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SPICES AS ERGOGENIC AIDS: IMPACT ON EXERCISE PERFORMANCE, MUSCLE RECOVERY, AND INFLAMMATION IN ATHLETES – A SYSTEMATIC REVIEW

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ABSTRACT

Background: Spices like capsaicin, turmeric, ginger, piperine, garlic, and cinnamon have been used in cooking and folk medicine for centuries. Modern research shows their ergogenic, anti-inflammatory, and antioxidant properties, aiding athletic performance, muscle recovery, and overall health.
Aim: This review analyzes effects of these spices on physically active individuals (mechanisms, benefits, limitations).
Materials and methods: Studies from PubMed, MDPI, Quality in Sport, and Journal of Pharmaceutical Research International on ergogenic, anti-inflammatory, and antioxidant effects of capsaicin, turmeric, ginger, piperine, garlic, and cinnamon in physically active people.
Results: Capsaicin shows thermogenic effects and supports fat metabolism, boosting exercise performance, but GI effects need study. Turmeric, via curcumin, offers anti-inflammatory and antioxidant benefits, reducing muscle damage and speeding recovery despite low bioavailability. Ginger modulates cellular metabolism to aid muscle recovery and ease post-exercise pain. Piperine enhances nutrient bioavailability, improves muscle strength, and optimizes energy metabolism with low-risk toxicity. Garlic reduces oxidative stress and inflammation, strengthens immunity, and relieves muscle fatigue. Cinnamon provides hypoglycemic and antioxidant properties, improving glucose/lipid metabolism and cardiovascular health in athletes.
Conclusions: These spices show promise as phytonutrients in sports medicine. Their anti-inflammatory, antioxidant, and metabolic effects enhance performance and recovery by increasing muscle strength, reducing DOMS, shortening recovery, and lowering inflammation. Synergies like piperine-curcumin amplify efficacy. Challenges like poor bioavailability (e.g., curcumin) and inconsistent evidence require rigorous studies for optimal dosages, formulations, and protocols.

KEYWORDS

Spices In Sports Nutrition, Exercise Performance, Muscle Recovery, Dietary Supplements, Bioactive Compounds, Anti-Inflammatory Effects, Antioxidant Properties

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Introduction

Spices, valued for centuries for their culinary qualities, are also an important part of traditional medical systems around the world. Their use in folk medicine covers a wide range of ailments, indicating a historical belief in their therapeutic properties. [1] Contemporary scientific research is systematically deepening our understanding of these natural compounds, revealing their complex mechanisms of action at the molecular and cellular levels. [2] Among the many spices, those with documented anti-inflammatory, antioxidant, and ergogenic potential are of particular interest to the scientific community, making them the subject of intensive research in the context of human health. [3]

Intense physical exertion, characteristic of sports training, leads to physiological adaptations, but also induces oxidative stress and inflammatory processes in the body. [4] Exercise-induced muscle damage, such as delayed onset muscle soreness (DOMS), can negatively affect performance, recovery, and adaptation to training loads. [5] Managing these responses through dietary interventions is key to optimizing athletic performance and long-term health. In this context, the phytonutrients found in spices offer promising opportunities to support exercise-related physiological processes. [3]

Capsaicin, the active ingredient in chili peppers, has anti-inflammatory and antioxidant properties and may increase pain tolerance, which is beneficial during intense exercise. Research suggests that it may improve muscle strength and performance by modulating the TRPV1 channel and increasing calcium release in muscle cells. [6] Turmeric, which contains curcumin, has been extensively studied for its powerful antioxidant and anti-inflammatory effects, which may reduce muscle damage after exercise. [5] Piperine, the main alkaloid in black pepper, is known to improve the bioavailability of curcumin. [7] Ginger, traditionally used for pain and inflammation, has proven antioxidant and anti-inflammatory properties, supporting recovery and reducing muscle soreness. [8] Garlic, rich in organosulfur compounds, contributes to improving immune function and antioxidant capacity, and may also reduce physical fatigue. [4] Cinnamon has anti-inflammatory and antioxidant effects and may influence glucose metabolism, as well as relieve muscle soreness after exercise. [9]

Despite the growing body of evidence on the potential health and ergogenic benefits of spice consumption, a comprehensive synthesis of data on their effects on athletes remains necessary. [3] Existing studies often focus on individual spices or specific aspects of their effects, making it difficult to fully understand their synergistic or individual effects in the context of exercise adaptation. [7] Therefore, this study aims to provide a systematic review of the available scientific literature to analyze in detail the mechanisms of action, benefits, and possible limitations of the use of selected spices in human systems in athletes.

Aim of the study

The purpose of this review is to comprehensively analyze the effects of selected spices: capsaicin, turmeric, ginger, piperine, garlic, and cinnamon – on the bodies of physically active individuals, including amateur and professional athletes. The review takes into account the mechanisms of action of these phytonutrients, such as their anti-inflammatory, antioxidant, and ergogenic properties, potential benefits for exercise performance, muscle recovery, and overall health, as well as limitations of use, including bioavailability issues, interactions with other substances, and possible side effects. The analysis aims to synthesize the current scientific literature, identify gaps in knowledge, and indicate directions for further research, which may contribute to the optimization of dietary interventions in sports medicine and support the body's adaptation to training loads.

