European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: http://www.tandfonline.com/loi/tejs20

Caffeine ingestion acutely enhances muscular strength and power but not muscular endurance in resistance-trained men

Jozo Grgic & Pavle Mikulic

To cite this article: Jozo Grgic & Pavle Mikulic (2017): Caffeine ingestion acutely enhances muscular strength and power but not muscular endurance in resistance-trained men, European Journal of Sport Science

To link to this article: http://dx.doi.org/10.1080/17461391.2017.1330362

Published online: 24 May 2017.

European Journal of Sport Science, 2017
https://doi.org/10.1080/17461391.2017.1330362

Routledge
Taylor & Francis Group

Caffeine ingestion acutely enhances muscular strength and power but not muscular endurance in resistance-trained men

JOZO GRGIC[1] & PAVLE MIKULIC[2]

[1]*Institute of Sport, Exercise and Active Living (ISEAL), Victoria University, Melbourne, Australia &* [2]*Faculty of Kinesiology, University of Zagreb, Zagreb, Croatia*

Abstract
The goal of this randomized, double-blind, cross-over study was to assess the acute effects of caffeine ingestion on muscular strength and power, muscular endurance, rate of perceived exertion (RPE), and pain perception (PP) in resistance-trained men. Seventeen volunteers (mean ± SD: age = 26 ± 6 years, stature = 182 ± 9 cm, body mass = 84 ± 9 kg, resistance training experience = 7 ± 3 years) consumed placebo or 6 mg kg^{-1} of anhydrous caffeine 1 h before testing. Muscular power was assessed with seated medicine ball throw and vertical jump exercises, muscular strength with one-repetition maximum (1RM) barbell back squat and bench press exercises, and muscular endurance with repetitions of back squat and bench press exercises (load corresponding to 60% of 1RM) to momentary muscular failure. RPE and PP were assessed immediately after the completion of the back squat and bench press exercises. Compared to placebo, caffeine intake enhanced 1RM back squat performance (+2.8%; effect size [ES] = 0.19; $p = .016$), which was accompanied by a reduced RPE (+7%; ES = 0.53; $p = .037$), and seated medicine ball throw performance (+4.3%, ES = 0.32; $p = .009$). Improvements in 1RM bench press were not noted although there were significant ($p = .029$) decreases in PP related to this exercise when participants ingested caffeine. The results point to an acute benefit of caffeine intake in enhancing lower-body strength, likely due to a decrease in RPE; upper-, but not lower-body power; and no effects on muscular endurance, in resistance-trained men. Individuals competing in events in which strength and power are important performance-related factors may consider taking 6 mg kg^{-1} of caffeine pre-training/competition for performance enhancement.

Keywords: Fatigue, metabolism, nutrition, performance

Highlights

- Caffeine ingestion one hour before exercise may enhance lower-body strength while reducing the rate of perceived exertion.
- Due to inter-individual variability in responses to caffeine consumption, it must be used in an individualized manner.

Introduction

It is assumed that coffee is mainly consumed for the caffeine benefits, as these include increased wakefulness, focus, and alertness (Glade, 2010). Caffeine has received attention from researchers for its benefits related to the enhancement of athletic performance. The research examining the effects of caffeine on athletic performance initially mainly focused on endurance-type sports (i.e. cycling, rowing, distance running, and cross-country skiing; Berglund & Hemmingsson, 1982; Bruce et al., 2000; Pasman, van Baak, Jeukendrup, & de Haan, 1995; Wiles, Bird, Hopkins, & Riley, 1992). In recent years, however, the general focus has shifted towards investigating the effects of caffeine intake on performance in resistance-exercise protocols.

Caffeine is often consumed before resistance training sessions, most commonly in form of a pre-workout supplement. Athletes report that the primary motives for the consumption of pre-workout drinks are to "increase athletic endurance" and "increase strength/power" (Sassone, 2016). However, discrepant evidence has been presented in the literature regarding the effects of caffeine on resistance-exercise performance or, more precisely, on muscular strength and power, and muscular endurance. For example, while some studies

Correspondence: Jozo Grgic, Institute of Sport, Exercise and Active Living (ISEAL), Victoria University, Melbourne, Australia. E-mail: jozo990@hotmail.com

suggest that caffeine intake may acutely enhance muscular strength (Beck et al., 2006; Goldstein, Jacobs, Whitehurst, Penhollow, & Antonio, 2010), other studies indicate no improvement in strength-exercise performance (Astorino, Rohmann, & Firth, 2008; Beck, Housh, Malek, Mielke, & Hendrix, 2008). A recent meta-analysis conducted by Warren, Park, Maresca, McKibans, and Millard-Stafford (2010) suggested that caffeine intake may improve maximal voluntary contraction in the knee extensors by approximately 7%. However, isometric exercise has low utility value to the everyday resistance training practice as most exercises intended to enhance muscular strength include traditional dynamic exercises involving coupled concentric and eccentric muscle actions.

