Effects of Vitamin D Supplementation in Elite Athletes: A Systematic Review

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Background: Deficiency in vitamin D has been shown to increase the risk of injury.

Purpose: To synthesize current placebo-controlled randomized trials investigating the effect of vitamin D supplementation in elite athletes on (1) aerobic capacity; (2) anaerobic measures, such as strength, speed, and anaerobic power; (3) serum biomarkers of inflammation; and (4) bone health.

Study Design: Systematic review; Level of evidence, 1.

Methods: A literature search was conducted on November 30, 2022, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Included were randomized, placebo-controlled studies of longer than 2 weeks on subjects with active participation in organized sport. Excluded were nonrandomized controlled trial study designs, vitamin D administration routes other than oral, studies that did not use vitamin D supplementation as the sole intervention, and studies with nonathletic or military populations.

Results: Out of 2331 initial studies, 14 studies (482 athletes) were included. Of the 3 studies that assessed aerobic capacity, 2 demonstrated significantly greater improvements in maximal oxygen uptake and physical working capacity-170 ($P < .05$) in supplemented versus nonsupplemented athletes. Measurements of anaerobic power and strength were consistently increased in supplemented groups compared with nonsupplemented groups in 5 out of the 7 studies that assessed this. Of the 6 studies that assessed sprint speed, 4 found no significant difference between supplemented and nonsupplemented groups. Aside from 1 study that found significantly lower interleukin-6 levels in supplemented athletes, measures of other inflammatory cytokines were not affected consistently by supplementation. The 4 studies that assessed markers of bone health were conflicting regarding benefits of supplementation. One study found demonstrated improvements in bone mineral density in response to supplementation ($P = .02$) compared with control whereas another found no significant difference between supplemented and nonsupplemented groups. However, in 3 other studies, serum biomarkers of bone turnover such as bone-specific alkaline phosphatase, parathyroid hormone, and N-terminal telopeptide appeared to be higher in subjects with lower serum vitamin D levels ($P < .05$).

Conclusion: Results of this systematic review indicated that the greatest benefit of vitamin D supplementation in elite athletes may be improving aerobic endurance, anaerobic power, and strength. More research is needed to determine the effect of vitamin D supplementation on bone health and injury risk in this population.

Keywords: athletics; cholecalciferol; sport; vitamin D; vitamin D deficiency

The prevalence of vitamin D deficiency is increasing worldwide at a rate and distribution consistent with a pandemic.[10,17] The percentage of adult Americans with vitamin D deficiency ranges from 36% to 57%,[23,40] and as few as 2% of North Americans achieve the recommended vitamin D daily intake.[27] The prevalence of vitamin D deficiency in athletes worldwide follows the prevalence of nonathletic populations and is becoming a growing concern as it pertains to athletic performance, aerobic endurance, and injury risk.[§] Previous studies have shown that the

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[§]References 14, 20, 22, 37, 41, 42, 45, 52.

prevalence of vitamin D deficiency may be up to 26% in professional American football players and 36% of English Premiere League soccer players in Liverpool, England.[41,45] Vitamin D has gained popularity in the medical community in recent decades as a hormone-like chemical that influences between 5% and 10% of the total genome.[53] However, determining the precise effects of this important vitamin is not straightforward, and neither is our understanding of its widespread physiological effect.

Vitamin D deficiency, which has been defined differently by multiple authors,[51,53] can have detrimental effects on bone, muscle, respiratory, neurological, and respiratory health.[53] Pludowski et al[51] defined vitamin D deficiency as less than 50 nmol/L serum concentration. Athletes who are at highest risk for developing vitamin D deficiency are those who train early in the morning or late at night, those who wear sport kits (ultraviolet B light coverage), and indoor athletes.[47] Previous research has demonstrated that low vitamin D levels are associated with injuries in athletes,[3] particularly bone stress injuries.[3] Serum 25-hydroxyvitamin D (25[OH]D) levels below 30 to 50 nmol/L appear to be associated with increased risk of such injuries.[16,57]

To our knowledge, no previous systematic review has synthesized multiple placebo-controlled randomized controlled trials investigating the effect of vitamin D supplementation on fitness and sport performance in athletes. The objective of this systematic review was to analyze the current body of literature regarding the effect of vitamin D supplementation on (1) aerobic capacity; (2) anaerobic measures, such as strength, speed, and anaerobic power; (3) serum biomarkers of inflammation; and (4) bone health. We hypothesized that vitamin D supplementation would have a positive effect on all 4 of these outcomes.