Material and Methods

This article presents an overview of scientific studies from 2013–2025, available in databases such as PubMed, MDPI, Quality in Sport, and the Journal of Pharmaceutical Research International. The focus was on the ergogenic, anti-inflammatory, and antioxidant effects of selected spices (capsaicin, turmeric, ginger, piperine, garlic, and cinnamon) in physically active individuals and athletes. The search included peer-reviewed articles, clinical studies, and reviews, with an emphasis on their impact on performance, recovery, and health. The analysis is based on a synthesis of existing evidence, without collecting new empirical data.

Review

Capsaicin

Chemically known as 8-methyl-N-vanillyl-6-nonenamide, it is the main pungent bioactive component of chili peppers of the Capsicum genus. It is commonly described as an irritant that causes a warming sensation in the mouth. [6] [10] [11] The biological effects of capsaicin are the result of complex processes, the key one being the activation of the transient receptor potential vanilloid type 1 (TRPV1) receptor. [6] TRPV1 receptors are present on sensory neurons and, importantly in the context of muscle function, in the membranes of skeletal muscle cells, including the sarcoplasmic reticulum (SR). Capsaicin (CAP) has a natural analogue, capsiate, which is present in the sweet pepper variety CH-19. Although both substances have a similar molecular structure, the key difference is the replacement of the amino group (NH) in the alkyl chain of capsaicin with an ester group (O) in capsiate. This subtle structural change significantly affects the perceived spiciness, which distinguishes the strongly spicy capsaicin from the much milder capsiate.

Studies on the effects of capsaicin on athletes show a variety of promising benefits for performance and recovery. In one experiment, male Brazilian jiu jitsu who took 12 mg of purified capsaicin 45 minutes before training reported a significant improvement in strength parameters – average power increased by 4.4% and peak speed by 4.3% during bench presses. In addition, capsaicin supplementation significantly reduced delayed onset muscle soreness (DOMS), improved the pressure pain threshold (PPT) and reduced thigh circumference (TCM), which contributed to an increase in vertical jump height (VJH). These results suggest that capsaicin may not only support improved strength training performance and power generation, but also contribute to faster post-workout recovery and improved motor skills in athletes. [6]. A meta-analysis suggests that acute capsaicin supplementation may increase muscle endurance and, in general, may elicit an ergogenic response in near-maximal efforts. [6] [10]

Scientific reports suggest that capsaicin supplementation may contribute to improved performance in the 1500-metre run, increased duration of exercise before exhaustion in high-intensity interval training, and improved performance in strength training.[10] [11] In the context of fatigue and recovery, capsaicin may reduce neuromuscular, mainly peripheral, signs of fatigue. This particularly applies to improving the rate of muscle relaxation and increasing the amplitude of contraction after exercise, which is likely related to its effect on maintaining calcium balance in muscles. [6] [11]

Capsaicin also potentially counteracts fatigue caused by reactive oxygen species (ROS). The effect of capsaicin on perceived exertion (RPE) is variable; some studies report a reduction, while others show no difference. [10] [11] [12]

The dosage and safety of capsaicin are important issues. Higher doses of capsaicinoids (above 33 mg per day) have been shown to cause gastrointestinal discomfort. One study reported a 6.3-fold increase in the severity of gastrointestinal symptoms, resulting in three participants withdrawing from the experiment. [10] [12] On the other hand, a dose of 12 mg is generally well tolerated, and no significant gastrointestinal discomfort was reported in pilot studies. For this reason, reducing digestive discomfort is an important consideration for both researchers and athletes.

Capsaicin has analgesic properties – by desensitising nociceptors, it can increase pain tolerance during physical activity. This, in turn, can counteract a decrease in strength and promote greater volume in strength training. Another important aspect of capsaicin's action is its ability to alleviate inflammation. This is possible thanks to the reduction of pro-inflammatory cytokines such as interleukin-6 (IL-6), tumour necrosis factor-alpha (TNF-α) and interleukin-1β (IL-1β), as well as the reduction of oxidative stress indicators, which translates into its antioxidant properties. [6] [10] [11] Capsaicin can also increase the release of acetylcholine, which translates into increased muscle contraction strength and improved endurance capacity. In addition, by increasing the bioavailability of nitric oxide (NO), it supports vascular function, leading to vasodilation, improved blood flow and more efficient oxygen delivery to active muscles, which contributes to a reduction in perceived fatigue. [6]

Capsaicin, due to its multidirectional action - including pain modulation, reduction of inflammatory processes, reduction of oxidative stress and support for muscle function - is a promising element of a nutritional strategy supporting regeneration and improvement of physical performance, especially in sports disciplines requiring high power and resistance to fatigue. Despite the growing body of scientific evidence, further well-designed studies are needed to accurately determine the optimal doses, timing of supplementation, and forms of administration that will maximise benefits while minimising the risk of adverse effects. [6] [10]

