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Abstract

Purpose: To explore the effects of three doses of caffeine on muscle strength and muscle endurance.

Methods: Twenty-eight resistance-trained men completed the testing sessions under five conditions: no-placebo control, placebo-control, and with caffeine doses of 2, 4, and 6 $mg \cdot kg^{-1}$. Muscle strength was assessed using the one-repetition maximum (1RM) test; muscle endurance was assessed by having the participants perform a maximal number of repetitions with 60% 1RM.

Results: In comparisons with both control conditions, only a caffeine dose of 2 $mg \cdot kg^{-1}$ enhanced lower-body strength (*d*=0.13–0.15). In comparisons with the no-placebo control condition, caffeine doses of 4 $mg \cdot kg^{-1}$ and 6 $mg \cdot kg^{-1}$ enhanced upper-body strength (*d*=0.07–0.09) with a significant linear trend for the effectiveness of different doses of caffeine (*p*=0.020). Compared to both control conditions, all three caffeine doses enhanced lower-body muscle endurance (*d*=0.46–0.68). For upper-body muscle endurance, we did not find significant effects of caffeine.

Conclusions: We found a linear trend between the dose of caffeine and its effects on upper-body strength. This study found no clear association between the dose of caffeine and the magnitude of its ergogenic effects on lower-body strength and muscle endurance. From a practical standpoint, the magnitude of caffeine's effects on strength is of questionable relevance. A low dose of caffeine (2 $mg \cdot kg^{-1}$)—for an 80kg individual, this dose of caffeine contained in one to two cups of coffee—may produce substantial improvements in lower-body muscle endurance with the magnitude of the effect being similar to that attained using higher doses of caffeine.

Introduction

The use of caffeine is highly prevalent among both the general population and athletes.[1,2] The International Olympic Committee has also identified caffeine as having strong scientific support for its ergogenic effects on exercise performance.[3] There is good evidence that caffeine ingestion can acutely enhance aerobic and muscle endurance, muscle strength, power, jumping height, and exercise speed.[4,5]

In research studies, caffeine is often administered in moderate to high doses (3 to 6 $mg\cdot kg^{-1}$), with 6 $mg\cdot kg^{-1}$ being the most common.[4] There is, however, emerging interest in exploring the effects of lower doses of caffeine (≤3 $mg\cdot kg^{-1}$) on exercise performance as such doses generally provide an ergogenic benefit with minimal side-effects.[6] While lower doses are ergogenic for exercise performance, there is a lack of studies exploring whether they provide similar performance-enhancing effects as more conventionally recommended intakes (i.e., 3 to 6 $mg\cdot kg^{-1}$). Additionally, the evidence for the ergogenic effects of low doses of caffeine is largely based on studies using tests of aerobic endurance.[6] There is a paucity of studies exploring the effects of such doses of caffeine on high-intensity, short-duration exercise performance (such as resistance exercise).[6]

Caffeine ingestion has been demonstrated to be ergogenic for muscle strength and muscle endurance.[7] One meta-analysis[8] reported a significant effect of caffeine ingestion on one-repetition maximum (1RM) strength. Of the ten studies included in that meta-analysis, nine used a single dose of caffeine (most commonly 6 $mg\cdot kg^{-1}$). One study used two different doses of caffeine (2 $mg\cdot kg^{-1}$ versus 5 $mg\cdot kg^{-1}$); however, their results were inconclusive given that neither dose was associated with increased muscle strength.[9] Another meta-analysis pooled the evidence for the effects of caffeine ingestion on muscle endurance.[10] As with strength, the authors observed an ergogenic effect of caffeine. Of the sixteen studies that met the inclusion criteria for that review, all of them used a single caffeine dose (relative doses of ≥4 mg·kg^{-1}). Therefore, minimal effective doses of caffeine for muscle strength and endurance remain unclear due to the lack of studies using multiple doses of caffeine.

To glean new insights into this topic, in the present study we aimed to explore the acute effects of three doses of caffeine (2, 4, and 6 mg·kg^{-1}) on muscle strength and muscle endurance in resistance-trained men. We hypothesized that all doses of caffeine would enhance upper- and lower-body muscle strength and muscle endurance.