METHODS

This was a systematic review of randomized, placebo-controlled trials published before November 30, 2022, that investigated the effect of supplementation of vitamin D in athletic populations. This study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for reporting systematic reviews,[49] and the protocol was registered on PROSPERO (CRD42022381494).

Search Strategy

One author (J.C.) searched the PubMed/Medline, Cochrane, CINAHL, and Embase (OVID) databases on November 30, 2022, using the keywords, "athlete," "sport," "athletic performance," "cholecalciferol," "vitamin D," and "ergocalciferol." A more detailed summary of the search strategy can be found in the Online Appendix.

Screening and Study Inclusion/Exclusion Criteria

Duplicates and papers written in languages other than English were excluded. Two authors (P.B.W. and C.R.R.) independently screened all articles returned from the initial search using this review's inclusion and exclusion criteria. Each study was first reviewed by title and abstract then by full text if more detail was required to make the decision of inclusion. Conflicts were resolved by a neutral third author (J.R.S.). Inclusion criteria were as follows: randomized, placebo-controlled study design with a duration of longer than 2 weeks and subjects with active participation in organized sport. Exclusion criteria were as follows: nonrandomized controlled trial study designs, vitamin D administration routes other than oral, studies that did not use vitamin D supplementation as the sole intervention in the experimental group, and studies with nonathletic or military populations.

Data Extraction

Data were extracted independently by 2 authors (P.B.W. and C.R.R.). The data that were systematically extracted included salient findings pertaining to vitamin D supplementation's effect on athletic performance, bone health, injury recovery/prevention, biochemical markers, and plasma 25(OH)D levels. The initial search returned 2331 articles. After duplicates were removed (n = 656), 1675 articles were remaining, of which 1596 articles were excluded based on title and abstract screening. This left 79 articles for full-text screening, of which 65 were excluded. A total of 16 studies remained for quality assessment after full-text screening.[‖] The inclusion/exclusion process is depicted in Figure 1.

Quality Assessment

Two authors (P.B.W. and C.R.R.) assessed each of the 16 studies for risk of bias using the Cochrane Risk of Bias 2 tool for assessing the methodological quality and risk of

[‖]References 1, 7, 8, 11, 13, 21, 26, 29-31, 33, 39, 43, 50, 55, 63.

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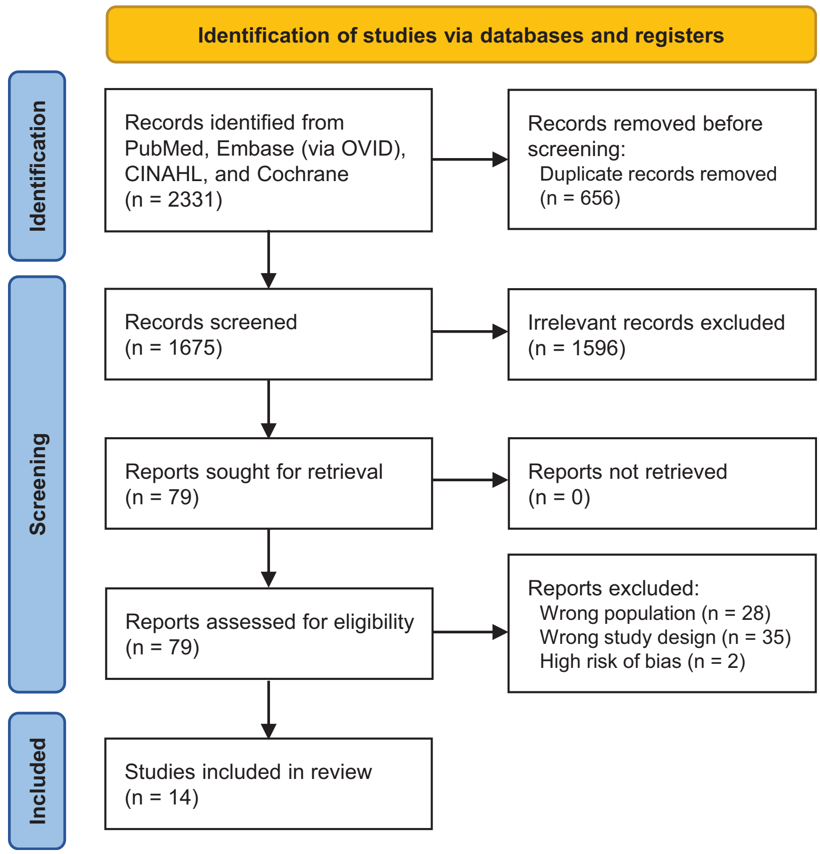

