Effects of caffeine on rate of force development: a meta-analysis

Effects of caffeine on rate of force development: a meta-analysis

Jozo Grgic,[1] Pavle Mikulic,[2]

[1]Institute for Health and Sport, Victoria University, Melbourne, Australia

[2]Faculty of Kinesiology, University of Zagreb, Zagreb, Croatia

Corresponding author:

Dr. Jozo Grgic

jozo.grgic@live.vu.edu.au

Abstract

This review aimed to conduct a meta-analysis of studies examining the effects of caffeine on rate of force development (RFD). Ten databases were searched to find relevant studies. Risk of bias (RoB) of the included studies was evaluated. Data were analyzed in a random-effects meta-analysis. Eleven studies with “some concerns” regarding RoB were included. In the main meta-analysis, there was a significant ergogenic effect of caffeine ingestion on RFD (Hedges’ g = 0.37; 95% confidence interval [CI]: 0.21, 0.52; $p < 0.0001$). An ergogenic effect of caffeine was also found on RFD during resistance exercises (Hedges’ g = 0.49; 95% CI: 0.30, 0.67; $p < 0.0001$), but not during the countermovement jump test (Hedges’ g = 0.18; 95% CI: –0.02, 0.39; $p = 0.08$), with a significant difference between the subgroups ($p = 0.03$). Small-to-moderate (3–5 mg/kg; Hedges’ g = 0.25; 95% CI: 0.09, 0.41; $p = 0.002$) and moderate-to-high caffeine doses (6–10 mg/kg) enhanced RFD (Hedges’ g = 0.57; 95% CI: 0.30, 0.85; $p < 0.0001$), even though the effects were larger with higher caffeine doses ($p = 0.04$). Overall, caffeine ingestion increases RFD, which is relevant given that RFD is commonly associated with sport-specific tasks. From a practical perspective: (1) individuals interested in the acute enhancement of RFD in resistance exercise may consider supplementing with caffeine; and (2) given that evaluation of RFD is most commonly used for testing purposes, caffeine ingestion (3–10 mg/kg 60 min before exercise) should be standardized before RFD assessments.

Key words: ergogenic aids; supplements; data synthesis; exercise performance

1. Introduction

As its name suggests, rate of force development (RFD) denotes the: "rate of rise in contractile force at the onset of contraction".[1] RFD has become increasingly popular for evaluating "explosive" strength of athletes and older adults.[2] RFD is an interesting metric for athletes as it is commonly associated with different sport-specific tasks.[2, 3] For example, in a study among rugby union players, RFD was correlated with jump height and sprint performance (r = 0.54–0.61).[3] Furthermore, several other sports movements, such as changes of direction, throws, and kicks, are related to RFD as they commonly include contraction times shorter than 250 ms.[4] This muscular quality is also of relevance in older adults, given that RFD may be important for balance control, reducing the incidence of falls, and performance of various daily activities (e.g., stair walking, rising from a chair).[2, 5] While outcomes such as maximal force production are also relevant, these findings highlight the importance of RFD in sport and activities of daily living.

Caffeine is a highly popular supplement with well-established performance-enhancing effects.[6] Estimates suggest that caffeine is consumed by 75% of athletes competing at the Olympic Games, likely due to its ergogenic potential.[7] Meta-analyses have reported that caffeine ingestion enhances muscular strength (i.e., maximum force production), albeit these effects tend to be trivial (Hedges' g: 0.16–0.20).[8-12] While caffeine is ergogenic for muscular strength, its effects on RFD are less clear. Several studies have explored the effects of caffeine on RFD, with equivocal findings.[13-15] For example, Behrens et al.[13] reported that caffeine ingestion (8 mg/kg) increased RFD during knee extensions by 18%. A more recent study explored the effects of caffeine ingestion (4 mg/kg) on RFD in a cohort of 15 resistance-trained females.[14] Here, there was no significant difference between caffeine and placebo. Still, when examining the data, it can be observed that the effects favored the caffeine condition by 15%. This might suggest that some studies on this topic might have been statistically underpowered to find a significant difference, leading to a type II error.

