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Performance improvement in sport through vitamin D – a narrative review

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Abstract. – OBJECTIVE: It is well known that vitamin D deficiency can lead to various health problems. However, it is not common knowledge among athletes and doctors that vitamin D deficiency is prevalent in sports. This deficiency can severely impact performance, while vitamin D supplementation can alleviate this effect and potentially improve performance.

MATERIALS AND METHODS: This narrative review aims to compile the current state of knowledge about the importance of vitamin D in increasing performance for active people. To this end, we searched the 'Scopus' and 'PubMed' databases for the terms 'vitamin D – athlete – performance' with an end date of 30 June 2022.

RESULTS: Study results indicated that the therapeutic impact of vitamin D on aerobic capacity, recovery, strength and sprint performance remains controversial.

CONCLUSIONS: Based on the previous findings on recovery, strength and performance, 4,000-5,000 IU of vitamin D per day may be a safe dose that can improve athletic performance.

Key Words:
Vitamin D, Deficiency, Aerobic capacity, Strength performance, Recovery.

Introduction

It is well known that a vitamin D deficiency can lead to various health problems. Vitamin D refers to the organic compound cholecalciferol and, when hormonally active, calcitriol[1]. Historically, vitamin D is an essential component of calcium and phosphate homeostasis and metabolism within bones and skeletal muscles[2]. It has also been implicated in several other physiological functions throughout the body[3]. There are two primary forms of vitamin D in humans, cholecalciferol (vitamin D_3, from animal sources) and ergocalciferol (vitamin D_2, from plant sources), both of which can be ingested through food, dietary supplementation, or sun exposure[4].

Risk factors of a vitamin D deficiency have been well described in the general population[5-7]. Multiple studies[8-12] on vitamin D levels in various groups of athletes, including runners, basketball players, jockeys, gymnasts and even dancers, have been conducted in the last decade, showing that they were comparable to those of the general population. However, athletes and doctors are unlikely to be aware that vitamin D deficiency is prevalent in sports[13,14] depending on the season[15,16]. This deficiency can negatively affect muscle strength, power, and endurance[13]. Furthermore, low vitamin D levels can increase the occurrence of stress fractures and other musculoskeletal injuries and can affect acute muscle injuries and inflammation following high intensity exercises[13]. Vitamin D deficiency can severely limit athletic performance[17-19], but it has been shown that vitamin D supplementation can alleviate this effect and improve performance[20-22].

Multiple reviews[13,16,23,24], about the potential ergogenic effects of vitamin D on athletic performance have been published. In 2015, the aspects of skeletal muscle function, increased force and power production combined with decreased recovery times were studied[23]. In 2020 the aspects of the immune system and musculoskeletal function were considered[16]. Again in 2020, the aspects of muscular strength, cardiovascular health and the incidence of illness, including upper respira-

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tory tract infections, were investigated[24], and in 2021 physical performance and musculoskeletal injuries in athletes were considered[13]. At the time of writing, there is no review exploring vitamin D deficiency in endurance and strength athletes and the potential ergogenic effects of vitamin D supplementation. Therefore, this narrative review aims to compile the current research about the importance of vitamin D and its impact on the performance of endurance and strength athletes.

Materials and Methods

This review utilized a narrative review method described by Grant and Booth[25]. We searched two significant databases (Scopus and PubMed) using terms related to vitamin D and athletic performance (vitamin D; athletic performance; sports performance; athlete; professional athlete; elite athletes; college athletes; sports; performance improvement) for articles published before July 2022. The authors sorted the search results (case reports, original papers and review articles) and were included in this review based on their clinical relevance to athletes and practitioners.

Definition of Vitamin D Deficiency

An essential factor to consider when determining vitamin D levels is the classification of the limit for a deficiency (Table I). There has been a significant debate around the definitions of deficiency and insufficiency in recent years[1]. Vitamin D deficiency is generally divided into vitamin D insufficiency (50-75 nmol/l), a vitamin D deficit (<50 nmol/l) and severe vitamin D deficit (<25 nmol/l)[26]. Elsewhere, a vitamin D deficit of <50 nmol/l and a vitamin D insufficiency of 50-75 nmol/l are reported[27]. Even though the recommendations highlight the importance of vitamin D, consensus statements differ depending on the specific society or regulatory body[1]. Therefore, it is essential to consider particular countries' guidelines when determining vitamin D deficiency.

Another significant issue arising from various recommendations is the measurement units used. Some classifications use nmol/l and others ng/ml[27]. In the past, vitamin D levels of <10 ng/ml were defined as a deficit because the serum level of vitamin D and calcium absorption decreased significantly beneath this threshold[28,29]. However, the WHO[30] defines vitamin D insufficiency as a serum concentration of 25 hydroxyvitamin D [25(OH)D] <20 ng/ml (<50 nmol/l). Elsewhere, the vitamin D deficit is defined with a serum concentration of 25(OH)D <20 ng/ml (<50 nmol/l) and vitamin D insufficiency with a serum concentration of 25(OH)D <30 ng/ml (<75 nmol/l)[31]. Since the classification varies, we have used the term vitamin D deficiency unless otherwise described.

