BALNEO RESEARCH Balneo and PRM Research Journal
English Edition
e ISSN 2734 - 8458 p ISSN 2734 - 844X ROMANIAN ASSOCIATION OF BALNEOLOGY

Review

Caffeine as a Therapeutic Adjunct in Physical Rehabilitation: Effects on Balance, Muscle Recovery, and Inflammatory Modulation

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Citation: Ionescu C., Rarinca V., Visternicu M., Ciobica A., Burlui V., Gheban D., Tomita D. - Caffeine as a Therapeutic Adjunct in Physical Rehabilitation: Effects on Balance, Muscle Recovery, and Inflammatory Modulation
Balneo and PRM Research Journal **2026**, *17(1): 1010*

Academic Editor(s):
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Production Officer:
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Received: 17.11.2025
Published: 31.03.2026

Reviewers:
Andreea Suciu
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Abstract: Caffeine, a widely consumed natural stimulant, has potential as an adjunct in physical rehabilitation due to its multifaceted effects on neuromuscular performance, cognitive function, muscle recovery, and anti-inflammatory responses. By antagonizing adenosine receptors, caffeine enhances alertness, reduces perceived effort, and improves muscle activation, calcium handling, and energy metabolism, contributing to better functional performance and potentially supporting balance and postural control. Evidence suggests caffeine may augment muscular endurance, power, and movement velocity, while also mitigating delayed-onset muscle soreness and facilitating glycogen restoration when combined with appropriate nutritional strategies. Additionally, caffeine and its bioactive components exhibit antioxidant and anti-inflammatory properties, reducing oxidative stress and pro-inflammatory markers, which may support tissue recovery and overall rehabilitation outcomes. While findings indicate promising benefits, variability in individual response, dosage, and habitual intake necessitates careful consideration in clinical and rehabilitative applications. Overall, caffeine represents a versatile adjunct that can enhance physical and cognitive performance, promote muscle recovery, and modulate inflammation, highlighting its potential utility in rehabilitation settings.

Keywords: Caffeine, Physical Rehabilitation, Muscle Recovery, Balance, Neuromuscular Performance, Anti-Inflammatory, Antioxidant, Functional Performance

1. Introduction

Caffeine is a natural stimulant found in various plants like beans, leaves, and fruits, commonly consumed in drinks and medications. It works by blocking adenosine receptors, which normally promote sedation, leading to increased alertness and potentially enhanced physical performance [1]. The amount of caffeine varies widely across different sources. In addition to dietary sources, caffeine is commonly included in over-the-counter and prescription medications to enhance pain relief, reduce inflammation, or treat conditions such as migraines. Therapeutically, caffeine is also used to counteract drowsiness, support respiratory function in neonates, assist in electroconvulsive therapy, and manage conditions like postprandial hypotension, obesity, and attention deficits [2,3]. It can enhance strength, power, endurance, and the execution of functional tasks through mechanisms such as central nervous system stimulation, improved neuromuscular activation, and reduced perception of effort. These properties make caffeine a versatile aid, potentially supporting performance across a wide range of activities and intensities. Research also indicates benefits for coordination, alertness, and movement efficiency, which are relevant not only in sports but also in rehabilitation settings [4].

These diverse actions, together with its stimulant and pain-modulating properties, suggest that caffeine may be a valuable adjunct in rehabilitation, helping patients maintain alertness, reduce perceived effort or discomfort during exercises, and improve adherence to functional training programs.

2. Methodology

This article represents a narrative review of the current literature regarding caffeine's potential role as an adjunct in physical rehabilitation.

A literature search was conducted using electronic databases including PubMed, Scopus, and Web of Science. Keywords used individually and in combination included: "caffeine", "physical rehabilitation", "muscle recovery", "balance", "postural control", "neuromuscular performance", "inflammation", and "oxidative stress".

The review focused primarily on peer-reviewed articles published in English, including randomized controlled trials, experimental studies, meta-analyses, and relevant review articles. No strict time restriction was applied, although emphasis was placed on recent publications to reflect current scientific understanding.

