REVIEW ARTICLE

Effect of Vitamin D on athletic performance: A systematic review

Nader Maai . *Center for Musculoskeletal Infections (ZMSI). University Hospital Basel. Basel, Switzerland. Department of Orthopedic and Trauma Surgery. University Hospital Basel. Basel, Switzerland.*
Florian A. Frank. *Center for Musculoskeletal Infections (ZMSI). University Hospital Basel. Basel, Switzerland. Department of Orthopedic and Trauma Surgery. University Hospital Basel. Basel, Switzerland.*
Arthur Meuris. *KL Leuven. Leuven, Belgium.*
Nando Ferreira. *Division of Orthopaedic Surgery. Department of Surgical Sciences. Faculty of Medicine and Health Sciences. Stellenbosch University. Cape Town, South Africa.*

ABSTRACT

Vitamin D is essential for optimal athletic performance; however, the evidence for its effect on athletic performance remains inconclusive. This systematic review aimed to investigate the effect of vitamin D supplementation on athletic performance in athletes. A comprehensive and systematic search of six electronic databases was conducted in accordance with PRISMA reporting guidelines, using a combination of Boolean operators and MeSH keywords. A total of 13 studies were included in the review. The included studies demonstrated that vitamin D supplementation consistently elevates serum 25(OH)D levels in athletes. A subset of the included studies reported significant improvements in athletic performance following the administration of vitamin D supplements, particularly in those athletes with low vitamin D status initially. Another cluster of studies focused on the effects of vitamin D supplementation on parameters of haematological and muscle recovery, with mixed results. Additionally, there were observations of seasonal fluctuations in vitamin D levels, which highlight the importance of considering the timing of supplementation. Vitamin D supplementation has been linked to improved athletic performance, particularly in athletes with low initial vitamin D status. However, the impact of this intervention is influenced by individual characteristics, the type of exercise, and the specific dosage and duration of supplementation. To gain a more comprehensive understanding of the mechanisms and optimal protocols for vitamin D supplementation in athletes, further research is required.

Keywords: Vitamin D, Athletic performance, Supplementation, Systematic review, Athletes.

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Corresponding author. *Centre for Musculoskeletal Infections (ZMSI), University Hospital Basel, Basel, Switzerland, Department of Orthopedic and Trauma Surgery, University Hospital Basel, Basel, Switzerland.*
E-mail: NaderMaai@gmail.com
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INTRODUCTION

Researchers and clinicians have long been interested in understanding the complex relationship between diet and exercise outcomes, particularly the intricate connection between nutrition and athletic performance (Holick et al., 2011). Micronutrients have garnered significant attention in this context, as even small excesses or deficiencies can greatly impact sports performance (Książek et al., 2019). Among these, vitamin D—a fat-soluble secosteroid hormone—stands out as crucial for maintaining normal physiological function. It plays a key role in immune system performance, musculoskeletal health, and overall well-being (Bikle, 2009; Wiciński et al., 2019).

Vitamin D is a crucial regulator of calcium metabolism, essential for maintaining muscle strength, power, and endurance (Trybek et al., 2018). It also plays a fundamental role in modulating muscle function (Lai & Fang, 2013). The vitamin D receptor, a nuclear receptor present in various tissues including skeletal muscle, regulates the expression of genes involved in muscle growth, differentiation, and function (Grant, 2020; Kopeć et al., 2013). Additionally, vitamin D is implicated in the regulation of inflammatory responses, with its anti-inflammatory properties potentially mitigating oxidative stress and muscle damage associated with exercise (Bezuglov, Tikhonova, Zueva, Khaitin, Lyubushkina, et al., 2019; Michalczyk et al., 2020; Solarz et al., 2014).

Despite its well-established importance for overall health, athletes are particularly prone to vitamin D deficiency, raising concerns about the potential impact of low vitamin D levels on sports performance (Bezuglov, Tikhonova, Zueva, Khaitin, Lyubushkina, et al., 2019; Bezuglov, Tikhonova, Zueva, Khaitin, Waśkiewicz, et al., 2019; Wilson-Barnes et al., 2020). Factors contributing to vitamin D deficiency include insufficient sun exposure, skin pigmentation, geographic location, and inadequate dietary intake (Lai & Fang, 2013; Michalczyk et al., 2020). This deficiency can adversely affect athletic performance by reducing immune system function, increasing the risk of injury, and impairing muscular function (Abushamma, 2022; Bezuglov, Tikhonova, Zueva, Khaitin, Waśkiewicz, et al., 2019; Wilson-Barnes et al., 2020). Collectively, these effects can significantly hinder athletic success.

Despite the growing body of evidence, the precise relationship between vitamin D and athletic performance remains unclear. This is likely due to variations in study design, population characteristics, and outcome measures. To address these gaps in understanding, we aimed to systematically analyse the existing literature to elucidate the connection between vitamin D and athletic performance. In addition, we sought to evaluate the potential effectiveness of vitamin D supplementation as an ergogenic aid for athletes.