A common caveat in studies investigating the effects of caffeine on resistance-exercise performance is that "further research is needed to draw stronger conclusions". We feel that, in particular, studies involving resistance-trained participants are lacking, as findings of studies involving untrained or recreationally trained individuals restrict the generalizability of conclusions to more advanced individuals and, as such, reduce the practical usability of recommendations for many trained individuals and athletes. Studies examining the effects of caffeine intake on muscular strength, power, and muscular endurance are of significant value to various competitive athletes since, as of 2004, caffeine is no longer listed on the World Anti-Doping Agency's List of Prohibited Substances and Methods. With that in mind, the primary aim of the present study is to examine the effects of anhydrous caffeine ingestion ($6\ \text{mg kg}^{-1}$) on muscular strength and power, muscular endurance, rating of perceived exertion (RPE), and pain perception (PP) in resistance-trained men.

We aimed to assess the impact of caffeine on strength using the barbell back squat exercise performance as a measure of lower-body strength. We selected the back squat exercise as it represents an integral part of most resistance training programmes of athletes and trained individuals. Despite this and perhaps surprisingly enough, free weight back squat has not been previously used in empirical studies aiming to assess the effects of caffeine on lower-body maximal strength performance.

We hypothesized that caffeine intake would enhance muscular strength and power as well as muscular endurance, and reduce RPE and PP. The findings of our study may benefit coaches and athletes regarding the optimization of pre-training and pre-competition protocols aimed at athletic performance improvement.

Methods

Participants

Following the approval by the Committee for Scientific Research and Ethics of the Faculty of Kinesiology at the University of Zagreb, the research commenced. Twenty resistance-trained men satisfied the inclusion criteria and volunteered to participate in the study. The inclusion criteria were as follows: (a) free from neuromuscular and musculoskeletal disorders, aged 18–45 years; (b) the participants were able to perform successful back squat and bench press exercises with load corresponding to 125% and 100% of their current body mass, respectively; and (c) the participants had a minimum of 12 months of experience in resistance training and were actively involved in resistance training at least 3 times per week over the last 6 months. The experimental procedures, including possible risks and discomforts, were verbally explained to the participants after which they signed informed consent. Of the 20 participants that started the study, 3 failed to complete all study protocols. Two participants reported discomforts during the testing protocol (elbow and shoulder issues during the bench press exercise) and one participant dropped out due to private reasons, so the final number of participants included in the analysis was 17 (mean ± SD: age = 26 ± 6 years, stature = 182 ± 9 cm, body mass = 84 ± 9 kg, resistance training experience = 7 ± 3 years). The participants also filled out the Physical Activity Readiness Questionnaire (PAR-Q) in order to confirm that there were no contraindicated health conditions. All participants answered "No" to all the questions on the PAR-Q.

Experimental protocol

This study used a randomized, double-blind, cross-over design. A total of three sessions were completed. The first session was a familiarization session during which the participants' performance of the back squat and the bench press exercises was checked by a certified personal trainer. To estimate their one-repetition maximum (1RM) for the back squat and bench press exercises during this first session, the participants performed a set of repetitions of both exercises to momentary muscular failure with a load at which they could perform a maximum of 12 successful repetitions. The estimation of 1RM was then calculated using the equation proposed by Brzycki (1993), where W stands for weight and R for repetitions:

$$1\text{RM} = W \times (36/(37 - R)).$$

The equation has been found to have a high correlation coefficient ($r > 0.95$) between the predicted and achieved 1RM both for the squat and the bench press exercises (LeSuer, McCormick, Mayhew, Wasserstein, & Arnold, 1997).

During the first session, the participants were also introduced to the Borg scale (Borg, 1970) for estimation of the RPE, and to the PP scale (described in Cook, O'Connor, Oliver, & Lee, 1998) which ranged from 0 to 10, with 0 marking "no pain at all" and 10 marking "extremely intense pain". They were also re-introduced to the scales before both subsequent assessment sessions. Before the second and the third sessions that contained identical assessment protocols, spaced 7 days apart, the participants ingested either caffeine or placebo in a randomized order.