There is inconsistency in the classification of a deficiency. Although vitamin D deficiency is generally divided into two categories, vitamin D insufficiency and vitamin D deficit, different scientific societies and international agencies refer to the cut-off values of serum vitamin D concentrations differently (Figure 1). For example, the National Academy of Medicine (former Institute of Medicine) reported serum 25(OH)D concentration below 12 ng/ml (<30 nmol/L) as vitamin D deficiency and below 20 ng/mL (<30 nmol/L) as vitamin D insufficiency[4]. At the same time, the European Society of Endocrinology defines serum 25(OH)D concentration below <20 ng/ml (<50 nmol/L) as vitamin D deficiency and between 20-30 ng/ml (<50-75 nmol/L) as vitamin D insufficiency[32]. For this reason, different cut-off values were used when interpreting the results of studies on vitamin D and athletic performance[9,17,18]. In addition, a comprehensive review of vitamin D in athletes recommended 30 ng/mL (75 nmol/L) as the cut-off value for vitamin D adequacy when assessing serum concentrations in athletes before vitamin D supplementation[33].

Vitamin D and Athletic Performance

In recent years vitamin D was suggested to have ergogenic properties that may improve sports performance. Willis et al[34] recently highlighted that a surprisingly high percentage of athletes are probably vitamin D deficient, especially those exercising an indoor sport. New studies[35-38] clearly show a connection between vitamin D status and performance. However, this relationship could be gender-specific and age-dependent[38] favoring young men[17]. A recent double-blind study[39] in non-diabetic men found that supplementation of 3,332 IU/day of vitamin D significantly increased the serum levels of 25(OH)D, total testosterone, bioactive testosterone, and free testosterone levels.

Vitamin D_3 receptors (VDR) are found in human skeletal muscle tissue[40,41], suggesting that 1,25-dihydroxy vitamin D may directly influence skeletal muscle activity. Furthermore, detecting the VDR in the muscles indicated that vitamin D may have an essential function in them[42,43]. The question arose as to whether a lack of vitamin D could influence skeletal muscle damage caused by overuse[43].

Studies on the effects of vitamin D_3 in muscles[21] have been limited primarily to population groups with diseases[44] or healthy, untrained adults[45]. Until recently, studies[44-46] have shown that increasing serums 25(OH)D levels in specific populations positively affects muscle strength and muscle mass. Contrary to those findings, the only study that investigated these effects in athletes showed different results[47]. In addition, von Hurst and Beck[47] concluded that the optimal dosage of 25(OH)D serum concentrations in athletes cannot be conclusively assessed yet.

The Importance of Vitamin D on Maximum Oxygen Uptake

In athletes, the effect of vitamin D was mainly investigated concerning maximum oxygen uptake (VO_2max)[48-51], endurance[52] and strength performance[53-56]. While VO_2max, endurance and strength performance seemed to be positively influenced, the anaerobic performance was not affected[57].

The mechanism that acts on VO_2max when serum 25(OH)D levels are increasing is still unclear[50]. However, this could be explained by the CYP enzymes (cytochrome P), which activate vitamin D_3 to 1,25-dihydroxy vitamin D_3, contain heme-containing proteins[58] and could influence the binding affinity of oxygen to hemoglobin. In addition, VDRs are present in the myocardial and vascular tissue[59], suggesting that 1,25-dihydroxy vitamin D may influence VO_2max *via* the ability to transport and increase oxygen in the blood. Several studies[48,50,60] have shown a positive association between VO_2max and the serum 25(OH)D concentration in non-athletes. However, additional variables were not considered, such as the simultaneous use of multivitamin preparations[48] and dietary supplements[50,60].

Studies on the interaction between aerobic power (determined by VO_2max) and vitamin D in athletes are contradictory. Koundourakis et al[61] found a significant correlation between 25(OH)D values and selected performance parameters in male professional footballers. A linear relationship was seen between 25(OH)D values before and after the season with measurements of concentric muscle strength and VO_2max[61]. In another study[62], youth soccer players received either vitamin D (5,000 IU/day) or a placebo during eight weeks of intensive training (high-intensity interval training, HIIT). In the supplementation group, vitamin D concentration increased by 119% and VO_2max by 20%; in the placebo group, vitamin D concentration decreased by 8.4% and VO_2max increased by 13%, suggesting that vitamin D supplementation may have a beneficial, though moderate, impact on aerobic capacity in youth soccer players.