Figure 1. PRISMA flow diagram of study inclusion in the review. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

bias in randomized controlled trials involving human subjects.[44,54] Of the included articles, 11 studies were determined to have a low risk of bias,[¶] 3 studies were determined to have "some concerns" regarding risk of bias,[11,29,39] and 2 studies were identified as having high concerns for risk of bias and were therefore excluded from the primary analysis.[26,50]

Outcomes of Interest

All reported outcomes in the included studies were considered of interest in this review.

RESULTS

Characteristics of the Included Studies

After the screening process was completed, 14 studies were selected for inclusion in this systematic review.[#] The characteristics of the included studies are summarized in Appendix Table A1. There were a total of 482 participants (350 male, 72 female). Two studies did not report participant sex,[29,31] leaving a total of 60 subjects of unknown sex. The average age of participants among the studies was 20.87 years (range, 17.20-27.00 years). The most common sport investigated in the included studies was outdoor soccer, totaling 226 subjects across 6 studies.[1,7,8,13,29-31] Other sports included were rugby (n = 72),[13,21] rowing (n = 36),[43] taekwondo (n = 35),[33] swimming and diving (n = 83),[11,39,55] and ultramarathon running (n = 24).[63]

Method of Vitamin D Supplementation

All studies employed oral formulations of vitamin D3. Three studies used oral droplets,[29-31] whereas the remaining 11 studies used capsules and identically-appearing placebo capsules.[**] Dosage ranged from 2000 international units (IU)/day to 7142.86 IU/day,[1,21,63] with an average daily dose of 4959.12 IU/day. Eight studies used daily dosing of vitamin D3 (range, 3000-5000 IU/day)[11,29-31,33,39,43,55]; 1 study used twice daily dosing (1000 IU/dose)[63]; 2 studies used weekly dosing (range, 20,000-50,000 IU/week)[1,13];

¶References 1, 7, 8, 13, 21, 30, 31, 33, 43, 55, 63.

#References 1, 7, 8, 11, 13, 21, 29-31, 33, 39, 43, 55, 63.

**References 1, 7, 8, 11, 13, 21, 33, 39, 43, 55, 63.

2 studies using biweekly dosing (both 20,000 IU twice weekly)[7,8]; and 1 study used 1 dose of 50,000 IU every 2 weeks.[21] Importantly, only 1 participant among all the studies reported an adverse effect: constipation.[55] More details regarding methods of supplementation can be found in Appendix Table A1.

Geographic Location of Studies

The latitudinal location of the studies in the northern hemisphere ranged from 32.43° N to 54.51° N,[1,7,8] with an average latitude of 45.53° N. One study was conducted at 45° S to 46.5° S in New Zealand.[21] The specific latitudinal location for each study is provided in Appendix Table A1.

Aerobic Capacity

Improvements in maximal oxygen uptake ($VO2_{max}$) were seen in 2 studies.[7,31] One study on Polish soccer players demonstrated a significant correlation between increases serum 25(OH)D concentrations and increases in $VO2_{max}$ (r = 0.4192, P = .0024).[7] Jastrzębska et al[31] found an increase in $VO2_{max}$ of 8.65 ± 3.57 mL/kg/min in the vitamin D3-supplemented group compared with 5.03 ± 2.02 mL/kg/min in a nonsupplemented group of soccer players (P = .021). Their study on supplemented Polish soccer athletes demonstrated a significant increase in physical working capacity-170 (PWC-170; a measure of aerobic power) compared with nonsupplemented controls (supplemented group, 5.03 ± 2.02 kGm/kg/min; nonsupplemented group, 3.34 ± 2.28 kgm/kg/min; P = .027).[31] Conversely, a previous study by the same group found no significant difference in PWC-170 in a similar group of Polish soccer players ($P > .05$).[30]

