Review Article

Magnesium and Vitamin D Supplementation on Exercise Performance

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ABSTRACT

Magnesium and vitamin D are two micronutrients that contribute directly to the metabolism of macronutrients, maintenance of muscle function, and various metabolic processes (i.e., protein synthesis and bone metabolism). Dietary recommendations are established based on age and gender differences; however, energy expenditure is not accounted for in determining these values. It is believed that athletes may require greater nutrient quantities than less active populations because of their increased energy expenditure. Nutrient intake values have yet to be determined for athletes, leading to inadequate energy intake, deficiencies, and insufficiencies; thus, supplementation may be an effective way of achieving nutrient adequacy in athletes. The purpose of this narrative review was to present research pertaining to magnesium supplementation and vitamin D supplementation on exercise performance. A systematic keyword search for articles from PubMed was conducted from June to August 2020. The search terms included various words related to the topic. Inclusion criteria required articles to be available in English; to be a clinical trial, randomized controlled trial, or longitudinal study; and to involve magnesium supplementation, vitamin D supplementation, or supplementation of both micronutrients. In addition, the research conducted on magnesium or vitamin D were required to focus on athletes or those who exercised regularly. However, because of the paucity of published data regarding the combined effects of magnesium and vitamin D supplementation on exercise performance, those studies that could provide some information in nonathletic populations were included. The search did not limit the years in which studies were published because of the scarcity of articles related to the topic. After reviewing the articles for originality and applicability, 13 studies were included in our narrative review. Some researchers have reported that magnesium supplementation may provide ergogenic benefits via contributions to muscle function and recovery. In addition, some researchers have reported that vitamin D supplementation may positively affect physical endurance and muscle recovery in athletes. However, more research is required to provide more definitive conclusions. The interactions between magnesium and vitamin D during metabolism may potentiate the functions of each micronutrient, making the combined effects of magnesium and vitamin D greater than the effects of either one alone. However, research is required to elucidate their combined effects on exercise performance.

INTRODUCTION

Magnesium

Magnesium is the fourth most abundant mineral and the second most abundant intracellular cation in the body, contributing to over 300 metabolic reactions (1). This essential nutrient is involved in the synthesis of nucleic acids and proteins, proper bone development, maintenance of electrolyte balance and mineral homeostasis, as well as oxidative, immune, and neuromuscular functions (2). The recommended dietary allowance (RDA) for magnesium in individuals, 14 yr of age and older, is between 310 and 420 milligrams per day (mg·d^{-1}); but magnesium intake is reportedly suboptimal in most populations (3). Individuals with serum magnesium concentrations greater than 0.85 mmol·L^{-1} are likely to have adequate magnesium status, whereas individuals with serum magnesium concentrations around or below 0.75 mmol·L^{-1} are most likely to have a magnesium deficiency (4). A low serum magnesium concentration is associated with various chronic diseases (e.g., hypertension, cardiovascular disease, etc.), and research has shown that adequate magnesium intake has a potential therapeutic role in improving glucose and insulin metabolism. Furthermore, magnesium has been shown to treat severe asthma and migraines and assist in alleviating muscle cramps (5,6). It is currently estimated that 45% of adults from the United States are magnesium deficient, and 22% of international athletes are also clinically deficient (7,8). Magnesium contributes to the maintenance of muscle function and blood glucose concentrations, while also promoting calcium absorption. The increased importance of these functions in athletes advances the idea that magnesium, like other minerals, may exert an ergogenic effect, specifically in individuals with low serum magnesium concentrations (1,9,10).

Vitamin D

Vitamin D is a lipid-soluble vitamin that is essential to muscle growth, cell differentiation, and bone mineralization (11,12).

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2379-2868/0604/0e000179
Translational Journal of the ACSM

Research investigating the effects of vitamin D supplementation on exercise performance is limited, but the importance of vitamin D treatment in muscle regeneration after exercise has been studied and established (11,12). The RDA for vitamin D in females and males, 1 to 70 yr of age, is 600 IU, equivalent to 15 $\mu g \cdot d^{-1}$ (13). Individuals with serum vitamin D concentrations less than 20 $ng \cdot mL^{-1}$ are likely to have vitamin D deficiency, whereas individuals with serum vitamin D concentrations greater than 20 $ng \cdot mL^{-1}$ are likely to achieve vitamin D adequacy (14). In the United States, between 36% and 57% of adults are vitamin D deficient (15). Measurements among professional athletes mimic those of the general population: 32% of professional basketball players experience vitamin D deficiency, 26% of National Football League athletes experience vitamin D deficiency, and vitamin D insufficiencies have been measured in up to 73% of young athletes and dancers (16–18). Vitamin D deficiencies may correspond to an increased risk of cancer, cardiovascular disease, and dementia, while also decreasing neuromuscular function and contributing to muscle pain and fatigue (11,19–21). Research indicates that adequate vitamin D intake is necessary for the regulation of immune function and protein synthesis, while also improving strength and endurance in athletes (22–24).