Studies addressing both healthy individuals and clinical populations were considered, particularly those examining functional performance, muscle recovery, balance control, and inflammatory responses.

The selected literature was analyzed qualitatively and organized thematically according to mechanisms of action, functional performance outcomes, muscle recovery, and anti-inflammatory/antioxidant effects.

3. Results

3.1 Mechanisms of Action of Caffeine Relevant to Rehabilitation

Caffeine (1,3,7-trimethylxanthine) is widely used for its ability to enhance physical and neuromuscular performance. It works primarily by blocking adenosine receptors, which improves muscle activation, increases calcium availability in muscle cells, and supports energy metabolism. These effects can benefit a range of activities, from endurance and high-intensity movements to functional tasks in rehabilitation, with peak effects occurring roughly an hour after consumption [5]. It is rapidly absorbed, distributed to tissues, and crosses the blood-brain barrier, with peak blood levels reached within about an hour. Its main action is blocking A1 and A2a adenosine receptors, which enhances neuromuscular activation, alertness, and reduces fatigue. At physiologically relevant doses, caffeine may also slightly increase calcium release in muscles, improving contractile force, and potentially stimulating nitric oxide production, supporting functional performance and rehabilitation outcomes [6].

In addition to these central and peripheral effects, caffeine modulates the perception of effort and discomfort during physical tasks, which can help patients perform exercises more effectively and consistently in rehabilitation settings. By enhancing neurotransmitter activity, it may also support cognitive functions such as attention, working memory, and motor planning, further contributing to improved functional outcomes.

These combined effects make caffeine a potential adjunct for optimizing both neuromuscular and cognitive aspects of rehabilitation [7].

3.2 Effects of Caffeine on Functional Performance and Balance

Caffeine is known to enhance functional performance by increasing work capacity, improving muscle strength and power, and reducing glycogen use during prolonged activity, with benefits observed in tasks requiring endurance, speed, or power across sexes (**Figure 1**) [8].

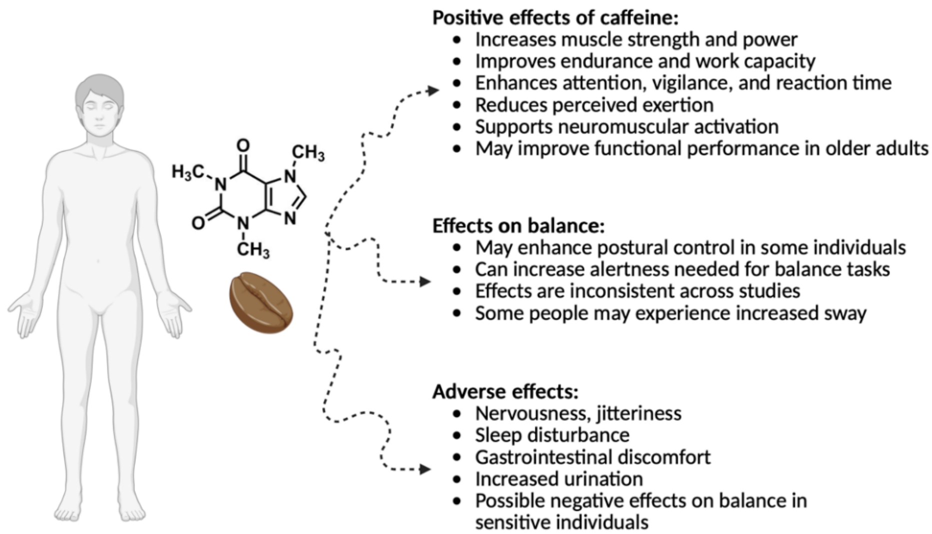

Figure 1. Positive and negative effects of caffeine on physical and cognitive performance, including its potential impact on balance

These effects typically appear at doses of 3–6 mg/kg, though variability in caffeine content across products complicates accurate dosing. While blood and saliva concentrations peak about 60 minutes post-ingestion, late consumption may impair sleep and recovery, potentially diminishing its ergogenic value. Side effects such as nervousness, gastrointestinal discomfort, insomnia, and increased urination vary with dose and timing [6,8].