Methods

Participants

To be included in the present study, participants had to satisfy the following criteria: (a) be apparently healthy men, aged between 18 and 45 years; (b) be resistance-trained, defined as having a minimum of one year of resistance training experience with a minimum weekly training frequency of two times per week (on most weeks); and (c) have the ability to perform the bench press and back squat exercises with a load corresponding to at least 100% of their body mass. Based on a power analysis using the G*Power software (Germany, Düsseldorf, version 3), with an effect size f of 0.10 for lower-body muscle endurance, alpha error of 0.05, statistical power of 80%, and r of 0.90,[11] the minimum required sample size for this study was estimated to be 26 participants. To factor in possible dropouts, we initially recruited a sample of 32 men. During the study, four participants dropped out due to personal reasons. A sample of 28 participants (mean ± standard deviation of age: 25±6 years, height: 185±6 cm, body mass: 89±11 kg), completed the trials. Habitual caffeine intake was assessed via a validated food frequency questionnaire (FFQ).[12] A qualified nutritionist estimated the daily caffeine intake based on the responses to the FFQ. The mean ± standard deviation habitual caffeine intake of the whole sample was 112±165 $mg \cdot day^{-1}$. Ethical approval was requested and granted from the Committee for Scientific Research and Ethics of the Faculty of Kinesiology at the University of Zagreb, where the study was conducted. All participants were informed about the study requirements, benefits, and risks and provided their written informed consent before the involvement in the study.

Experimental design

Following the familiarization session, the participants were randomly assigned to five experimental conditions in a counterbalanced fashion. The conditions were: no-placebo control condition, placebo-control condition, and three caffeine conditions with caffeine doses of 2, 4, and 6 $mg \cdot kg^{-1}$. The placebo and caffeine powders were weighted using a high precision electronic digital scale and were administered in capsules of identical appearance to maintain a double-blind design. The testing sessions consisted of upper- and lower-body muscle strength and muscle endurance tests (Figure 1).

To ensure that the exercise performance was not affected by circadian variation, all testing sessions were conducted at the same time of the day for each participant (23 participants were tested in the evening hours and five were tested in the morning hours). The participants came to each session after a three-hour fasting period. Testing was then carried out sixty minutes after supplement ingestion. Sessions were separated by no less than five and no more than seven days. Between the conditions, the participants were advised to maintain their usual training routines. The participants were instructed not to perform any vigorous exercise, to maintain their usual hydration, dietary habits, and sleep patterns in the 24 hours prior to each session. Also, the participants were requested to refrain from any caffeine ingestion 12 hours before the five sessions. Caffeine has a half-life of four to six hours; therefore, stopping its ingestion around 12 hours before the testing session is deemed sufficient to avoid potential confounding by prior caffeine ingestion.[1] To facilitate this process, the participants were provided with a comprehensive list of food and drink products containing caffeine that they should avoid consuming in that period.

Testing protocol

Upper-body muscle strength and muscle endurance were assessed first, using the barbell bench press exercise. After the bench press exercise, lower-body muscle strength and muscle endurance were evaluated using the barbell back squat exercise. In the eccentric phase of the squat exercise, the participants were required to squat to a depth where the hips were at the same level as the knees for the attempt to be considered valid. None of the participants used knee wraps during the tests; five participants used a weight lifting belt, but its use was standardized across all conditions. Participants initially performed a self-selected warm-up lasting 10 minutes. For the 1RM, the first warm-up set included eight to ten repetitions with 50% of the participants' estimated 1RM. The second warm-up set included three to five repetitions with ~75% of the estimated 1RM. Participants then completed one repetition with ~95% of their estimated 1RM. Based on whether the participant successfully lifted the load or not, the weight was increased or decreased on subsequent attempts. Three to five minutes were given between the 1RM attempts, and all 1RM values were obtained within five attempts. After a five-minute rest period, muscle endurance was assessed with one 'all-out' set with a load corresponding to 60% of 1RM performed to momentary concentric failure.

The test was terminated when the participants could not maintain the prescribed cadence (1-2 seconds for both concentric and eccentric muscle actions) and/or could not maintain the whole range of motion of for the exercise. Following a five minute rest, the same procedure was repeated for lower-body muscle strength and muscle endurance.