MATERIALS AND METHODS

Eligibility criteria

This review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021), which ensure transparency, reproducibility, and methodological accuracy. A PECO (Population, Exposure, Comparator, Outcome) framework was employed to guide the systematic review, facilitating the implementation of a comprehensive and targeted literature search. The population of interest was defined as athletes and individuals who engage in regular physical activity. The variable of interest was vitamin D supplementation, which was categorised according to form and dosage. The comparator groups were either placebo or no intervention. The principal outcome under examination was the performance of athletes, including measures of muscle strength, power, and endurance. Moreover, we investigated the potential moderating effects of age, sex, and athletic level on the relationship between vitamin D and athletic performance. The inclusion and exclusion criteria employed in this review are outlined in Figure 1.

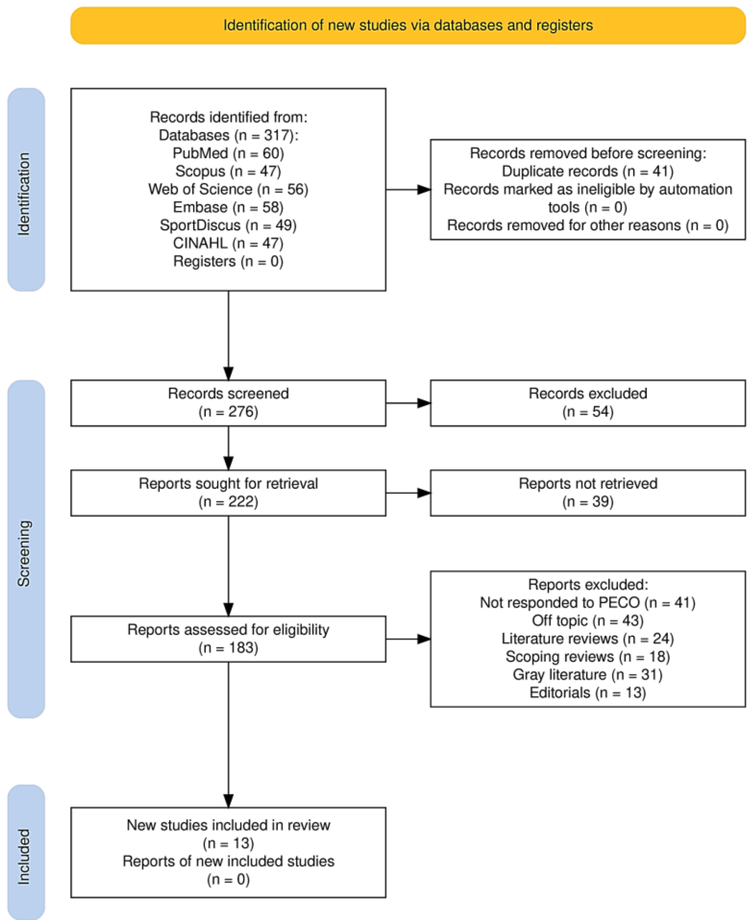

Figure 1. PRISMA protocol representation of the study inclusion process for the review.

Database search protocol

To execute a thorough and systematic review of the literature, we accessed six electronic databases—PubMed, Scopus, Web of Science, Embase, SportDiscus, and CINAHL—employing a mix of Boolean operators and MeSH keywords. Table 1 delineates the search strings utilized across these databases.

Table 1. Selection criteria utilised in this review.

Category	Inclusion Criteria	Exclusion Criteria
Study Design	Randomized Controlled Trials (RCTs), Case-Control Studies	Cross-sectional, Cohort, Observational studies
Population	Athletes, Individuals engaging in physical activity	Non-athletic populations, Sedentary individuals
Intervention	Vitamin D supplementation	Other forms of nutrition or ergogenic aids
Comparator	Placebo or no intervention	Active comparators (other nutrients or supplements)
Outcome	Athletic performance metrics	Other health outcomes (cardiovascular, metabolic, etc.)
Language	English	Non-English language publications
Publication Date	No restrictions	-

Data items extracted

In order to ensure the systematic and thorough extraction of data from the selected studies, a standardised protocol for data extraction was established. Two independent reviewers extracted the data from each study using a form that had been meticulously designed for this purpose. The form was subjected to pilot testing and subsequent refinement in order to guarantee the comprehensive capture of all pertinent data elements.

The data elements selected for analysis were comprehensive and encompassed four principal categories. At the outset, the characteristics of the studies were documented, including authorship, publication year, country of origin, study design, sample size, demographic details of the population (such as age and sex), and the study duration. Subsequently, the characteristics of the interventions were delineated. This included noting the type of vitamin D supplementation, dosage, duration, administration frequency and route of administration. In the third stage, the outcome measures were recorded, with a particular focus on indicators of athletic performance, including muscle strength, power and endurance. Lastly, the methodological rigour of each study was evaluated, with particular attention paid to aspects such as randomisation, allocation concealment, blinding, and adherence to the intention-to-treat principle.