In another study[63], lightweight rowers with sufficiently high vitamin D levels (> 30 ng/ml) were observed during an eight-week training phase where either 6,000 units of vitamin D or placebo were administered daily. It came to a significant increase in VO_2max (12.1% compared to 10.3%) and an increase in vitamin D levels by around 400%[63]. On the other hand, a more recent study[64] showed no correlation between 25(OH)D and VO_2max in ice hockey players. In addition, the relationship usually observed between the serum concentration of 25(OH)D and VO_2max is inversely correlated with increased physical activity and training regimen[50]. Similar interactions were observed in Polish elite footballers[30] and young Russian footballers[19]. In addition, a study of Gaelic football players[51] stated that even 72% of participants had inadequate levels of vitamin D. The daily intake of 3,000 IU vitamin D_3 for 12 weeks only corrected the vitamin D deficit but had no meaningful effect on VO_2max[51]. Further studies are needed to explore this interaction and verify whether athletes with a severe deficiency of 25(OH)D or an ergogenic effect exist and whether it is the supraphysiological doses of vitamin D_3, as used by Jastrzębski[63], that have an ergogenic effect.

The Importance of Vitamin D on Strength Performance

Recent studies show several connections between vitamin D levels and strength performance in healthy individuals[37,45,53-56,64-66] and athletes[37,45,53-56,64-66]. It is suggested that vitamin D_3 may increase the strength and performance of skeletal muscle tissue[43,67], possibly through sensitization of the calcium-binding sites on the sarcoplasmic reticulum, which leads to increased muscle contractions[68]. There is also further evidence that vitamin D_3 may increase the size and the number of type II muscle fibres[69-71] and improve muscle function through morphological adjustments and improved calcium availability[69]. However, these findings have yet to be verified in studies with athletes.

So far, it seems questionable whether low vitamin D levels correlate to poor performance and whether consuming high doses of vitamin D improves performance. Cross-sectional studies indicated that vitamin D concentrations were associated with muscular performance in col-

Table I. Summary of the outcomes from controlled studies investigating the potential efficacy of Vit D supplementation on performance in athletes.

Country	Study design	N (men/ women)/age	Participants	Baseline 25(OH)D	Vitamin D dose/duration	25(OH)D concentrations after intervention	Outcomes	Ref.
USA	RCT	19 (6/13) / 20.1±1.6 yrs (Vit D) - 19.7±0.8 yrs (PLA)	College Swimmers	58±21.75 nmol/L	5,000 IU Vit D3/12 wks	8% increase in Vit D group; 44% decrease in PLA group	↑ in squats, vertical jump, and deadlifts ⇔in bench press, standing long jump, dips and pull-ups performance	114
Tunisia	RCT	36 (36/0) / 10.7±2.15 yrs (Vit D) - 10.8±12.2 yrs (PLA)	Recreational footballers	12.4±3.49 ng/ml (Vit D) - 12.1±3.93 (PLA)	200,000 IU Vit D3/ a bolus dose	28.6±5.34 ng/ml (Vit D) - 19.3±4.87 (PLA)	↑ in vertical jump, triple hop, 10m/30m sprints and shuttle run, ⇔in long jump while standing	115
UK	RCT	30 (30/0)/ 22±2 yrs (20,000 IU/wk group); 21±1 yrs (40,000 IU/wk group); 21±1 yrs (PLA)	Club-level athletes (football, rugby)	53±26 nmol/L (20,000 IU/ wk group); 51±26 (40,000 IU/ wk group); 52±27 nmol/L (PLA)	20,000 or 40,000 IU Vit D3 per wk/12 wks	Supplementation with 40,000 IU Vit D induced greater values than 20,000 IU Vit D	⇔in physical performance parameters	80
UK	Controlled prospective study	24 (11/5)/ 26±4.57 yrs	Classic Ballet dancers	NS	2,000 IU Vit D3/ 4wks	NS	↑ in isometric strength and vertical jump	116
Brazil	Single blind/ Crossover study	27 (27/0)/24±4 yrs	Combat sports athletes (MMA, Jiu-jitsu and boxers)	-	50,000 IU/ 80,000 IU/ 110,000 IU per wk/ 6wks Vit D3 followed by 6 weeks placebo	-	↑ in upper and lower body VO_2peak, upper body Wingate performance - Suppl with more than 50,000 IU vit D showed no additional benefit	117
Spain	RCT	36 (36/0)/27±6 yrs	Elite rowers	26.24±8.18 ng/mL (Vit D); 30.76±6.95 ng/mL (PLA)	3,000 IU Vit D3/ 8 weeks	48.12±10.88 ng/ml (Vit D) ; 35.14±7.96 ng/ml)	⇔in muscle recovery	96
UK	RCT	10 (10/0)/ average age of 18 yrs	Soccer players	Presented in figure/ Numerical data NS	5,000 IU Vit D3/ 8 weeks	Serum vit D cons increased in Vit D group	↑ in 1-RM bench press and 1-RM back squat, ⇔in 30-m sprint and Illinois agility run	54
Iran	RCT	69 (36/33)/18-23 yrs	Football and futsal elite athletes	27.5±17.9 ng/mL (Vit D); 24.4±12.7 ng/ mL (PLA)	50,000 IU Vit D3 per week/ 8 weeks	44.9±19.8 ng/mL (Vit D); 21.3±8.9 ng/mL (PLA)	↑in the strength leg press test and sprint test, ⇔in the ergo jump test, vertical jump test, Illinois agility test, 40-yard speed test	72