Strength, Speed, and Anaerobic Power

Results regarding anaerobic capacity, strength, and agility are heterogeneous between studies. In the present review, 5 studies demonstrated improvements in anaerobic power/strength or sprint speed,[1,21,29,33,55] while 3 studies did not demonstrate a significant difference between supplemented and nonsupplemented groups.[7,13,31] Sprint speeds were found to be increased in 2 studies on soccer players compared with nonsupplemented groups (P = .03).[1,29] Four studies on soccer and rugby players found no significant difference between groups in sprint speeds ($P > .05$).[7,13,21,30] All sprint distances tested were no longer than 30 m.

Inconsistent findings regarding strength were found among previous studies. The power/strength tests that were found to significantly improve in supplemented groups were predicted 1-repetition maximum weighted reverse-grip chin-ups (increased by 5.5 kg [95% confidence interval (CI), 2.0-8.9 kg]; P = .0002)[21]; isokinetic knee extension strength (P = .019)[33]; squat, deadlift, and vertical jump ($P < .05$)[55]; and leg press (P = .034).[1] Anerobic power measured by the Wingate test (performed on lower body ergometer) was found to increase significantly in supplemented taekwondo athletes.[33] However, another study found no significant differences in lactate threshold between groups of soccer players (see Appendix Table A1 for more details).[31]

Serum Biomarkers and Immune Modulation

All supplemented groups in the included studies demonstrated significantly higher postintervention serum 25(OH)D levels compared with nonsupplemented groups. In 2 studies,[31,33] all subjects had baseline serum 25(OH)D concentrations less than 50 nmol/L, which is the proposed as the cut-off for vitamin D "deficiency" by Pludowski et al.[51] All but 1 of the remaining studies had a mix of vitamin D-deficient and -sufficient subjects.[21] The average change in serum 25(OH)D concentration from baseline across the 15 supplemented groups (1 study had 2 supplemented groups) was +38.03 nmol/L. Only 1 study reported a decrease in 25(OH)D serum levels in both the supplemented and nonsupplemented groups.[11] This decrease was somewhat expected as the baseline serum 25(OH)D concentrations were much higher than in other studies (average of 130 nmol/L in the supplemented group). This could be due to the study being conducted at a latitude closer to the equator (38° N) and the sport (swimming and diving) being indoors. Nonetheless, the decrease in this group was significantly smaller in the supplemented group compared with control.[11] Serum levels decreased by only 2.5 nmol/L in a supplemented group compared with 50 nmol/L over 6 months ($P < .05$) in the placebo group.[11]

A significant negative correlation was found between serum 25(OH)D levels and C-reactive protein (CRP) in a group of soccer players (r = -0.459, P = .021).[8] In a subsequent analysis, the magnitude of this effect was greater in supplemented subjects with suboptimal baseline 25(OH)D serum levels (defined as <75 nmol/L). Two studies found no significant correlation between serum 25(OH)D levels and interleukin (IL)-6 levels (an inflammatory cytokine),[8,39] whereas another found significantly lower IL-6 levels in a supplemented group versus placebo ($P < .01$).[63] Other inflammatory cytokines, such as tumor necrosis factor alpha (TNF-α) and IL-1β appeared to have no significant correlation with serum 25(OH)D levels.[39]

One study found a significant increase (20%; $P < .001$) in parathyroid hormone (PTH) levels after 8 weeks in a nonsupplemented group.[1] No significant increase was observed in the supplemented group in this study. Another study found no significant change in PTH levels throughout the study,[55] whereas another study found changes in PTH were not associated with 25(OH)D serum concentrations.[39]

Supplementation appeared to be sufficient to prevent a decline in transferrin (P = .007), hemoglobin (P = .009), and hematocrit (P = .019) in a group of elite male rowers compared with a nonsupplemented group of controls.[43] In addition, higher 25(OH)D serum concentrations were significantly correlated with serum total testosterone levels, but supplementation did not appear to be sufficient to significantly increase total testosterone concentrations.

