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Magnesium and Zinc as Vital Micronutrients Enhancing Athletic Performance and Recovery – a Review

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ABSTRACT

Introduction and Aim of the Review

Magnesium and zinc are vital for cellular metabolism and maintaining homeostasis, playing a particularly significant role for athletes. Magnesium, which is largely stored in bones and muscles, is essential for protein synthesis. Zinc, a critical trace element found in muscle and bone tissue, participates in over 300 enzymatic reactions, acts as an antioxidant and making both minerals crucial for physical performance. This study aims to explore the physiological role of magnesium (Mg) and zinc (Zn) in the context of athletic performance and to examine their impact on energy metabolism, muscle function, protein synthesis and potential benefits of Mg and Zn supplementation for improving athletic outcomes and post-exercise recovery.

Methods
A comprehensive review of scientific literature was conducted through a thorough search of the PubMed database to explore the latest findings on the utility of magnesium and zinc in sports. Only articles in English were considered.
Current Knowledge
The review results indicate that Mg and Zn play critical roles in energy metabolism, muscle and immune system health. Mg deficiency can impair muscle function and reduce endurance, while its supplementation supports muscle relaxation, cardiovascular health, and respiratory efficiency. Although required in small amounts, Zn is indispensable for enzymatic activity, protein synthesis, hormonal balance, and muscle recovery, making it vital for post-exercise recovery and immune response modulation.
Conclusions
Available data suggest that Mg and Zn supplementation may positively influence athletic performance, energy metabolism, and recovery post-exercise, though further research is needed to establish specific supplementation guidelines. This review provides a foundation for developing supplementation strategies aimed at enhancing athletic performance and supporting healthy recovery.

Keywords: (Magnesium; Zinc; Athletes; Endurance; Supplementation; Athletic Performance)

1. INTRODUCTION

Homeostasis refers to a state of equilibrium within the internal environment of an organism, allowing optimal maintenance of functions despite changing external conditions. Various chemical compounds are essential for organism's proper functioning on a daily basis. The importance of these compounds' cooperation, including both micro- and macroelements, is particularly evident during intense physical exertion and is a critical aspect of daily life for individuals, especially athletes.

In this review, we focus on selected macroelements, with a particular emphasis on zinc (Zn) and magnesium (Mg), as well as micronutrients like calcium, iron, and vitamins C and D3, which have a significant impact on athletic performance. [1].

MAGNESIUM

Magnesium plays a critical role in cellular metabolism, supporting homeostasis throughout the body. It is essential for protein synthesis, energy production, and other vital enzymatic reactions – over 600 in total, including oxidative phosphorylation, glycolysis, and the synthesis of proteins and nucleic acids. [2] As the second-most concentrated intracellular ion in body fluids, after potassium (K), magnesium's importance is evident in therapeutic effectiveness for conditions such as preeclampsia, migraines[3], and depression – disorders often linked with hypomagnesemia. These health issues, especially for athletes, not only impact overall wellness but also hinder physical development and limit potential athletic performance.

Approximately 24g of magnesium are stored in the human body, with most found in bones and muscles. [4] The distribution, along with its role in the musculoskeletal system, underscores its particular significance for athletes.

In the brain, magnesium modulates the function of N-methyl-D-aspartate (NMDA) receptors, which are crucial for neuroplasticity processes like memory and learning. Magnesium ions also have mild calcium-antagonist properties, supporting structural functions, such as multi-enzyme complexes (e.g. G-proteins) and GABA receptor regulation. [2] Interestingly, low magnesium levels appear to be linked to neurodegenerative conditions like Parkinson's disease and stroke. [5]