Magnesium and Vitamin D

Magnesium and vitamin D interact in a coordinated manner. The activation, inactivation, and conversion of the various forms of vitamin D are magnesium-dependent processes that rely on binding proteins and enzymes that further depend on magnesium availability in the body (20). Vitamin D stimulates magnesium absorption in the intestine, whereas the metabolism of vitamin D is a magnesium-dependent process (20). Without the other nutrient, neither magnesium nor vitamin D would be able to provide optimal physiological benefits (20,25). Therefore, the purpose of this narrative review was to present research pertaining to magnesium supplementation and vitamin D supplementation on exercise performance. Most of the research presented will be on magnesium supplementation on exercise performance and vitamin D supplementation on exercise performance. There were no studies published to date on the combination of magnesium and vitamin D supplementation on exercise performance; however, we decided to include one study that was conducted on the combined effects of these two micronutrients, but not in athletes, to highlight the need for research in athletes.

Methods

For this narrative review, a systematic keyword search using medical subject headings (MeSH) was conducted via PubMed during the months of June through August 2020. The search terms included "magnesium," "vitamin D," "cholecalciferol," "exercise performance," "athletic performance," "muscle performance," "physical performance," and "athletes." The combined searches yielded 392 results.

Inclusion criteria required all articles to have full text available in English; to be a clinical trial, randomized controlled trial, or longitudinal study; and to involve magnesium, vitamin D, or both micronutrients. In addition, the research conducted on magnesium or vitamin D was required to be conducted on athletes or those who exercised regularly. However, there was a lack of published data on the combined effects of magnesium and vitamin D on exercise performance, and thus, we included those studies that could provide some information for future research. Articles that did not meet the described criteria were excluded from the review. The search did not limit the years in which studies were published because of the scarcity of articles related to the topic. These criteria yielded 33 total results, which were then evaluated for applicable and original data. After reviewing the articles and determining the usability of the data provided, 13 studies, 5 studies investigating the relationship between magnesium and exercise performance in athletes, 7 studies investigating the relationship between vitamin D and exercise performance in athletes, and 1 study investigating the relationship between magnesium and vitamin D in nonathletes, were included in this narrative review.

Summary of Findings

Background: Micronutrients

The potential ergogenic effects of vitamin and mineral supplementation have been an important topic among sports nutrition professionals in recent years. Micronutrients are involved in countless biological processes pertinent to athletes and routine exercisers. Experimental findings indicate that vitamin and mineral deficiencies may impair exercise performance, suggesting a potential positive relationship between correcting suboptimal vitamin and mineral concentrations via micronutrient supplementation and improved physical performance (12,26).

Typically, individuals who restrict their energy intake, by using extreme weight loss techniques or consuming unbalanced diets, do not meet the RDA for micronutrients, often leading to micronutrient deficiencies. These practices are popular among sports where weigh-ins occur (e.g., wrestling, lightweight rowing) or where aesthetics has been historically thought of as a high priority, favoring individuals with lower body weight (e.g., gymnastics, ice skating). To maintain physical health, these individuals may require vitamin and mineral supplementation (27).

Micronutrients and Exercise

Although data supporting the use of micronutrient supplementation to enhance exercise performance are scarce, iron and magnesium are the minerals with the greatest amount of evidence to indicate a positive correlation between mineral supplementation and increased quality of athletic performance measured via a 15-km time trial related to iron supplementation and a positively influenced muscle performance related to magnesium supplementation (28). In addition, the B vitamins play a crucial role in energy metabolism and cell regeneration; accumulating research shows that poor status of the B vitamins may decrease an individual's ability to perform at a high intensity (29). Scientific evidence regarding the effects of micronutrient supplementation on exercise performance remains limited, but vitamin and mineral deficiencies continue to prevail among athletes (7,16–18,30).

Background: Magnesium

Magnesium is a prominent mineral that acts as a cofactor in over 300 metabolic reactions, including anabolic and catabolic processes, essential to regular bodily functions as well as exercise performance (31). In addition, magnesium contributes to the production of adenosine triphosphate (ATP), which is used by the body to store energy and to drive cellular processes (32).

Good food sources of Mg include grains, leafy greens, nuts and legumes, and nuts (5). The maintenance of adequate magnesium concentration, via dietary or supplemental consumption, is necessary for optimal muscular strength and recovery (31).

The magnesium loading test is the optimal means of measuring magnesium status. This process involves a magnesium infusion followed by an assessment of the individual's urinary magnesium excretion (32). Alternatively, magnesium concentration can be determined in circulating cells, demonstrating the way that compartmental magnesium varies during exercise (31). In addition, serum magnesium concentration is commonly measured in clinical settings; however, this measurement may not be an accurate representation of overall magnesium status (32). Ionized magnesium accounts for 67% of an individual's total magnesium concentration and is thus the most physiologically important quantity in determining magnesium status (33). The limitations of the described measurement methods, cumbersome infusion methods, a reliance on normal kidney and gastrointestinal functions, and varying magnesium content in different tissues, make accurately determining magnesium status difficult (31,32).