The participants were instructed to follow their general nutrition and exercise practices. They were instructed to keep track of their calorie and caffeine intake using the "Myfitness pal" software (http://www.myfitnesspal.com). Calorie intake was tracked and replicated before the third session. In addition, the participants had to refrain from caffeine intake after 6 pm the day prior to testing, as done in previous research (Duncan, Stanley, Parkhouse, Cook, & Smith, 2013), to reduce withdrawal symptoms in caffeine users such as headaches and lethargy. In the 24 h preceding the testing, as well as on the testing days, the participants refrained from vigorous exercise. Adherence to these regulations was checked with a brief questionnaire. Caffeine intake from 24-h diet recall was calculated using a SELF Nutrition Data software (http://nutritiondata.self.com). Caffeine intake was equal to 58 ± 92 (range 0–320) mg day^{-1}.

Supplementation protocol

The amount of 6 mg kg^{-1} of caffeine was chosen because it has been shown to maximize plasma levels of caffeine (Graham & Spriet, 1995). The prescribed amount of anhydrous caffeine (Proteka, Split, Croatia) was diluted in 250 ml of water and 20 g of granulated orange-tasting beverage (Cedevita, Zagreb, Croatia) containing 65 calories (0 g of protein, 16 g of carbohydrates, and 0 g of fat). Placebo was administrated in the same fashion without the anhydrous caffeine. The beverage was served in opaque shaker bottles. The assignment to either condition was blinded both to the participants and the investigators.

Testing procedures

All assessments were performed at the same time of the day for each participant to avoid circadian variation. Sixty minutes after the consumption, when plasma concentration of caffeine is considered to be at its highest (Graham, 2001), the testing procedure began. First, the participants warmed up for 5 min by cycling on a stationary bicycle. Then, they performed several repetitions of push-ups or "walk-outs" to additionally activate the upper-body musculature. The sequence of measures is explained in the following sections. A 5-min rest interval was employed between performance tests.

Muscle power was assessed first. For the assessment of lower-body power, the vertical jump test was used (for a detailed description of testing procedure, see Martinez, Campbell, Franek, Buchanan, & Colquhoun, 2016). The assessment of upper-body power was conducted using the seated medicine ball throw test, as described by Clemons, Campbell, and Jeansonne (2010).

The barbell back squat was used for the assessment of lower-body strength. During the first visit, one-repetition maximum was estimated as described above. During the subsequent two visits, 50% of the estimated 1RM was used for the first set, during which a participant performed 12–15 repetitions. For the second set, 60% of the estimated 1RM was used for 5 repetitions, 75% of the estimated 1RM was used for the third set (3 repetitions), and 90% of the estimated 1RM for the fourth set (1 repetition). In the fifth set, a participant tried to perform a successful attempt with a load corresponding to the estimated 1RM. If unsuccessful, the load was decreased by 2.5 kg for further attempts until a successful attempt was recorded. If successful, the load was increased by 2.5 kg until the participant was no longer able to record a successful attempt. The participants rested for 3 min between sets. After the final 1RM attempt, the participants rested for 5 min, and then completed the repetitions to a momentary muscular failure of the back squat exercise with a load corresponding to 60% of 1RM. This exercise was used to assess lower-body muscular endurance. The barbell bench press was used for the assessment of the upper-body muscular strength and muscular endurance. The same procedures, as described for the barbell back squat exercise, were also used for the barbell bench press exercise. Within 5 s of the successful 1RM attempts for all back squat and bench press exercises, the participants were asked to indicate their levels of perceived exertion and pain on the relevant scales.

Statistical analyses

We tested the normality of data for all variables both numerically using a Shapiro–Wilk test of normality, and graphically by visually inspecting the normal *Q–Q* plots. A series of one-way repeated measures analysis of variance (ANOVA), provided in a computer software SPSS version 20 (Chicago, IL, USA), was used to compare the differences between conditions (caffeine, placebo) for all measures. Statistical significance was set at $p < .05$. Ninety-five per cent confidence intervals (95% CIs) were calculated using Microsoft Excel software (Microsoft Corporation, WA, USA). An effect size (ES; Cohen (1988)) was calculated for all differences. All results are presented as mean ± SD.

The following scale, proposed by Hopkins (2002), was observed to determine the magnitude of an effect: 0–0.2 was considered as trivial, 0.2–0.6 was considered as small, 0.6–1.2 was considered as moderate, 1.2–2.0 was considered as large, and >2.0 was considered as very large magnitude of an effect. Relative differences (i.e. in percentages) between conditions were also calculated.

