitamin D optimization provides clinically meaningful benefits for athletes [6,28].

5. Conclusions

Current evidence supports a biologically plausible but clinically nuanced role for vitamin D in post-exercise skeletal muscle recovery. The expression of vitamin D receptors in mature

myofibers and satellite cells indicates that skeletal muscle is a target tissue for vitamin D signaling, which may influence processes involved in muscle adaptation, including myogenic regulation, mitochondrial function, oxidative balance, and immune modulation [6,14,15,21,28]. However, the translation of these molecular mechanisms into consistent clinical benefits remains incomplete. Available intervention studies indicate that vitamin D optimization may influence selected biomarkers of exercise-induced muscle damage (EIMD), such as CK, LDH, and myoglobin, as well as inflammatory mediators like IL-6 and TNF- α , particularly among individuals with insufficient baseline 25(OH)D concentrations. In contrast, routine supplementation in vitamin D-sufficient athletes generally provides more limited measurable effects [1,2], although targeted optimization in extreme endurance athletes exposed to severe mechanical loading may still attenuate post-exercise muscle damage and inflammation even when baseline levels are adequate [13]. Current evidence does not support vitamin D as a universal ergogenic intervention. Although supplementation may improve selected aspects of muscular function in individuals with inadequate vitamin D status, meta-analytical data have not demonstrated consistent improvements in maximal strength, power, or endurance performance among athletes without baseline vitamin D insufficiency [7–9,11,12,19,26]. Similarly, while adequate vitamin D status may contribute to musculoskeletal health and recovery processes, evidence supporting a direct causal role in injury prevention remains insufficient [24,29,30]. Therefore, vitamin D should primarily be considered a nutrient required for maintaining physiological skeletal muscle function rather than a performance-enhancing agent. Its clinical relevance in athletes appears greatest in individuals at increased risk of deficiency, where targeted assessment and individualized supplementation may help restore adequate status and support normal adaptation to training [16–19,26]. Current guidelines emphasize risk-based approaches rather than universal screening or supplementation strategies in healthy populations [16–18]. Future research should focus on well-designed randomized controlled trials using standardized exercise models, stratification according to baseline vitamin D status, and comprehensive functional outcomes to determine the specific conditions under which vitamin D optimization meaningfully contributes to post-exercise recovery and long-term athletic health.

Disclosure

Supplementary Materials

Not applicable.

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References

1. Bello HJ, Caballero-García A, Pérez-Valdecantos D, Roche E, Noriega DC, Córdova A. Effects of vitamin D in post-exercise muscle recovery: a systematic review and meta-analysis. *Nutrients*. 2021;13(11):4013. <https://doi.org/10.3390/nu13114013>
2. Rojano-Ortega D, Berral-de la Rosa FJ. Effects of vitamin D supplementation on muscle function and recovery after exercise-induced muscle damage: a systematic review. *J Hum Nutr Diet*. 2023;36(3):1068-1078. <https://doi.org/10.1111/jhn.13084>
3. Pilch W, Kita B, Piotrowska A, et al. The effect of vitamin D supplementation on the muscle damage after eccentric exercise in young men: a randomized, control trial. *J Int Soc Sports Nutr*. 2020;17(1):53. <https://doi.org/10.1186/s12970-020-00386-1>
4. Liu MC, Weng PW, Chien LH, Kumar S, Yang MT. Immunologic, anti-inflammatory, and anti-muscle damage profile of supplemented vitamin D3 in healthy adults on strenuous endurance exercise. *Biology (Basel)*. 2023;12(5):657. <https://doi.org/10.3390/biology12050657>
5. Mieszkowski J, Kochanowicz A, Niespodziński B, et al. Single high-dose vitamin D supplementation as an approach for reducing ultramarathon-induced inflammation. *Nutrients*. 2021;13(4):1280. <https://doi.org/10.3390/nu13041280>
6. Latham CM, Brightwell CR, Keeble AR, et al. Vitamin D Promotes Skeletal Muscle Regeneration and Mitochondrial Health. *Front Physiol*. 2021;12:660498. <https://doi.org/10.3389/fphys.2021.660498>
7. Dahlquist DT, Dieter BP, Koehle MS. Plausible ergogenic effects of vitamin D on athletic performance and recovery. *J Int Soc Sports Nutr*. 2015;12:33. <https://doi.org/10.1186/s12970-015-0093-8>
8. Sist M, Zou L, Galloway SDR, Rodriguez-Sanchez N. Effects of vitamin D supplementation on maximal strength and power in athletes: a systematic review and