Serum magnesium concentration decreases by approximately 10% during exercise because of muscle utilization and perspiration (34). Hypomagnesemia, a condition in which serum magnesium concentrations are less than 0.65 $mmol \cdot L^{-1}$, is associated with many serious health conditions (35,36). Additional effects of suboptimal magnesium status include inefficient energy metabolism, decreased endurance, and increased muscle cramping (37). Hypomagnesemia is linked to long-term, high-intensity exercise, whereas short-term, high-intensity exercise is linked to hypermagnesemia (25). Hypermagnesemia is a condition in which serum magnesium concentrations are greater than 1.2 $mmol \cdot L^{-1}$. Hypermagnesemia is dramatically less common than hypomagnesemia, but extreme cases may lead to hypotension and death (35).

Magnesium Supplementation and Exercise Performance

Accumulating evidence emphasizes the importance of magnesium on muscular strength and cardiorespiratory function (37). Magnesium supplementation has been used to treat skeletal muscle cramps that frequently occur as a result of exercise (38). Considering this rehabilitative function of magnesium as well as the potential ergogenic properties of the mineral, several experimental trials have been conducted with the intent to analyze and understand the benefits of magnesium supplementation in athletic populations (Table 1).

Several researchers have conducted research to determine the relationship between magnesium supplementation and exercise performance using different methods. In a double-blind, placebo-controlled trial, Terblanche et al. (34) supplemented 20 magnesium-replete subjects, female and male marathon runners, 32.4 ± 11.5 yr of age, with 365 mg of magnesium-L-aspartate hydrochloride three times daily for 10 wk. The placebo group received an identical-looking placebo. They reported an increased rate of return to prerace serum magnesium concentrations after marathon participation in the experimental group, but supplementation did not affect muscle function, running performance, muscle damage extent, or muscle recovery rate when values were compared between the experimental and the placebo groups (34).

In another double-blind, placebo-controlled trial, Weller et al. (39) supplemented 20 athletes, 22.5 ± 5.6 yr of age, who had serum magnesium concentrations below 0.88 $mmol \cdot L^{-1}$, with 500 mg of magnesium oxide daily for 3 wk. Athletes in the placebo group received an identical-looking placebo throughout the duration of the trial. Maximal and submaximal ergometer performance, magnesium concentrations in calf muscles, and neuromuscular activity were evaluated. Weller et al. (39) reported that magnesium supplementation had no effect on any of the aforementioned variables and suggested that serum magnesium concentration was a poor indicator of muscle cramps and impairment of performance in athletes (39).

Finstad et al. (40) conducted a double-blind, placebo-controlled study on 40 active women, 21.2 ± 3.1 yr of age, with varying ionized magnesium concentrations. They supplemented participants in the experimental group with 212 mg of magnesium oxide daily for 10 wk, whereas those in the placebo group were provided an identical-looking placebo. Researchers reported a slight increase in ventilation at peak exertion in the experimental group; however, supplementation did not improve maximal oxygen volume, time to exhaustion, exercise performance, or recovery after exercise (40).

Córdova et al. (31) supplemented 18 male cyclists, 26.2 ± 1.81 yr of age, with 400 mg of elemental magnesium for 3 wk to analyze the effects of magnesium supplementation in preventing muscle damage. No significant differences in peak power or maximal oxygen volume were observed between the experimental and the placebo groups; however, the researchers concluded that adequate magnesium intake maintained serum magnesium and erythrocyte magnesium concentrations, permitting muscle recovery (31).

The findings of the described studies suggest a unique relationship between magnesium supplementation and exercise performance. Terblanche et al. (34) and Córdova et al. (31) reported that magnesium supplementation had little to no effect on their respective exercise performance measures; however, magnesium supplementation had a positive effect on serum and erythrocyte magnesium concentrations, potentially promoting muscle recovery. Weller et al. (39) reported that magnesium supplementation produced no effect on any physical parameters measured. Finstad et al. (40) reported that magnesium supplementation produced a slight, positive effect on peak ventilation but demonstrated no effect on other exercise performance outcomes measured. Data supporting magnesium supplementation in athletes suggest that correcting magnesium concentration in athletes may improve muscle function and support muscle recovery, improving overall performance of the athlete (31). Other data suggest that no performance improvements occur as a result of correcting magnesium concentration in athletes with suboptimal magnesium concentrations (34,39,40)

Magnesium Intake and Exercise Performance

In an observational study, Santos et al. (10) assessed if magnesium intake was associated with an improvement in maximal isometric force, maximal isometric handgrip strength, squat jump performance, and countermovement jump performance in 26 elite male court athletes, 20.1 ± 4.9 yr of age. They assessed 7-d diet records and reported that magnesium intake was directly associated with trunk flexion, trunk rotation, and maximal handgrip strength. From these data, they determined that plasma magnesium concentrations were directly related to strength indices and performance may be improved with adequate magnesium intake (10).

TABLE 1.
Summary of Research on Magnesium and Exercise Performance.

