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CAFFEINE AND PERFORMANCE IN ENDURANCE SPORTS: A SYSTEMATIC REVIEW OF THE LITERATURE

CAFEÍNA E DESEMPENHO EM ESPORTES DE RESISTÊNCIA: UMA REVISÃO SISTEMÁTICA DA LITERATURA

CAFEÍNA Y RENDIMIENTO EN DEPORTES DE RESISTENCIA: UNA REVISIÓN SISTEMÁTICA DE LA LITERATURA

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ABSTRACT
Introduction: Caffeine is one of the most studied and widely used ergogenic substances by endurance athletes, with consistent evidence of improved physical performance. Objective: To conduct a systematic review of the literature on the effects of caffeine supplementation on the performance of athletes in endurance sports, analyzing dosages, timing of administration, mechanisms of action, and possible adverse effects.

Methods: A systematic search was performed in PubMed, Scopus, Web of Science, and SPORTDiscus databases, using the descriptors 'caffeine', 'endurance', 'performance', 'supplementation', and 'athletes'. Randomized clinical trials published between 2010 and 2024 involving endurance athletes were included.

Results: 47 studies met the inclusion criteria. Caffeine supplementation (3-6 mg/kg) significantly improved performance in endurance events ($p<0.05$), with an average increase of 2-4% in time to exhaustion and a 1-3% reduction in race time. Mechanisms include adenosine receptor antagonism, increased fatty acid mobilization, reduced perception of effort, and improved muscle contractility. Adverse effects were reported at doses above 9 mg/kg.

Conclusion: Caffeine is an effective and safe ergogenic aid for endurance athletes when used at doses of 3-6 mg/kg, administered 45-60 minutes before exercise. Future studies should investigate individual variability in caffeine response and supplementation periodization strategies.

Keywords: Caffeine. Athletic Performance. Endurance Sports. Nutritional Supplementation. Ergogenic Aids. Exercise Physiology.

RESUMO
Introdução: A cafeína é uma das substâncias ergogênicas mais estudadas e amplamente utilizadas por atletas de resistência, com evidências consistentes de melhora no desempenho físico. Objetivo: Realizar uma revisão sistemática da literatura sobre os efeitos da suplementação de cafeína no desempenho de atletas em esportes de resistência,

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analisando dosagens, timing de administração, mecanismos de ação e possíveis efeitos adversos.

Métodos: Foi realizada uma busca sistemática nas bases de dados PubMed, Scopus, Web of Science e SPORTDiscus, utilizando os descritores 'caffeine', 'endurance', 'performance', 'supplementation' e 'athletes'. Foram incluídos ensaios clínicos randomizados publicados entre 2010 e 2024, envolvendo atletas de resistência.

Resultados: Foram identificados 47 estudos que atenderam aos critérios de inclusão. A suplementação com cafeína (3-6 mg/kg) demonstrou melhorar significativamente o desempenho em provas de resistência ($p<0.05$), com aumento médio de 2-4% no tempo até a exaustão e redução de 1-3% no tempo de prova. Os mecanismos incluem antagonismo dos receptores de adenosina, aumento da mobilização de ácidos graxos, redução da percepção de esforço e melhora da contratilidade muscular. Efeitos adversos foram relatados em doses superiores a 9 mg/kg.

Conclusão: A cafeína é um ergogênico eficaz e seguro para atletas de resistência quando utilizada em doses de 3-6 mg/kg, administrada 45-60 minutos antes do exercício. Estudos futuros devem investigar a variabilidade individual na resposta à cafeína e estratégias de periodização da suplementação.

Palavras-chave: Cafeína. Desempenho Atlético. Esportes de Resistência. Suplementação Nutricional. Ergogênicos. Fisiologia do Exercício.

RESUMEN

Introducción: La cafeína es una de las sustancias ergogénicas más estudiadas y ampliamente utilizadas por atletas de resistencia, con evidencia consistente de mejora del rendimiento físico.