Beyond its physical effects, caffeine can enhance cognitive and psychomotor functions, including attention, reaction time, and anticipatory timing like abilities that tend to decline with age [9]. Some evidence suggests improvements in endurance, walking distance, muscle strength, and perceived exertion, supporting the idea that caffeine can bolster both physical and cognitive readiness for exercise, particularly in older adults [10].

Through its actions on both the central nervous system and skeletal muscle, caffeine may also influence sensorimotor tasks like balance, which depend on lower-limb muscle activation, sensory integration, and cognitive processing. Enhanced alertness, mood, and neuromuscular function could support postural control, though stimulatory effects such as increased ventilation may conversely disrupt stability [11,12]. This is particularly relevant for older adults, who exhibit age-related sensory, muscular, and cognitive deterioration and often metabolize caffeine more slowly. Despite its potential to influence balance, current evidence remains inconclusive, especially in aging populations [11].

Findings regarding caffeine's effects on postural stability are mixed: some research reports increased postural sway, while other studies observe no significant changes.

Questions remain about the influence of placebo effects, individual sensitivity, and habitual caffeine use. Balance is commonly assessed via posturography, with computerized dynamic posturography, comprising the Sensory Organization Test, Head Shake SOT (The head shake sensory organization test) is an expansion of the sensory organization test (SOT), Limits of Stability, and Adaptation Test, serving as the gold standard for evaluating vestibular and sensory contributions to balance [11,13].

Because balance depends on coordinated muscle function and cognitive resources like attention and perception, caffeine may either enhance or impair postural control depending on individual characteristics, physiological responses, and task demands. These inconsistent findings highlight caffeine's potential relevance for groups with compromised balance, such as older adults or clinical populations, while emphasizing that evidence remains preliminary [14].

3.3. Caffeine and Muscle Recovery

Caffeine's performance-enhancing potential has been widely studied, initially focusing on aerobic exercise and more recently extending to anaerobic outcomes, including muscular endurance, maximal strength, and muscle power [15]. While its positive effects on muscular endurance are well-supported, findings on maximal strength (e.g., one-repetition maximum) and muscle power (e.g., vertical jump) remain inconsistent. Early studies in resistance-trained men reported negligible strength improvements, whereas later research observed modest gains in both upper and lower body strength with caffeine ingestion. Similarly, results for muscle power are mixed, with some studies showing improvements in jump height and peak force, while others found no effect [16].

Evidence suggests that caffeine may enhance resistance exercise performance more by improving muscular power and movement velocity than by increasing absolute maximal strength. This effect translates into a greater ability to generate force quickly and efficiently during dynamic movements, such as squats or bench presses, where both speed and power output are crucial [17]. However, the ergogenic effects of caffeine can vary depending on factors such as sex, habitual caffeine intake, dose, and the type of supplement consumed, highlighting the role of individual and contextual differences in determining its effectiveness. This variability underscores the need to consider personal and situational factors when using caffeine as an adjunct to optimize muscular strength and power [18].

Carbohydrates are essential for restoring energy stores after exercise, particularly for endurance activities, and timely nutritional intake supports optimal glycogen resynthesis. Coffee contains bioactive compounds, including caffeine, caffeic acid, and cafestol, which may improve glucose metabolism and enhance post-exercise glycogen recovery when consumed alongside carbohydrates. While the specific impact of coffee combined with carbohydrate intake on muscle glycogen restoration has not been fully explored, including protein- and carbohydrate-rich beverages such as milk may further support recovery through rehydration and promotion of muscle protein synthesis [19]. These findings suggest that caffeine, as part of a post-exercise nutritional strategy, could play a supportive role in accelerating recovery and preparing muscles for subsequent training or functional activities [20].