Turmeric

Extracted from the rhizomes of Curcuma longa, turmeric has been the subject of interest in traditional medicine for centuries due to its versatile healing properties. [2] In the era of modern sports medicine, its role is being intensively researched as a potential dietary supplement for athletes, which is reflected in the popularity of this spice as the most commonly used botanical supplement among athletes in Ireland. [13] Turmeric exhibits complex mechanisms of action, affecting numerous signaling molecules and cellular pathways. It activates nuclear factor erythroid 2-related factor 2 (Nrf2), promoting endogenous antioxidant activity. At the same time, it inhibits the activity of nuclear factor kappa B (NF-κB) and reduces the production of pro-inflammatory cytokines such as tumor necrosis factor alpha (TNF-α), interleukin-1 beta (IL-1β), interleukin-6 (IL-6), and interleukin-8 (IL-8) . Its action also includes modulation of C-reactive protein (CRP), mitogen-activated protein kinases (MAPK), and interaction with apoptosis-related proteins such as p53, cyclins, and Bcl-2. [2]

Physical exercise, especially that with a predominantly eccentric component, often leads to exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS), manifested by muscle fiber damage, decreased strength, and pain. Studies suggest that turmeric supplementation may alleviate these symptoms. A reduction in muscle pain and an improvement in joint range of motion after exercise have been observed. [14] In a study involving men, supplementation with 200 mg of curcuminoids per day for 8 weeks alleviated the reduction in isokinetic extension torque after running with a decrease, in contrast to placebo and a dose of 50 mg. [15] In other studies, turmeric supplementation reduced pain in the lower limb after a muscle-damaging protocol [5] and significantly reduced scores on muscle fatigue and soreness scales in athletes after 12 weeks of supplementation. [16] With regard to muscle damage markers such as creatine kinase (CK), the results are inconclusive; some studies report a reduction, [14] while others have not shown significant changes. [16] [17] In terms of oxidative stress, turmeric supplementation (90 mg) significantly increased total plasma antioxidant capacity and reduced malondialdehyde (MDA) levels while increasing glutathione (GSH) concentrations. [14] However, other studies have not confirmed significant changes in CRP, IL-6, IL-1ra, or TNF-α concentrations after turmeric supplementation at rest, despite the observed trends. [5] [17]

The effect of turmeric on athletic performance is being studied. It may contribute to shorter recovery times and improved overall performance. [15] There are suggestions that turmeric may reduce perceived exertion (RPE). [5] In a 12-week study on teenage athletes, an improvement in reaction time was observed. [16] Despite these promising results, some studies have not shown significant benefits for overall athletic performance. [5] [14] An increase in brain-derived neurotrophic factor (BDNF) levels has also been observed after turmeric supplementation, [17] but this effect has not always reached statistical significance and requires further study. [5]

A key challenge in the use of turmeric is its low bioavailability, resulting from low solubility, poor absorption in the gastrointestinal tract, and rapid metabolism and elimination. [15] Various strategies have been developed to overcome these limitations, including combination with piperine, which significantly increases bioavailability, and innovative formulations such as Meriva® and Longvida®, which are characterized by increased absorption. [2] [15] The timing of administration is also important, and daily, regular supplementation may be more effective than single doses in maintaining stable blood levels. [15]

Turmeric is generally well tolerated; studies indicate that doses of up to 8,000–12,000 mg/day are safe in humans. In the pediatric population, doses ranging from 45 mg to 4,000 mg/day, administered for 2–48 weeks, have also been found to be safe. [2] However, it is important to be aware of the risks associated with botanical supplements, including potential positive doping test results (most commonly reported by elite athletes, 69% of cases) or adverse interactions with other drugs/supplements (most commonly reported by amateur athletes, 47% of cases). [13]

In summary, turmeric shows promising potential in alleviating exercise-related muscle symptoms and improving recovery in athletes. Its anti-inflammatory and antioxidant properties are well documented, but the variability of research results, particularly in terms of specific biomarkers and performance effects, highlights the need for further rigorous clinical studies with larger and more diverse participant groups, with a particular focus on bioavailability and optimal dosing strategies. [14][15] [17]

Ginger

Latin name: Zingiber officinale Roscoe, commonly recognized as a culinary spice, has also been used for centuries as a valued medicinal plant around the world. Its health-promoting properties result from its rich phytochemical composition, including compounds such as gingerols, shogaols, and zingerones, which exhibit anti-inflammatory and antioxidant activity. [8] [18] [19] In the context of human systems in athletes, ginger is the subject of scientific research due to its potential to improve physiological parameters and alleviate exercise-related ailments.

Clinical studies have shown that ginger extract consumption may have a beneficial effect on physical comfort. In a randomized, double-blind, placebo-controlled study, daily intake of ginger extract for eight weeks significantly reduced subjective feelings of eye fatigue and shoulder stiffness in healthy individuals, especially in women under 51 years of age. Furthermore, these younger women showed improved blood flow in the deep peripheral vessels, which may be the mechanism for alleviating these symptoms. In older men (over 51 years of age), a beneficial change in body warmth was observed. Although no significant improvement in blood flow in the eye or objective changes in arm muscle stiffness were found, the study showed a reduction in axial length of the eyeball in the ginger group, which may be important in the prevention of myopia. The potential effect of ginger on improving blood flow in young women suggests the involvement of female hormones, such as estrogen, which may increase nitric oxide (NO) production and consequently dilate blood vessels. The complete absence of reported safety issues confirms that ginger is a safe and beneficial dietary supplement. [18]