Continued

Table I. Summary of the outcomes from controlled studies investigating the potential efficacy of Vit D supplementation on performance in athletes.

Country	Study design	N (men/ women)/ age	Participants	Baseline 25(OH)D	Vitamin D dose/duration	25(OH)D concentrations after intervention	Outcomes	Ref.
UK	RCT	22 (22/0)/29±10 yrs (Vit D)- 26±7 (placebo)	Elite indoor athletes (Judokas)	13.16±3.75 ng/mL (Vit D); 16.33±2.73 ng/mL (PLA)	150,000 IU a bolus dose	16.76±3.21 ng/mL (Vit D); 16.33±2.56 ng/mL (PLA)	↑ in muscle strength ten days after supplementation	118
New Zealand	Prospective, double blind, placebo-controlled study	57 (57/0)/ average age of 21.5 yrs (Vit D)- 20.9 yrs (placebo)	Rugby players	93±19nmol/L (Vit D); 95±17 nmol/L (PLA)	50,000 IU biweekly/ 12 weeks	111±18 nmol/L (Vit D-wks 5-6); 114±19 nmol/L 8Vit D-wks 11-12) 85±17 (PLA-wks 5-6); 80±21 (PLA-wks 11-12)	⇔in five of six physical performance parameters including 30m sprint time; ↑ in the weighted reverse-grip chin up performance	82
South Korea	RCT	35(21/14)/ 20.1±0.15 yrs	Collegiate Taekwondo athletes	27.3±1.18 nmol/L (Vit D); 30.9±1.95 nmol/l (PLA)	5,000 IU/ 4 weeks	96.0±3.77 nmol/l (Vit D); 32.7±2.4 nmol/l (PLA)	↑ in peak performance and isokinetic knee extension at 180º ⇔in Wingate test, endurance, counter-movement jump, sit-ups, agility test, 20m pacer)	119
Poland	RCT	36 (36/0)/ average age of 17-19 yrs	Football players	48.5±8.6 nmol/L (Vit D) 47.5±16.2 nmol/L (placebo)	5,000 IU Vit D3/8 weeks	The mean change of serum Vit D; 57.8±21.7 nmol/l (Vit D); -4.0±12.7 nmol/l (PLA)	⇔in Wingate test, 5-, 10-, 20-, 30-m sprints, knee bend jumps, counter-movement jumps, small field games, interval running at AT	81
Ireland	Double-blind, placebo-controlled study	42 (18/24)/ average age of 20±2 yrs	Gaelic football players	47.37±13.29 nmol/L (Vit D); 43.10±22.00 (PLA)	3,000 IU Vit D/ 12 weeks	83.68±32.98 nmol/l (Vit D); 49.22±25.40 nmol/l (PLA)	No change in physical performance (VO2max, vertical jump height, left and right handgrip strength, forced vital capacity, forced expiratory volume at 1s)	51
Poland	RCT	36 (sex was not defined) average age of 17.5±0.6 yrs	Football players	48.5±8.6 mmol/l (Vit D); 47.5±16.2 mmol/l (PLA)	6,000 IU Vit D/ 8 weeks	106.3±26.6 mmol/l (Vit D); 42.5±16.7 mmol/l (PLA)	↑aerobic capacity in both groups (20% in the Vit D group; 13% in the PLA group)	62
Poland	RCT	28 (sex and age were not defined)	Elite football players	32.37±6.3 ng/ml (Vit D); 25-30 ng/ml (PLA)	6,000 IU/ 6 weeks	54.03±7.4 ng/ml (Vit D); 35-40 ng/ml (PLA)	Improvement in 5-m sprint, no change in VO2max and 30-m sprint performance	120