Bias assessment protocol

For the randomized controlled trials (RCTs), we employed the Cochrane Risk of Bias 2.0 tool (Sterne et al., 2019) to evaluate the risk of bias. Conversely, for the non-randomized studies, we applied the ROBINS-I method (Igelström et al., 2021) to assess the risk of bias across multiple domains. This approach enabled us to identify potential sources of bias and assess their influence on the outcomes of the study.

RESULTS

Article selection schematics

The initial phase of our methodology involved identifying relevant records from various sources, including databases and registries, as depicted in Figure 2.

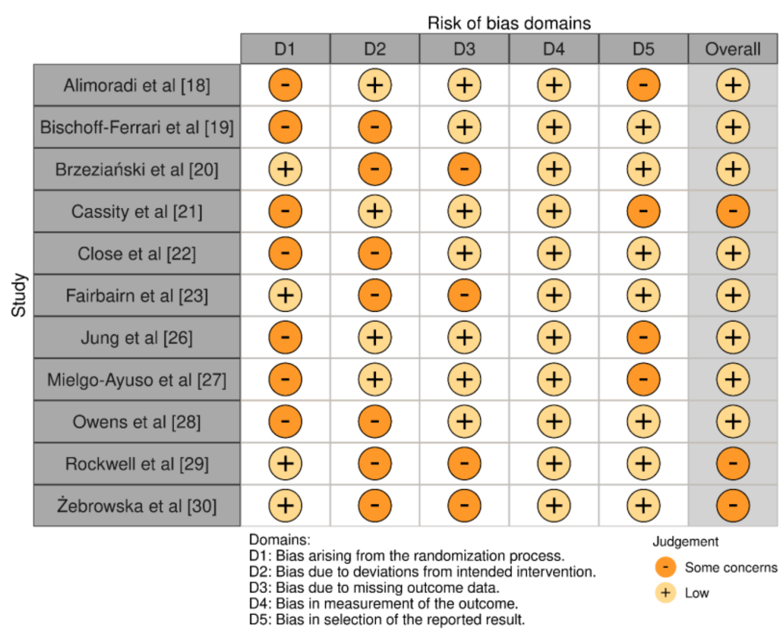

Figure 2. Bias assessment using the RoB 2.0 tool.

Although no records were retrieved from registries, a total of 317 records were obtained from databases. Prior to screening, 41 records were removed due to duplication, with no records excluded for any other reason, leaving 276 records for review.

During the screening phase, each record was meticulously evaluated to determine its relevance to the review. Of the 276 records scrutinized, 54 were excluded due to the unavailability of the full text. Subsequent requests for retrieval resulted in 222 reports being obtained. However, 39 reports remained unretrievable, leaving 183 reports to be assessed for eligibility.

The eligibility assessment involved a detailed review of each report against the PECO criteria. As a result, 43 reports were deemed off-topic, and 41 were excluded for not addressing the PECO criteria. Additionally, 24 literature reviews, 18 scoping reviews, 31 grey literature reports, and 13 editorials were excluded for not meeting the inclusion criteria. Ultimately, 13 trials (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020) were determined to be eligible and were included in the evaluation.

Assessed levels of bias

The protocol for assessing bias depicted a varied risk of bias across the studies included. Utilizing the Cochrane Risk of Bias 2.0 tool (Figure 3), a substantial number of studies predominantly exhibited "*some concerns*" regarding bias stemming from the randomization process, including studies by Alimoradi et al.(Alimoradi et al., 2019), Bischoff-Ferrari et al.(Bischoff-Ferrari et al., 2020), Cassity et al.(Cassity et al., 2016), Close et al.(Close et al., 2013), Jung et al. (Jung et al., 2018), Mielgo-Ayuso et al.(Mielgo-Ayuso et al., 2018), Owens et al.(Owens et al., 2017), and Rockwell et al.(Rockwell et al., 2020). Additionally, fewer studies demonstrated "*some concerns*" in the domains of bias due to deviations from intended interventions (Bischoff-Ferrari et al.(Bischoff-Ferrari et al., 2020), Close et al.(Close et al., 2013), Rockwell et al. (Rockwell et al., 2020)) and bias in outcome measurement (Alimoradi et al.(Alimoradi et al., 2019), Cassity et al.(Cassity et al., 2016), Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018)).

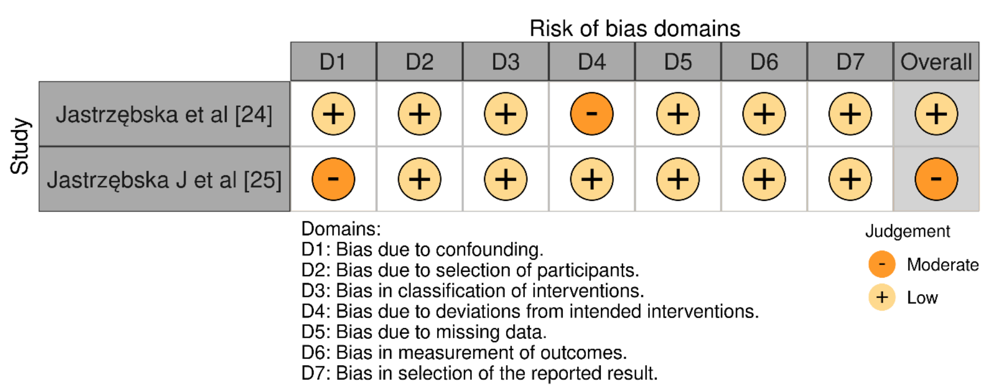

Figure 3. Bias assessment using ROBINS-I tool.