Rating of perceived exertion (RPE) and pain perception (PP)

Within five seconds of a successful 1RM attempt, as well as following the final repetition in the muscle endurance tests (after re-racking the weight), the participants indicated their perceived levels of exertion on the RPE scale.[13] Furthermore, the participants indicated their levels of PP on a previously validated scale.[14] For the RPE scale, the responses ranged from 6 to 20, while on the PP scale, the responses ranged from 0 to 10. Before the familiarization session, the participants were instructed on the proper use of the scales. Before the subsequent assessments, the participants were re-introduced with the scales.

Assessment of blinding

We tested the effectiveness of blinding by asking the participants to identify the supplement they had ingested. The question for this assessment was based on the study by Saunders et al.[15] and was phrased: “Which supplement do you think you have ingested?” Its response scale included five possible answers: (a) caffeine 2 $mg{\cdot}kg^{-1}$; (b) caffeine 4 $mg{\cdot}kg^{-1}$; (c) caffeine 6 $mg{\cdot}kg^{-1}$; (d) placebo; (e) do not know. This assessment was conducted pre- and post-exercise given that the opinion of participants might change pre- to post-exercise.[15]

Statistical analyses

A series of repeated measures analysis of variance (ANOVA) was used to analyze the differences in performance and subjective responses between the conditions. In cases of a significant main effect, post hoc comparisons were conducted using Dunnett's test so that each caffeine condition was compared to the placebo-control condition (i.e., 2 $mg·kg^{-1}$ vs. placebo-control, 4 $mg·kg^{-1}$ vs. placebo-control, and 6 $mg·kg^{-1}$ vs. placebo-control) and to the no-placebo control condition (i.e., 2 $mg·kg^{-1}$ vs. no-placebo control, 4 $mg·kg^{-1}$ vs. no-placebo control, and 6 $mg·kg^{-1}$ vs. no-placebo control). We have also calculated *p*-values for the linear and quadratic trends between the doses of caffeine. The statistical significance threshold was set at $p<0.05$. Relative effect sizes were calculated using Cohen's *d* with 95% confidence intervals (95% CI) for repeated measures. Effect sizes of <0.20, 0.20 to 0.49, 0.50 to 0.79, and ≥0.80 were considered to represent trivial, small, moderate, and large effects, respectively. In addition to relative effect sizes, we also calculated the raw mean differences between the trials and their 95% CIs. The blinding data were examined using the Bang's Blinding Index with all three possible responses for caffeine (i.e., 2, 4, and 6 $mg·kg^{-1}$) collapsed into a single caffeine response. The values in this index range from –1.0 which indicates opposite guessing to 1.0 which indicates complete unblinding; here, we reported these data as a percentage of individuals who identified the correct condition beyond chance. All analyses were performed using the STATISTICA software (version 13.0; StatSoft, Tulsa, OK, USA).

Results

Lower-body muscle strength

For 1RM strength in the back squat exercise a significant main effect of condition was observed ($p=0.008$; Table 1). In comparisons with the no-placebo control condition, post hoc test revealed that a dose of 2 $mg·kg^{-1}$ of caffeine acutely enhanced lower-body strength (*d*=0.15; +3.5 kg; *p*=0.003). In comparisons with the no-placebo control condition, no significant differences were observed for 4 mg·kg^{-1} (*d*=0.09; +2.1 kg; *p*=0.069) and 6 mg·kg^{-1} of caffeine (*d*=0.08; +2.0 kg; *p*=0.083). In comparisons with placebo-control condition, post hoc tests revealed that a dose of 2 mg·kg^{-1} of caffeine also acutely enhanced lower-body strength (*d*=0.13; +3.0 kg; *p*=0.009). In comparisons with placebo-control condition, no significant differences were observed for 4 mg·kg^{-1} (*d*=0.07; +1.6 kg; *p*=0.159) and 6 mg·kg^{-1} of caffeine (*d*=0.06; +1.5 kg; *p*=0.185). The linear trend for the effectiveness of different doses of caffeine was not significant (*p*=0.162). The quadratic trend for the effectiveness of different doses of caffeine was not significant (*p*=0.541).