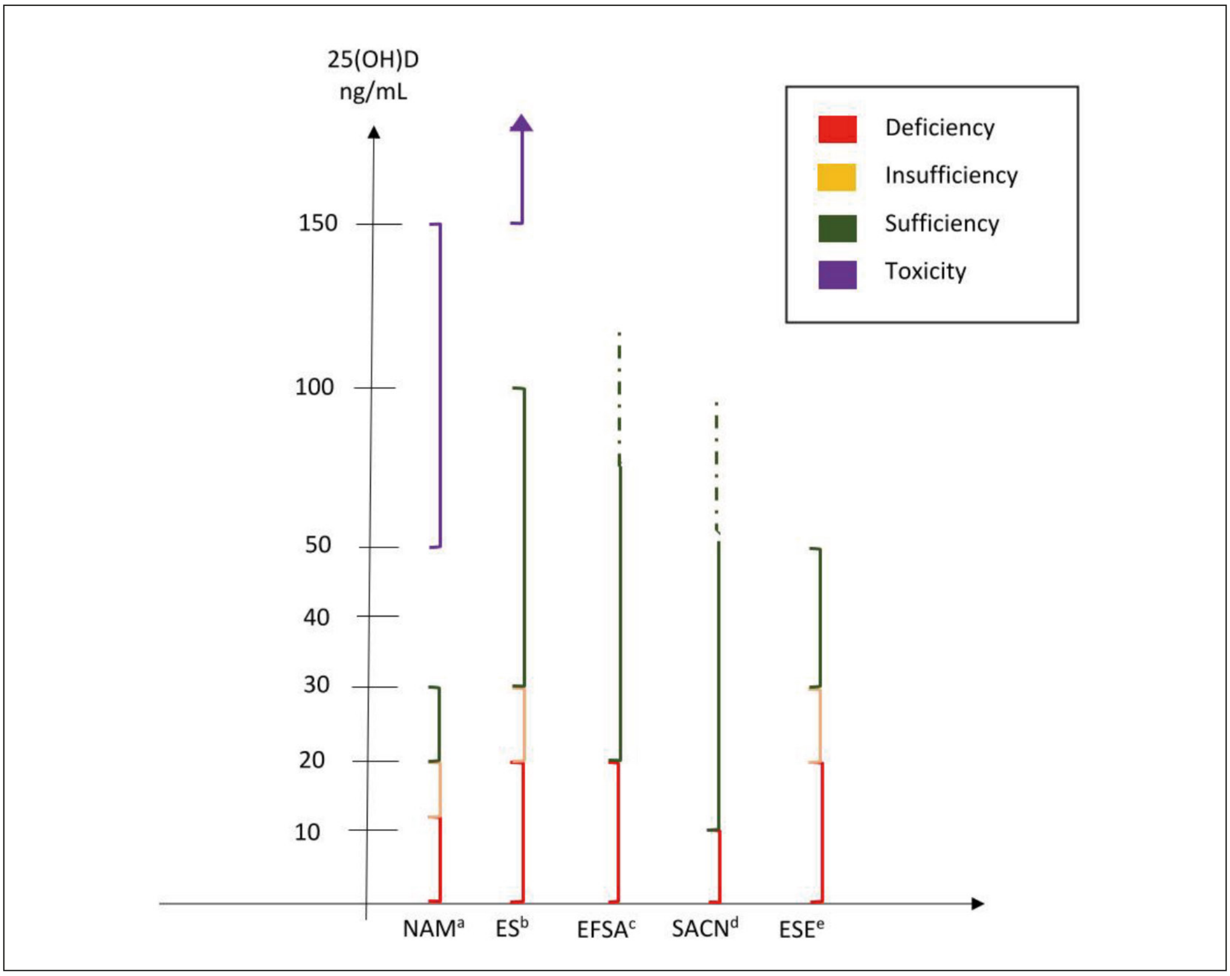

Figure 1. Different scientific societies developed diverse serum 25(OH)D concentrations [ng/mL]. NAM: National Academy of Medicine, US; ES: Endocrine Society, US; EFSA: European Food Safety Authority, Europe; SACN: Scientific Advisory Committee on Nutrition, UK; European Society of Endocrinology, Europe.

legiate athletes[37], UK-based athletes[54], young Danish elite swimmers[37,45,53-56,64-66], and skeletal muscle strength and muscle power in young Polish elite judokas[37,45,53-56,64-66]. In addition, a randomized-controlled trial[72] of 70 Iranian athletes who received 50,000 IU of vitamin D per week for eight weeks indicated a meaningful improvement in strength performance (leg press). However, inconsistent with those studies, no association was observed between vitamin D serum concentrations and strength performance in studies with Polish elite footballers[49], young Russian footballers[19], Swedish female soccer players[73], and Gaelic football players[51].

Data on muscle strength and athletic performance in athletes is limited, and results are controversial. The few studies[14,74] that explored the interaction between muscle strength and serum vitamin D status in athletes found no significant association between them. A comparison between athletes with sufficient (>50 nmol/l) and athletes with insufficient (<50 nmol/l) vitamin D status showed no differences in counter-movement jump and aerobic fitness (VO_2max)[74]. Similar findings were reported in a study investigating male professional basketballers. In athletes with deficient (<20 ng/ml), insufficient (20-32 ng/ml), and sufficient vitamin D (>32 ng/ml), muscle strength of knee extension/flexion and ankle dorsiflexion/plantarflexion was investigated. Interestingly, the isokinetic lower limb strength was not significantly different when all three groups were compared[14].