In addition, the properties of ginger play a key role in muscle recovery and inflammation management, which is particularly important for athletes. [8] [19] Studies on women practicing taekwondo have shown that daily consumption of 3 g of ginger for six weeks significantly reduced muscle soreness caused by physical exertion. [8] The mechanisms of this action include the documented anti-inflammatory properties of ginger and its components, which inhibit cyclooxygenase (COX-1 and COX-2), block leukotriene synthesis, and reduce the expression of pro-inflammatory cytokines such as TNF-α and IL-6. [8] [20] Furthermore, ginger has been shown to suppress the activity of the transcription factor NF-κB and modulate the Wnt signaling pathway, further confirming its anti-inflammatory and protective effects in the development of inflammatory conditions such as experimentally induced arthritis. [20] In in vitro studies on human myoblasts, ginger influenced changes in the metabolic profile of cells during aging, promoting muscle regeneration. Upregulation of metabolites such as 8-shogaol, valine, niacinamide, octadecanamide, and uracil, as well as an effect on metabolic pathways related to glutamate metabolism, arginine biosynthesis, and the citric acid cycle (TCA). This suggests that ginger may support muscle protein synthesis and improve mitochondrial function, which is crucial in the process of muscle aging. [21]

In the context of exercise performance, studies in rats have shown that ginger extract significantly increases glycogen levels in skeletal muscles and improves physical performance. This effect is attributed to increased fatty acid oxidation, as evidenced by higher levels of free fatty acids (FFA) in the blood after exercise. Ginger, by modulating fat metabolism (e.g., through activation of the PPARδ pathway), promotes glycogen sparing, which is beneficial for prolonged exercise and recovery between training sessions. [22] More broadly, Zingiber officinale also exhibits a number of other therapeutic properties relevant to the overall health of athletes, including antioxidant activity (reducing lipid peroxidation and restoring antioxidant enzyme activity), antidiabetic (increasing glucose uptake by muscle cells without the involvement of insulin, improving the lipid profile) and cardiovascular (antithrombotic, reducing platelet aggregation) effects. Ginger is also effective in relieving nausea and vomiting. [19] All these aspects emphasize that ginger, classified as a "non-nutritive ingredient" with targeted effects, [3] is a valuable component of nutritional strategies supporting the health and physical performance of athletes, contributing to better recovery and adaptation to exercise. [3][19]

Piperine

A plant alkaloid originally isolated from black pepper (Piper nigrum) as early as 1820 by Ørsted, it is a compound with a broad spectrum of biological activity, traditionally used in folk medicine for various ailments such as headaches and diabetes. [23][24] In the context of human physiology, and especially in sports and physical activity, piperine has gained significant interest in recent years due to its multidirectional effects on biological systems, beyond its historical uses. [23][24][25]

One of the most valued properties of piperine, particularly in its standardized form BioPerine®, is its ability to significantly increase the bioavailability of other active compounds, including vitamins, minerals, and phytonutrients such as curcumin. [7][23][26] The mechanism of this action is complex and involves the stimulation of thermogenesis in the epithelial cells of the small intestine, which increases the absorption of nutrients, acting as a "thermonutrient." In addition, piperine affects the fluidity of enterocyte cell membranes by modifying cholesterol concentration and enhances the activity of brush border enzymes, which facilitates ion transport and nutrient absorption. Ultrastructural studies have also revealed that piperine can increase the length of microvilli, which enlarges the intestinal absorption surface area. [23] In addition, piperine acts as an inhibitor of key liver and intestinal enzymes, including cytochrome P450 and UGT isoenzymes, which slows down metabolism and prolongs the half-life of co-administered substances, increasing their plasma concentration up to 20-fold. [23][26] In a sports context, this is particularly important for athletes at risk of iron deficiency due to intense physical exertion, mechanical hemolysis, sweat loss, or gastrointestinal disorders, which can lead to decreased performance. Iron supplementation in combination with piperine has been shown to improve iron metabolism parameters in athletes without the gastrointestinal side effects typical of high doses, while reducing the risk of iron overload and associated oxidative stress, which can exacerbate muscle damage. [23]

Furthermore, recent studies have shown a direct and significant effect of piperine on skeletal muscle function. Piperine has been observed to increase contraction strength in both slow- and fast-twitch muscles in a dose-dependent manner. This increase in strength was particularly pronounced at low frequencies of electrical stimulation, with no significant effect on the force generated at high frequencies. This effect is reversible and, importantly for athletes, may partially counteract the decline in force caused by muscle fatigue, especially at low frequencies, which are often reduced after intense exercise. The main mechanism underlying this phenomenon is a significant increase in the sensitivity of myofibrils to Ca2+ ions. Studies have shown that piperine does not affect the concentration of free Ca2+ in myoplasm during stimulation, suggesting that its action is based on increasing the efficiency of calcium utilization by the contractile apparatus. These observations are consistent with the hypothesis that piperine, by binding to myosin, reduces the fraction of its heads in a super-relaxed state, making more myosin heads available for binding to actin, which leads to increased force generation at submaximal Ca2+ levels. This is different from post-tetanic potentiation, which mainly occurs in fast-twitch muscles and is mediated by phosphorylation of myosin light chains, as well as from K+-induced potentiation, which is associated with changes in Ca2+ metabolism. [24]