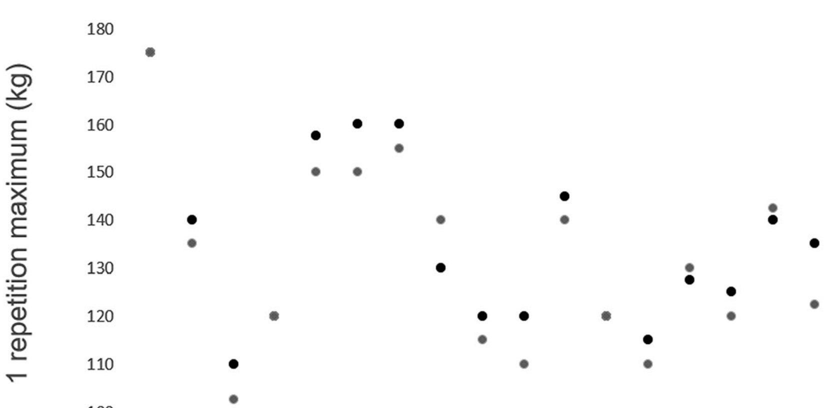
Results

One-way ANOVA revealed a significant within-participants effect for the back squat exercise ($p = .016$; ES = 0.19), RPE for the back squat exercise ($p = .037$; ES = 0.53), the seated medicine ball throw ($p = .009$; ES = 0.32), and pain perception for the 1RM bench press exercise ($p = .029$; ES = 0.49). Individual responses for the 1RM back squat and the seated medicine ball throw test are presented in Figure 1 and Figure 2, respectively. None of the other differences between conditions reached significance. The results for both the placebo and caffeine conditions for measures of performance responses and measures of subjective responses are presented in Table I and Table II, respectively, along with the 95% CI. A total of nine ES were small, four ES were trivial, and one ES was negative (i.e. an increase in pain perception in 1RM back squat exercise in caffeine condition). All participants tolerated caffeine well, with two participants reporting a feeling of slight nausea after ingestion.

Discussion

The current study evaluated the acute effects of caffeine ingestion on physical performance requiring muscular strength and power, and muscular endurance, in resistance-trained individuals. In addition, the effects on perception of pain and perceived exertion were also evaluated. The major finding of this study is that caffeine ingestion acutely enhances lower-body strength performance, and this enhancement in performance is accompanied by a reduced perception of exertion. Positive effects of caffeine ingestion were also observed for the upper- but not for the lower-body power. No effects were observed for the upper-body strength nor for the muscular endurance and corresponding RPE and pain perception values. Taken together, these results only partially confirm our initial hypothesis.

Our findings indicate that 6 mg kg^{-1} of caffeine acutely enhances lower- but not upper-body strength in resistance-trained men. Although only a trivial effect size and a small per cent increase were observed (0.19 and 2.8%, respectively), improvements in performance by as little as 3% in some events may mean the difference between winning and not even being at the podium (Le Meur, Hausswirth, & Mujika, 2012; Pyne, Mujika, & Reilly, 2009).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
● Caffeine condition	175	140	110	120	158	160	160	130	120	120	145	120	115	128	125	140	135
● Placebo condition	175	135	103	120	150	150	155	140	115	110	140	120	110	130	120	143	123

Figure 1. Individual responses of the resistance-trained participants ($n = 17$) to the 1RM back squat test.

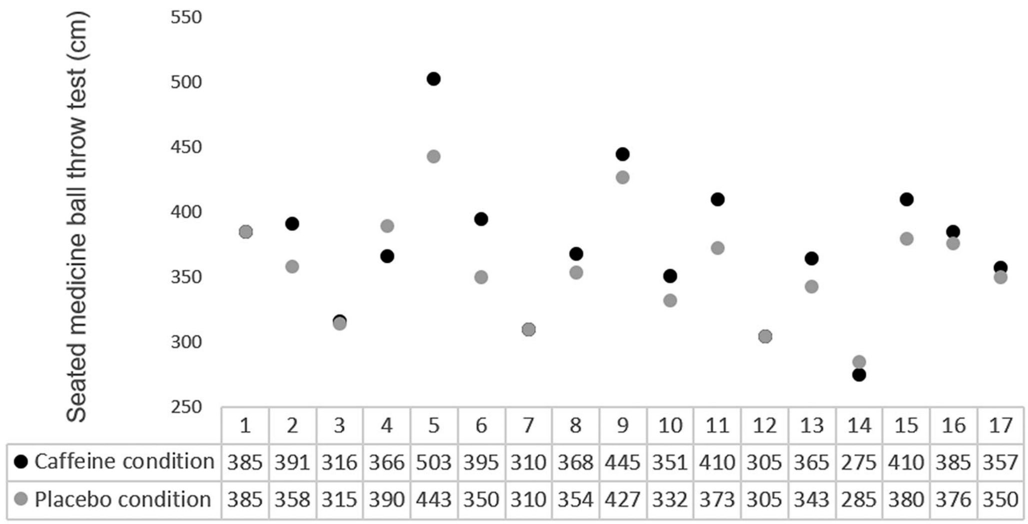


Figure 2. Individual responses of the resistance-trained participants ($n = 17$) to the seated medicine ball throw test.