Magnesium also exerts broncho- and vasodilatory effects, though the precise mechanism remains unclear. It appears to operate independently of nitric oxide (NO) by inhibiting the release of acetylcysteine and histamine, both of which are strong bronchoconstrictors. By expanding bronchial passages, magnesium enhances alveolar ventilation and gas exchange, prolonging muscle endurance. Additionally, vasodilation improves blood flow, aiding oxygen and nutrient transport and promoting the removal of metabolic waste. In the cardiovascular system, magnesium influences heart function through ion channel regulation and vasodilation, acting as a natural calcium antagonist in muscle cells. In the myocardium, magnesium binds to calmodulin and troponin C, thereby affecting calcium levels essential for cardiac activity. [6]

ZINC

Zinc is an essential trace element with high concentration in muscle and bones. Although the total body zinc content is only 2-2.5g, it is involved in over 300 enzymatic reactions, often via zinc finger motifs – protein domains present in DNA-binding proteins, particularly in transcription factors. Zinc plays both structural and catalytic roles in enzymes. [7] Additionally, it contributes to coenzyme synthesis, such as Flavin Adenine Dinucleotide (FAD), and serves as a protective factor against lipid peroxidation in the mitochondria and microsomes. Zinc also helps maintain osmotic stability in erythrocytes.

A significant function of zinc is its antioxidant capability [8], which helps to neutralize free radicals that cause metabolic stress and cellular damage. Zinc is an essential micronutrient critical for growth, development, and the support of immune function. It influences all organs and cell types, serving as a fundamental component of the human proteome [9]. Zinc achieves this by stabilizing sulfhydryl groups or reducing the formation of reactive hydroxyl (·OH) radicals from hydrogen peroxide and superoxide, primarily by counteracting redox-active metals like iron and copper. [7] Zinc deficiencies can result from inadequate intake or excessive loss, with conditions like kidney or gastrointestinal diseases causing a self-perpetuating cycle of deficiency. Zinc deficiency also appears to be involved in depression pathogenesis, possibly due to impaired synaptic transmission and effects on cognitive processes like learning and memory. [10]

CALCIUM

Calcium (Ca) is a chemical element with a molar mass of 40g, and the daily requirement for adults is between 2000-2500 mg/day. As a component of bones, calcium is responsible for supporting passive movement. A deficiency of calcium can lead directly to osteoporosis and pathological fractures[11]. These conditions often require long-term treatment and rehabilitation, significantly limiting athletic performance. Calcium is also essential for muscle function, specifically in muscle contraction, which occurs when calcium binds to troponin C. A deficiency can cause painful muscle cramps. Most athletes can meet their calcium needs through a diet rich in dairy products, which also provide protein important for muscle mass growth. [12]

IRON

Iron is a vital micronutrient for physical performance and overall health. As a component of hemoglobin and myoglobin, iron plays a critical role in oxygen transport to tissues and its storage in muscles. The liver stores the largest amount of iron in the body (60%), with the remainder primarily in muscles. [13] The most common manifestation of iron deficiency is iron deficiency anemia (IDA), particularly prevalent among menstruating women who follow nutrient-deficient diets and engage in intense training. Symptoms of iron deficiency include tachycardia, palpitations, shortness of breath, fatigue, and weakness, all of which can reduce athletic performance. Even without anemia, low iron levels may impair enzyme functions an metabolic processes, causing symptoms like fatigue and concentration difficulties. [14]

VITAMIN C

Although vitamin C (ascorbic acid) deficiencies are rare today, athletes on highly restrictive weight-loss diets low in vitamin C-rich foods (like citrus fruits, strawberries, vegetables, and fermented products) may still be at risk. Excessive intake of vitamin C supplements, however, can lead to side effects such as kidney stones, nausea, and diarrhea. [1] Studies, including those conducted by Morrison and Dale in 2014, show inconclusive evidence of the benefits of vitamin C supplementation on athletic performance beyond what a balanced diet already provides. [15]