Upper-body muscle strength

For 1RM strength in the bench press exercise a significant main effect of condition was observed (*p*=0.025). In comparisons with the no-placebo control condition, post hoc test revealed that doses of 4 mg·kg^{-1} (*d*=0.07; +1.6 kg; *p*=0.044) and 6 mg·kg^{-1} (*d*=0.09; +2.1 kg; *p*=0.007) of caffeine acutely enhanced upper-body strength. In comparisons with no-placebo control condition, no significant differences were observed for 2 mg·kg^{-1} (*d*=0.01; +0.2 kg; *p*=0.656). In comparisons with placebo-control condition, post hoc tests revealed no significant differences for 2 mg·kg^{-1} (*d*=–0.03; –0.5 kg; *p*=0.923), 4 mg·kg^{-1} (*d*=0.04; +0.9 kg; *p*=0.287) and for 6 mg·kg^{-1} (*d*=0.06; +1.4 kg; *p*=0.100) doses of caffeine. We found a significant linear trend for the effectiveness of different doses of caffeine (*p*=0.020). The quadratic trend for the effectiveness of different doses of caffeine was not significant (*p*=0.508).

Lower-body muscle endurance

For the number of repetitions in the back squat exercise a significant main effect of caffeine was observed (*p*=0.004). As compared to no-placebo control condition, post hoc tests revealed that doses of 2 mg·kg^{-1} (*d*=0.55; +4.2 repetitions; *p*=0.011), 4 mg·kg^{-1} (*d*=0.52; +3.3 repetitions; *p*=0.046), and 6 mg·kg^{-1} (*d*=0.46; +3.9 repetitions; *p*=0.018) acutely enhanced lower-body muscle endurance. As compared to placebo-control condition, post hoc tests revealed that 2 mg·kg^{-1} of caffeine (*d*=0.67; +4.8 repetitions; *p*=0.008), 4 mg·kg^{-1} (*d*=0.68; +3.9 repetitions; *p*=0.032) and 6 mg·kg^{-1} (*d*=0.56; +4.5 repetitions; *p*=0.014) acutely enhanced lower-body muscle endurance. The linear trend for the effectiveness of different doses of caffeine was not significant (*p*=0.802). The quadratic trend for the effectiveness of different doses of caffeine was not significant (*p*=0.633).

Upper-body muscle endurance

The repeated measures ANOVA conducted for the number of repetitions in the bench press exercise did not show a significant main effect (*p*=0.470), and therefore no post hoc analysis was performed.

RPE and PP

None of the comparisons for the RPE or the PP were significant (*p*>0.05 for all). All data are presented in Table 2.

Effectiveness of blinding

Just before exercise, in the placebo-control, and the 2, 4, and 6 mg·kg^{-1} conditions, 1%, 11%, 29%, and 21% of the participants correctly guessed the treatment identity beyond chance, respectively. After exercise, in the placebo-control, and the 2, 4, and 6 mg·kg^{-1} conditions, 14%, 32%, 29%, and 25% of the participants correctly guessed the treatment identity beyond chance, respectively.

Discussion

This study found mixed effects of different doses of caffeine on muscle strength and endurance. Except for upper-body muscle strength, no clear dose-response trends were observed. The results suggested that only 2 mg·kg^{-1} of caffeine was ergogenic for lower-body strength, as compared to both control conditions. When considering the comparison with the no-placebo control condition, caffeine doses of 4 mg·kg^{-1} and 6 mg·kg^{-1} enhanced upper-body strength. Compared to both control conditions, all three caffeine doses were effective for acute improvements in lower-body muscle endurance, whereas no significant effects were found for any of the three caffeine doses on upper-body muscle endurance.

Effects of caffeine on muscle strength

Our results indicate that a caffeine dose of 2 mg·kg^{-1} acutely enhanced lower-body muscle strength. We did not find significant ergogenic effects for higher doses, even though the effect sizes favored the caffeine conditions. For upper-body strength, only 4 mg·kg^{-1} and 6 mg·kg^{-1} doses of caffeine were ergogenic. However, it is important to consider that the results for the upper-body were statistically significant only when compared to no-placebo control, but not with the placebo-control condition.