Bone Health

Serum levels of biomarkers of bone turnover, such as bone-specific alkaline phosphatase (BSAP) and N-terminal telopeptide (NTx), were not significantly different between supplemented and nonsupplemented groups ($P > .05$).[11,39] However, BSAP and NTx appeared to be significantly higher in subjects with larger decreases in serum 25(OH)D over the course of 1 study.[11] Concentrations of BSAP and NTx were not correlated significantly with measurements of bone mineral density (BMD).[11] However, BMD of the proximal femur ($P = .02$) and mineral-free lean mass ($P < .05$) were both found to be significantly correlated with serum 25(OH)D levels.[39] Conversely, Cassity et al[11] found that 6-month changes in body composition measures (total mass, lean mass, fat mass, BMD, and body mass index) were not significantly different between groups.

DISCUSSION

This systematic review showed promising, albeit heterogeneous, data supporting the use of vitamin D supplementation in athletes. Athletic measures that appeared to benefit most from vitamin D supplementation were measures of aerobic capacity ($VO2_{max}$, PWC-170) and some measures of strength and power (vertical jump, various measures of upper body strength).[1,7,21,31,33,55] Sprint speed was less affected by supplementation.[21,30] Biochemical comparison of supplemented and nonsupplemented athletes demonstrated a possible association between serum 25(OH)D levels and total testosterone.[43] Serum markers of inflammation, such as CRP, ILs, TNF-α, and cortisol were not affected consistently by supplementation.[8,39,63] Only 1 of the 2 studies that assessed BMD was able to demonstrate a positive correlation between serum 25(OH)D levels and BMD.[39] However, the biomarkers of bone turnover, such as PTH, BSAP, and NTx, were found to be higher in nonsupplemented groups and correlated negatively with serum 25(OH)D levels.[1,11,39]

As the prevalence of vitamin D deficiency rises in athletic populations, investigation of the effects of supplementation in this population is warranted. Previous studies have shown that vitamin D deficiency can increase the risk of bone injuries such as stress fracture in military and athletic populations.[15,36,39,46,62] Previous systematic reviews and meta-analyses have also shown that vitamin D supplementation can improve skeletal muscle strength[12,60] and may even play a role in reducing the risk of acute respiratory infections.[32] This systematic review demonstrates that oral vitamin D supplementation is an effective method of improving serum 25(OH)D levels and that supplementation has a positive effect on aerobic capacity, anaerobic capacity, and strength in athletes.

The Scientific Advisory Committee on Nutrition and the Food Standards Agency of the United Kingdom has defined vitamin D deficiency as a serum 25(OH)D concentration of less than 25 nmol/L.[24] However, more recent guidelines suggest a concentration of less than 50 nmol/L is necessary for identifying vitamin D deficiency.[51] These authors further define vitamin D "insufficiency" as a concentration of 50 to 75 nmol/L, with a target serum concentration of ranging from 75 to 125 nmol/L to 100 to 150 nmol/L.[51] Other authors have defined vitamin D "inadequacy" as a serum concentration of less than 80 nmol/L.[23] The lack of consistent terminology and numerical cut-offs makes it difficult to define an exact serum concentration for vitamin D deficiency. However, most studies, including the included studies in this review, considered values below 50 nmol/L to be "deficient."

The National Academy of Medicine (formerly known as the Institute of Medicine) has defined the tolerable upper limit of vitamin D supplementation as 4000 IU/day; the risk of adverse events increases at serum 25(OH)D levels greater than 125 nmol/L. However, the no-observed-adverse-effects level has been found to be 10,000 IU/day, established by the same group.[56] Doses higher than 70,000 IU/week have been shown to induce 24-hydroxylase after 12 weeks of supplementation. This enzyme converts 1,25(OH)D (the bioactive form of vitamin D) to 24,25(OH)D, which provides negative feedback on the activity of 1,25(OH)D. This produces a paradoxically decreased effect of 1,25(OH)D with high-dose vitamin D supplementation.[48] Therefore, more research is needed to determine an appropriate dose that will produce desired effects in athletic populations.

It is worth noting that all but 3 of the included studies were conducted at latitudes greater than 35° N.[1,21,33] It has been shown that ultraviolet B (UVB) radiation is nonexistent at latitudes greater than 35° N.[9,28,47] This reflects the higher prevalence of vitamin D inadequacy in athletes found by Farrokhyar et al[23] in a meta-analysis of 2313 international subjects. The authors calculated a risk ratio of 1.85 (95% CI, 1.25-2.53) for vitamin D inadequacy (<80 nmol/L) in athletes who lived above 40° N when outliers from studies in the Middle East were excluded. Supplementation should be considered for athletes living at UVB-deficient latitudes, especially in the winter months.