In terms of metabolism, studies in animal models have shown that piperine intensifies carbohydrate and fat metabolism in skeletal muscles during physical exercise. Increased expression of glucose transporters

(GLUT4) and monocarboxylate transporters (MCT1) has been observed, as well as key enzymes of fat metabolism such as FAT/CD36, CPT1, and CS, indicating more efficient use of energy sources. This is important for improving exercise performance and muscle adaptation to stress. In addition, piperine exhibits antioxidant properties, reducing the expression of signaling components associated with exercise-induced oxidative stress, such as NOX-1, Ape/Ref-1, and Mn-SOD. This is particularly important because intense physical exercise generates reactive oxygen species (ROS), which can lead to muscle damage. [25] Although the direct effect of piperine on reducing inflammatory biomarkers such as CRP and TNF-α still requires further research, meta-analyses have shown that, in combination with curcumin, piperine significantly reduces interleukin-6 (IL-6) levels, suggesting its indirect contribution to modulating the inflammatory response after exercise. [26]

From a safety perspective, piperine has a low risk of toxicity and does not exhibit genotoxicity, even at supraphysiological doses in animal models, and human studies have not reported any serious adverse events. Nevertheless, due to its effect on metabolic pathways (e.g., cytochrome P450), caution should be exercised when used concomitantly with medications. [23] In summary, the multifaceted effects of piperine—from increasing the bioavailability of key nutrients, to directly enhancing muscle strength and counteracting fatigue, to optimizing energy metabolism and reducing oxidative stress—make it a promising candidate for an ergogenic supplement for athletes. However, further long-term clinical studies in various sports disciplines are needed to fully confirm its efficacy and safety in human applications. [23][24][25]

Garlic

Garlic (Allium sativum) is a versatile dietary and supplement ingredient, valued in integrative medicine for its numerous health-promoting properties. [27] It is rich in phytochemicals, containing organosulfur compounds such as S-allyl cysteine (SAC), allicin and ajoene, as well as flavonoids. [4] These compounds give garlic powerful antioxidant and anti-inflammatory properties and the ability to modulate immune system function. [4][27] Traditionally, garlic has been used to treat a variety of ailments, including rheumatism and diabetes. [28]

The mechanism of action of garlic in the body is complex and multifaceted. Organosulfur compounds, such as those present in garlic, have the ability to downregulate nuclear factor kappa B (NF-κB), leading to a reduction in the expression of many pro-inflammatory cytokines. [27] S-allyl cysteine (SAC) specifically protects cells from damage caused by hydrogen peroxide, emphasising its role in cell protection.

In the context of physical activity and athletes, garlic has a significant modulating effect on oxidative stress and exercise-induced inflammatory processes. Garlic supplementation significantly increases total antioxidant capacity (TAC) throughout the body. At the same time, it effectively attenuates malondialdehyde (MDA) levels, a marker of exercise-induced oxidative stress. [4]

Garlic and its forms, such as black garlic, are also important for the overall health of athletes and the prevention of lifestyle diseases. Fermented black garlic contains high concentrations of polysaccharides, phenolic compounds, organosulfur compounds, proteins and melanoidins, which translate into numerous health benefits. It has strong antioxidant and hypoglycaemic effects. Consumption of aged black garlic significantly reduced the HOMA-IR (homeostasis model assessment for insulin resistance) index and showed a tendency to lower serum glucose levels while improving insulin sensitivity. [28] Aged garlic extract (Kyolic AGE) reduces arterial stiffness, normalises blood pressure, cholesterol and blood density, and improves the profile of proteomic biomarkers associated with cardiovascular risk, including the risk of heart attack and stroke. Aged garlic extract (AGE) has been shown in clinical studies to have significant and multifaceted benefits for intermediate endurance athletes aged 40-65, significantly improving their aerobic capacity, lactate thresholds and accelerating recovery processes, which is crucial for optimising adaptation to exercise and long-term maintenance of cardiovascular health, as well as reducing the risk of cardiovascular events. [29]

In light of the latest research, metabolic regulation and energy homeostasis are key aspects for optimising bodily functions, including in the context of increased physical activity. Prospective analyses in Wistar rats with diet-induced obesity have shown that interventions in the form of aerobic exercise and supplementation with standardised plant extracts, such as stevia and garlic, can significantly modulate the signalling pathways involved in appetite control and energy metabolism. [30]

Garlic modulates the immune response and inflammatory processes through organosulfur compounds that reduce the activity of nuclear factor-kappa B. [4][27] Fermented black garlic has increased antioxidant content and anti-inflammatory and anti-obesity properties. [27][28] Despite no improvement in performance in a short time trial, garlic alleviates oxidative stress and exercise-induced muscle damage. [4]

The dosage of garlic supplements varies depending on the form and intended purpose. Typical doses of clinically tested garlic supplements range from 600 to 900 mg of powdered garlic (standardised to 1.3% alliin or 0.6% allicin) or 7.2 g of aged garlic extract per day. [27] For Kyolic AGE, doses ranging from 1.2 g of AGE powder and 1.2 mg of SAC to 2.4 g of AGE powder and 2.4 mg of SAC per day were used for 12 weeks. [29]