Our results support the findings of a previous meta-analysis that caffeine ingestion may acutely enhance 1RM strength.[8] This meta-analysis found a pooled effect size of caffeine on strength of 0.20.[8] Even though caffeine was ergogenic in our study, the effect size for strength ranged from 0.07 to 0.15 which can be considered as ‘trivial’. Mean changes in weight lifted which ranged from +1.6 to +3.5 kg, can be considered relatively small from a practical perspective. Such increases in strength would likely only be worthwhile in strength-based sports such as powerlifting, in which, narrow margins determine the competition outcomes. While we did not include competitive powerlifters in the study, several of the participants did indeed exhibit very high levels of strength. One participant had a 1RM in the squat of 185 kg, and another successfully performed the 1RM in the bench press exercise with 147.5 kg. Such levels of strength are similar to those previously observed in national level powerlifters.[16] This coupled with the fact that all of the participants were resistance-trained individuals increases the generalizability of these findings to athletes competing in strength-based sports; however, future work examining these effects among athletes from strength-based sports is warranted. For upper-body strength, we observed a significant linear trend between the dose of caffeine and strength performance. Indeed, average 1RM bench press values with caffeine doses of 2, 4, and 6 $mg{\cdot}kg^{-1}$ amounted to 106.3 kg, 107.8 kg, and 108.3 kg, respectively. Again, it needs to be highlighted that these differences in weight lifted are relatively small, which may call into question the practical relevance of these findings for most individuals.

To date, only one study has explored the effects of multiple doses of caffeine on 1RM strength.[9] In that study, the researchers did not find any significant effects of 2 and 5 $mg{\cdot}kg^{-1}$ of caffeine on 1RM strength in the leg press exercise. There are several key differences in the study design between the present study and the work by Arazi et al.[9] that may explain inconsistent findings. The participants in our study were adult resistance-trained men, while the Arazi et al.[9] study was conducted in a sample of adolescent female karate athletes. This may be relevant given that the response to caffeine ingestion might not be uniform between men and women.[5] Also, there were substantial differences in the total sample size (10 vs. 28 participants), which may have affected statistical inferences. The average effect size for the effects of caffeine in the Arazi et al.[9] study was 0.35, which might suggest that the effects would be statistically significant if the study included a larger sample size.

Effects of caffeine on muscle endurance

For lower-body muscle endurance, all three doses of caffeine were found to be ergogenic, in comparison to both control conditions. The average relative effect size spanned from 0.46 to 0.67, which is considered as an indication of a 'moderate' effect. The mean differences in the number of performed repetitions in the back squat exercise ranged from 3 to 5. Such acute improvements in muscle endurance following caffeine ingestion are similar to those observed after eight weeks of regimented resistance exercise, which highlights the magnitude of these effects.[17,18] For upper-body muscle endurance, no significant differences were observed between the caffeine conditions versus the control conditions.

While caffeine is ergogenic for muscle endurance, these effects may be modulated by factors such as the size of the activated muscle.[19] Previous research has suggested that the lower- and upper-body musculature exhibit divergent responses to caffeine ingestion with the effects being more pronounced in the lower-body musculature.[20,21] In support of this idea, Warren et al.[19] reported that caffeine has a greater ergogenic effect on the knee extensor muscles as compared to the smaller muscle groups such as the elbow flexors. During maximal voluntary contractions, knee extensor activation level is generally 85% to 95%.[22] However, smaller muscle groups reach up to 99% of their maximum activation.[22,23] Given these baseline differences in muscle activation levels between muscle groups, Warren et al.[19] suggested that larger muscles, such as the knee extensors, are more responsive to the ergogenic effects of caffeine. In one study, at baseline, the percentage of motor-unit recruitment of the knee extensors and elbow flexors during maximal contractions—as assessed using the interpolated-twitch electrical stimulation—was at 83% and 97%, respectively.[20] Due to the lower muscle activation level at baseline, after the ingestion of caffeine, performance was only improved for the lower- but not the upper-body.[20] These results might explain why we did not observe significant improvements in upper-body muscle endurance. Additionally, these results might explain why we did not find significant increases in upper-body strength following caffeine ingestion when compared to the placebo-control conditions.

Thus far, only Polito and colleagues[24] conducted a study that had a similar design to ours. In this study, 14 resistance-trained men performed three upper-body resistance exercises (chest press, shoulder press, and biceps curl exercises) for three sets until exhaustion with 70% of 1RM after the ingestion of either 3 or 6 $mg{\cdot}kg^{-1}$ of caffeine. The results indicated that both doses of caffeine acutely increased the number of repetitions performed in the three upper-body exercises. The reason for the discrepancies between the studies could be related to the protocol used. In the study by Polito et al.[24] study, the participants performed a total of nine sets (three sets for each of the three exercises), whereas we used one 'all-out' set. Caffeine ingestion attenuates the fatigue-induced decline in muscle contractile properties,[25] which may explain why caffeine was effective for upper-body muscles over a multiple set protocol, as in the study by Polito and colleagues, but not when using a single set. Given the overall lack of studies on this topic, future work is warranted to provide further insights into the determinants of caffeine's effects on muscle endurance such as the exercise type (e.g. single vs. multiple sets).