The gold standard for measuring aerobic capacity is $VO2_{max}$, a measurement of maximal oxygen consumption.[31,35] $VO2_{max}$ is extrapolated most commonly from graded exercise testing on a leg cycle ergometer or treadmill.[35] The mechanism behind the positive correlation of serum 25(OH)D levels on $VO2_{max}$ is poorly understood but may be related to increased erythropoiesis.[58] This hypothesis is supported by the findings of this review that hemoglobin, hematocrit, and transferrin all were found to increase in a supplemented group of rowers.[43] The current review agrees with earlier literature suggesting that $VO2_{max}$ is correlated positively with serum 25(OH)D levels in vitamin D-deficient athletes as well as in nonathletic adult populations.[4,61] On the other hand, some studies have reported no correlation in serum 25(OH)D status and $VO2_{max}$.[25,34] Variability in $VO2_{max}$ between studies is expected as $VO2_{max}$ is heavily influenced by a multitude of factors such as age, sex, body composition, heredity, cardiac output, pulmonary blood flow, lung diffusion capacity, and lung ventilation.[6]

The effect of vitamin D supplementation on strength and power appears to be inconsistent and is influenced heavily by the type of training that is undertaken in each study. The inconsistency in the effect of vitamin D on anaerobic strength/power and sprint speed among the included studies is likely owed to the variability in training modality and sport-specific metabolic demands.

A previous systematic review and meta-analysis of 310 young and active participants concluded that vitamin D supplementation was associated with increased upper (P = .005) and lower (P = .04) body strength.[60] Strength gains associated with vitamin D supplementation have been estimated to range from 1.37% to 18.75%.[12] These effects have been hypothesized to be due to promotion of skeletal muscle regeneration and maintenance of mitochondrial health, according to stem cell models.[38] Furthermore, vitamin D receptor expression in skeletal muscle is highly expressed and focused within regenerating muscle fibers after injury (ie, high-intensity exercise).[59] Activation of the vitamin D receptor by 1,25-hydroxyvitamin D appears to have many roles in the regeneration of skeletal muscle, including increased satellite (stem) cell regeneration and increasing mitochondrial turnover by promoting mitophagy and mitochondrial biogenesis and fusion signaling.[38]

Immune modulation is a function of vitamin D that is poorly understood. Previous studies have shown that vitamin D supplementation may safely reduce risk of acute respiratory infections.[32] Others have shown that supplementation may also inhibit the expression of proinflammatory cytokines such as IL-1, -6, -8, and -12[2] and even decrease serum levels of these substances.[18,19] The current review similarly demonstrates that serum IL-6 and CRP concentrations may be correlated negatively with serum 25(OH)D levels and improve with supplementation - especially in 25(OH)D-deficient subjects.[8,63] However, 1 included study reported no significant effect of supplementation on inflammatory cytokines.[39] This difference may be due to different training intensities and variability in the duration of study.

Limitations

Our study is not without limitations. This study is limited primarily by the high heterogeneity of training protocol, geographical location, and inclusion of both indoor and outdoor sports. In addition, it is difficult to determine how the outcomes were affected by the variable serum 25(OH)D concentrations among subjects at baseline. Further, this study was limited due to a lack of a meta-analysis, which we determined was impractical considering the variability in protocols and outcome reporting methods between studies. Despite these limitations, findings from this review successfully identified several positive, albeit inconsistent, effects of vitamin D supplementation that can direct further randomized controlled trials on this topic.

CONCLUSION

The benefits of vitamin D supplementation in athletes remain unclear and inconsistent. However, its greatest benefit in this population may be improving aerobic endurance, anaerobic power, and strength. Given the high prevalence of vitamin D deficiency in this population, supplementation in the winter months should be considered, especially for those in geographic areas that receive less sunlight. Future studies should investigate the benefits of long-term supplementation towards outcomes such as injury prevention.