Employing the ROBINS-I tool (Figure 4), the sole non-randomized study by Jastrzębska et al. (Jastrzębska et al., 2018) was evaluated as having a "*moderate*" risk of bias in the domain of confounding, while the risks in other domains were deemed "*low*". A subsequent study by Jastrzębska J et al. (Jastrzębska et al., 2022)was similarly assessed to have a "*moderate*" risk of bias in the domain of confounding.

Baseline characteristics

Table 2 presents a summary of the assessments conducted across all the trials included in this review (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020). A detailed analysis of the table indicates that the majority of these studies (9 out of 12) utilized a randomized controlled trial (RCT) design, which is recognized as the gold standard for assessing the efficacy of interventions (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Rockwell et al., 2020). Notably, two studies implemented specific designs: one employed a double-blind, placebo-controlled factorial RCT design (Bischoff-Ferrari et al., 2020), and the other a repeated measures design(Owens et al., 2017). Only one study adopted a longitudinal design (Brzeziański et al., 2022). The participant demographics across the studies were quite diverse, covering a range of populations from young soccer players (Brzeziański et al., 2022; Jastrzębska et al., 2022; Jastrzębska et al., 2018) to collegiate swimmers and divers(Cassity et al., 2016), professional rugby players(Fairbairn et al., 2018), elite male rowers (Mielgo-Ayuso et al., 2018), and endurance runners (Żebrowska et al., 2020). The sizes of the study samples also varied significantly, from as few as 19 participants (Rockwell et al., 2020) to as many as 2157(Bischoff-Ferrari et al., 2020). Most studies targeted athletes who exhibited low levels of vitamin D or were at risk of deficiency (Alimoradi et al., 2019; Jung et al., 2018).

Table 2. Search phrases utilised across the databases.

Database	Search string
PubMed	(vitamin D OR cholecalciferol OR ergocalciferol) AND (athletic performance OR exercise performance OR physical performance) AND (randomized controlled trial OR RCT OR controlled clinical trial OR case-control study)
Scopus	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (article OR review OR conference paper) AND (English language OR language: English)
Web of Science	(vitamin D* OR cholecalciferol* OR ergocalciferol*) AND (athletic perform* OR exercise perform* OR physical perform*) AND (article OR review OR proceeding paper) AND (English language OR language: English)
Embase	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (human OR human studies) AND (English language OR language: English)
SportDiscus	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic perform* OR exercise perform* OR physical perform*) AND (human OR human studies) AND (English language OR language: English)
CINAHL	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (research article OR journal article OR peer-reviewed) AND (English language OR language: English)

Parameters and outcomes assessed

Alimoradi et al. (Alimoradi et al., 2019)explored the effect of vitamin D supplementation on the athletic performance of Iranian athletes. Their findings indicated that an 8-week regimen of weekly vitamin D supplementation, at a dose of 50,000 IU, significantly increased circulating 25(OH)D levels and improved performance in athletic tests. In a separate study, Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020) conducted a large-scale, double-blind, placebo-controlled trial to assess the effects of omega-3 fatty acids, exercise, and vitamin D3 on various health outcomes in elderly individuals. The results demonstrated that daily administration of 2000 IU of vitamin D3 over three years significantly enhanced blood pressure, and physical function, and reduced the incidence of infections and nonvertebral fractures.

Brzeziański et al. (Brzeziański et al., 2022) investigated the effects of vitamin D supplementation on the exercise performance of young soccer players. The study found that administering 20,000 IU of vitamin D twice weekly over eight weeks improved sprint testing, explosive power, VO2 max, and 25(OH)D levels. Similarly, Cassity et al. (Cassity et al., 2016) explored the influence of daily vitamin D3 supplementation on bone turnover markers, body composition, and 25(OH)D levels among collegiate swimmers and divers. Their findings indicated that 4000 IU of vitamin D3 daily for six months significantly increased 25(OH)D levels and reduced bone turnover indicators.

Table 3. Studies included in the review and their observed assessments.