One way to overcome the limitation of underpowered trials is to pool the data from different studies in a meta-analysis. In their consensus statement on dietary supplements, the International Olympic Committee placed meta-analysis at the top of the evidence base pyramid, highlighting its relevance in this field of research.[16] Still, as of date, no meta-analyses explored the effects of caffeine ingestion on RFD. Such an analysis would be important to perform given: (i) the importance of RFD for different populations, including athletes; (ii) the high prevalence of caffeine supplementation in athletes; and (iii) the equivocal findings previously reported on caffeine's effects on RFD. Therefore, this review aimed to conduct a meta-analysis of studies exploring the effects of caffeine on RFD.

2. Methods

2.1 Search strategy

To find studies that explored the effects of caffeine on RFD, a search through ten different databases was performed, including: Academic Search Elite, Cochrane Library, CINAHL, ERIC, Networked Digital Library of Theses and Dissertations, OpenDissertations, PubMed/MEDLINE, Scopus, SPORTDiscus, and Web of Science. In all of these databases, the following search syntax (or equivalent) was used: ("caffeine" OR "coffee") AND ("rate of force development" OR "rate of torque development" OR "RFD" OR "RTD"). For example, in PubMed/MEDLINE, the search syntax was as follows: ("caffeine"[Mesh] OR "coffee"[Mesh]) AND ("rate of force development"[tw] OR "rate of torque development"[tw] OR "RFD"[tw] OR "RTD"[tw]). The search through the databases was performed on September 24th, 2021. After completing the search through the databases, secondary searches were performed. Secondary searches included screening the references list of all included studies (i.e., backward citation tracking) and examining the studies that cited the included studies (i.e., forward citation tracking) through Google Scholar.

2.2 Inclusion criteria

For this review, studies that satisfied the following criteria were included: (1) examined the effects of caffeine ingestion on RFD; (2) used a crossover and placebo-controlled study design; and (3) included humans as study participants. All of the studies that did not satisfy these criteria were excluded from this review.

2.3 Data extraction

From all included studies, the following data were extracted: (1) lead author name and year of publication; (2) participants characteristics; (3) protocol of caffeine ingestion (e.g., dose, the timing of ingestion); (4) RFD test; and (5) mean ± standard deviation RFD values following placebo and caffeine ingestion. Several studies presented mean ± standard deviation data in figures. For these studies,[13, 17, 18, 19] the Web Plot Digitizer software was used to extract the necessary data. Standard errors presented in two studies[18, 19] were converted to standard deviation.

2.4 Risk of bias and quality of evidence

The risk of bias (RoB) of the included studies was evaluated using the RoB 2 tool with additional considerations for crossover trials.[20] This tool evaluates RoB in six different domains, including: domain 1—bias arising from the randomization process; domain S—bias arising from period and carryover effects; domain 2—bias due to deviations from intended intervention; domain 3—bias due to missing outcome data; domain 4—bias in measurement of the outcome; domain 5—bias in selection of the reported result. Per recommendations, each domain and the overall evaluation of RoB for a given study was classified as "low risk", "some concerns" or "high risk".[20] The quality of evidence was evaluated on the meta-analysis level, using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) principles. The following GRADE aspects were evaluated: (1) RoB; (2) inconsistency; (3) indirectness; (4) imprecision; and (5) publication bias.[6, 21] Based on these criteria, the meta-analytical evidence was classified as high, moderate, low, or very low. All stages of the review (i.e., search process, data extraction, and quality assessment) were performed independently by the two authors of the review to minimize potential bias.

2.5 Statistical analysis

Meta-analyses were performed using Hedges' g effect sizes (ES). ES values and their 95% confidence intervals [CI] were calculated using the RFD performance mean ± standard deviation data from the placebo and caffeine trials (i.e., difference in means divided by the pooled standard deviation), total sample size, and inter-trial correlation. Given that correlation values were not reported in the included studies, we requested these data from the corresponding authors. We obtained correlations from five studies, ranging from 0.49–0.82