It is stated that although vitamin D may have beneficial effects on skeletal muscles in athletes, it has no effect on the performance of athletes that do not exhibit a vitamin D deficiency[75]. However, some studies[64,76,77] on muscle strength and vitamin D in athletes showed no effect on performance even though the vitamin D level was deficient. For example, in the study[64] examining hockey players with vitamin D deficiency, no relationship was found between serum vitamin D levels and physiological performance variables. Another study[76] investigated an association between vitamin D and lower extremity muscle strength in 342 football players. Although 84% of the athletes had vitamin D deficiency, no correlation was detected between low vitamin D levels and lower extremity muscle strength. A study[77] including 80 competitive swimmers (42 vitamin D insufficient and 11 vitamin D deficient) found no association between vitamin D levels and various performance parameters. In particular, there were no differences between athletes with and without vitamin D deficiency.

In some studies, muscle function[47] and athletic performance[71] were only improved in athletes with a vitamin D deficiency. In addition, a study[52] including people with paraplegia stated that vitamin D supplementation improved strength performance in more than 60% of the study participants, but not endurance. However, opposite results have also been obtained. Racing car drivers taking 3,800 IU of vitamin D_2 per day for six weeks observed an increase in vitamin D_2 levels with a decrease in vitamin D_3 levels, but no improvement in muscle function tests[78]. Another study[79] on vitamin D deficient college athletes noted that a 600 IU intake of vitamin D_2 led to an increase in blood levels of vitamin D_2 and D_3 but had no effect on the parameters of muscle strength or muscle damage. Similar to other studies[80], supplementation with 20,000 and 40,000 IU of vitamin D over 6 and 12 weeks in club-level athletes increased vitamin D concentration, but no improvement in the performance was observed.

It is also suggested that only substantial daily doses of vitamin D of 4,000-5,000 IU per day can improve athletic performance[23]. Therefore, the dosage applied in studies that showed no benefit of vitamin D supplementation may have changed the study results. For instance, in a study[79] with young athletes, the daily intake of 600 IU of vitamin D for six weeks did not affect muscle function or exercise-induced muscle damage despite an increase in the vitamin D levels in the blood.

Vitamin D and Sprint Performance

Randomized-controlled trials (RCTs)[54,67,72,77,81,82] have examined the influence of vitamin D on strength development and performance in sprinting. However, the study results are controversial. Twenty-four elite young soccer players participated in a cross-sectional polish study[83] where they received 5,000 IU of vitamin D daily for one year. A significant negative correlation was found between the 25(OH)D concentration and sprint times at distances of 10 m and 30 m. Supplementing high doses of vitamin D (5,000 IU) daily for eight weeks[54] or loading doses (50,000 IU) weekly for eight weeks[72] improved strength performance. Another RCT study[84] of 25 young soccer players who received 20,000 IU of vitamin D_3 twice a week for eight weeks has shown that the 25(OH)D concentration was significantly and positively correlated to the level of aerobic power. However, it could not be associated with a clear improvement in muscle strength/power. Inconsistent with these studies, another RCT study of 57 male rugby players supplemented with biweekly for 12 weeks indicated no alteration in sprint performance[82]. Similar to this study, other RCT studies of football players supplemented with 5,000 IU vitamin D for eight weeks[81], and adolescent swimmers supplemented with 2,000 IU vitamin D for 12 weeks[77] showed no alterations in sprint performance. Another RCT study[85] of collegiate basketball players supplemented with 2,000 IU vitamin D daily for three months did not elicit statistically significant performance improvements (peak power). Although several RCTs investigate the association, we need more RCTs with larger sample sizes to clarify the interaction between vitamin D supplementation and athlete sprint performance.

The Importance of Vitamin D in the Recovery Phase

Rapid recovery provides a significant advantage to athletes facing exercise-associated stress, inflammation, and post-exercise remodeling of muscle intracellular components and enables high-intensity training more frequently[86]. The potential efficacy of vitamin D on recovery is attributed to its essential role in inflammation modification throughout both innate and acquired immunity[8,87]. The human skeletal muscle tissue reacts to training stimulation and tissue damage by remodeling its intracellular muscle components[88-90]. During regeneration, 1,25-dihydroxy vitamin D increases myogenic differentiation and proliferation[91] and regulates myostatin in cell cultures as an inhibitory regulator of the muscle C2C12 myoblastsynthesis[92]. Stratos et al[93] showed this increased skeletal muscle regeneration in animal models. The reaction of the *m. soleus* of the rat to 332,000 IU of vitamin D per kg of muscle weight *vs.* 33,200 IU of vitamin D per kg of muscle weight showed that the muscle with the higher vitamin D dose went into apoptosis much later than the muscle with the lower dose as a sign of an increase in cellular matrix proteins[93] which are essential for the repair of the skeletal muscles[94]. This increased cellular turnover accelerates recovery and improves strength performance[93].