Study	Design & Participants	Interventions	Duration	Primary Outcomes	Key Results	Overall conclusion observed
Alimoradi et al.	Randomized controlled trial; 70 Iranian athletes	Weekly Vitamin D (50,000 IU) vs. placebo	8 weeks	Circulating 25(OH)D, athletic performance tests	25(OH)D: D group +17.3 ± 16.9 ng/mL, *p* < .001; P group -3.1 ± 8.4 ng/mL, *p* = .040 Performance: Significant improvement in leg press (*p* = .034) and sprint (*p* = .030) in D group	Weekly 50,000 IU Vitamin D increased 25(OH)D by ~17 ng/mL, improving power leg press and sprint performance.
Bischoff-Ferrari et al.	Double-blind, placebo-controlled factorial RCT; 2157 older adults	Vitamin D3 (2000 IU/day), omega-3s (1 g/day), exercise, placebo	3 years	BP, SPPB, MoCA, nonvertebral fractures, infection rates	BP: No significant change (e.g., Systolic BP: -0.8 mm Hg, *p* < .13) Infections: Omega-3s reduced IR by 0.13, ratio 0.89 (*p* = .02) Other outcomes: No significant changes	No statistically significant benefits of Vitamin D3, omega-3s, or exercise alone or combined on primary outcomes over 3 years.
Brzeziański et al.	RCT; 25 young soccer players	Vitamin D (20,000 IU twice/week) vs. none	8 weeks	25(OH)D, VO2max, sprint tests, explosive power	25(OH)D: GS + (*p* = .002; ES = 0.36) VO2max: GS + (*p* = .031) Explosive Power: Insignificant (*p* = .07)	Vitamin D supplementation improved VO2max in young soccer players but had a trivial effect on explosive power.
Cassity et al.	RCT; 32 collegiate swimmers and divers	Vitamin D3 (4000 IU/day) vs. placebo	6 months	25(OH)D, bone turnover markers, body composition	25(OH)D: BMI - correlated with 6-month change (R = -0.496; *p* = .03) Bone turnover: High turnover = greater 25(OH)D loss (*p* = .03)	Normal BMI athletes showed a diminished response to vitamin D3; high bone turnover may compromise vitamin D status.
Close et al.	RCT; 30 club-level athletes	Placebo, 20,000 or 40,000 IU/week vitamin D3	12 weeks	25(OH)D, 1-RM bench press, leg press, vertical jump	25(OH)D: Increased in all (e.g., 20,000 IU: 79 ± 14 nmol/l at 12 weeks) Performance: No significant effect (*p* > .05)	Vitamin D3 supplementation increased serum levels but did not improve physical performance measures.
Fairbairn et al.	RCT; 57 professional rugby players in New Zealand	50,000 IU cholecalciferol (3,570 IU/day) vs. placebo	11-12 weeks	25(OH)D, 30m sprint, weighted reverse-grip chin up	25(OH)D: +32 nmol/L vs. placebo (*p* < .001) Performance: No difference except in chin up (+5.5 kg, *p* = .002)	Vitamin D significantly increased serum levels but had minimal impact on performance, except in chin-up strength.
Jastrzębska et al.	RCT; 36 soccer players undergoing HIIT	Vitamin D supplementation vs. placebo	8 weeks	25(OH)D, PWC170, lactate threshold (LT), VO2max	25(OH)D: SG +119%, PG -8.4% VO2max: SG +20%, PG +13% LT Velocity: Similar in both groups	Vitamin D showed a moderate positive impact on aerobic capacity in soccer players.
Jastrzębska J et al.	Longitudinal study; 24	Vitamin D supplementation vs. placebo	1 year	25(OH)D, Ca, P, PTH, aerobic	25(OH)D: Highest in summer (T1: 94 nmol/L, T4: 94 nmol/L)	Vitamin D levels fluctuated seasonally; supplementation did

	young soccer players			capacity, speed, power	Aerobic Capacity: Significant time x group effect	not have a sustained effect on 25(OH)D levels.
Jung et al.	RCT; 35 collegiate TKD athletes with low 25(OH)D	Vitamin D3 (5,000 IU/day) vs. placebo	4 weeks	25(OH)D, Wingate test, isokinetic strength, CMJ, sit-ups, agility, 20 m pacer	25(OH)D: VD + (96.0 ± 3.77 nmol/L), PG no change (F = 242.44, p = .000) Performance: Significant for anaerobic peak power (F = 7.49, p = .010) and isokinetic knee extension (F = 6.08, p = .019)	Vitamin D3 improved some aspects of performance, but not all, in TKD athletes with low 25(OH)D levels.
Mielgo-Ayuso et al.	RCT; 36 elite male rowers	Vitamin D3 (3000 IU/day) vs. control	8 weeks	Haematological and iron metabolism, testosterone, cortisol	25(OH)D: VD3G + (26.24 ± 8.18 to 48.12 ± 10.88 ng/mL, p < .001) Haemoglobin: CG -2.89 ± 2.29%, VD3G +0.71 ± 1.91% (p = .009) Haematocrit: CG -1.57 ± 2.49%, VD3G +1.16 ± 1.81% (p = .019)	Vitamin D3 supplementation improved haematological parameters but did not significantly enhance muscle recovery.
Owens et al.	Repeated measures; 46 elite European athletes	Vitamin D3 (35,000 or 70,000 IU/week)	12 weeks	Vitamin D metabolites, PTH levels	25(OH)D: Both doses + PTH: Decreased by week 6 70,000 IU: Increased 24,25[OH]2D (p < .05)	High-dose vitamin D3 may be detrimental due to increased 24,25[OH]2D; lower, frequent doses are preferable.
Rockwell et al.	RCT; 19 NCAA Division I swimmers	Vitamin D3 (5000 IU/day) vs. placebo	12 weeks	25(OH)D, body composition, strength/power, anabolic hormones	25(OH)D: VITD +8%, PLA -44% Fat-free mass: VITD + (56.4 to 59.1 kg, p < .05) Strength/Power: Significant for dead lift (F = 21.577, p < .01) and vertical jump (F = 11.219, p < .01)	Vitamin D supplementation maintained 25(OH)D levels and enhanced fat-free mass and some strength/power aspects.
Żebrowska et al.	RCT; 24 endurance runners	Vitamin D (2000 IU/day) vs. placebo	3 weeks	25(OH)D, muscle biomarkers (troponin, myoglobin, CK, LDH)	25(OH)D: VD + (40.3 ± 4.9 ng/mL), PL - (31.8 ± 4.2 ng/mL) Biomarkers: VD reduced post-exercise troponin, myoglobin, TNF-α, and CK levels	Vitamin D supplementation improved 25(OH)D levels and reduced muscle injury biomarkers in runners.