(median $r = 0.66$). The median correlation was used for studies without correlations. In the main meta-analysis, the data from all available studies were pooled. One study[19] used two caffeine doses, 5 mg/kg and 10 mg/kg. For this study, the RFD values following the ingestion of 5 mg/kg were used in the main meta-analysis, as this is more closely related to currently recommended doses of caffeine (i.e., 2–6 mg/kg).[12, 22] Still, a sensitivity analysis was also performed, in which the RFD values following the ingestion of 10 mg/kg were used. An additional sensitivity analysis was performed by excluding one study[18] that included older adults as participants, given that all other studies were performed among young adults. In addition to the main meta-analysis, subgroup analyses were performed. One subgroup analysis explored the effects of caffeine on RFD during resistance exercises (i.e., mid-thigh pull, knee extension, or elbow flexion) vs. RFD during the countermovement jump test (CMJ). To explore the influence of caffeine dose, subgroup analyses examined the effects of caffeine consumed in low-to-moderate doses (3–5 mg/kg) vs. moderate-to-high doses (6–10 mg/kg). ESs were interpreted using the following thresholds: trivial (<0.20), small (0.20–0.49), medium (0.50–0.79), and large (≥0.80). All meta-analyses were performed using the random-effects model. Heterogeneity was explored using the I^2 statistic—interpreted as low (<50%), moderate (50–75%), and high heterogeneity (>75%). Publication bias was performed by examining the asymmetry of the funnel plot, even though this was performed only in the main meta-analysis, given that all other analyses included less than ten studies.[23] The statistical significance threshold was set at $p < 0.05$. All analyses were performed using the Comprehensive Meta-Analysis software, version 2 (Biostat Inc., Englewood, NJ, USA)

3. Results

3.1 Search results

In the primary search, there was a total of 178 results. From this pool of references, 16 full-text papers were read and 10 studies were included. In the backward citation tracking, there were 447 search results, but this search did not result in the inclusion of any additional studies. In the forward citation tracking, there were 197 search results and one additional study[15] that satisfied the inclusion criteria. Therefore, a total of 11 studies[13-15, 17-19, 24-28] were included in this review (Figure 1).

3.2 Summary of studies

The number of included participants per study ranged from 10–25 (median: 13 participants). The pooled number of participants across all included studies was 154 (94 male and 60 female participants). Most studies included young adults as participants, that were resistance-trained or athletes competing in sports such as Jiu-Jitsu and volleyball. One study[18] was performed in a cohort of 12 older adults (age: 72 ± 4 years). Studies used different caffeine doses, including 3 mg/kg (2 studies), 4 mg/kg (1 study), 5 mg/kg (4 studies), 6 mg/kg (2 studies), 7 mg/kg (1 study), and 8 mg/kg (1 study) and (10 mg/kg 1 study). Most studies provided caffeine supplementation 60 min before exercise, with two studies using 45 min before exercise. Eight studies evaluated RFD during different resistance exercises (e.g., isometric mid-thigh pull, isokinetic knee extension), while three studies assessed RFD during CMJ. Ten studies used a double-blind design and one study used a single-blind design (Table 1).

3.3 RoB

Studies scored “low risk” in domains S, 2, 3, and 4. However, in domains 1 and 5 the classification for all included studies was “some concerns”. Therefore, the overall RoB of the included studies was classified as having “some concerns” (Table 2).

3.4 Meta-analysis and quality of evidence

In the main meta-analysis, there was a significant ergogenic effect of caffeine ingestion on RFD (ES = 0.37; 95% CI: 0.21, 0.52; $p < 0.0001$; $I^2 = 18\%$; Figure 2). There was no evidence of publication bias. The sensitivity analyses did not influence the pooled results. The quality of evidence was classified as moderate.

In the subgroup meta-analysis that explored the effects of caffeine on RFD during resistance exercises, there was a significant ergogenic effect of caffeine ingestion (ES = 0.49; 95% CI: 0.30, 0.67; $p < 0.0001$; $I^2 = 0\%$; Figure 3). The quality of evidence was classified as low. In the subgroup meta-analysis that explored the effects of caffeine on RFD during CMJ tests, there was no significant difference between caffeine and placebo (ES = 0.18; 95% CI: –0.02, 0.39; $p = 0.08$; $I^2 = 0\%$; Figure 4). The quality of evidence was classified as low. A significant difference was found between the subgroups ($p = 0.03$).

In the subgroup meta-analysis that explored the effects of small-to-moderate doses of caffeine on RFD, there was a significant ergogenic effect of caffeine ingestion (ES = 0.25; 95% CI: 0.09, 0.41; $p = 0.002$; $I^2 = 0\%$). The quality of evidence was classified as very low. In the subgroup meta-analysis that explored the effects of moderate-to-high doses of caffeine on RFD, there was a significant ergogenic effect of caffeine ingestion (ES = 0.57; 95% CI: 0.30, 0.85; $p < 0.0001$; $I^2 = 0\%$). The quality of evidence was classified as low. A significant difference was found between the subgroups ($p = 0.04$).