VITAMIN D

Vitamin D3 is synthetized in the human body, beginning in the skin under UVB light, where cholecalciferol forms from 7-dehydrocholesterol. It is then transported to the liver and kidneys, where it undergoes enzymatic conversion into calcitriol – 1,25-$(OH)_2$D3. Despite its endogenous enzymatic production, vitamin D3 needs to be supplemented, not only in athletes, but in the general population as well, due to limited sunlight exposure during certain parts of the year, which inhibits synthesis. [15] Vitamin D3 primarily increases serum calcium levels by enhancing calcium absorption in the intestines. With adequate dietary calcium, it promotes bone mineralization, but in cases of low calcium, it mobilizes calcium from bones by stimulating osteoclasts to break down bone tissue. [16] Vitamin D3 also plays a significant role in immune system function, influencing the terminal differentiation of promyelocytes to monocytes and affecting T-cell function. [15]

A dietary supplement is defined as a food product designed to supplement the diet, containing a concentrated source of vitamins, minerals, or other beneficial substances. With the widespread availability of supplements, it is essential to highlight rational usage criteria based on current medical research. This review aims to synthesize findings on micronutrient effects on athletic performance, presenting comprehensive knowledge on the physiological action of specific micronutrients, recommendations for supplementation, and their impact on enhancing athletic performance. For athletes, who are subject to intense physical demands, it is essential to prioritize bodily homeostasis and overall health overachieving peak performance.

Therefore, supplementation decisions should always consider the athlete's full clinical picture. This review includes publications accessible through the PubMed database.

2. PHYSIOLOGICAL ROLES OF MAGNESIUM AND ZINC IN ATHLETES

● 2.1 MAGNESIUM: FUNCTIONS IN MUSCLE CONTRACTION AND ENERGY METABOLISM

In muscle cells, magnesium ions (Mg^{2+}) function as natural antagonists to calcium ions (Ca^{2+}) in Ca^{2+}-permeable channels and Ca^{2+}-binding proteins. During muscle contraction, depolarization of the muscle cell membrane triggers the release of calcium from the sarcoplasmic reticulum via ryanodine receptors (RyR). The binding of calcium to troponin allows actin to interact with myosin heads leading to ATP hydrolysis and the subsequent sliding of myosin and actin filaments, which causes muscle contraction. Magnesium competes with calcium at binding sites on RyR, and while calcium has a higher affinity, the higher intracellular concentration of magnesium balances this difference. Magnesium, a critical cofactor for ATP, also facilitates ATP production in mitochondria by forming Mg-ATP complexes essential for muscle function. [17]

Chronic hypomagnesemia is often associated with muscle cramps, although the underlying mechanism is not fully understood. This may be linked to magnesium's antagonistic relationship with calcium in muscle contraction pathways, as well as its role in preventing neuronal hyperexcitability, which can contribute to muscular contractions. [2]

● 2.2 ZINC: ROLE IN PROTEIN SYNTHESIS AND IMMUNE FUNCTION

Zinc is predominantly stored in muscles and bones, and only free ions exhibit biological activity [7]. It plays a fundamental role in gene expression, cellular differentiation, and protein synthesis. Zinc activates aminoacyl-tRNA synthetase, which supports protein synthesis in bone and other tissues. [10] [18] In cases of zinc deficiency, protein synthesis rates decrease before tissue deficits manifest, indicating zinc's role in protein metabolism is critical for maintaining cellular health. [19] Zinc deficiency impairs immune function, as zinc is essential for lymphocyte activation and is the only natural lymphocytic mitogen. Zinc also reduces free radical release during phagocytosis and supports immune defense against viral infections by modulating Intracellular Adhesion Molecule 1 (ICAM-1), which mediates cell adhesion during viral entry. [7]

Both magnesium and zinc contribute to immune function: magnesium has anti-inflammatory effects and regulates T lymphocyte function, while zinc boosts cellular and humoral immunity, particularly in peripheral lymphocytes.[20]

● 2.3 MICRONUTRIENT DEFICIENCIES IN ATHLETES: PREVALENCE AND IMPACT

Despite the emphasis athletes place on peak performance, studies reveal that increased physical activity may predispose them to deficiencies in essential nutrients like iron, calcium, vitamin D, and antioxidants. These deficiencies may impair endurance, delay recovery, and increase susceptibility to injuries. Athletes may be prone to micronutrient loss through mechanisms like increased metabolic demand and excessive sweating, and they may also experience deficiencies from calorie-restrictive diets.