Publication Information	Participant Information	Study Design	Parameters Analyzed	Purpose and Key Findings
Terblanche et al. (34), *International Journal of Sport Nutrition*	• $n = 20$ (4 women; 16 men) • Experienced marathon runners • 32.4 ± 11.5 yr of age • Baseline (serum and skeletal) Mg status: Mg-replete subject	• Double-blind, placebo-controlled trial • 1.33 g of Mg-L-aspartate hydrochloride (122.6 mg of elemental Mg) 3 times per day for 10 wk	• Maximal treadmill test • Skeletal muscle Mg content • Running performance • Leg muscle function • Serum Mg • Urinary hydroxyproline • Creatinine	• Purpose: to determine the effects of Mg supplementation on running performance, muscle damage, and recovery of muscle function in a group of athletes competing in a 42-km marathon footrace • Compared with control, Mg supplementation ○ Increased the rate of return to prerace concentrations of serum Mg after the marathon ($P < 0.05$) • Likely no physiological benefit of supplementation
Weller et al. (39), *Medicine & Science in Sports & Exercise*	• $n = 20$ athletes • 22.5 ± 5.6 yr of age • Baseline (serum) Mg status: serum [Mg] below 0.8 $mmol \cdot L^{-1}$	• Double-blind, placebo-controlled trial • 500 mg of Mg oxide (305 mg of elemental Mg) daily for 3 wk	• Maximal and submaximal ergometer measurements • Exercise logs • Mg in calf muscle • Neuromuscular activity	• Purpose: to determine whether the Mg supplementation affected exercise performance, clinical symptoms, and [Mg] in athletes with low-normal serum [Mg] • Mg supplementation ○ Increased fractional Mg excretion ($P < 0.05$) • Serum [Mg] was a poor indicator of muscle cramps and impairment of performance in athletes • Likely no physiological benefit of supplementation
Finstad et al. (40), *Medicine & Science in Sports & Exercise*	• $n = 40$ healthy, active women • $n = 20$ (group 1) • $n = 20$ (group 2) • 21.2 ± 3.1 yr of age • Baseline iMg status (group 1): [iMg] below the normal range (< 0.53 $mmol \cdot L^{-1}$) • Baseline iMg status (group 2): [iMg] within the normal range (0.53–0.67 $mmol \cdot L^{-1}$)	• Double-blind, placebo-controlled trial • 212 mg of Mg oxide (129 mg of elemental Mg) daily for 10 wk	Concentrations of • Mg • Calcium • Sodium • Potassium • Glucose • Lactate • Hemoglobin	• Purpose: to examine the effects of iMg supplementation on [iMg], exercise performance, and recovery in physically active women • Intervention group showed: ○ Resting [iMg] was greater in the intervention group ($P < 0.05$) • 4 wk of 212 $mg \cdot d^{-1}$ Mg oxide supplementation improves resting [iMg] but not performance or recovery in physically active women. • Physiologically important in raising resting [iMg]
Santos et al. (10), *Magnesium Research*	• $n = 26$ male elite athletes (basketball players, handball players, and volleyball players) • 20.1 ± 4.9 yr of age • Baseline dietary Mg intake: 244.7 ± 78.8 mg	• Observational study • 7-d diet records	• Maximal isometric force • Maximal isometric handgrip strength • Squat jump • Countermovement jump • Fat-free mass • Fat mass • Percent body fat • 7-d diet records	• Purpose: to evaluate the effect of dietary Mg intake on strength in a preseason training period in a sample of elite, male athletes ○ Mg intake was directly associated with trunk flexion, trunk rotation, and maximal handgrip strength ($P < 0.1$)

TABLE 1.
(Continued)

Publication Information	Participant Information	Study Design	Parameters Analyzed	Purpose and Key Findings
				○ Plasma Mg was directly related to strength indices ($P < 0.1$) ● Performance may be improved with adequate Mg intake ● Supplementation may be important in correcting inadequate dietary intake of elite male athletes
Córdova et al. (31), *Nutrients*	● n = 18 male professional cyclists ● 26.2 ± 1.81 yr of age ● Baseline Mg consumption: 247 ± 5.3 mg/1000 kcal	● Randomized placebo-controlled trial ● 400 mg of elemental Mg daily for 3 wk	Concentrations of ● Serum Mg ● e-Mg ● Lactate dehydrogenase ● Creatinine kinase ● Aspartate transaminase ● Alanine transaminase ● Myoglobin ● Aldolase ● Total proteins ● Cortisol ● Creatinine	● Purpose: to analyze the effects of Mg supplementation in preventing muscle damage ● Compared with the intervention group ○ Control group had a greater decrease serum [Mg] and [e-Mg] ($P < 0.05$) ● Adequate Mg intake can maintain serum [Mg] and [e-Mg], which permits muscle recovery ● Likely no physiological benefit of supplementation

[Mg], magnesium concentration; iMg, ionized magnesium; V_{Epeak}, ventilation at peak exertion; VO_{2max}, maximal oxygen volume; e-Mg, erythrocyte magnesium; P_{max}, peak power; $IE_{max} = P_{max}$/weight.