Animal model regeneration capabilities are significantly higher than humans and cannot be transferred to humans in their totality. The discovery that vitamin D supplementation increases the recovery of muscular strength shortly after intense physical activity was supported by human studies with less active people and low doses[95]. In a randomized, double-blind, placebo-controlled study, Barker et al[95] showed that 4,000 IU per day for 35 days in healthy and moderately active adults reduced the increase in the liver biomarkers alanine (ALT) and aspartate (AST) immediately after ten sets of ten repetitions of isometric concentric jumps. Although the maximum performance decreased in both groups, the performance only decreased by 6% in the group with supplementation, while the performance of the placebo group decreased by 32% after training[95]. This discrepancy persisted even after 48 hours.

Although animal studies and studies on active adults indicated promising results, few studies examining the effect of vitamin D on recovery and fatigue have claimed controversial results[87,96]. A study with elite rowers showed that the daily intake of 3,000 IU of vitamin D_3 was beneficial for iron metabolism but insufficient for adequate muscle recovery[96]. Another placebo-controlled study[87] with 22 football players supplemented with 50,000 IU of vitamin D per week for eight weeks emphasized that although there was an increase in vitamin D in the serum, there was no change in muscle damage parameters. Therefore, further studies are required to elucidate the potential impact of vitamin D on the recovery phase.

Results

In Table I, we present 15 controlled studies investigating a potential influence on performance after supplementation with vitamin D in the athletic population. Of these 15 studies, 11 showed an improvement in laboratory tests, whereas, in 4 studies, no effect of the supplementation could be demonstrated.

The Dosage of Vitamin D for Optimal Performance

Given the substantial interest in vitamin D and its potential impact on sports performance, many athletes have been administered vitamin D to improve their performance[51,97]. However, the optimal vitamin D dose and its determination are controversial[98,99]. There is increasing evidence that 600-800 IU of vitamin D per day may not suffice for optimal vitamin D levels, especially for athletes[100] since 25(OH)D serum concentrations of >100 nmol/l have been suggested for an optimal function of the skeletal muscles of the lower extremities[101]. In addition, low vitamin D levels are associated with increased bone turnover, which increases the risk of stress fractures[102]. From all available sources, it has been shown that approximately 2,000 to 5,000 IU of vitamin D per day is required to maintain serum 25(OH)D levels of 75-80 nmol/l and optimize bone health[101,103-105]. In addition, athletes with a vitamin D deficiency should strive to raise their levels to normal[51,106]. Since the vitamin D level fluctuates seasonally, it should be measured at the end of winter to detect an actual deficiency[107]. Therefore, seasonal winter supplementation may be sufficient for athletes[108-110]. D_2 and D_3 supplementation can increase the 25(OH)D plasma concentration. However, vitamin D_3 supplementation may be more effective than vitamin D_2[111,112]. It should be noted that vitamin D_2 is less bioavailable and less stable with increasing age. Some clinical studies[69,111,113] have shown that vitamin D_2 absorption is significantly lower than the absorption of vitamin D_3. In addition, vitamin D_2 has a lower affinity for the VDR and is deactivated as soon as it is hydroxylated in the kidney. Therefore, vitamin D_3 supplementation has been commonly preferred over vitamin D_2 supplementation.

Since vitamin D_3 proved to be more effective, the optimal dosage depends on the person (age, gender, etc.) and the institution issuing the guidelines. However, different institutes and authorities suggested different daily vitamin D supplementation doses. For instance, The Institute of Medicine (IOM) recommends 400-800 IU of vitamin D per day for children, adults and people over 70 to keep the vitamin D in the serum at >50 nmol/l[121,122]. Alternatively, the Endocrine Society (ES) recommends a slightly higher intake with doses of 400-1,000 IU vitamin D per day for infants, 600-1,000 IU vitamin D per day for children and 1,500-2,000 IU vitamin D per day for adults to achieve vitamin D concentrations of 75 nmol/l in serum[123]. These recommendations correspond to a review from 2004[124], which states that 70 nmol/l is the lowest acceptable serum concentration to avoid adverse health effects. Other recommendations[124,125] suggest that the optimal values could be between 90 and more than 120 nmol/l. These are estimates based on people who live in very sunny surroundings[103] and examinations that have shown that the lower extremities are functioning optimally[101]. The serum concentration should be at least 50 ng/ml to protect athletes from acute and chronic diseases[71].