Female athletes, in particular, are vulnerable to iron deficiency due to menstrual blood loss, which can lower performance and has broader health implications. [21]

Not all deficiencies, however, directly impact athletic performance. For instance, deficiencies in certain B vitamins (B2, B5, B6) appear to have minimal effect on performance metrics. [22]

3. MAGNESIUM SUPPLEMENTATION AND ATHLETIC PERFORMANCE

- ### 3.1 INDICATIONS FOR SUPPLEMENTATION

The athletic population is diverse, ranging from highly experienced professionals with access to comprehensive dietary guidance to less experienced athletes who may rely heavily on supplements without a balanced diet. Supplements can seem like a simple solution, but unless a specific deficiency is identified, supplementation may not improve performance and can sometimes have adverse effects[23]. Rational supplementation should prioritize addressing proven deficiencies through diet first, with supplements as a secondary measure [24].

- ### 3.2 PREVALENCE OF SUPPLEMENTATION IN ATHLETES

Supplement use is common among athletes, with a trend showing a correlation between competition level and supplement consumption. While studies on vitamin D3, zinc, iron, copper, vitamin E, and magnesium have reported mixed results regarding their impact on performance, supplementation in elite sports remains widespread, driven by both potential performance benefits and industry marketing. [22]

- ### 3.3 EFFECTS ON MUSCULAR FUNCTION IN ATHLETES

Muscle performance is a key focus for athletes, many of whom use supplements to enhance muscular strength and endurance. Magnesium appears to benefit muscle function by improving glucose bioavailability in tissues, delaying lactate accumulation, and reducing muscle oxygen demand during exercise. Studies indicate that magnesium levels correlate positively with muscle efficiency metrics, including grip strength, jump height, trunk flexion strength, and isokinetic strength. Magnesium deficiency, conversely, may impair endurance and reduce the metabolic efficiency of muscle tissue. [25] [26]

- ### 3.4 IMPACT ON CARDIOVASCULAR PERFORMANCE AND ENERGY EFFICIENCY

Magnesium supports cardiovascular function and energy efficiency, both critical for athletic performance. Through its vasodilatory effects, magnesium improves blood flow and oxygen delivery to muscles, which can enhance endurance. Daily intake of magnesium has been shown to modestly lower blood pressure, contributing to cardiovascular health. [27] The effect of magnesium supplementation on cardiovascular performance may also include improved heart muscle metabolism, enhanced cardiac output, and reductions in peripheral resistance. [28]

- **3.5 MAGNESIUM STATUS AND RECOVERY**

The daily recommended intake of magnesium is 400–420 mg for males and 310–320 mg for females, but athletes often require higher amounts due to increased physical demands. Magnesium’s anti-inflammatory properties reduce reactive oxygen species (ROS) production during muscle activity, minimizing exercise-induced muscle trauma and accelerating recovery. It facilitates ATP availability, which supports post-exercise muscle recovery and may limit lactate accumulation, further enhancing regeneration. Zinc, as a complementary micronutrient, also possesses anti-inflammatory properties that help mitigate oxidative stress induced by physical exertion [22] [25]