- meta-analysis of randomized controlled trials. *Front Nutr.* 2023;10:1163313. <https://doi.org/10.3389/fnut.2023.1163313>
9. Zhang L, Quan M, Cao ZB. Effect of vitamin D supplementation on upper and lower limb muscle strength and muscle power in athletes: A meta-analysis. *PLoS One.* 2019 Apr 30;14(4):e0215826. <https://doi.org/10.1371/journal.pone.0215826>
 10. Wyatt PB, Reiter CR, Satalich JR, et al. Effects of Vitamin D Supplementation in Elite Athletes: A Systematic Review. *Orthop J Sports Med.* 2024;12(1):23259671231220371. <https://doi.org/10.1177/23259671231220371>
 11. Han Q, Li X, Tan Q, Shao J, Yi M. Effects of vitamin D3 supplementation on serum 25(OH)D concentration and strength in athletes: a systematic review and meta-analysis of RCTs. *J Int Soc Sports Nutr.* 2019;16(1):55. <https://doi.org/10.1186/s12970-019-0323-6>
 12. Knechtle B, Nikolaidis PT. Vitamin D and Sport Performance. *Nutrients.* 2020;12(3):841. <https://doi.org/10.3390/nu12030841>
 13. Żebrowska A, Sadowska-Krępa E, Stanula A, et al. The effect of vitamin D supplementation on serum total 25(OH) levels and biochemical markers of skeletal muscles in runners. *J Int Soc Sports Nutr.* 2020;17(1):18. <https://doi.org/10.1186/s12970-020-00347-8>
 14. Saedmocheshi S, Amiri E, Mehdipour A, Stefani GP. The Effect of Vitamin D Consumption on Pro-Inflammatory Cytokines in Athletes: A Systematic Review of RCTs. *Sports (Basel).* 2024;12(1):32. <https://doi.org/10.3390/sports12010032>
 15. Crescioli C. Vitamin D, exercise, and immune health in athletes: a narrative review. *Front Immunol.* 2022;13:954994. <https://doi.org/10.3389/fimmu.2022.954994>
 16. Płudowski P, Kos-Kudła B, Walczak M, et al. Guidelines for Preventing and Treating Vitamin D Deficiency: A 2023 Update in Poland. *Nutrients.* 2023;15(3):695. <https://doi.org/10.3390/nu15030695>
 17. Demay MB, Pittas AG, Bikle DD, et al. Vitamin D for the Prevention of Disease: An Endocrine Society Clinical Practice Guideline. *J Clin Endocrinol Metab.* 2024;109(8):1907-1947. <https://doi.org/10.1210/clinem/dgae290>
 18. Giustina A, Bouillon R, Binkley N, et al. Consensus Statement on Vitamin D Status Assessment and Supplementation. *Endocr Rev.* 2024;45(5):625-654. <https://doi.org/10.1210/endrev/bnae009>

19. de la Puente Yagüe M, Collado Yurrita L, Ciudad Cabañas MJ, Cuadrado Cenxual MA. Role of Vitamin D in Athletes and Their Performance: Current Concepts and New Trends. *Nutrients*. 2020;12(2):579. <https://doi.org/10.3390/nu12020579>
20. Ip TS, Fu SC, Ong MT, Yung PS. Vitamin D deficiency in athletes: Laboratory, clinical and field integration. *Asia Pac J Sports Med Arthrosc Rehabil Technol*. 2022;29:22-29. <https://doi.org/10.1016/j.asmart.2022.06.001>
21. Dzik KP, Kaczor JJ. Mechanisms of vitamin D on skeletal muscle function: oxidative stress, energy metabolism and anabolic state. *Eur J Appl Physiol*. 2019;119:825–839. <https://doi.org/10.1007/s00421-019-04104-x>
22. Caballero-García A, Córdova-Martínez A, Vicente-Salar N, Roche E, Pérez-Valdecantos D. Vitamin D, Its Role in Recovery after Muscular Damage Following Exercise. *Nutrients*. 2021;13(7):2336. <https://doi.org/10.3390/nu13072336>
23. Owens DJ, Allison R, Close GL. Vitamin D and the Athlete: Current Perspectives and New Challenges. *Sports Med*. 2018 Mar;48(Suppl 1):3-16. <https://doi.org/10.1007/s40279-017-0841-9>
24. Maai N, Frank FA, Meuris A, Ferreira N. Association Between Vitamin D and Musculoskeletal Injuries: A Systematic Review. *Cureus*. 2025 Apr 18;17(4):e82495. <https://doi.org/10.7759/cureus.82495>
25. Rawson ES, Miles MP, Larson-Meyer DE. Dietary Supplements for Health, Adaptation, and Recovery in Athletes. *Int J Sport Nutr Exerc Metab*. 2018;28(2):188-199. <https://doi.org/10.1123/ijsnem.2017-0340>
26. Maai N, Frank FA, Meuris A, Ferreira N. Effect of Vitamin D on athletic performance: A systematic review. *J Hum Sport Exerc*. 2025;20(3):771-786. <https://doi.org/10.55860/r03ayc39>
27. Abrahamsen B, Harvey NC. Vitamin D supplementation for musculoskeletal health outcomes in adults - The end of the beginning? *Maturitas*. 2019 Apr;122:87-88. <https://doi.org/10.1016/j.maturitas.2018.10.011>
28. Agoncillo M, Yu J, Gunton JE. The Role of Vitamin D in Skeletal Muscle Repair and Regeneration in Animal Models and Humans: A Systematic Review. *Nutrients*. 2023;15(20):4377. <https://doi.org/10.3390/nu15204377>
29. Barker T, Henriksen VT, Martins TB, et al. Higher serum 25-hydroxyvitamin D concentrations associate with a faster recovery of skeletal muscle strength after muscular injury. *Nutrients*. 2013;5(4):1253-75. <https://doi.org/10.3390/nu5041253>

30. Farrokhyar F, Tabasinejad R, Dao D, et al. Prevalence of Vitamin D Inadequacy in Athletes: A Systematic-Review and Meta-Analysis. *Sports Med.* 2015;45(3):365-78. <https://doi.org/10.1007/s40279-014-0267-6>
31. Tripkovic L, Lambert H, Hart K, et al. Comparison of vitamin D2 and vitamin D3 supplementation in raising serum 25-hydroxyvitamin D status: a systematic review and meta-analysis. *Am J Clin Nutr.* 2012;95(6):1357-64. <https://doi.org/10.3945/ajcn.111.031070>
32. Maughan RJ, Burke LM, Dvorak J, et al. IOC Consensus Statement: Dietary Supplements and the High-Performance Athlete. *Int J Sport Nutr Exerc Metab.* 2018;28(2):104-125. <https://doi.org/10.1123/ijsnem.2018-0020>