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APPENDIX

APPENDIX TABLE A1
Summary of Included Studies[a]

Lead Author (Year)	N	Sport (Indoor/Outdoor)	Latitudinal Location	Vitamin D Administration Protocol	Salient Findings
Jastrzębska[31] (2018)	36	Soccer (outdoor)	52° N	• Experimental group: vitamin D3 oral drops, 5000 IU/day for 8 weeks • Control group: placebo oral drops	Vitamin D supplementation augmented the training response of $VO2_{max}$ (P = .021) and PWC-170 to an 8-week sport-specific training program (P = .027)
Jastrzębska[29] (2022)	24	Soccer (outdoor)	52° N	• Experimental group: vitamin D3 oral drops, 5000 IU/day for 8 weeks • Control group: placebo oral drops	Higher 25(OH)D plasma levels were negatively correlated with sprint times at 10 m (r = -0.32, P = .006) and 30 m (r = -0.36, P = .002)
Jung[33] (2018)	35	Taekwondo (indoor)	33° N	• Experimental group: vitamin D3 oral capsule, 5000 IU/day for 4 weeks • Control group: placebo capsule	• Peak anaerobic power improved in both groups, but significantly more in the experimental group, as measured by the Wingate anaerobic test (F = 7.486, P = .010). • Changes in plasma 25(OH)D concentration were correlated positively with changes in peak power (r = 0.443, P = .009) • Isokinetic knee extension strength at 180° improved significantly in the experimental group, but not in the control group (F = 6.078, P = .019)
Brzeziański[7] (2022)	25	Soccer (outdoor)	54.51° N	• Experimental group: vitamin D3 oral capsule, 20,000 IU, given twice weekly for 8 weeks • Control group: placebo capsule	Positive correlation between serum 25(OH)D levels and $VO2_{max}$ (r = 0.4192, P = .0024)
Jastrzębska[30] (2016)	36	Soccer (outdoor)	52° N	• Experimental group: vitamin D3 oral drops, 5000 IU/day for 8 weeks • Control group: placebo capsule	No significant differences in sprint speed, jump distance, or peak power/total work in Wingate test or PWC-170.
Brzeziański[8] (2022)	25	Soccer (outdoor)	54.51° N	• Experimental group: vitamin D3 oral capsule, 20,000 IU, given twice weekly for 8 weeks • Control group: placebo capsule	Negative correlation between serum 25(OH)D levels and C-reactive protein levels in both groups (r = -0.459, P = .021)

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APPENDIX TABLE A1
(continued)

Lead Author (Year)	N	Sport (Indoor/Outdoor)	Latitudinal Location	Vitamin D Administration Protocol	Salient Findings
Rockwell[55] (2020)	19	Swimming (outdoor and indoor)	37.23° N	• Experimental group: vitamin D3 oral capsule, 5000 IU/day for 12 weeks	• Squat, deadlift, and vertical jump performance improved significantly in the experimental group, but not the control group ($P < .05$). • Fat-free body mass increased by 13.6% in the supplemental group ($P < .05$) but did not change in the control group. • Significant decrease in total testosterone in males and females in the placebo group over the course of the intervention period ($P < .05$). Experimental group also decreased, but not at a statistically significant rate ($P > .05$). • Regression analysis showed that serum 25(OH)D levels predicted free testosterone ($R^2 = 0.4906$, $P < .05$)
Mielgo-Ayuso[43] (2018)	36	Rowing (outdoor)	43.16° N	• Experimental group: vitamin D3 oral capsule, 3000 IU/day for 8 weeks • Control group: placebo capsule	• Placebo group demonstrated a decrease in both plasma hemoglobin and hematocrit levels (group-time interaction was -1.57% ± 2.29%, $P = .009$; -1.57% ± 2.49% for hemoglobin and hematocrit, respectively). Experimental group demonstrated no such decline in either measurement • Transferrin levels increased in experimental group compared with the control group (group-time interaction was 6.51% ± 4.36% in the experimental group versus 0.67% ± 4.88% in the control group ($P = .007$) • There was a positive association between 25(OH)D levels and testosterone and cortisol; however, supplementation was not sufficient to change these hormone levels significantly
Alimoradi[1] (2019)	69	Soccer (outdoor)	32.43° N	• Experimental group: vitamin D3 oral capsule 50,000 IU, once weekly for 8 weeks • Control group: placebo capsule	• Significantly greater increase in leg press strength seen in the experimental group ($P = .034$), but no difference in ergo jump, vertical jump, or agility tests. • Experimental group showed a significant improvement in maximal sprint speed ($P = .03$) while the control group did not; however, no between group significant differences ($P > .05$). • Placebo group demonstrated a 20% increase in PTH ($P < .001$). No significant increase in the experimental group
Cassity[11] (2016)	32	Swimming and diving (indoor)	38° N	• Experimental group: vitamin D3 oral capsule, 4000 IU/day for 6 months • Control group: placebo capsule	• No significant difference between groups in bone turnover markers. • However, athletes with higher bone turnover markers showed significantly greater decreases in serum 25(OH)D ($P = .03$). • In the experimental group, there was a significant negative correlation between BMI and 6-month increase in serum 25(OH)D measurements ($r = -0.496$, $P = .03$).