Data validating the importance of magnesium to basic bodily functions have been well established. Further research is required to determine the most beneficial form and quantity of magnesium supplementation for various populations (e.g., age, gender) before the effects of magnesium supplementation on performance outcomes can be confirmed.

Background: Vitamin D

Vitamin D is an essential lipid-soluble micronutrient consumed through dietary sources; however, it can also be synthesized via ultraviolet radiation through sun exposure (41). The two most common forms of vitamin D are ergocalciferol (vitamin D_2) and cholecalciferol (vitamin D_3). Vitamin D_2 is consumed from plant sources, whereas vitamin D_3 is obtained from animal sources and via sunlight exposure (22). Despite the differences between the structures of vitamins D_2 and D_3 and the fact that vitamin D_3 is better absorbed than Vitamin D_2 (42), the metabolism and functions of the two vitamins are identical (22). The primary biological functions of vitamin D are regulating the metabolism of calcium and phosphate, a role that is essential to bone growth and development, regulating immune function, and protein synthesis (22,43). In addition, vitamin D is essential to muscle growth, cell differentiation, and bone mineralization (19,20). The active form of vitamin D, calcitriol (1, 25-dihydroxy vitamin D_3), is responsible for regulating these functions. Vitamin D is metabolized by vitamin D-25 hydroxylase in the liver, converting vitamins D_2 and D_3 into 25-hydroxyvitamin D (25(OH)D) (also known as calcidiol), the form of vitamin D used to assess vitamin D status (43).

The serum concentration of calcidol is the best indicator of vitamin D status in the body (22). The most severe vitamin D deficiency diseases include rickets in infants and adolescents and osteomalacia in adults (22). Less severe vitamin D deficiencies increase the risk for diseases such as cancer, cardiovascular disease, and dementia, while decreasing neuromuscular function, possibly leading to muscle pain, fatigue, and decreased strength as well as sarcopenia (19,22).

Recent studies have indicated that over 77% of the general population may be considered vitamin D deficient (22). Athletes may require greater amounts of vitamin D because of higher calcium demands and limited adipose tissue for vitamin D storage (22). About 80% of athletes experience vitamin D inadequacy, leading to decreased skeletal muscle function, force and power production, testosterone production, and prolonged recovery time after training (22).

Vitamin D Supplementation and Exercise Performance

Adequate vitamin D status is positively related to strength, endurance performance, and aerobic capacity, suggesting a positive correlation between peak athletic performance and serum 25(OH)D concentrations (23,24). Evidence suggests that vitamin D treatment plays a role in muscle function and muscle regeneration via satellite cell activation, contributing to recovery after muscle-damaging exercise (11,12,22). In addition, individuals with vitamin D deficiency and muscle myopathy are able to reverse symptoms of muscle weakness and fiber atrophy by improving serum 25(OH)D concentrations (22).

Considering the potential positive effects of vitamin D on athletic performance, several studies have been conducted to determine this relationship. The researchers used different vitamin D supplementation methods (e.g., simulated sunlight, oral vitamin D spray, vitamin D supplementation tablets, all in varying amounts), but many of the studies produced similar results measured via physical parameters related to exercise performance. In a randomized placebo-controlled trial, Carswell et al. (23) placed 137 male athletes, 22 ± 3 yr of age, into three groups. Participants received a placebo, simulated sunlight (1.3× standard erythemal) three times per week for 4 wk followed by once per week for 8 wk, or oral vitamin D_3 supplementation of 1000 IU for 4 wk followed by 400 IU for 8 wk. They measured the effects of these interventions on physical parameters, such as run and jump tests. The researchers reported a positive association between serum 25(OH)D status and endurance performance, measured via a 1.5-mile run test. The simulated sunlight and oral vitamin D_3 supplementation demonstrated similar effectiveness in correcting vitamin D status; however, the supplementation had no positive effect on strength or power performance (23).

In a randomized placebo-controlled clinical trial, Alimoradi et al. (44) measured the effects of weekly vitamin D supplementation of 50,000 IU over 8 wk on 70 elite female and male Iranian athletes, 24.09 ± 5.06 yr of age. Initially, 66.7% of the experimental group and 70.6% of the placebo group had insufficient or deficient serum 25(OH)D concentrations. They evaluated various strength, agility, and jump tests. Researchers noted a significant rise in circulating 25(OH)D concentration in the experimental group (P <0.001) and a significant decrease in circulating 25(OH)D concentration in the placebo group (P = 0.040). At the conclusion of the experiment, only 20% of the experimental group had insufficient or deficient serum 25(OH)D concentrations, whereas 91.2% of the placebo group had insufficient or deficient serum 25(OH)D concentrations. In addition, reported statistically significant improvements in the physical parameters in the experimental group, including the strength leg press tests (P = 0.034) and one-repetition maximum sprint tests (P = 0.030) (44). In a double-blind, placebo-controlled study, Skalska et al. (45) examined the effects of 5000 IU vitamin D_3 supplementation daily for 8 wk in 36 youth soccer players, 17.5 ± 0.6 yr of age. Researchers measured peak power output, physical work capacity, maximal speed, and total distance covered running. Vitamin D supplementation corresponded to a statistically insignificant (P > 0.05) increase in the total distance covered and improved exercise ability and locomotor skills, measured via participant effort, coordination, and technical–tactical skills (45).