Close et al. (Close et al., 2013) investigated the effects of vitamin D3 supplementation on the athletic performance of club-level athletes. The study found that after 12 weeks of supplementation with either 20,000 or 40,000 IU of vitamin D3 per week, there were improvements in 1-RM bench press, leg press, vertical jump, and 25(OH)D levels. Similarly, Fairbairn et al. (Fairbairn et al., 2018) explored the impact of vitamin D supplementation on professional rugby players in New Zealand. Their findings indicated that administering 75-100 IU of vitamin D for 11–12 weeks enhanced 25(OH)D levels, 30 m sprint times, and performance in weighted reverse-grip chin-ups.

Jastrzębska et al. (Jastrzębska et al., 2018)aimed to explore the impact of vitamin D supplementation on exercise performance in soccer players undergoing high-intensity interval training (HIIT). The research revealed that eight weeks of vitamin D supplementation led to significant improvements in VO2max, PWC170, lactate threshold (LT), and 25-hydroxyvitamin D (25(OH)D) levels. In a subsequent longitudinal study, Jastrzębska et al. (Jastrzębska et al., 2022) examined the effects of vitamin D supplementation on the aerobic capacity, speed, and power of young soccer players. The outcomes of this year-long investigation demonstrated that vitamin D administration was associated with enhancements in power, speed, aerobic capacity, and 25(OH)D concentrations.

Jung et al. (Jung et al., 2018) investigated the effects of vitamin D3 supplementation on the physical performance of collegiate Taekwondo athletes exhibiting low serum 25-hydroxyvitamin D (25(OH)D) levels. Their findings indicated that supplementation with 5,000 IU/day of vitamin D3 for four weeks led to improvements in 25(OH)D levels, performance on the Wingate test, isokinetic strength, and counter-movement jump (CMJ) outcomes. Similarly, Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) explored the effects of vitamin D3 supplementation on hormonal balance and metabolic functions in elite male rowers. The study revealed that 8 weeks of supplementation with 3,000 IU/day of vitamin D3 enhanced levels of cortisol and testosterone, as well as haematopoietic and iron metabolism.

Owens et al. (Owens et al., 2017) investigated the effects of vitamin D supplementation on parathyroid hormone (PTH) levels and vitamin D metabolites in elite European athletes. Their findings indicated that 12 weeks of vitamin D supplementation, at doses of either 35,000 or 70,000 IU per week, significantly improved PTH levels and vitamin D metabolites. Rockwell et al. (Rockwell et al., 2020) explored the influence of vitamin D3 supplementation on anabolic hormones, strength, power, and body composition among NCAA Division I swimmers. The study revealed enhancements in anabolic hormones, body composition, strength, power, and 25-hydroxyvitamin D (25(OH)D) levels following 12 weeks of treatment with 5000 IU of vitamin D3 per day. Additionally, Żebrowska et al. (Żebrowska et al., 2020) examined the impact of vitamin D supplementation on muscle biomarkers in endurance runners. The results demonstrated that a three-week regimen of vitamin D supplementation, at 2000 IU per day, increased levels of 25(OH)D and decreased muscle biomarkers, including myoglobin, troponin, creatine kinase (CK), and lactate dehydrogenase (LDH).

Findings observed

Research conducted by Alimoradi et al. (Alimoradi et al., 2019) found that administration of vitamin D significantly increased 25(OH)D levels and improved athletic performance, notably in leg press and sprint tests. Conversely, Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020)observed that omega-3 supplementation reduced the risk of infections, whereas vitamin D supplementation had no significant effect on blood pressure or other measured outcomes. Similar to that Brzeziański et al. (Brzeziański et al., 2022) reported that while vitamin D administration raised 25(OH)D levels and VO2max, it did not significantly affect explosive power.