Delayed-onset muscle soreness (DOMS) arises 1–2 days after unfamiliar or eccentric exercise and reflects exercise-induced muscle damage (EIMD), characterized by soreness, reduced strength, limited range of motion, swelling, and elevated muscle enzymes [21]. Mechanical stress during exercise triggers inflammatory responses and reactive oxygen species production, limiting functional performance. Caffeine, a widely consumed stimulant, has been used as an ergogenic aid to enhance endurance and mitigate DOMS. Its beneficial effects may involve increased release of cortisol and beta-endorphins, enhanced calcium handling in muscles, direct calcium sensitization, and improved Na^+–K^+–ATPase activity. These mechanisms can reduce perceived fatigue, support muscle contractility, and potentially attenuate post-exercise soreness. Although evidence from studies is mixed, with some reporting reductions in DOMS and improvements in muscle strength and power while others show limited effects, caffeine remains a promising adjunct to support recovery and maintain functional performance following muscle-damaging exercise [22].

Recent studies have investigated caffeine's role in recovery across different sports, including soccer. Early research suggested that caffeine could negatively affect recovery, whereas later studies found that caffeine supplementation improves performance without exacerbating muscle damage. These mixed findings highlight the importance of understanding how caffeine can enhance performance while maintaining safe recovery, particularly in contexts such as official soccer championships where athletes face intense demands and limited recovery periods [23].

The effects of caffeine on maximal voluntary contraction (MVC) strength appear to be variable and may depend on the specific muscle group and type of contraction. Evidence suggests that caffeine can enhance voluntary activation and MVC strength in some muscles, such as the knee extensors under isometric conditions, whereas other muscles, like the plantar flexors, may not show measurable improvements [24]. Similarly, the type of contraction,static versus dynamic, seems to influence caffeine's ergogenic potential, with isometric contractions more consistently showing benefits than isokinetic or eccentric contractions. These differences may reflect the distinct contributions of central and spinal neural mechanisms to muscle activation, with caffeine likely exerting its effects primarily through central modulation. However, data on concentric and eccentric voluntary contractions are limited, leaving questions about caffeine's influence on dynamic muscle strength and the underlying neural mechanisms in these contexts [25].

3.4. Caffeine and Anti-Inflammatory/Antioxidant Responses

Oxidative stress and inflammation are closely linked processes that can impair tissue repair and contribute to chronic diseases, including neurodegenerative disorders. reactive oxygen species (ROS) and inflammatory mediators disrupt cellular function, while compounds in coffee, such as caffeine and chlorogenic acids, may provide antioxidant and anti-inflammatory benefits. These properties suggest a potential role for coffee and its components in supporting recovery and rehabilitation [26,27].

Caffeine and other bioactive compounds in coffee, such as chlorogenic acids, cafestol, kahweol, and caffeic acid, have notable antioxidant properties. They help neutralize ROS and support the body's defense systems, reducing oxidative stress (OS), which is linked to aging, neurodegenerative diseases, cardiovascular disorders, and cancer. These compounds can activate cellular pathways like Nrf2, enhancing the production of antioxidant enzymes and detoxifying harmful molecules [28]. Both coffee consumption and direct caffeine intake have been associated with reduced lipid peroxidation, increased glutathione levels, and overall improved antioxidant capacity, potentially contributing to cell protection, reduced inflammation, and better recovery after physical stress [29].

Caffeine exhibits antioxidant and anti-inflammatory properties. In vitro, it scavenges reactive species such as hydroxyl radicals, while in vivo studies show it reduces lipid peroxidation and increases activity of antioxidant enzymes like superoxide dismutase and glutathione peroxidase [30]. Caffeine also appears to protect against oxidative stress in neurodegenerative conditions and reduces inflammatory markers, including myeloperoxidase (MPO) and pro-inflammatory cytokines, partly through inhibition of acetylcholinesterase, which increases acetylcholine levels and supports anti-inflammatory signaling. Importantly, these effects occur independently of exercise [31]. Experimental studies in rats indicate that chronic caffeine intake, with or without exercise, does not alter liver mitochondrial function, ROS production, or mitochondrial morphology, but does reduce MPO and acetylcholinesterase activity, confirming its anti-inflammatory action without interfering with physiological adaptation to training. Overall, caffeine may offer a safe way to mitigate inflammation and oxidative stress without impairing cellular adaptation processes [32].