There is increasing evidence[100] that 600-800 IU of vitamin D per day may not be sufficient for optimal vitamin D levels, especially for athletes. It has been suggested that 25(OH)D serum concentrations >100 nmol/l are optimal for the lower extremities' skeletal muscle functionality[101]. So far, however, the effects of vitamin D supplementation and skeletal muscle function in athletes with 25(OH)D levels ≥100 nmol/l have not been investigated in any study[47]. Therefore, it is still relatively unclear whether athletes could benefit from 25(OH)D levels ≥ 100 nmol/l to increase skeletal muscle function and reduce the risk of stress fractures. In addition, low vitamin D levels are associated with increased bone turnover, which increases the risk of stress fractures[102]. From all available sources, it has been shown that around 2,000 to 5,000 IU of vitamin D per day is required to maintain bone health by maintaining serum 25(OH)D levels of 75-80 nmol/l to optimize[101,103-105].

In addition, this dosage would not be achievable through natural UVB exposure in the months of October to April in latitudes from 42.2 to 52 °N[126], which is due to the high prevalence of vitamin D deficient indoor and outdoor athletes has been documented in a large number of different disciplines[127-131]. Athletes with a vitamin D deficiency require 2,200 IU of vitamin D per day to have the normal level after three months[106].

Vitamin D Toxicity and Hypercalcemia

Despite the reported positive effects of high vitamin D doses, the danger of overdosing should not be ignored[132]. 1,25-dihydroxyvitamin D works synergistically with calcium, absorbing it from the gastrointestinal tract and stimulating mature osteoblasts to produce a Receptor Activator of NF-κB Ligand (RANKL)[133]. RANKL, in turn, stimulates mineralization and bone resorption through osteoclastogenesis. Increased concentrations of 25(OH)D can accelerate this process, leading to an increase in the calcium concentration in the blood, a higher rate of absorption of calcium by the kidneys, possibly kidney stones and possible calcification of the blood vessels[134]. As reported, vitamin D toxicity could occur after a prolonged period at doses ≥ 10,000 IU per day[101,103], which leads to side effects, such as hypercalcemia. However, it is unclear which levels of vitamin D cause toxicity[101,135] and, for ethical reasons, no prospective studies have analyzed the effects of vitamin D intoxication in humans. As recently reported[136], an accidental overdose of 2,000,000 IU of vitamin D_3 in two elderly patients caused no adverse effects and slightly increased the serum calcium concentration. Adverse effects have only been reported at serum concentrations of 25(OH)D >200 nmol/l, which would require daily doses of 40,000 IU or more[103] and have not been associated with hypercalcemia.

Conclusions

In summary, animal experiments have shown that supraphysiological doses of vitamin D_3 have potential ergogenic effects on the human metabolic system and lead to multiple physiological improvements[23]. These dosages can increase aerobic capacity, muscle growth, strength, and energy production, decrease post-exercise recovery time, and improve bone density[23]. If such a treatment effect exists, the most significant performance improvements will probably occur in those with the lowest levels. A significant improvement in athletic performance may occur when levels increase from 15 to 30 ng/ml, but minor improvements will occur when levels increase from 30 to 50 ng/ml[71]. However, human studies on recovery, aerobic capacity, strength, and sprint performance in athletes with different sports/performance levels have shown controversial results. Both a deficiency (12.5 to 50 nmol/l) and a high vitamin D level (>100 nmol/l) can have adverse side effects and possibly increase mortality[137]. Therefore, maintaining optimal serum levels between 75 and 100 nmol/l[121,124] and ensuring balanced and adequate levels of essential nutrients, including vitamin K, are critical to health and performance. Doctors and caregivers should recommend that their athletes have their plasma 25(OH)D measured to determine whether supplementation is necessary[138]. For bones to stay healthy, athletes need to eat enough, do strength training, and have a high enough intake while paying attention to vitamin D and calcium[139]. Multiple controlled trials[140,141] have suggested that a dose of 4,000-5,000 IU of vitamin D_3 could be a safe dose to improve athletic performance as it was shown to be positively correlated with preserving bone, decreasing the risk of injury, and maintaining 25(OH)D levels[140], while enhancing skeletal muscle recovery[141]. Additionally, vitamin D3 supplementation may be effective in reducing the symptoms of upper respiratory tract infections during winter training[142]. After all, no study in the athletic population has increased serum levels of 25(OH)D above 100 nmol/l (optimal range for skeletal muscle function) at doses of 1,000 to 5,000 IU per day. Therefore, future studies should investigate the physiological effects of higher doses (5,000 IU to 10,000 IU per day or more) of vitamin D_3 combined with different doses of vitamin K_1 and vitamin K_2 in the sports population to achieve the optimal dosages to maximize performance.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Ethical Committee Approval

No Ethical approval is requested for this study.

Authors' Contributions

Conceptualization, K.W. and B.K.; methodology, K.W. and B.K.; writing—original draft preparation, K.W. and B.K.; writing—review and editing, A.D.L, Z.J., P.T.N., and L.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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