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APPENDIX TABLE A1
(continued)

Lead Author (Year)	N	Sport (Indoor/Outdoor)	Latitudinal Location	Vitamin D Administration Protocol	Salient Findings
Żebrowska[63] (2020)	24	Ultramarathon running (outdoor)	52° N	• Experimental group: vitamin D3 oral capsule, 1000 IU, twice daily for 3 weeks • Control group: placebo capsule	• Experimental group demonstrated significantly decreased levels of max troponin (P = .004), 1-hour postexercise troponin (P = .03), 1-hour postexercise myoglobin concentration (P = .01), 24-hour postexercise creatine kinase (P < .05), and TNF-α (P < .03) at the end of the 3 weeks when compared with the control group • Significant negative correlation between postexercise 25(OH)D levels and myoglobin levels (r = -0.57, P = .05) and TNF-α (r = -0.58, P = .05) in the experimental group
Lewis[39] (2013)	32	Swimming/ diving (indoor)	38° N	• Experimental group: vitamin D3 oral capsule, 4000 IU/day for 6 months • Control group: placebo capsule	Changes in 25(OH)D serum concentrations did not correlate significantly with changes in bone turnover markers (BSAP or NTx) at any timepoint • Serum 25(OH)D was not positively correlated with BMD in the proximal femur or lumbar spine. • In men, total body (r = 0.48, P = .03) and trunk (P = .04) mineral-free lean mass correlated positively with serum 25(OH)D levels • In women, right femoral neck BMD (P = .02) was correlated positively with serum 25(OH)D • There was no correlation between serum 25(OH)D levels and inflammatory cytokine levels any time point in either group (TNF-α, IL-6, or IL-1β)
Close[13] (2013)	30	Rugby and soccer (outdoor)	53° N	• Experimental group 1: vitamin D3 oral capsule, 40,000 IU once per week for 12 weeks • Experimental group 2: vitamin D3 oral capsule, 20,000 IU once per week for 12 weeks • Control group: placebo capsule	• Significantly higher serum 25(OH)D levels in the 40,000 IU group at 6 weeks when compared with the 20,000 IU group (P = .016); however, there was no significant difference between these 2 groups at 12 weeks • The control group saw a progressive decline in serum 25(OH)D throughout the course of the study (P < .01) • No significant differences in 1-repetition maximum bench press, leg press, vertical jump height, or 20-m sprint (P > .1 for all)
Fairbairn[21] (2018)	57	Rugby (outdoor)	45°-46.5° S	• Experimental group: vitamin D3 oral capsule, 50,000 IU once every 2 weeks for 11-12 weeks • Control group: placebo capsule once daily	• Significant increase in predicted 1-repetition maximum chin-up performance in the experimental group when compared with the control group (5.5 kg, 95% CI, 2.0-8.9 kg, P = .0002). • No significant difference in 30-m sprint, 10-m sprint, yoyo intermittent exercise recovery test, or predicted 1-repetition maximum bench pull and bench press between groups.

[a]25(OH)D, 25-hydroxyvitamin D; BMD, bone mineral density; BMI, body mass index; BSAP, bone-specific alkaline phosphatase; CI, confidence interval; IL-1β, interleukin-1β; IL-6, interleukin-6; IU, international units; NTx, N-terminal telopeptide; PTH, parathyroid hormone; PWC-170, power working capacity-170; TNF-α, tumor necrosis factor-alpha; vitamin D3, cholecalciferol; $VO2_{max}$, maximal rate of oxygen consumption by working tissue.