Beyond its psychoactive effects, caffeine influences multiple physiological systems and exerts notable antioxidant and anti-inflammatory actions. It reduces ROS, limits lipid peroxidation, and improves redox balance, particularly in the brain. These effects are linked to lower production of proinflammatory cytokines such as Tumor necrosis factor (TNF-α) and IL-1β and modulation of inflammatory pathways like factor nuclear kappa B (NF-κB). By mitigating oxidative stress and inflammation, caffeine may help preserve cellular function, protect tissues, and support recovery processes, suggesting potential benefits in rehabilitation and functional performance contexts [26,30].

4. Discussion

The present narrative review highlights caffeine's potential as a multifaceted adjunct in physical rehabilitation, acting through central and peripheral mechanisms that influence neuromuscular performance, cognitive function, and recovery processes. The evidence suggests that caffeine may enhance voluntary activation, reduce perceived exertion, and improve muscular endurance and movement velocity, factors that can positively influence participation and performance during rehabilitation exercises [6,15,17].

However, findings regarding balance and postural control remain inconclusive. While improved alertness and psychomotor performance may theoretically support sensorimotor integration, some studies report increased postural sway following caffeine ingestion. These discrepancies may be explained by interindividual variability in caffeine sensitivity, habitual intake, dosage, age-related metabolic differences, and task complexity. In older adults or clinical populations, where balance control depends heavily on cognitive and neuromuscular integration, caffeine's stimulatory effects may produce heterogeneous outcomes [11,12,14].

Regarding muscle recovery, caffeine appears to modulate pain perception and may attenuate delayed-onset muscle soreness, potentially supporting continued functional training. Additionally, its interaction with carbohydrate metabolism suggests a possible role in optimizing glycogen restoration. Nevertheless, effects on maximal strength recovery and dynamic contractions remain variable, indicating that caffeine's ergogenic influence may be context-dependent [19, 22, 24].

The antioxidant and anti-inflammatory properties of caffeine further expand its relevance in rehabilitation settings. By reducing oxidative stress and modulating inflammatory pathways without impairing physiological adaptation to exercise, caffeine may contribute to tissue protection and functional recovery [26, 30, 32].

Despite these promising findings, several limitations must be acknowledged. Most evidence derives from healthy, physically active individuals rather than clinical rehabilitation populations. Variability in study design, dosage protocols, and outcome measures complicates direct comparisons. Therefore, while caffeine appears to be a safe and potentially beneficial adjunct, individualized dosing strategies and careful consideration of patient characteristics are essential [6, 18].

Future research should focus on randomized controlled trials in clinical rehabilitation settings to clarify optimal dosing, timing, and long-term safety across diverse patient populations.

6. Conclusions

Caffeine may represent a valuable adjunct in physical rehabilitation by enhancing neuromuscular performance, cognitive function, and aspects of functional capacity. Through its central and peripheral mechanisms of action, caffeine can improve voluntary activation, reduce perceived exertion, and support the execution of therapeutic exercises, potentially increasing engagement and overall training efficiency. In addition to its performance-related benefits, caffeine may contribute to muscle recovery by attenuating delayed-onset muscle soreness and supporting metabolic processes involved in post-exercise glycogen restoration. Its antioxidant and anti-inflammatory properties further suggest a protective role against exercise-induced oxidative stress and inflammation, factors that are particularly relevant in rehabilitation contexts.

Although the magnitude of these effects depends on dosage, timing of ingestion, and individual variability, current evidence indicates that caffeine can be a safe, accessible, and practical strategy to complement rehabilitation interventions when applied judiciously and in accordance with patient-specific considerations.

Author Contributions: Conceptualization, C.I. and V.R..; validation, A.C., M.V.; writing—original draft preparation, C.I., V.R., M.V..; writing—review and editing, C.I., V.R., M.V..; visualization, A.C..; supervision, A.C.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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