4. ZINC SUPPLEMENTATION AND ATHLETIC PERFORMANCE

- **4.1 ZINC'S INFLUENCE ON MUSCLE GROWTH AND REPAIR**

Zinc, with approximately 57% of its total body pool located in muscle tissue [29], plays a fundamental role in muscle cell biogenesis, activation, proliferation, differentiation, and regeneration [30]. Studies on the C2C12 skeletal muscle cell line in mice have shown that increased zinc concentrations in the growth medium stimulate the proliferation and activation of myoblasts as well as the differentiation and maturation of myofibers [31, 32]. This suggests that zinc release following muscle damage may promote muscle regeneration by activating muscle satellite cells [32]. Upon entry into the cell via Zrt- and Irt-like Protein (ZIP) transporters, cytosolic zinc induces phosphorylation and activates ZIP7, a zinc transporter within the endoplasmic reticulum, releasing Zn^{2+} ions into the cytosol. This process promotes phosphorylation of Akt, which is essential for myogenic differentiation. Research further indicates that zinc supplementation impacts exercise-related blood viscosity reduction, potentially improving muscle oxygen delivery, aerobic performance, and muscle regeneration [33]. Additionally, zinc-deficient diets have been shown to impair muscle protein synthesis, highlighting zinc's importance in muscle repair and growth [34].

- **4.2 EFFECTS OF ZINC ON HORMONAL REGULATION IN ATHLETES**

The impact of zinc supplementation on hormonal regulation has been studied for decades, yet evidence for a direct effect remains limited. However, zinc has been shown to positively influence insulin resistance and leptin levels [34]. Zinc supplementation elevates serum zinc levels and lowers serum copper levels, affecting the zinc ratio. This adjustment has been associated with a 27% increase in insulin and a 47% increase in HOMA2-IR (a measure of insulin resistance) [35]. Additionally, the zinc-associated protein zinc-α2-glycoprotein aids in binding peroxisome proliferator-activated receptor and early B-cell factor 2 to the PR domain, promoting adipose tissue browning and increasing energy expenditure. Zinc also influences thyroid hormone regulation, affecting the conversion of pre-thyrotropin-releasing hormone to pro-thyrotropin-releasing hormone and modulating T3 receptors and thyroid transcription factor 2, though this requires further investigation. Zinc supplementation may impact testosterone levels in athletes [36], potentially enhancing performance, though its direct effects on athletic metrics such as power, endurance, and muscle strength require additional research [37].

- **4.3 IMPACT OF ZINC ON IMMUNE FUNCTION AND RECOVERY POST-EXERCISE**

Zinc is a vital micronutrient for immune-related enzymes and plays a key role in immune function. During physical activity, both adipose tissue and muscles release interleukin 6 (IL-6), an adipomyokine that stimulates muscle cell regeneration. Studies have found a positive correlation between IL-6 levels and daily nutrient intake, including zinc, before exercise[38]. Although the International Olympic Committee cites limited evidence for zinc's immune benefits, zinc supplementation is commonly employed to support recovery after intense physical activity. Contrarily, some studies have suggested that excessive zinc supplementation may suppress immune function [39].

● **4.4 ZINC DEFICIENCY AND ITS CONSEQUENCES ON ATHLETIC PERFORMANCE**

Unlike iron, which is stored in ferritin, zinc lacks a specific storage protein or tissue reservoir [40], making it essential to maintain adequate daily intake [41]. The largest zinc reserves are found in muscle tissue, where a deficiency reduces the activity of key metalloproteinases involved in myogenesis. Low plasma zinc concentrations have been linked to decreased work capacity in shoulder and knee flexors and extensors. This may result from increased lactic acid levels in zinc-deficient muscles, which stem from reduced activity of lactate dehydrogenase, an enzyme reliant on zinc for optimal function [42]. This relationship underscores that zinc deficiency may negatively affect physical performance and hinder adaptation.