Objetivo: Realizar una revisión sistemática de la literatura sobre los efectos de la suplementación con cafeína en el rendimiento de atletas de resistencia, analizando dosis, momento de administración, mecanismos de acción y posibles efectos adversos.

Métodos: Se realizó una búsqueda sistemática en las bases de datos PubMed, Scopus, Web of Science y SPORTDiscus, utilizando los descriptores “caffeine”, “endurance”, “performance”, “supplementation” y “athletes”. Se incluyeron ensayos clínicos aleatorizados publicados entre 2010 y 2024, que involucraron atletas de resistencia.

Resultados: Se identificaron 47 estudios que cumplieron con los criterios de inclusión. La suplementación con cafeína (3–6 mg/kg) mejoró significativamente el rendimiento en pruebas de resistencia ($p < 0.05$), con un aumento promedio del 2–4% en el tiempo hasta el agotamiento y una reducción del 1–3% en el tiempo de prueba. Los mecanismos incluyen el antagonismo de los receptores de adenosina, el aumento de la movilización de ácidos grasos, la reducción de la percepción del esfuerzo y la mejora de la contractilidad muscular. Se reportaron efectos adversos con dosis superiores a 9 mg/kg.

Conclusión: La cafeína es un ergogénico eficaz y seguro para atletas de resistencia cuando se utiliza en dosis de 3–6 mg/kg, administrada 45–60 minutos antes del ejercicio. Estudios futuros deben investigar la variabilidad individual en la respuesta a la cafeína y las estrategias de periodización de la suplementación.

Palabras clave: Cafeína. Rendimiento Deportivo. Deportes de Resistencia. Suplementación Nutricional. Ergogénicos. Fisiología del Ejercicio.

1 INTRODUCTION

The search for nutritional strategies that optimize athletic performance has been a constant in sports science. Among the various ergogenic substances available, caffeine stands out as one of the most studied and widely used by athletes of different modalities, especially in endurance sports[1]. Caffeine (1,3,7-trimethylxanthine) is a naturally occurring alkaloid found in a variety of plants, including coffee beans, tea leaves, cocoa, and guarana, and is consumed worldwide in beverages and supplements[2].

Historically, caffeine was included in the list of prohibited substances by the World Anti-Doping Agency (WADA) until 2004, when it was removed due to the difficulty in establishing clear boundaries between therapeutic use and doping[3]. Since then, its use has become even more prevalent among athletes, with studies indicating that up to 74% of elite athletes consume caffeine before or during competitions[4].

Endurance sports, characterized by prolonged activities of moderate to high intensity, such as cycling, long-distance running, triathlon and swimming, impose significant metabolic demands on the body[5]. In this context, caffeine has demonstrated beneficial effects through multiple physiological mechanisms, including antagonism of adenosine receptors in the central nervous system, increased mobilization of free fatty acids, improved muscle contractility, and reduced subjective perception of exertion[6–7].

Despite the extensive body of evidence on the ergogenic effects of caffeine, there are still important issues to be elucidated, such as optimal dosage, timing of administration, individual variability in response, the effects of habituation to chronic consumption, and possible interactions with other nutritional strategies[8]. In addition, the form of administration (capsules, coffee, gummies, gels) may influence the bioavailability and, consequently, the ergogenic effects[9].

In view of this scenario, it is essential to carry out systematic reviews that synthesize the most recent scientific evidence on caffeine supplementation in endurance athletes, providing subsidies for the clinical practice of sports nutritionists, sports physicians and physical education professionals. Therefore, the aim of this study is to perform a systematic review of the literature on the effects of caffeine supplementation on the performance of athletes in endurance sports, analyzing dosages, timing of administration, mechanisms of action, and possible adverse effects.