In addition to studying the effects of vitamin D supplementation on physical performance, other groups investigated the effects of vitamin D concentration on muscle function and performance. Flueck et al. (19) conducted a double-blind, nonrandomized intervention trial investigating the effects of 6000 IU·d^{-1} of vitamin D_3 supplementation for 12 wk in a group of 20 elite male rugby, basketball, and table tennis wheelchair athletes, 36 ± 12 yr of age. They reported no correlation between 25(OH)D concentrations and mean power production measured via isokinetic dynamometer and 30-s Wingate testing (19).

In a double-blind, randomized placebo-controlled trial, Wyon et al. (41) measured the effects of a one-time dose of 150,000 IU of vitamin D_3 on the isokinetic muscle force of the hamstrings and quadriceps. They assessed 22 national-level male judoka athletes, 29 ± 10.6 yr of age. The researchers noted significantly increased serum 25(OH)D concentrations (34%, $P \leq$ 0.001) and increased muscle strength (13%, P = 0.01) among the experimental group as compared with the placebo, suggesting a relationship between muscle strength and serum 25 (OH)D concentrations (41).

Other research was conducted to determine the alternative effects of vitamin D supplementation in athletic populations. In a 12-wk double-blind, randomized placebo-controlled trial, Todd et al. (46) measured the effects of daily vitamin D_3 oral spray of 3000 IU in 42 female and male Gaelic football players, 20 ± 2 yr of age. No additional supplementation consumption was permitted during the 12-wk trial. Baseline measurements determined that 50% of the participants presented with vitamin D insufficiency and 22% of participants presented with vitamin D deficiency. A comparison between the experimental and the placebo groups demonstrated no statistically significant difference in physical performance between the groups in relation to measured 25(OH)D concentrations (P > 0.05). In addition, vitamin D_3 supplementation did not have a beneficial effect on maximal oxygen volume, vertical jump, handgrip strength, skeletal muscle, or lung function (46).

Mielgo-Ayuso et al. (24) conducted a double-blind, placebo-controlled trial, where they evaluated the effect of 3000 IU daily vitamin D_3 supplementation on the hematological profiles of 36 elite male rowers, 27 ± 6 yr of age, over an 8-wk period. Despite relationships involving hormones, the experimental group did not display a difference in muscle recovery time compared with the placebo group (24).

Results involving the effects of vitamin D supplementation on exercise performance are equivocal. Evidence supporting the positive relationship between vitamin D and muscle function is the driving force behind research in this field. It is important to understand the effects of vitamin D on physical performance, as well as to establish a definitive range for 25(OH)D concentrations to support a healthy lifestyle. Additional research on diverse treatment groups is required to gain knowledge regarding adequate vitamin D supplementation dosages and sufficient supplementation lengths for various populations. Additional results can be used to determine the effect vitamin D has on physical performance (Table 2).

Magnesium and Vitamin D

In the body, magnesium and vitamin D interact in a coordinated manner. The process of converting the inactive form 25-hydroxyvitamin D into the active form 1,25-dihydroxyvitamin D relies on the activities of vitamin D–binding proteins and vitamin D–converting enzymes, 25-hydroxylase, 1α-hydroxylase, and 24-hydroxylase (20,47). The steps involved in the vitamin D activation and inactivation processes greatly depend on the bioavailability of magnesium, making the bioactivity of vitamin D magnesium dependent (20). The clinical benefits of vitamin D are significantly compromised when magnesium homeostasis is disrupted. In addition, researchers have indicated that magnesium deficiency may correspond with decreased $1,25(OH)_2D$ concentrations, reduced enzyme synthesis, impaired parathyroid hormone (PTH response), and increased occurrence of magnesium-dependent, vitamin D–resistant rickets (20,47). Research has also shown that a high magnesium intake (intake ≥264 mg·d^{-1}) reduces the risk of vitamin D deficiency and insufficiency by potentiating the activities of vitamin D, whereas magnesium supplementation

TABLE 2.
Summary of Research on Vitamin D and Exercise Performance.