RPE and PP

When analyzing the responses of the participants in the RPE and PP scales, no significant effects between the conditions were observed. These results suggest that mechanisms other than a reduction in RPE or PP are responsible for the ergogenic effects of caffeine. The ergogenic effects of caffeine in the present study might be explained by caffeine's effects on increasing muscle fiber conduction velocity and motor unit recruitment.[19,26] Nonetheless, it is also important to consider that the use of multiple tests of performance might have influenced the estimated effects of caffeine on RPE. For example, testing of strength in the bench press first in the testing session might have impacted the RPE responses in the upper-body muscle endurance test.

Limitations of the study

One of the limitations of the present study is that we did not measure blood caffeine concentrations, and therefore, the amount of caffeine absorption in the blood with different doses of caffeine remains unclear. Additionally, even though the majority of the participants were considered as 'low' habitual users (caffeine intake of <100 mg per day), several of the participants were moderate-to-high caffeine users with habitual intakes of >100 mg per day. Caffeine's ergogenic effect might be more pronounced in individuals with low habitual caffeine consumption.[27] Even though the findings from the studies on this matter are equivocal,[27-29] this still needs to be acknowledged as a potential limitation of the current study. The wide inter-individual variation in responses to caffeine has been associated with variation in the *CYP1A2* gene. The *CYP1A2* gene affects caffeine metabolism; individuals with the AA genotype seems to experience greater improvements in exercise performance than those with the AC/CC genotype.[30] In this study, we did not collect data on genotype variations which is something that future studies may consider. Finally, the blinding of the participants was generally effective, even though the percentage of those that correctly guessed the treatment identity beyond chance increased pre to post-exercise. In this context, it is possible that the pre-exercise responses are of greater importance, given that the post-exercise responses might be influenced by the improved performance (or lack thereof) during the testing session.

Practical implications

As little as 2 mg·kg^{-1} of caffeine may enhance lower-body muscle endurance. While caffeine ingestion was ergogenic for lower and upper-body strength, the magnitude of these effects can be categorized as trivial.

Conclusions

In this study, we found a linear trend between the dose of caffeine and its effects on upper-body strength. However, this study found no clear association between the dose of caffeine and the magnitude of its ergogenic effects for lower-body strength and muscle endurance. While our findings indicate that caffeine ingestion may enhance upper- and lower-body strength, from a practical standpoint, the magnitude of this effect is of questionable relevance. A low dose of caffeine (i.e., 2 mg·kg^{-1})—for an 80 kg individual this dose of caffeine is contained in one to two cups of coffee—may produce substantial improvements in lower-body resistance exercise performance with the magnitude of the effect being similar to that attained using higher doses of caffeine.

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Figure 1. An overview of the experimental protocol. 1RM: one repetition maximum, RPE: completing the rating of perceived exertion scale; PP: completing the pain perception scale; minutes above the arrows denote rest interval time. The order of the conditions was randomized.