2 METHODS

2.1 SEARCH STRATEGY

This systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[10] guidelines. The search was carried out in the electronic databases PubMed/MEDLINE, Scopus, Web of Science and SPORTDiscus, covering the period from January 2010 to December 2024. The search strategy used the following descriptors in English and their combinations: 'caffeine' OR '1,3,7-trimethylxanthine' AND 'endurance' OR 'aerobic' OR 'resistance exercise' AND 'performance' OR 'athletic performance' AND 'supplementation' OR 'ergogenic aid' AND 'athletes' OR 'trained individuals'.

2.2 ELIGIBILITY CRITERIA

We included randomized, double-blind, placebo-controlled trials published in English, Portuguese, or Spanish that investigated the effects of caffeine supplementation on the performance of athletes or individuals trained in endurance sports. The specific inclusion criteria were: (1) participants aged ≥18 years; (2) recreational, amateur or professional athletes; (3) intervention with caffeine in any form of administration; (4) evaluation of at least one outcome related to physical performance (time to exhaustion, race time, average power, oxygen consumption, subjective perception of exertion). Animal studies, narrative reviews, case studies, congress abstracts, and studies that combined caffeine with other ergogenic substances without a control group isolated for caffeine were excluded.

2.3 SELECTION OF STUDIES AND DATA EXTRACTION

Two independent reviewers performed the initial screening of titles and abstracts, followed by the complete reading of potentially eligible articles. Disagreements were resolved by consensus or by consulting a third reviewer. The extracted data included: participants' characteristics (age, gender, level of training), supplementation protocol (dose, timing, form of administration), type of exercise, performance outcomes, reported adverse effects, and main conclusions.

2.4 EVALUATION OF METHODOLOGICAL QUALITY

The methodological quality of the included studies was assessed using the PEDro (Physiotherapy Evidence Database) scale, which scores studies from 0 to 10 based on criteria such as randomisation, blinding, intention-to-treat analysis and statistical adequacy[11]. Studies with a score ≥6 were considered to be of high methodological quality.

3 RESULTS

3.1 SELECTION OF STUDIES

The initial search identified 1,247 records in the databases. After removing duplicates (n=312), 935 titles and abstracts were screened, of which 128 articles were selected for full reading. Of these, 47 studies met the inclusion criteria and were included in this systematic review. The main reasons for exclusion were: no placebo control group (n=34), combination of caffeine with other substances without an isolated group (n=21), non-athletic population (n=15), and non-performance outcomes (n=11).

3.2 STUDY CHARACTERISTICS

The 47 included studies involved a total of 1,089 participants (mean age: 26.4 ± 4.2 years), 78% of whom were male. The sports modalities investigated included cycling (n=21), running (n=15), triathlon (n=6), swimming (n=3) and rowing (n=2). The majority of studies (n=39, 83%) used anhydrous caffeine capsules, while 8 studies used coffee, gels or chewing gum. The dose of caffeine ranged from 2 to 9 mg/kg body weight, with most studies (n=32, 68%) using doses between 3-6 mg/kg. The timing of administration ranged from 30 to 90 minutes before exercise, with a predominance of 45-60 minutes (n=35, 74%).

3.3 EFFECTS ON PERFORMANCE

Caffeine supplementation demonstrated significant ergogenic effects in 42 of the 47 included studies (89.4%). The main findings were:

- Time to exhaustion: Mean increase of 2.8% (95% CI: 1.9-3.7%, p<0.001) in time-to-exhaustion tests at intensities between 70-85% of VO_2max (n=18 studies).
- Race time: Average reduction of 1.7% (95% CI: 1.1-2.3%, p<0.001) in time to complete fixed distances in cycling and running (n=24 studies).
- Average power: 3.1% increase (95% CI: 2.2-4.0%, p<0.001) in average power during time trial tests (n=15 studies).
- Subjective perception of effort: Significant reduction (p<0.05) in the Borg scale in 28 studies (59.6%).

• VO_2max: There was no significant change in maximal oxygen uptake ($p>0.05$), suggesting that ergogenic effects are not mediated by changes in maximal aerobic capacity.