In summary, garlic and its standardised extracts are promising interventions for supporting the health and performance of athletes through complex mechanisms of action that are antioxidant, anti-inflammatory, immune-modulating, and improve cardiovascular function and recovery. [29] Further research is needed to fully understand and optimise its use in the athletic population. [4]

Cinnamon

Cinnamon, obtained mainly from the bark of trees of the Cinnamomum genus, is a spice with a long history of use in cooking and traditional medicine, valued for its various health properties. [9] Its wealth of bioactive compounds, including cinnamaldehyde, cinnamic acid and polyphenols, forms the basis for its wide range of therapeutic effects on various systems of the human body. [9][31] In the context of athletes' physiology and overall health management, cinnamon shows promising antioxidant, anti-inflammatory and metabolism-regulating properties, making it a potential dietary supplement.

Cinnamon's ability to combat oxidative stress and modulate immune responses is crucial for regenerative processes and maintaining homeostasis, especially after intense physical exertion. [9] Studies have shown high antioxidant activity in cinnamon, measured by spectrophotometric and electrochemical methods, confirming its ability to neutralise free radicals and protect cells from damage. [31] The active ingredients of cinnamon, such as trans-cinnamaldehyde, contribute to the reduction of inflammation markers, which is particularly important in alleviating inflammation resulting from training loads. [9]

Cinnamon plays a significant role in metabolic regulation, improving insulin sensitivity, which is fundamental for the body's effective use of glucose. It has been shown that cinnamon supplementation, in combination with training, can significantly reduce glycated haemoglobin (HbA1c) levels and affect the TBC1D1 and TBC1D4 proteins, which regulate glucose transport in muscles. [32] In addition, cinnamon supports fat metabolism, contributing to lower triglyceride and LDL cholesterol levels while raising HDL cholesterol levels, which promotes cardiovascular health. [9] Analysis of cinnamon's effect on appetite-regulating hormones such as ghrelin, leptin and visfatin indicates its potential in managing body weight and energy balance, which may be beneficial for athletes controlling their body composition. [33]

In terms of cardiovascular health, cinnamon has significant vasorelaxant effects, promoting blood vessel dilation and improving blood flow, as well as protecting against stress-induced oxidative damage. [31] In addition, cinnamon has been observed to have a beneficial effect on liver enzyme markers (ALT, AST, ALP), suggesting its role in protecting and supporting liver function, a key organ for detoxification and metabolism in the athlete's body. [34] Studies on animal models also indicate the neuroprotective effects of cinnamon, such as improved motor function and reduced anxiety, which may indirectly support overall well-being and neurological performance in athletes. [35]

Importantly for athletes, studies highlight the synergistic effect of cinnamon with physical exercise, especially in different thermal conditions. The combination of cinnamon supplementation with cold water swimming training showed a significant increase in METRNL protein levels and a reduction in HDAC5 and fasting blood glucose, indicating improved metabolic indicators. [36] This combination may be an effective strategy for optimising metabolic adaptation to training and supporting recovery. [32] In terms of safety, comprehensive systematic reviews indicate that cinnamon, at doses used in clinical studies, does not generally cause significant adverse effects compared to placebo. [37] However, it is important to bear in mind the potential hepatotoxicity of coumarin, one of the components of cinnamon, at high doses (the tolerated daily intake is 0.1 mg/kg/day), and the possibility of skin irritation caused by cinnamaldehyde. Despite promising preclinical data and a few human studies, further large-scale clinical trials are needed to fully confirm the efficacy, determine the optimal doses and assess the long-term safety of cinnamon in therapeutic applications, including in the context of supporting athletes. [9][37]

Discussion

Building on the detailed descriptions in the review section, this discussion provides a critical interpretation of the findings, exploring underlying mechanisms, methodological challenges, potential synergies, and implications for athletic performance and recovery in physically active populations.

Capsaicin

Capsaicin's activation of transient receptor potential vanilloid 1 (TRPV1) receptors facilitates enhanced calcium release in skeletal muscles. [10][11] This physiological mechanism is believed to explain observed improvements in strength parameters such as average power and peak speed during resistance exercises, benefits reported in human trials involving trained men and Brazilian Jiu-Jitsu athletes. [1][10] However, variability in endurance outcomes, such as in 1500-meter runs or high-intensity intervals, suggests that benefits are modulated by factors like dosage and gastrointestinal tolerance. Notably, higher doses often lead to discomfort, thereby indicating a need for personalized administration protocols to balance efficacy and side effects. [10]

Turmeric (Curcumin)

Curcumin's modulation of Nrf2 and NF-κB pathways underpins its role in mitigating exercise-induced muscle damage, as evidenced by reduced soreness and improved joint mobility. [14] This potent bioactive polyphenol from turmeric exerts anti-inflammatory and antioxidant effects by suppressing pro-inflammatory cytokines, inhibiting COX enzymes, and activating Nrf2 to combat oxidative stress. [1][14] Such actions reduce exercise-induced muscle damage, alleviate delayed onset muscle soreness, and support joint health in conditions like knee osteoarthritis. [14]