Our findings indicating enhanced strength performance following caffeine ingestion are in contrast with the current data. Brooks, Wyld, and Chrismas (2015) found no increase in 1RM machine-based back squat exercise in a group of seven trained males. Likewise, Trexler, Smith-Ryan, Roelofs, Hirsch, and Mock (2016) and Astorino et al. (2008) found no improvements in lower-body strength using leg press exercise as an assessment tool. The discrepancies between the studies may be due to the following: Brooks et al. (2015) used back squat exercise performed on the Smith machine, a lower dose (5 mg kg^{-1}) and a different form (capsule) of caffeine. Trexler et al. (2016) used a fixed dose of anhydrous caffeine (i.e. 300 mg) which yielded a smaller mean amount (3.9 mg kg^{-1}; range 3–5 mg kg^{-1}) of caffeine per participant. Furthermore, Trexler et al. (2016) performed the testing sessions 30 min after caffeine ingestion, while in the present study the testing sessions were performed 60 min after caffeine ingestion. Ingestion of caffeine 60 min before exercise may be optimal as plasma concentrations approximate a maximum level in 1 h (Graham, 2001). However, it seems that peak saliva levels vary depending on the source of caffeine. As shown by Liguori, Hughes, and Grass (1997), saliva caffeine levels may peak sooner when caffeine is ingested via coffee (42 ± 5 min) and cola (39 ± 5 min) but later if ingested via the capsule (67 ± 7 min). Astorino et al. (2008) reported a habitual intake of 110 ± 152 mg of caffeine per day, while our participants reported a smaller caffeine intake of 58 ± 92 mg per day, with 10 participants reporting no regular caffeine intake. While it may be hypothesized that a reduction in effects is caused by caffeine habits, the differences caused by caffeine habits do not appear to be major (Graham, 2001). However, it is important to emphasize that individual factors determine responsiveness, as there probably are "responders" and "non-responders" (Butler, Iwasaki, Guengerich, & Kadlubar, 1989). These variations in a response to caffeine intake have been

Table I. Differences in placebo vs. caffeine conditions in measures of performance responses.

Measure	Placebo condition (mean ± SD)	Caffeine condition (mean ± SD)	95% CI for the caffeine condition	Relative effects (%)	Effect size – magnitude	*p*-Value
Vertical jump (cm)	66.1 ± 7.7	68.0 ± 7.1	64.6–71.4	2.8	0.25 – small	0.067
Seated medicine ball throw (cm)	357.4 ± 41.9	372.8 ± 54.9	346.7–398.9	4.3	0.32 – small	0.009*
1RM back squat (kg)	131.6 ± 19.2	135.3 ± 18.7	126.4–144.2	2.8	0.19 – trivial	0.016*
Back squat – repetitions to failure with 60% of 1RM	22.5 ± 8.4	23.4 ± 8.1	19.5–27.2	3.9	0.11 – trivial	0.484
1RM bench press (kg)	106.9 ± 11.9	107.9 ± 11.9	102.3–113.6	1.0	0.09 – trivial	0.275
Bench press – repetitions to failure with 60% of 1RM	20.8 ± 3.0	21.5 ± 3.0	20.0–22.9	3.1	0.21 – small	0.315

Note: CI: confidence interval; 1RM: one-repetition maximum.
*Statistically significant difference between conditions.

Table II. Differences in placebo vs. caffeine conditions in measures of subjective responses.

Measure	Placebo condition (mean ± SD)	Caffeine condition (mean ± SD)	95% CI for the caffeine condition	Relative effects (%)	Effect size – magnitude	*p*-Value
RPE for 1RM back squat	16.7 ± 1.9	15.5 ± 2.5	14.4–16.7	7.0	0.53 – small	0.037*
PP for 1RM back squat	2.7 ± 1.4	2.8 ± 1.5	2.1–3.5	−4.3	−0.08 – negative effect	0.778
RPE for back squat repetitions to failure	16.8 ± 2.6	16.0 ± 2.4	14.4–17.1	4.9	0.33 – small	0.115
PP for back squat repetitions to failure	5.4 ± 2.1	4.9 ± 2.4	3.8–6.1	9.2	0.22 – small	0.408
RPE for 1RM bench press	16.4 ± 2.4	15.5 ± 2.7	14.2–16.8	5.4	0.35 – small	0.140
PP for 1RM bench press	2.6 ± 1.4	2.0 ± 1.3	1.4–2.6	24.7	0.49 – small	0.029*
RPE for bench press repetitions to failure	15.6 ± 2.3	15.5 ± 2.2	14.5–16.6	0.4	0.03 – trivial	0.921
PP for bench press repetitions to failure	3.8 ± 1.2	3.2 ± 1.5	2.5–3.9	14.8	0.41 – small	0.106