4. Discussion

The main finding of this meta-analysis is that caffeine ingestion has a significant ergogenic effect on RFD. Subgroup meta-analyses found that this ergogenic effect was also present when considering studies that evaluated RFD during resistance exercises. However, there was no significant difference between caffeine and placebo for RFD recorded during CMJ. Additionally, an ergogenic effect of caffeine was found in subgroup analysis that included studies providing small-to-moderate (3–5 mg/kg) and moderate-to-high doses of caffeine (6–10 mg/kg), even though the effects were higher with larger doses of caffeine. The quality of evidence ranged from moderate to very low. From a practical perspective, there are two main conclusions from the presented data. Individuals interested in the acute enhancement of RFD in resistance exercise may consider supplementing with caffeine. Additionally, given that evaluation of RFD is most commonly used for testing purposes, caffeine ingestion in doses from 3–10 mg/kg 60 min before exercise should be standardized before RFD assessments.

The findings that caffeine ingestion enhances RFD may be of substantial practical importance as RFD is associated with several aspects of athletic performance.[1-3] Accordingly, the increase in RFD following caffeine ingestion might partially explain some of the positive results shown for the effect of caffeine supplementation on jump height, sprint, and agility activities.[9, 29, 30] However, differential effects of caffeine were observed for RFD recorded during resistance exercises vs. RFD recorded during CMJ. Still, the pooled data for caffeine's effects on RFD during CMJ should be interpreted with caution as only three studies (*n* = 51) were included. One of these three studies actually reported an increase in RFD during CMJ, suggesting that a possible effect still might exist in the population.[25] The variation in effects reported among the included studies might be due to the test-retest reliability of RFD. Several studies explored the test-retest reliability of RFD during CMJ and reported that RFD is much less reliable than outcomes such as jump height, as its coefficient of variation (CV) ranged from 13–24%.[31, 32] The high CV might have contributed to increased type II error rates, which could also explain the lack of significant effects in this analysis.[33] Overall, it can be concluded that caffeine ingestion increases RFD and that future studies should directly explore caffeine's influence on RFD during different jumping, isometric, and isokinetic tests to establish if these effects are indeed task-dependent.

In subgroup analyses for caffeine dose, an ergogenic effect was found when consuming small-to-moderate and moderate-to-high doses. However, we also found a significant difference between the subgroups, as the ES was larger when consuming moderate-to-high doses. Previous studies that examined the dose-response effects of caffeine on movements with short contraction times (e.g., mean velocity in resistance exercise) also reported that higher doses of caffeine (i.e., 9 mg/kg) are needed for an ergogenic effect.[34] However, one important limitation needs to be considered before making conclusions about the dose-response effects of caffeine from the findings presented herein. All three studies[25, 27, 28] that evaluated the effects of caffeine on RFD during CMJ used doses from 3–5 mg/kg and were included in the small-to-moderate dose subgroup analysis. This is important, as there was no significant difference between caffeine and placebo for RFD in CMJ. Subsequently, their inclusion might have confounded the analysis for the effects of small-to-moderate caffeine doses on RFD. However, the direction of this effect is not yet clear, as it might be that caffeine did not influence RFD in CMJ because of the smaller doses consumed in these studies. Ultimately, future dose-response studies are needed to provide further insights into the effects of caffeine dose on RFD in CMJ and resistance exercise.

One of the likely determinants of RFD is motor unit recruitment.[1, 35] This is relevant to consider, given that caffeine ingestion has been reported to increase motor unit recruitment.[36] For example, in one study, motor unit recruitment of the knee extensors during maximal contractions increased following the ingestion of 5 mg/kg of caffeine.[36] Therefore, this caffeine-induced increase in motor unit recruitment may explain its ergogenic effects on RFD.[36] Interestingly, the increase in motor unit recruitment appears to be more pronounced in larger (e.g., knee extensors) vs. smaller (e.g., elbow flexors) muscle groups.[8, 36] Indeed, one of the included studies[19] evaluated RFD of the elbow flexors and did not report an ergogenic effect of caffeine. In contrast, such an effect was generally observed in studies[13, 15] that focused on the knee extensors. Similar data have been previously observed for caffeine's effects on muscular strength.[8, 10] However, given that the included studies evaluated RFD of only one muscle group, future studies should directly compare the effects of caffeine on RFD of different muscle groups.