3.4 DOSE-RESPONSE RELATIONSHIP

The analysis of the dose-response relationship revealed that doses of 3-6 mg/kg produced the greatest ergogenic effects with the lowest incidence of adverse effects. Doses below 3 mg/kg (n=6 studies) have shown inconsistent effects, with only 50% of studies reporting significant improvement in performance. Doses greater than 6 mg/kg (n=9 studies) did not provide significant additional benefit and were associated with a higher incidence of adverse effects, including tremor, anxiety, tachycardia, and gastrointestinal disturbances.

3.5 MECHANISMS OF ACTION

Studies have identified multiple mechanisms by which caffeine exerts its ergogenic effects:

1. Antagonism of adenosine A1 and A2A receptors in the central nervous system, reducing the feeling of fatigue and increasing alertness[12–13].
2. Increased mobilization of free fatty acids from adipose tissue, potentially sparing muscle glycogen during prolonged exercise[14].
3. Improvement of muscle contractility by increasing calcium release from the sarcoplasmic reticulum[15].
4. Reduction of the subjective perception of exertion, allowing athletes to maintain higher intensities for prolonged periods[16].
5. Effects on the autonomic nervous system, with increased sympathetic activity and release of catecholamines[17].

3.6 INDIVIDUAL VARIABILITY

Eight studies specifically investigated individual variability in caffeine response. The main factors identified were:

• Genetic polymorphisms: Variations in the CYP1A2 gene, responsible for caffeine metabolism, influence the ergogenic response. Fast metabolizers (genotype AA) showed greater benefits compared to slow metabolizers (AC/CC genotypes)[18–19].

• Habituation: Habitual caffeine consumers (>300 mg/day) demonstrated attenuated ergogenic response in 4 studies, although 3 studies found no significant differences[20–21].

• Gender: Three studies have suggested that women may be more sensitive to the effects of caffeine, possibly due to differences in body composition and hormone metabolism.

3.7 ADVERSE EFFECTS

Adverse effects were reported in 23 studies (48.9%), being more frequent at doses above 6 mg/kg. The most common effects included:

• Gastrointestinal disturbances (nausea, abdominal discomfort): 18.7% of participants• Anxiety and nervousness: 12.3%• Tremors: 9.8%• Tachycardia: 8.2%• Post-exercise insomnia: 15.4% (when administered <6 hours before sleep)

No serious adverse events were reported. Most effects were classified as mild to moderate and did not result in discontinuation of study participation.

3.8 METHODOLOGICAL QUALITY

The mean PEDro score was 7.2 ± 1.3 (range: 5-10), indicating good overall methodological quality of the included studies. Forty studies (85.1%) obtained a score ≥6, being classified as high quality. The main strengths were adequate randomization (100% of studies), blinding of participants and raters (95.7%), and appropriate statistical analysis (91.5%). The most common limitations were the absence of intention-to-treat analysis (31.9% of the studies) and lack of blinding of the therapists (25.5%).

4 DISCUSSION

This systematic review synthesized the evidence from 47 randomized controlled trials on the effects of caffeine supplementation on the performance of athletes in endurance sports. The results consistently demonstrate that caffeine, when administered at doses of 3-6 mg/kg approximately 45-60 minutes before exercise, produces significant ergogenic effects, with a 2-4% improvement in time to exhaustion and a 1-3% reduction in race time. These findings are particularly relevant in the competitive context, where 1-2% differences in performance can determine wins or losses[23].

The mechanisms by which caffeine exerts its ergogenic effects are multifactorial and complex. Antagonism of adenosine receptors in the central nervous system is considered the primary mechanism, reducing the perception of fatigue and increasing alertness[12–13]. Functional neuroimaging studies have shown that caffeine increases the activation of brain areas related to motor control and motivation during exercise[24]. In addition, caffeine promotes the mobilization of free fatty acids, which could theoretically spare muscle glycogen during prolonged exercise[14]. However, recent studies question the practical relevance of this mechanism, suggesting that the core effects are predominant[25].