- **4.5 IMPACT ON INFLAMMATION AND OXIDATIVE STRESS REDUCTION**

Exercise-induced oxidative stress in muscle tissues results from lipid and protein oxidation [43]. Zinc accumulation in mitochondria, regulated through ZnTs, ZIPs, and MTs, influences mitochondrial function and reduces oxidative stress production [44]. Zinc is also a cofactor for enzymes like superoxide dismutase (SOD) and carbonic anhydrase, which help erythrocytes mitigate oxidative damage during exercise [45]. During hemolysis, zinc is released from erythrocytes, increasing plasma zinc concentration, which enables intact erythrocytes to bind zinc and reduce oxidative damage [46]. These observations suggest a potential benefit of zinc supplementation in managing oxidative stress induced by physical activity [47] [48].

5. COMBINED EFFECTS OF MAGNESIUM AND ZINC SUPPLEMENTATION

Studies on combined magnesium and zinc supplementation are limited but suggest positive effects. Eight weeks of supplementation with both elements led to approximately 10% greater torque and a 12–15% increase in power output in the quadriceps and hamstrings compared to a placebo group. This improvement is likely due to increased testosterone and insulin growth factor 1 (IGF-1) levels associated with Zn and Mg supplementation. Although there is a theory linking zinc supplementation with improved cognitive function due to enhanced zinc transport across the blood-brain barrier, subsequent research has shown that this supplementation strategy does not influence cognitive performance [49].

6. SUPPLEMENTATION STRATEGIES AND DOSAGES FOR ATHLETES

● 6.1 Recommended Daily Intakes for Magnesium and Zinc

Physical activity increases magnesium requirements by 10–20% over sedentary needs due to increased sweating and excretion. The general recommended daily intake is 350–400 mg for men and 300 mg for women. Studies in Japan and the United States suggest that athletes, despite higher demands, often consume less magnesium than recommended [50]. While no definitive recommendations exist for zinc supplementation in athletes, studies show that athletes often have lower serum zinc levels compared to non-athletes, despite similar or higher intake levels [51]. Adequate zinc intake is essential for supporting energy metabolism and preventing deficiency [52].

● 6.2 FORMULATIONS OF SUPPLEMENTATION

A study evaluating 15 commercially available magnesium formulations using a gastrointestinal microbiome simulator and dissolution tests revealed significant differences in absorption and dissolution rates. Further in vivo analysis of two products with extreme in vitro results showed substantial differences in serum magnesium levels and total area under the curve (AUC) [53]. Additionally, in a study by Ates et al., magnesium levels were assessed using different compounds (magnesium citrate, malate, acetyltaurinate, and glycinate). Results indicated that magnesium acetyltaurinate increased brain magnesium levels, and magnesium citrate increased levels in muscle and brain tissues, making it a promising alternative for maintaining zinc levels and managing digestive issues [28].

● 6.3 POTENTIAL RISKS OF OVER-SUPPLEMENTATION AND TOXICITY

Excessive zinc intake may interfere with copper absorption, leading to copper deficiency [54]. High zinc intake has also been linked to immune suppression, although evidence is limited [39]. General side effects of zinc overdose include gastrointestinal issues (diarrhea, abdominal cramping, nausea, and vomiting) and symptoms of copper deficiency, such as irregular heartbeat and thyroid dysfunction. Due to limited evidence on high zinc intake in athletes, careful monitoring of supplementation is recommended to avoid adverse, performance-impeding effects [55].

7. CONCLUSION

Magnesium and zinc play pivotal roles in human physiology, impacting DNA synthesis, protein production, and metabolism. Deficiencies in these elements are particularly problematic for athletes, as they can limit endurance, impair muscle metabolism, and disrupt muscle regeneration. The findings suggest that adequate magnesium intake may enhance performance by increasing glucose bioavailability, reducing lactic acid buildup, and improving energy metabolism. Similarly, zinc plays a multifaceted role in muscle function, immune response, and hormonal balance, though more research is needed to confirm its impact on athletic performance.

Both zinc and magnesium may influence testosterone levels, potentially enhancing performance in specific sports. However, further studies are necessary to establish precise dosing guidelines for athletes and to assess the combined effects on physical performance across different disciplines.

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