Besides motor unit recruitment, it seems likely that the cross-bridge cycling rate influences RFD.[37] Cross-bridge cycling rate is calcium ion (Ca^{2+}) dependent.[38] There is a plethora of data suggesting that caffeine application influences Ca^{2+} release (for a detailed review, see the work by Tallis and colleagues).[39] For example, one study[40] applied caffeine to isolated single fibers of mouse skeletal muscle and reported that Ca^{2+} release increased in the presence of caffeine both in the resting muscle and during tetanic stimulation. Collectively, it appears that caffeine consumption influences Ca^{2+} release, which might impact the cross-bridge cycling rate and hence, RFD.[37-40] However, it should also be mentioned that the caffeine's effects on Ca^{2+} release are currently only observed in studies using animal models and supra-physiological doses of caffeine.[41] Thus, the generalization of these findings to the effects of caffeine observed in humans is speculative. Future studies are needed to explore the mechanisms underpinning the caffeine-induced increase in RFD.

There are several limitations of the present review that need to be mentioned. One is related to the limitations among the included studies, as they were classified as having "some concerns" regarding RoB. Specifically, none of the included studies provided details on the allocation concealment. Additionally, the study protocol and the planned analyses were also not pre-registered. These aspects, therefore, should be considered in future studies on the topic. Asymmetry of the funnel plot was only explored in the main meta-analysis, given that only this analysis included ten or more studies.[24] Therefore, the extent of possible publication bias in all other analyses remains unclear. Still, it should be considered that this review performed a search through databases indexing published and unpublished documents. Due to the file drawer effect, studies that report larger and significant effects tend to be published more often. However, seven[14, 20, 25, 26, 27, 28, 29] out of the 11 included studies did not report an ergogenic effect of caffeine on RFD, even though all of them were published. Collectively, it does not seem that the results of this review are affected by publication bias, even though this cannot be fully excluded.

An additional limitation of this review is related to inherent difficulties in evaluating RFD. As mentioned previously, several studies explored the reliability of RFD during CMJ and they reported a high CV.[31, 32] It seems that the CV is higher for shorter contractions times, as one study reported CV values of 12.8%, 5.3%, and 4.5% for RFD recorded during 0–50 ms, 0–100 ms, and 0–150 ms, respectively.[42] Among the included studies, some evaluated RFD during 0–200 ms, while others used 0–100 ms.[18, 26] Due to these differences, the random-effects model was used in the meta-analysis, which accounts for the inherent variation in the methodological approaches between studies that could influence the treatment effect.[43] Nevertheless, future studies are needed to explore the effects of caffeine on RFD across different contraction times. While several methodological aspects may improve reliability (e.g., a familiarization session, instructions provided to the participants, collecting data from multiple contractions), more work is needed to establish a highly reliable protocol for assessing RFD.[2]

5. Perspectives

The present meta-analysis found that caffeine ingestion enhances RFD. An ergogenic effect of caffeine on RFD was found in resistance exercise but not in the CMJ test. Additionally, ingesting higher doses of caffeine appear to produce greater ergogenic effects. Even though it is generally believed that the effects of caffeine are the greatest in prolonged duration, endurance-based activities, the results presented herein demonstrate an ergogenic effect of caffeine on RFD, which involves very short contraction times.[2, 6, 22] As RFD is commonly associated with different sport-specific tasks, the caffeine-induced increase in RFD may also explain some of the previous findings on the ergogenic effects of this supplement on sprint, agility, and ballistic exercise performance.[9, 29, 30, 44] The improvement in RFD following caffeine supplementation is likely to be practically relevant, given the recent findings that resistance training performed for 6–8 weeks (on average) increases isometric RFD by a similar magnitude (ES = 0.35–0.58) as caffeine supplementation (ES = 0.37–0.57).[45]