Cassity et al. (Cassity et al., 2016) identified a negative correlation between BMI and 25(OH)D levels with vitamin D supplementation, noting that greater losses of 25(OH)D were associated with higher bone turnover rates. Meanwhile, research by Close et al. (Close et al., 2013)demonstrated that although vitamin D supplementation consistently increased 25(OH)D levels, it did not yield a noticeable enhancement in sports performance. Fairbairn et al. (Fairbairn et al., 2018) found that vitamin D supplementation not only elevated 25(OH)D levels but also improved performance in chin-up tests, though it showed no significant impact on other performance indicators.

Jastrzębska et al. (Jastrzębska et al., 2018) observed no significant differences in the improvements of 25(OH)D levels, VO2max, and lactate threshold velocity following vitamin D supplementation. Conversely, Jastrzębska et al. (Jastrzębska et al., 2022) noted significant time x group effects attributed to vitamin D supplementation, which enhanced aerobic capacity, anaerobic peak power, and 25(OH)D levels. Jung et al. (Jung et al., 2018) reported a significant positive impact of vitamin D supplementation on performance, evidenced by increased 25(OH)D levels, anaerobic peak power, and isokinetic knee extension strength.

Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) identified significant group differences in the enhancement of haematological parameters and iron metabolism, specifically haemoglobin and haematocrit, following vitamin D supplementation. Owens et al. (Owens et al., 2017) found that vitamin D supplementation elevated 25(OH)D levels and reduced PTH levels, demonstrating significant effects on vitamin D metabolites at higher dosages.

Rockwell et al. (Rockwell et al., 2020) reported significant improvements in 25(OH)D levels, fat-free mass, strength, and power due to vitamin D supplementation, which also affected performance metrics such as the deadlift and vertical jump. Lastly, Żebrowska et al. (Żebrowska et al., 2020) found that vitamin D supplementation post-exercise led to decreased muscle biomarkers including troponin, myoglobin, TNF-α, and CK levels, while increasing 25(OH)D levels.

DISCUSSION AND CONCLUSION

A comprehensive analysis of the included trials (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020) highlights several trends and connections that elucidate the collective findings. Notably, a consistent increase in serum 25(OH)D levels following vitamin D supplementation was observed in 12 of the 13 studies. This finding suggests that vitamin D status in athletes can be effectively enhanced through supplementation. A specific subset of studies (Alimoradi et al., 2019; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Rockwell et al., 2020) reported significant improvements in power, strength, and aerobic capacity among athletes following vitamin D administration. These athletes presented with low baseline vitamin D levels, and the dosages of supplementation varied between 50,000 and 70,000 IU per week, indicating a pattern across these investigations. In contrast, studies involving athletes with normal initial vitamin D levels or those receiving lower doses of supplementation showed no significant enhancements in performance(Bischoff-Ferrari et al., 2020; Close et al., 2013; Fairbairn et al., 2018).

A subset of studies (Cassity et al., 2016; Mielgo-Ayuso et al., 2018; Owens et al., 2017) focused on the impact of vitamin D supplementation on muscle and haematological recovery metrics. Cassity et al. (Cassity et al., 2016) found no significant effects on muscle recovery, although Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) reported improvements in haematological markers. Owens et al. (Owens et al., 2017) suggested that increased levels of 24,25[OH]2D might render high-dose vitamin D3 supplementation detrimental. These findings underscore the complexity of vitamin D's influence on physiological outcomes and the necessity for further research. Seasonal fluctuations in vitamin D levels were documented by Fairbairn et al. (Fairbairn et al., 2018)and Żebrowska et al. (Żebrowska et al., 2020), emphasizing the importance of timing in supplementation strategies. Additionally, Żebrowska et al. (Żebrowska et al., 2020) demonstrated that vitamin D supplementation could reduce muscle injury biomarkers in runners, potentially influencing injury prevention strategies.

The study conducted by Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020), which analysed primary outcomes over a three-year period, did not demonstrate any statistically significant effects from the individual or combined interventions of omega-3 fatty acids, exercise, or vitamin D3. This study is distinguished by its unique methodology and focus on long-term outcomes, setting it apart from other research in the field. Conversely, several studies included in the review (Alimoradi et al., 2019; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Rockwell et al., 2020) present consistent findings, indicating that vitamin D supplementation significantly enhances athletic performance. Another subset of research (Cassity et al., 2016; Mielgo-Ayuso et al., 2018; Owens et al., 2017) primarily investigates markers of muscular and haematological recovery. The remaining studies, which vary in their conclusions and methodologies, exhibit less congruence (Bischoff-Ferrari et al., 2020; Close et al., 2013; Fairbairn et al., 2018; Żebrowska et al., 2020).