Note: CI: confidence interval; 1RM: one-repetition maximum; RPE: rating of perceived exertion (expressed on a 6–20 scale); PP: pain perception (expressed on a 0–10 scale).
*Statistically significant difference between conditions.

observed in the present study as well, as in some participants the back squat performance decreased with caffeine intake by 7%, while in one participant it increased by as much as 10%. These acute increases in strength performance may probably be attributed to better motor unit recruitment; however, discussing the physiological effects of caffeine is beyond the scope of this article (for a review, see Graham, 2001; Tarnopolsky, 2008).

Improvements in lower-body strength performance were accompanied by a reduction in RPE. By contrast, the perception of pain did not change significantly among conditions in the 1RM back squat exercise, while it was significantly lower for the caffeine condition in the 1RM bench press exercise. No differences in RPE were noted for the bench press exercise, possibly because the bench press exercise is a less complex and less demanding exercise than the squat; however, this remains unclear. It has been suggested by Warren et al. (2010) that smaller muscles, such as muscles of the upper arm, have a limited ability for increased motor unit recruitment with caffeine ingestion. Differences in the effects of caffeine on upper and lower body were also noted in a recent study by Black, Waddell, and Gonglach (2015). These authors (Black et al., 2015) reported increases (+6.3%) in maximal voluntary strength in the lower (i.e. knee extensors), but not the upper body (i.e. elbow flexors) when assessed 60 min following the ingestion of a 5-mg kg^{-1}; dose of caffeine. Further studies are warranted to assess for possible differences in upper- vs. lower-body strength after caffeine ingestion. Based on these findings, we may surmise that acute increases in strength may mainly be attributed to a reduction in perceived exertion that allows an individual to perform more work (Tarnopolsky, 2008). We would like to stress that the bench press exercise was the very last test performed in the assessment procedure, and the performance of the participants, therefore, may have been affected by the accumulated fatigue.

A novel finding of this study is that caffeine ingestion may enhance performance in exercises that require upper-body power. This is in contrast to the findings of Martinez et al. (2016) who showed that consuming a pre-workout supplement containing caffeine does not enhance upper-body power performance; however, the participants in that study refrained from caffeine ingestion only 3 h prior to testing, while our participants ceased consumption the day prior to testing. The comparison of conditions for the lower-body power, as assessed using the vertical jump test, indicated no significant differences ($p = .067$), although an ES of 0.25 was observed. The prevailing body of literature indicates acute improvements in lower-body power (Bloms, Fitzgerald, Short, & Whitehead, 2016; Del Coso et al., 2012), with a dose of caffeine in the range of 3–6 mg kg^{-1} being the most desirable to reduce the possible side-effects such as jitters, increased heart rate, and performance impairment (Graham & Spriet, 1995).

The effects of caffeine intake on muscular endurance in resistance-trained population were previously assessed in few studies (Astorino et al., 2008; Beck et al., 2006; Hudson, Green, Bishop, & Richardson, 2008) with equivocal results. Tarnopolsky (2008) suggested that caffeine intake should have a considerable positive effect on muscular endurance; however, our results do not support this suggestion. We did not observe improvements in our participants' upper- nor lower-body muscular endurance with caffeine ingestion. Also, we did not observe a difference in RPE nor PP among conditions. Similar results were obtained by Richardson and Clarke (2016), who reported no improvement in muscular endurance performance assessed 60 min after ingestion of 5 mg kg^{-1} of anhydrous caffeine in a cohort of resistance-trained men. However, our findings are in contrast with the recent meta-analysis performed by Polito, Souza, Casonatto, and Farinatti (2016) who concluded that caffeine intake can have a significant performance improvement effect on muscular endurance when consumed 60 min before testing. We emphasize that, in our study, muscular endurance was assessed in the latter part of the testing sequence, so the accumulated fatigue may have played a role, and different outcomes might have been observed if muscular endurance had been assessed at the beginning of the testing session.