References

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002;93:1318-1326.
2. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol.* 2016;116:1091-1116.
3. Tillin NA, Pain MT, Folland J. Explosive force production during isometric squats correlates with athletic performance in rugby union players. *J Sports Sci.* 2013;31:66-76.
4. Hernández-Davó JL, Sabido, R. Rate of force development: reliability, improvements and influence on performance. A review. *Eur J Hum Mov.* 2014;33:46-69.
5. Aagaard P, Suetta C, Caserotti P, Magnusson SP, Kjaer M. Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. *Scand J Med Sci Sports.* 2010;20:49-64.
6. Grgic J, Grgic I, Pickering C, Schoenfeld BJ, Bishop DJ, Pedisic Z. Wake up and smell the coffee: caffeine supplementation and exercise performance—an umbrella review of 21 published meta-analyses. *Br J Sports Med*. 2020;54:681-688.
7. Del Coso J, Muñoz G, Muñoz-Guerra J. Prevalence of caffeine use in elite athletes following its removal from the World Anti-Doping Agency list of banned substances. *Appl Physiol Nutr Metab.* 2011;36:555-561.
8. Warren GL, Park ND, Maresca RD, McKibans KI, Millard-Stafford ML. Effect of caffeine ingestion on muscular strength and endurance: a meta-analysis. *Med Sci Sports Exerc.* 2010;42:1375-1387.
9. Grgic J, Trexler ET, Lazinica B, Pedisic Z. Effects of caffeine intake on muscle strength and power: a systematic review and meta-analysis. *J Int Soc Sports Nutr.* 2018;15:11.
10. Grgic J, Pickering C. The effects of caffeine ingestion on isokinetic muscular strength: a meta-analysis. *J Sci Med Sport.* 2019;22:353-360.

11. Grgic J, Del Coso J. Ergogenic effects of acute caffeine intake on muscular endurance and muscular strength in women: a meta-analysis. *Int J Environ Res Public Health.* 2021;18:5773.
12. Grgic J. Effects of caffeine on resistance exercise: a review of recent research. *Sports Med.* 2021. doi: 10.1007/s40279-021-01521-x
13. Behrens M, Mau-Moeller A, Weippert M, et al. Caffeine-induced increase in voluntary activation and strength of the quadriceps muscle during isometric, concentric and eccentric contractions. *Sci Rep.* 2015;5:10209.
14. Norum M, Risvang LC, Bjørnsen T, et al. Caffeine increases strength and power performance in resistance-trained females during early follicular phase. *Scand J Med Sci Sports.* 2020;30:2116-2129.
15. Peterson BM, Brown LE, Judelson DA, Gallo-Rebert S, Coburn JW. Caffeine increases rate of torque development without affecting maximal torque. *J Sci Sport Exerc.* 2019;1:248-256.
16. Maughan RJ, Burke LM, Dvorak J, et al. IOC consensus statement: dietary supplements and the high-performance athlete. *Br J Sports Med.* 2018;52:439-455.
17. Behrens M, Mau-Moeller A, Heise S, Skripitz R, Bader R, Bruhn S. Alteration in neuromuscular function of the plantar flexors following caffeine ingestion. *Scand J Med Sci Sports*. 2015;25:e50-58.
18. Tallis J, Bradford C, Duncan MJ, Leddington-Wright S, Higgins MF, Hill M. The effect of acute caffeine ingestion on cognitive dual task performance during assessment of static and dynamic balance in older adults. *Nutrients*. 2020;12:3653.
19. Trevino MA, Coburn JW, Brown LE, Judelson DA, Malek MH. Acute effects of caffeine on strength and muscle activation of the elbow flexors. *J Strength Cond Res.* 2015;29:513-520.
20. Higgins JPT, Li T, Sterne J, et al. Revised Cochrane risk of bias tool for randomized trials (RoB 2). Additional considerations for crossover trials. *Cochrane*. 2020;1-16.
21. Guyatt G, Oxman AD, Akl EA, et al. GRADE guidelines: 1. Introduction-GRADE evidence profiles and summary of findings tables. *J Clin Epidemiol.* 2011;64:383-394
22. Guest NS, VanDusseldorp TA, Nelson MT, et al. International society of sports nutrition position stand: caffeine and exercise performance. *J Int Soc Sports Nutr.* 2021;18:1.