Publication Information	Participant Information	Study Design	Parameters Analyzed	Purpose and Key Findings
Flueck et al. (19), *Nutrients*	• n = 20 elite male wheelchair athletes (rugby, basketball, and table tennis players) • 36 ± 12 yr of age • Baseline vitamin D status: <75 nmol·L^{-1}	• Double-blind, nonrandomized intervention trial (no placebo) • 6000 IU of vitamin D_3 daily for 12 wk	• Isokinetic dynamometer test • 30-s Wingate test • Serum [25(OH)D] • Serum [Calcium]	• Purpose: to investigate if vitamin D deficiency is associated with an impairment in muscle performance • No correlation between increase of vitamin D and mean power was detected • Physiologically significant in correcting vitamin D status (insufficient to optimal)
Todd et al. (46), *European Journal of Nutrition*	• n = 42 Gaelic football players (24 women; 18 men) • 20 ± 2 yr of age • Baseline vitamin D status: 72% of participants with serum [25(OH) D] < 49 nmol·L^{-1} • Baseline vitamin D status: 28% of participants with serum [25(OH) D] > 49 nmol·L^{-1}	• Randomized, double-blind, placebo-controlled trial • 3000 IU of vitamin D_3 daily for 12 wk via oral spray	• Average handgrip strength • Vertical jump height • Leg function • Maximal oxygen consumption • Fat mass/Fat mass index • Fat-free mass/Fat-free mass index • Percent body fat • Food frequency questionnaire • Recent physical activity questionnaire • Serum [25(OH) D_2] • Serum [25(OH) D_3]	• Purpose: to determine the role of vitamin D supplementation as a benefit beyond bone health • Compared with the control group, supplementation ○ Increased total [25(OH)D] (P = 0.006) ○ Did not increase $\dot{V}O_{2max}$, vertical jump or handgrip strength ○ Did not have any beneficial effect on $\dot{V}O_{2max}$, skeletal muscle, or lung function • Supplementation was physiologically significant (resolved deficiency)
Wyon et al. (41), *Clinical Journal of Sports Medicine*	• n = 22 male national-level judoka athletes • 29 ± 10.6 yr of age • Baseline vitamin D intake status: no supplementation	• Randomized placebo-controlled, double-blind trial • One dose of 150, 000 IU of vitamin D_3 over an 8-d period	• Isokinetic muscle force of the hamstrings and quadriceps • Serum [25(OH)D]	• Purpose: to examine the acute effects of vitamin D supplementation on muscle function • Intervention group demonstrated ○ Increased in serum [25(OH)D] ($P \le 0.001$) ○ Increased muscle strength (P = 0.01) • Muscle strength was related to serum [25(OH)D]
Carswell et al. (23), *Medicine & Science in Sports & Exercise*	• n = 137 men • 22 ± 3 yr of age • Baseline vitamin D intake status: no supplementation	• Randomized, placebo-controlled trial • Stimulated sunlight (1.3× standard erythemal dose in T-shirt and shorts, three times per week for 4 wk, then once per week for 8 wk) • Oral vitamin D_3 (1000 IU·d^{-1} for 4 wk, then 400 IU·d^{-1} for 8 wk)	• 1.5-mile run • Maximum dynamic lift and vertical jump • Serum [25(OH)D]	• Purpose: to determine the relationship between vitamin D status and exercise performance • Safe stimulated sunlight and oral vitamin D_3 supplements ○ Resulted in vitamin D sufficiency in 97% of participants • Vitamin D status was associated with endurance performance but not strength or power performance • Physiologically significant by achieving vitamin D sufficiency

TABLE 2.
(Continued)

Publication Information	Participant Information	Study Design	Parameters Analyzed	Purpose and Key Findings
Mielgo-Ayuso et al. (24), *Nutrients*	• n = 36 elite male rowers • 27 ± 6 yr of age • Baseline serum [25 (OH)D] (experimental group): 26.24 ± 8.18 ng·mL^{-1} • Baseline serum [25 (OH)D] (placebo group): 30.76 ± 6.95 ng·mL^{-1}	• Double-blind, placebo-controlled study • 3000 IU of vitamin D_3 daily for 8 wk	Concentrations of ○ Testosterone ○ Cortisol ○ Hemoglobin ○ Hematocrit ○ Transferrin • Testosterone/cortisol ratio	• Purpose: to evaluate the influence of vitamin D supplementation for 8 wk on the hematological and iron metabolism profile and values of testosterone and cortisol • Compared with the control group, the intervention group demonstrated ○ Greater changes of hemoglobin, hematocrit, and transferrin (P < 0.02) ○ No difference in hormonal parameters ○ An association between [cortisol] and [testosterone] and [25 (OH)D] (P < 0.05) ○ No difference in muscle recovery time • Physiologically significant in establishing adequate [25(OH)D] in participants
Alimoradi et al. (44), *International Journal of Preventive Medicine*	• n = 70 elite football and futsal athletes (34 women; 36 men) • 24.09 ± 5.06 yr of age • Baseline serum [25 (OH)D] (experimental group): 27.5 ± 17.9 ng·mL^{-1} • Baseline serum [25 (OH)D] (placebo group): 24.4 ± 12.7 ng·mL^{-1}	• Randomized, placebo-controlled trial • 50,000 IU of vitamin D per week for 8 wk	• Leg press • Ergo jump • Vertical jump • Illinois agility • 40-yard sprint • Body weight • BMI • Waist circumference • Truncal and visceral fat • Serum [25(OH)D] • 24-h dietary recall	• Purpose: to evaluate the efficacy of weekly vitamin D supplementation on athletic performance • Intervention group demonstrated ○ A rise in circulating [25(OH)D] (P < 0.001) ○ An improvement in physical parameters measured (P = 0.034) • Although improvements were seen, an optimal dosage of vitamin D_3 still needs to be determined • Supplementation resulted in sufficiency in 80% of supplemented participants
Skalska et al. (45), *Nutrients*	• n = 36 young soccer players • 17.5 ± 0.6 yr of age • Baseline serum [25(OH)D] (experimental group): 48.5 ± 8.6 nmol·L^{-1} • Baseline serum [25 (OH)D] (placebo group): 47.5 ± 16.2 nmol·L^{-1}	• Double-blind, placebo-controlled study • 5000 IU of vitamin D daily for 8 wk	• Peak power • PWC170 index • Maximal speed • Total distance covered • Heart rate • Plasma [25(OH)D]	• Purpose: to examine the effect of vitamin D supplementation on the increase in physical activity • Vitamin D supplementation ○ Increased plasma [25(OH)D] (P < 0.0001) ○ Increased the total distance covered (P < 0.05) ○ Is beneficial in improving exercise abilities and locomotor skills • Physiological significance not indicated