A limitation of the present study pertains to the fact that assessment procedures consisted of six exercise tests performed in succession. In a typical session lasting 70–90 min, this may have dampened performance in tests positioned later in the sequence. Also, only two testing sessions (placebo condition + caffeine condition) were employed. Future studies striving to examine the acute effects of caffeine on a range of physical abilities may benefit from splitting the assessment procedures into multiple sessions, thus minimizing the effects of accumulated fatigue and enabling the participants to give their maximal effort in each assessment procedure. On a final note, a limitation of the study also pertains to the lack of assessment of the effectiveness of blinding on the participants. Consequently, is not entirely clear if the results could be ascribed to the effects of caffeine consumption, or if they are merely placebo-induced. From previous work on the topic (Astorino et al., 2008; Astorino, Martin, Schachtsiek, Wong, & Ng, 2010; Duncan et al., 2013), we may only assume that the correct differentiation between the caffeine and placebo trials would have been in the 29–60% range. Researchers examining this issue in the future should circumvent these issues by asking the participants to indicate which trial they perceive to be the caffeine trial, and which trial they perceive to be the placebo trial.

Conclusion

Based on our findings, it may be suggested that trained individuals competing in events in which maximal strength and power are important performance-related factors (e.g. powerlifting, strongman, weightlifting, etc.) might consider taking 6 mg kg^{-1} of caffeine pre-training/competition for performance enhancement. The mentioned dose may be consumed with minimal health risks; however, due to individual responsiveness, this should be tested for each athlete individually before important competitions.

Acknowledgements

The authors would like to thank the participants for volunteering their time.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Astorino, T. A., Martin, B. J., Schachtsiek, L., Wong, K., & Ng, K. (2010). Minimal effect of acute caffeine ingestion on intense resistance training performance. *Journal of Strength and Conditioning Research*, *25*, 1752–1758.

Astorino, T. A., Rohmann, R. L., & Firth, K. (2008). Effect of caffeine ingestion one one-repetition maximum muscular strength. *European Journal of Applied Physiology*, *102*, 127–132.

Beck, T. W., Housh, T. J., Malek, M. H., Mielke, M., & Hendrix, R. (2008). The acute effects of a caffeine-containing supplement on bench press strength and time to running exhaustion. *Journal of Strength and Conditioning Research*, *22*, 1654–1658.

Beck, T. W., Housh, T. J., Schmidt, R. J., Johnson, G. O., Housh, D. J., Coburn, J. W., Malek M. H. (2006). The acute effects of a caffeine-containing supplement on strength, muscular endurance, and anaerobic capabilities. *Journal of Strength and Conditioning Research*, *20*, 506–510.

Berglund, B., & Hemmingsson, P. (1982). Effects of caffeine ingestion on exercise performance at low and high altitudes in cross-country skiers. *International Journal of Sports Medicine*, *3*, 234–236.

Black, C. D., Waddell, D. E., & Gonglach, A. R. (2015). Caffeine's ergogenic effects on cycling: Neuromuscular and perceptual factors. *Medicine and Science in Sport and Exercise*, *47*, 1145–1158.

Bloms, L. P., Fitzgerald, J. S., Short, M. W., & Whitehead, J. R. (2016). The effects of caffeine on vertical jump height and execution in collegiate athletes. *Journal of Strength and Conditioning Research*, *30*, 1855–1861.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine*, *2*, 92–98.

Brooks, J. H., Wyld, K., & Chrismas, B. C. R. (2015). Acute effects of caffeine on strength performance in trained and untrained individuals. *Journal of Athletic Enhancement*. doi:10.4172/2324-9080.1000217

Bruce, C. R., Anderson, M. E., Fraser, S. F., Stepto, N. K., Klein, R., Hopkins, W. G., Hawley, J. A., (2000). Enhancement of 2000-m rowing performance after caffeine ingestion. *Medicine and Science in Sport and Exercise*, *32*, 1958–1963.

Brzycki, M. (1993). Strength testing-predicting a one-rep max from reps-to-fatigue. *Journal of Physical Education, Recreation and Dance*, *64*, 88–90.

Butler, M. A., Iwasaki, M., Guengerich, F. P., & Kadlubar, F. F. (1989). Human cytochrome P-450PA (P-450IA2), the phenacetin O-deethylase, is primarily responsible for the hepatic 3-demethylation of caffeine and N-oxidation of carcinogenic arylamines. *Proceedings of the National Academy of Sciences of the United States of America*, *86*, 7696–7700.

Clemons, J. M., Campbell, B., & Jeansonne, C. (2010). Validity and reliability of a new test of upper body power. *Journal of Strength and Conditioning Research*, *24*, 1559–1565.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Earlbaum Associates.

Cook, D. B., O'Connor, P. J., Oliver, S. E., & Lee, Y. (1998). Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. *International Journal of Neuroscience*, *95*, 183–202.