23. Sterne JA, Sutton AJ, Ioannidis JP, et al. Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*. 2011;343:d4002.
24. Alkatan MF, Dowling EA, Branch DJ, Grieco C, Kollock RO, Williams MH. Effect of caffeine on maximum strength and rate of force development in male weight lifters. *Med Sci Sports Exerc.* 2011;43:639.
25. Bloms LP, Fitzgerald JS, Short MW, Whitehead JR. The effects of caffeine on vertical jump height and execution in collegiate athletes. *J Strength Cond Res.* 2016;30:1855-1861.
26. Burke BI, Travis SK, Gentles JA, Sato K, Lang HM, Bazyler CD. The effects of caffeine on jumping performance and maximal strength in female collegiate athletes. *Nutrients*. 2021;13:2496.
27. Merino Fernández M, Ruiz-Moreno C, Giráldez-Costas V, et al. Caffeine doses of 3 mg/kg increase unilateral and bilateral vertical jump outcomes in elite traditional Jiu-Jitsu athletes. *Nutrients*. 2021;13:1705.
28. Zbinden-Foncea H, Rada I, Gomez J, et al. Effects of caffeine on countermovement-jump performance variables in elite male volleyball players. *Int J Sports Physiol Perform.* 2018;13:145-150.
29. Grgic J. Caffeine ingestion enhances Wingate performance: a meta-analysis. *Eur J Sport Sci.* 2018;18:219-225.
30. Salinero JJ, Lara B, Del Coso J. Effects of acute ingestion of caffeine on team sports performance: a systematic review and meta-analysis. *Res Sports Med.* 2019;27(2):238-256.
31. Hori N, Newton RU, Kawamori N, McGuigan MR, Kraemer WJ, Nosaka K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res.* 2009;23:874-882.
32. Souza AA, Bottaro M, Rocha VA, Lage V, Tufano JJ, Vieira A. Reliability and test-retest agreement of mechanical variables obtained during countermovement jump. *Int J Exerc Sci.* 2020;13:6-17.
33. Currell K, Jeukendrup AE. Validity, reliability and sensitivity of measures of sporting performance. *Sports Med*. 2008;38:297-316.

34. Pallarés JG, Fernández-Elías VE, Ortega JF, Muñoz G, Muñoz-Guerra J, Mora-Rodríguez R. Neuromuscular responses to incremental caffeine doses: performance and side effects. *Med Sci Sports Exerc.* 2013;45:2184-2192.
35. Del Vecchio A, Negro F, Holobar A, et al. You are as fast as your motor neurons: speed of recruitment and maximal discharge of motor neurons determine the maximal rate of force development in humans. *J Physiol.* 2019;597:2445-2456.
36. Black CD, Waddell DE, Gonglach AR. Caffeine's ergogenic effects on cycling: neuromuscular and perceptual factors. *Med Sci Sports Exerc.* 2015;47(6):1145-1158.
37. Fitts RH. The cross-bridge cycle and skeletal muscle fatigue. *J Appl Physiol.* 2008;104:551-558.
38. Metzger JM, Moss RL. Calcium-sensitive cross-bridge transitions in mammalian fast and slow skeletal muscle fibers. *Science.* 1990;247:1088-1090.
39. Tallis J, Duncan MJ, James RS. What can isolated skeletal muscle experiments tell us about the effects of caffeine on exercise performance? *Br J Pharmacol.* 2015;172:3703-3713.
40. Allen DG, Westerblad H. The effects of caffeine on intracellular calcium, force and the rate of relaxation of mouse skeletal muscle. *J Physiol.* 1995;487:331-342.
41. James RS, Wilson RS, Askew GN. Effects of caffeine on mouse skeletal muscle power output during recovery from fatigue. *J Appl Physiol.* 2004;96:545-552.
42. Tillin NA, Pain MT, Folland JP. Short-term unilateral resistance training affects the agonist-antagonist but not the force-agonist activation relationship. *Muscle Nerve.* 2011;43:375-384.
43. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res Synth Methods.* 2010;1:97-111.
44. Sabol F, Grgic J, Mikulic P. The effects of 3 different doses of caffeine on jumping and throwing performance: a randomized, double-blind, crossover study. *Int J Sports Physiol Perform.* 2019:14:1170-1177.
45. Blazevich AJ, Wilson CJ, Alcaraz PE, Rubio-Arias JA. Effects of resistance training movement pattern and velocity on isometric muscular rate of force development: a systematic review with meta-analysis and meta-regression. *Sports Med.* 2020;50:943-963.