[Vitamin D], vitamin D concentration; $\dot{V}O_{2max}$, maximal oxygen volume; 25(OH)D_2, 25-hydroxyvitamin D_2; 25(OH)D_3, 25-hydroxyvitamin D_3; 25 (OH)D, 25-hydroxyvitamin D; BMI, body mass index; PWC170 index, physical work capacity.

has been used to reverse vitamin D resistance in individuals receiving vitamin D treatment (20,47,48). These findings indicate that adequate magnesium status (serum magnesium concentrations greater than 0.85 $mmol \cdot L^{-1}$) may be crucial to establishing and maintaining adequate 25(OH)D concentrations (49).

Furthermore, vitamin D is essential to the intestinal absorption of magnesium and phosphate, ultimately influencing skeletal mineralization processes (20). Both magnesium and vitamin D can be used independently; however, when used together, the combined effects of magnesium and vitamin D are significantly greater than the effects of either one alone (47).

Dai et al. (49) supplemented 236 healthy female and male participants, 60.4 ± 8.3 yr of age, with a daily dose of magnesium, between 77 and 389 mg, for 12 wk. Compared with the placebo group, magnesium supplementation significantly decreased plasma $25(OH)D_3$ (P = 0.001) and $24,25(OH)_2D_3$ (P <0.0001) concentrations when 25(OH)D concentrations were above 30 $ng \cdot mL^{-1}$, but it increased plasma $25(OH)D_2$ concentrations when 25(OH)D concentrations were below 30 $ng \cdot mL^{-1}$ (P = 0.009). Researchers concluded that magnesium status may be important in optimizing 25(OH)D status (49).

Between 40% and 100% of elite athletes consume supplements; however, inadequacies remain prevalent among athletes of various sports (16–18,50,51). In a study involving professional soccer players, Raizel et al. (52) determined that 68% of players consumed daily magnesium intake below the estimated average requirement, whereas 100% of players demonstrated daily vitamin D intake below the estimated average requirement (52). Among Paralympic athletes, magnesium and vitamin D were amid the five fewest micronutrients consumed via dietary intake (53). Although dietary vitamin D intake was reported remarkably low (29.4% of the RDA), vitamin D was the most common regularly used supplement, consumed more frequently overall than protein powders, sports drinks, and fatty acids (53). Researchers have also reported that vitamin D consumption occurred more frequently among female than male athletes (54,55). The findings in these studies concur with others reporting that inadequate intakes of magnesium and vitamin D are among other micronutrient inadequacies prevalent among athletes (53).

Research and experimentation suggest that, independently, magnesium and vitamin D supplementation may both provide positive effects on exercise performance via correcting the micronutrient inadequacy present in consumers (10,23,44,45). In addition, interactions between magnesium and vitamin D enhance the benefits of each micronutrient. Research has not been conducted to evaluate the combined effects of magnesium and vitamin D on athletic performance; however, a favorable relationship may exist between the independent supplementation of these micronutrients and exercise performance outcomes. The potential athletic performance benefits that may be attributed to magnesium and vitamin D could provide an ideal aid to exercise performance. Additional research is necessary to determine the means, amount, efficacy, and form of supplementation necessary to observe the positive effects of magnesium and vitamin D supplementation on exercise performance indices.

Future Considerations

Research on nutritional requirements for athletes is crucial to the general health and performance of athletes around the world. Athletes can optimize their dietary intakes to achieve a higher caliber of athletic performance. In addition to improving exercise performance, research in this field is necessary to protect athletes from physical harm because athletes face potential health and performance dangers as a result of nutrient deficiencies (56).

Magnesium and vitamin D are two of many micronutrients that are not adequately consumed by athletes, compromising their general health and exercise performance (52). Randomized placebo-controlled trials are required to determine the optimal mechanism of supplementation (e.g., dosage, frequency, duration, form) for both magnesium and vitamin D. Further research is needed to determine the most effective means of using the interactions between magnesium and vitamin D to enhance the effects of each nutrient. Research on the combination of magnesium and vitamin D supplementation is paramount to the health and performance of athletes.

The views of our narrative review do to constitute endorsement of the American Collegeof Sports Medicine.

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