Del Coso, J., Muñoz-Fernández, V. E., Muñoz, G., Fernández-Elías, V. E., Ortega, J. F., Hamouti, N. … Muñoz-Guerra, J. (2012). Effects of a caffeine-containing energy drink on simulated soccer performance. *PLoS One*, *7*, e31380.

Duncan, M. J., Stanley, M., Parkhouse, N., Cook, K., & Smith, M. (2013). Acute caffeine ingestion enhances strength performance and reduces perceived exertion and muscle pain perception during resistance exercise. *European Journal of Sports Science*, *13*, 392–399.

Glade, M. J. (2010). Caffeine-not just a stimulant. *Nutrition*, *26*, 932–938.

Goldstein, E., Jacobs, P. L., Whitehurst, M., Penhollow, T., & Antonio, J. (2010). Caffeine enhances upper body strength in resistance-trained women. *Journal of the International Society of Sports Nutrition*, *7*, 18.

Graham, T. E. (2001). Caffeine and exercise: Metabolism, endurance and performance. *Sports Medicine*, *31*, 785–807.

Graham, T. E., & Spriet, L. L. (1995). Metabolic, catecholamine, and exercise performance responses to various doses of caffeine. *Journal of Applied Physiology*, *78*, 867–874.

Hopkins, W. G. (2002). A scale of magnitudes for effect statistics. *Sportscience*, *5*, 1–7.

Hudson, G. M., Green, J. M., Bishop, P. A., & Richardson, M. T. (2008). Effects of caffeine and aspirin on light resistance training performance, perceived exertion, and pain perception. *Journal of Strength and Conditioning Research*, *22*, 1950–1957.

Le Meur, Y., Hausswirth, C., & Mujika, I. (2012). Tapering for competition: A review. *Science & Sports*, *27*, 77–87.

LeSuer, D. A., McCormick, J. H., Mayhew, J. L., Wasserstein, R. L., & Arnold, M. D. (1997). The accuracy of prediction equations for estimating 1-RM performance in the bench press, squat, and deadlift. *Journal of Strength and Conditioning Research*, *11*, 211–213.

Liguori, A., Hughes, J. R., & Grass, J. A. (1997). Absorption and subjective effects of caffeine from coffee, cola and capsules. *Pharmacology Biochemistry and Behavior*, *58*, 721–726.

Martinez, N., Campbell, B., Franek, M., Buchanan, L., & Colquhoun, R. (2016). The effect of acute pre-workout supplementation on power and strength performance. *Journal of the International Society of Sports Nutrition*, *13*, 15.

Pasman, W. J., van Baak, M. A., Jeukendrup, A. E., & de Haan, A. (1995). The effect of different dosages of caffeine on endurance performance time. *International Journal of Sports Medicine*, *16*, 225–230.

Polito, M. D., Souza, D. B., Casonatto, J., & Farinatti, P. (2016). Acute effect of caffeine consumption on isotonic muscular strength and endurance: A systematic review and meta-analysis. *Science & Sports*, *31*, 119–128.

Pyne, D. B., Mujika, I., & Reilly, T. (2009). Peaking for optimal performance: Research limitations and future directions. *Journal of Sports Sciences*, *27*, 195–202.

Richardson, D. L., & Clarke, N. D. (2016). Effect of coffee and caffeine ingestion on resistance exercise performance. *Journal of Strength and Conditioning Research*, *30*, 2892–2900.

Sassone, J. (2016). *Prevalence and predictors of high-risk supplement use among collegiate athletes* (Unpublished master's thesis). California State University, Long Beach.

Tarnopolsky, M. A. (2008). Effect of caffeine on the neuromuscular system – potential as an ergogenic aid. *Applied Physiology, Nutrition, and Metabolism*, *33*, 1284–1289.

Trexler, E. T., Smith-Ryan, A. E., Roelofs, E. J., Hirsch, K. R., & Mock, M. G. (2016). Effects of coffee and caffeine anhydrous on strength and sprint performance. *European Journal of Sports Science*, *16*, 702–710.

Warren, G. L., Park, N. D., Maresca, R. D., McKibans, K. I., & Millard-Stafford, M. L. (2010). Effect of caffeine ingestion on muscular strength and endurance: A meta-analysis. *Medicine and Science in Sport and Exercise*, *42*, 1375–1387.

Wiles, J. D., Bird, S. R., Hopkins, J., & Riley, M. (1992). Effect of caffeinated coffee on running speed, respiratory factors, blood lactate and perceived exertion during 1500-m treadmill running. *British Journal of Sports Medicine*, *26*, 116–120.