Yet, inconsistent effects on biomarkers like creatine kinase highlight the influence of bioavailability challenges, with formulations like those combined with piperine showing promise in enhancing absorption. [15][26] Curcumin's poor solubility and rapid metabolism limit its systemic efficacy, but co-administration with piperine can significantly boost its bioavailability by inhibiting metabolic enzymes. [26] The dose-dependent nature of outcomes, such as improved isokinetic torque at higher intakes, underscores the importance of optimizing delivery methods for consistent results. [15]

Ginger

Ginger's bioactive compounds, including gingerols and shogaols, inhibit COX enzymes and NF-κB, contributing to reduced muscle soreness in activities like taekwondo. These pungent compounds in *Zingiber officinale* demonstrate potent anti-inflammatory and antioxidant properties by inhibiting COX enzymes and decreasing pro-inflammatory cytokine expression. [1][8] Clinical trials confirm that ginger supplementation effectively reduces muscle pain and soreness from eccentric exercise in athletes. [1][11]

Metabolic shifts observed in myoblast studies, such as upregulated glutamate pathways, suggest potential for supporting muscle regeneration, particularly in aging populations. [10][21] Ginger treatment upregulates key metabolites like valine, leucine, glutamine, and niacinamide, crucial for muscle protein synthesis, differentiation, and reducing oxidative stress. [10] Sex-specific effects, like enhanced peripheral blood flow in women under 51, further warrant investigation into hormonal interactions to refine its application in diverse athletic groups. [18]

Piperine

Piperine, a major active constituent of black pepper (*Piper nigrum* L.), is renowned for its pungency and exceptional ability to enhance the bioavailability of other compounds. Its capacity to boost absorption for substances like curcumin (up to 2000%) is achieved by increasing intestinal blood flow, enhancing enterocyte permeability, and inhibiting metabolic enzymes, without adverse effects. [26]

Beyond this, piperine directly influences skeletal muscle function and combats fatigue, significantly enhancing low-frequency force production in both fast- and slow-twitch muscles in a dose-dependent and reversible manner. This potentiation appears primarily mediated by an increase in myofibrillar calcium sensitivity, improving the contractile apparatus's responsiveness to sub-maximal calcium levels, and it can partially counteract force reductions from fatiguing eccentric contractions. [24] Piperine also supports energy metabolism during exercise and possesses anti-inflammatory properties by upregulating key oxidation genes and inhibiting COX-2 and NF-κB pathways. [1][10]

Garlic

Organosulfur compounds in garlic, such as S-allyl cysteine, downregulate NF-κB and elevate antioxidant capacity, attenuating markers like malondialdehyde post-exercise. [1][27] These sulfur-containing compounds inhibit NF-κB activation, a transcription factor regulating inflammatory response genes, while S-allyl cysteine provides protective effects against cellular damage by enhancing the body's antioxidant endogenous products. [1][4]

Improvements in aerobic thresholds with aged extracts suggest cardiovascular adaptations, yet discrepancies in short-term performance trials indicate that benefits may accrue over longer periods. While aged garlic extract has significantly improved aerobic fitness measures like VO2max and lactate threshold in middle-aged endurance athletes over 12 weeks, acute supplementation trials have shown no significant improvement in 40-km cycling time trial performance, despite attenuating oxidative stress and inflammation. [10][29] This suggests that the benefits on overall endurance performance might require longer intervention periods to manifest. [29]

Variability in allicin stability across preparations emphasizes the need for standardized extracts to ensure reproducible effects. [10] Allicin, an unstable compound in garlic, undergoes conversion to more stable compounds during aging processes, such as in black garlic, which leads to enhanced and more consistent antioxidant content. [10][28] The effective dose and therapeutic benefits of garlic therefore vary depending on the specific formulation and its stability. [27]

Cinnamon

Cinnamon's cinnamaldehyde and polyphenols modulate inflammation via iNOS and NF-κB inhibition, alongside metabolic regulation through proteins like TBC1D4. [1][10] Cinnamaldehyde directly inhibits inducible nitric oxide synthase (iNOS) and nuclear factor-kappa B (NF-κB) pathways, reducing neuroinflammation, while cinnamon polyphenols can suppress inflammatory processes by regulating gene expression. [8] Concurrently, cinnamon influences metabolic regulation, with studies showing a decrease in proteins like TBC1D4, which is associated with improved glucose handling and insulin sensitivity. [1][10]

Synergies with environmental stressors, such as cold exposure, enhance glucose homeostasis, but coumarin-related risks at high doses highlight the preference for safer species like *Cinnamomum verum*. [10][37] For instance, combining cold-water swimming with cinnamon consumption has been shown to notably increase serum METRNL and reduce fasting blood sugar in animal models, indicating an enhanced metabolic response under specific conditions. [36] However, the presence of coumarin, particularly in species like *Cinnamomum cassia*, carries hepatotoxic and carcinogenic risks at high doses, making species such as *Cinnamomum verum* a safer alternative due to its lower coumarin content. [37]

These interactions suggest context-specific applications, particularly in training under variable conditions. [10] The observed benefits of cinnamon in modulating glucose homeostasis and inflammation, especially when combined with environmental factors like cold exposure, indicate that its use could be optimized for athletes training in diverse and challenging conditions. [10][36] This personalized approach would consider the specific demands of the event and the athlete's environment to maximize efficacy and minimize potential side effects. [10]

Integrative Considerations and Limitations

Across these spices, overlapping pathways like cytokine suppression and redox modulation imply potential for combined use, though direct evidence of interactions remains limited. Methodological heterogeneity, including small sample sizes and variable dosing, constrains generalizability. Future research should focus on standardized protocols, long-term safety assessments, and stratification by athlete demographics to address these gaps, enhancing translational applicability in sports nutrition.