Numerous studies (Abushamma, 2022; de La Puente Yagüe et al., 2020; Sist et al., 2023; Wyatt et al., 2024), along with this review, suggest that vitamin D supplementation could be advantageous for health and athletic performance, particularly in athletes with deficient initial levels of vitamin D. There is a continued need for research to determine optimal dosages of vitamin D supplements and their effects on various outcomes, such as bone health, risk of injury, and muscle recovery. Our analysis indicates that vitamin D supplementation consistently elevated serum 25(OH)D levels in athletes; moreover, a subset of studies reported notable improvements in strength, power, and aerobic capacity among athletes with initially low vitamin D levels. Conversely, Abushamma et al. (Abushamma, 2022) highlighted ongoing debates regarding the application of vitamin D supplementation in sports, emphasizing the necessity for further research to establish the ideal dosages for athletes. Wyatt et al. (Wyatt et al., 2024) also found that vitamin D supplementation could enhance elite athletes' strength, anaerobic power, and aerobic endurance; yet, more studies are needed to confirm its benefits on bone health and injury prevention.

Puente et al.'s research (de La Puente Yagüe et al., 2020) highlighted the critical role of vitamin D in bone health as well as its extra-skeletal functions, which influence athletic performance through mechanisms such as skeletal muscle growth, immune and cardiovascular responses, and inflammatory regulation. The study noted that vitamin D interacts with extra skeletal tissues, potentially affecting infection risk and influencing the rate of injury healing. Additionally, a meta-analysis conducted by Sist et al. (Sist et al., 2023)evaluated the effects of vitamin D supplementation on muscle strength and power in athletes. Their findings indicated that while vitamin D supplementation did not alter muscle power in athletes with normal or elevated baseline serum 25(OH)D levels, it did have a modest effect on both upper and lower body muscle strength in athletes with low baseline serum 25(OH)D concentrations.

The findings and conclusions of the studies exhibit considerable variability. For example, our analysis suggests that vitamin D supplementation may influence injury prevention, contrasting with Wyatt et al. (Wyatt et al., 2024), who report inconsistent evidence regarding its effects on bone health and injury risk. Additionally, we found that vitamin D supplementation could be beneficial for enhancing power, strength, and aerobic capacity, whereas Sist et al. (Sist et al., 2023) observed minimal effects on muscle strength and power.

A high prevalence of vitamin D deficiency is noted among athletic populations, with increased risk factors such as higher latitudes, the winter and early spring seasons, and participation in indoor sports (Farrokhyar et al., 2015). The definition of vitamin D deficiency, however, remains a subject of ongoing debate. While current evidence suggests that serum 25(OH)D concentrations below 75 nmol/L might be considered deficient in white male athletes (Ribbans et al., 2021), the relevance of this threshold for athletes from diverse ethnic backgrounds is uncertain. Notably, research indicates that while total 25(OH)D and vitamin D-binding protein (VDBP) levels are lower in black individuals compared to white individuals, the levels of bioavailable 25-hydroxyvitamin D are similar, suggesting that 1,25(OH)D may be a more accurate marker of vitamin D status (Powe et al., 2013). The deficiency of vitamin D has been associated with impaired muscle function, evidenced by proximal muscle weakness and reduced diameter of type II muscle fibres (Ceglia, 2008). Given the strong correlation between muscle function and force-time characteristics (Suchomel et al., 2016), as well as injury incidence (Hootman et al., 2007; Van Mechelen et al., 1992), the impact of vitamin D on muscle strength in athletes has attracted significant research interest. Despite the demonstrated effectiveness of vitamin D supplementation in improving vitamin D status (Farrokhyar et al., 2017), the evidence regarding its effects on maximal strength and power in athletes remains limited and currently inconsistent(Han et al., 2019; Zhang et al., 2019).

Limitations

There are a few caveats to consider when interpreting the results of this systematic study. First off, there's a chance that the varied study designs, populations, and supplementation strategies across the included studies contributed to the diversity in the findings. Furthermore, the bulk of the studies had small sample sizes, which would have reduced the findings' generalisability and estimate precision. Moreover, since the examination was restricted to works written in English, pertinent works written in other languages might have been overlooked. Despite being thorough, the search strategy might have overlooked some pertinent research, especially those that had unfavourable results that are frequently not publicly disclosed. Because the included studies' quality was not properly evaluated, bias may have been introduced into the interpretation of the findings. Finally, while investigating the possible pathways via which vitamin D supplementation may influence athletic performance would have yielded important insights into the physiological processes that underlie the effects, the review did not do so.

Clinical recommendations

The findings of the systematic review yield several recommendations. It can be posited that vitamin D supplementation may enhance athletic performance, in particular among athletes who have initially low vitamin D serum levels. Nevertheless, further research is necessary to ascertain the optimal doses and durations of supplementation. It should be noted that seasonal variations in vitamin D levels have the potential to influence the efficacy of supplementation, underscoring the importance of timing. Therefore, it is recommended that athletes and coaches consider these variations when devising training schedules. Additionally, due to the current lack of conclusive data, further research is necessary to assess the effects of vitamin D supplementation on haematological and muscle recovery metrics. To generate more precise estimations of vitamin D's impact on athletic performance, future research should prioritise high-quality, well-designed trials with large sample sizes.

AUTHOR CONTRIBUTIONS

The authors confirm that all authors have made substantial contributions to all of the following: the conception and design of the study, or acquisition of data, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be submitted; and sound scientific research practice.

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