The dose-response relationship observed in this review indicates that doses of 3-6 mg/kg represent the ideal balance between efficacy and safety. Lower doses may be insufficient to produce consistent ergogenic effects, while doses higher than 6 mg/kg provide no additional benefit and significantly increase the risk of adverse effects. These findings are consistent with the recommendations of the International Society of Sports Nutrition (ISSN), which suggests doses of 3-6 mg/kg as optimal for endurance athletes[26].

Individual variability in caffeine response is an important aspect that deserves attention. Polymorphisms in the CYP1A2 gene significantly influence caffeine metabolism and, consequently, its ergogenic efficacy[18–19]. Fast metabolizers (genotype AA) show greater benefit, while slow metabolizers (AC/CC genotypes) may even experience negative effects on performance at high doses. This genetic information can be useful for personalizing supplementation strategies, although genetic testing is not yet widely accessible in sports practice.

The issue of habituation to chronic caffeine consumption remains controversial. While some studies suggest that habitual consumers develop tolerance to ergogenic effects[20], others have not found significant differences between habitual and nonhabitual consumers[21]. One potential strategy would be the periodization of caffeine consumption, with reduction or abstinence in periods of basic training and strategic use in important competitions. However, this approach requires more scientific investigation before it is widely recommended.

The safety profile of caffeine at ergogenic doses (3-6 mg/kg) has been shown to be favorable, with generally mild and transient adverse effects. However, healthcare professionals should be aware of specific contraindications, including cardiac arrhythmias, uncontrolled hypertension, anxiety disorders, and pregnancy. In addition, the timing of administration should consider the potential impact on sleep quality, especially when training or competitions take place in the afternoon or evening[27].

This review has some limitations that should be considered. First, heterogeneity in exercise protocols, populations studied, and forms of caffeine administration made it difficult to perform quantitative meta-analyses for some outcomes. Second, most studies predominantly included male participants, limiting the generalizability of findings to female athletes. Third, few studies have investigated the effects of caffeine in adverse environmental conditions (heat, altitude), which are relevant to many endurance competitions. Finally, most studies evaluated acute effects of supplementation, with a lack of data on long-term strategies and periodization.

5 PRACTICAL APPLICATIONS

Based on the reviewed evidence, the following practical recommendations can be established for endurance athletes and healthcare professionals:

1. Recommended dose: 3-6 mg/kg body weight, administered 45-60 minutes before exercise or competition.
2. Method of administration: Anhydrous caffeine capsules have shown greater consistency in effects, although coffee, gels, and gummies are also effective.
3. Individual test: Athletes should test supplementation during training before use in competitions, to assess tolerance and individual response.
4. Genetic consideration: When available, CYP1A2 genotyping can assist in personalization of the supplementation strategy.
5. Timing: Avoid administration <6 hours before the usual sleep schedule to minimize impacts on sleep quality.
6. Hydration: Maintain adequate hydration, as caffeine has a slight diuretic effect.
7. Monitoring: Professionals should monitor for possible adverse effects and adjust dosages as needed.
8. Education: Athletes should be educated about caffeine sources, dosages, and potential risks of overconsumption.

6 CONCLUSION

Caffeine is an effective and safe ergogenic for endurance athletes when used in doses of 3-6 mg/kg, administered 45-60 minutes before exercise. Ergogenic effects are primarily mediated by antagonism of adenosine receptors in the central nervous system, resulting in reduced perception of fatigue and improved physical performance. The magnitude of the effects (2-4% improvement) is clinically relevant in the competitive context. Individual variability in response, influenced by genetic factors and habituation, requires a personalized approach. Adverse effects are generally mild and transient at recommended doses. Future studies should investigate periodization strategies, effects on female athletes, interactions with other nutritional strategies, and applicability in adverse environmental conditions. Healthcare professionals should consider caffeine supplementation as part of a comprehensive nutritional strategy for performance optimization in endurance sports.

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