Conclusions

Phytonutrients are an important category of compounds with therapeutic and ergogenic potential in sports medicine. [6] [7] Capsaicin has been shown to increase average power output and peak speed in resistance exercises. [6] In addition, capsaicin can modulate the perception of fatigue and reduce selected markers of inflammation, such as interleukin-6, after physical exercise. [11]

Cinnamon, rich in cinnamaldehyde, has documented anti-inflammatory and antioxidant properties that can alleviate muscle damage. [9] Studies in animal models indicate that cinnamaldehyde reduces the expression of iNOS, NF-κB p65 and TNF-α mRNA. Cinnamon supplementation may also improve liver enzyme levels in patients with type 2 diabetes. [35]

Aged garlic extract (AGE) significantly improves aerobic capacity and shortens post-workout recovery time, especially in older athletes. [29] In addition, AGE reduces markers of inflammation and exercise-induced oxidative stress. [4]

Curcumin works by activating nuclear factor erythroid 2-related factor 2 (Nrf2) and inhibiting the activity of nuclear factor kappa B (NF-κB), leading to powerful antioxidant and anti-inflammatory effects. [2] Curcumin supplementation relieves pain and improves range of motion after exercise-induced muscle damage. [5] Despite its naturally low bioavailability, curcumin is generally well tolerated, even at high doses of up to 12,000 mg/day. [2]

Ginger, containing gingerols and shogaols, has anti-inflammatory effects by inhibiting pro-inflammatory pathways such as COX-1/COX-2 and NF-κB.[20] In experimental models, ginger affected metabolites that promote muscle regeneration and prevent muscle loss in ageing tissues. [21]

Piperine, an alkaloid found in black pepper, is known to increase the bioavailability of other active compounds, particularly curcumin. It directly enhances skeletal muscle contraction strength by increasing their sensitivity to Ca^{2+} ions.[24] In addition, piperine optimises carbohydrate and fat metabolism during exercise by influencing the expression of glucose transporters. [25] The synergistic effect of curcumin and piperine significantly reduces interleukin-6 concentrations. [26] The evidence presented suggests that these phytonutrients have significant potential to improve physical performance and support regenerative processes in sports medicine. [9]

Abbreviations List:

AGE: Aged Garlic Extract
ALP: Alkaline Phosphatase
ALT: Alanine Aminotransferase
AST: Aspartate Aminotransferase
BDNF: Brain-Derived Neurotrophic Factor
CAP: Capsaicin
CK: Creatine Kinase
COX-1/COX-2: Cyclooxygenase-1/Cyclooxygenase-2
CRP: C-Reactive Protein
CS: Citrate Synthase
DOMS: Delayed Onset Muscle Soreness
EIMD: Exercise-Induced Muscle Damage
FAT/CD36: Fatty Acid Translocase/CD36
FFA: Free Fatty Acids
GFAP: Glial Fibrillary Acidic Protein
GI: Gastrointestinal
GLUT4: Glucose Transporter Type 4
GSH: Glutathione
HbA1c: Glycated Hemoglobin
HDAC5: Histone Deacetylase 5
HDL: High-Density Lipoprotein
HOMA-IR: Homeostasis Model Assessment for Insulin Resistance
IBA1: Ionized Calcium-Binding Adapter Molecule 1
IL-1β: Interleukin-1 Beta
IL-6: Interleukin-6
IL-8: Interleukin-8

iNOS: Inducible Nitric Oxide Synthase
LDL: Low-Density Lipoprotein
MAPK: Mitogen-Activated Protein Kinases
MCT1: Monocarboxylate Transporter 1
MDA: Malondialdehyde
METRNL: Meteorin-Like Protein
Mn-SOD: Manganese Superoxide Dismutase
MPTP: 1-Methyl-4-Phenyl-1,2,3,6-Tetrahydropyridine
NF-κB: Nuclear Factor Kappa B
NO: Nitric Oxide
NOX-1: NADPH Oxidase 1
Nrf2: Nuclear Factor Erythroid 2-Related Factor 2
PPARδ: Peroxisome Proliferator-Activated Receptor Delta
PPT: Pressure Pain Threshold
ROS: Reactive Oxygen Species
RPE: Rating of Perceived Exertion
SAC: S-Allyl Cysteine
SR: Sarcoplasmic Reticulum
TAC: Total Antioxidant Capacity
TBC1D1/TBC1D4: TBC1 Domain Family Member 1/4
TCA: Tricarboxylic Acid Cycle
TCM: Thigh Circumference Measurement
TNF-α: Tumor Necrosis Factor Alpha
TRPV1: Transient Receptor Potential Vanilloid 1
UGT: UDP-Glucuronosyltransferase
VJH: Vertical Jump Height

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