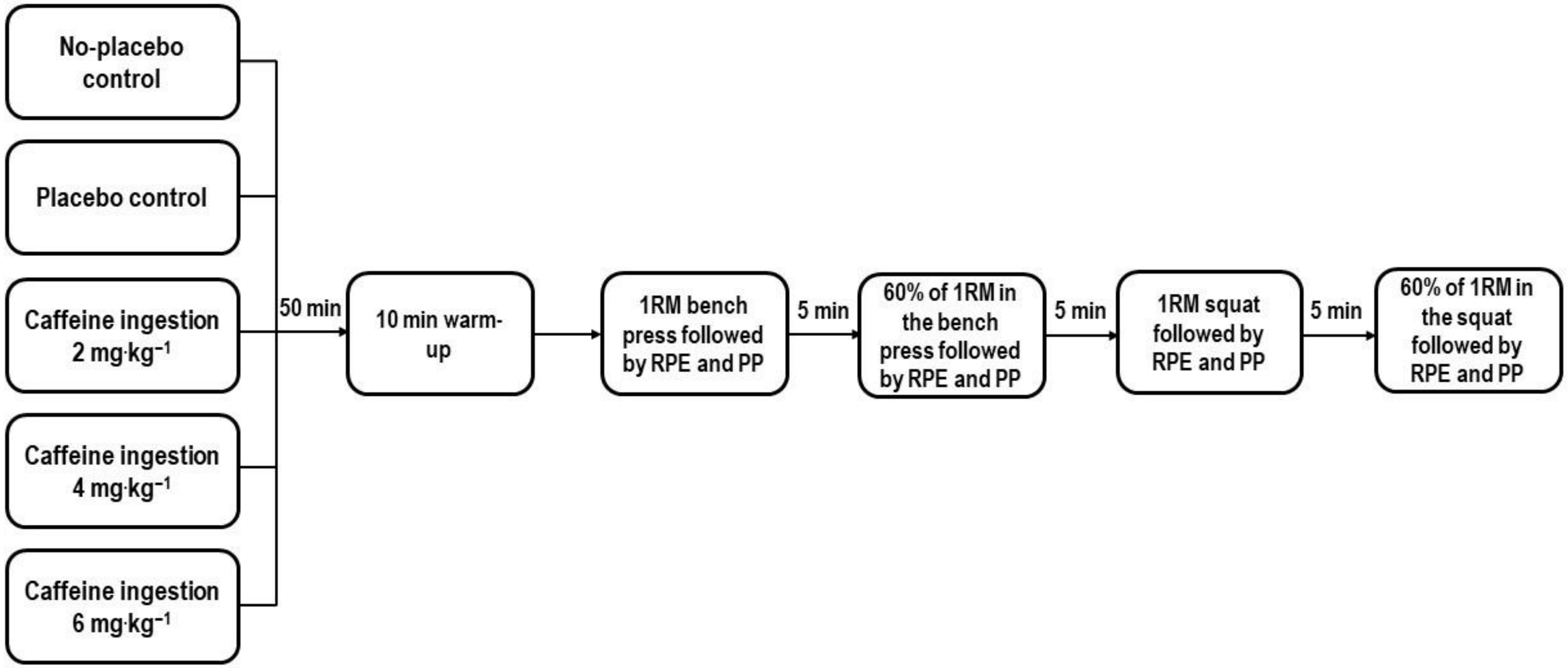

Table 1. Summary of the study comparision between the conditions

Outcome	Comparision	Cohen's *d* (95% CI)	Raw mean difference (95% CI)	*r*
Weight lifted in the 1RM barbell back squat test	No-placebo control vs. 2 mg·kg^{-1}	0.15 (0.08, 0.22)*	+3.5 kg (1.9, 5.1 kg)*	0.99
	No-placebo control vs. 4 mg·kg^{-1}	0.09 (–0.01, 0.19)	+2.1 kg (–0.2, 4.4 kg)	0.97
	No-placebo control vs. 6 mg·kg^{-1}	0.08 (0.00, 0.17)	+2.0 kg (0.0, 4.0 kg)	0.98
	Placebo-control vs. 2 mg·kg^{-1}	0.13 (0.06, 0.20)*	+3.0 kg (1.4, 4.6 kg)*	0.98
	Placebo-control vs. 4 mg·kg^{-1}	0.07 (–0.03, 0.17)	+1.6 kg (–0.6, 3.8 kg)	0.97
	Placebo-control vs. 6 mg·kg^{-1}	0.06 (–0.03, 0.16)	+1.5 kg (–0.5, 3.5 kg)	0.98
Weight lifted in the 1RM barbell bench press test	No-placebo control vs. 2 mg·kg^{-1}	0.01 (–0.05, 0.06)	+0.2 kg (–1.0, 1.4 kg)	0.99
	No-placebo control vs. 4 mg·kg^{-1}	0.07 (0.00, 0.15)*	+1.6 kg (0.0, 3.3 kg)*	0.98
	No-placebo control vs. 6 mg·kg^{-1}	0.09 (0.03, 0.16)*	+2.1 kg (0.9, 3.4 kg)*	0.99
	Placebo-control vs. 2 mg·kg^{-1}	–0.03 (–0.10, 0.05)	–0.5 kg (–2.0, 0.9 kg)	0.98
	Placebo-control vs. 4 mg·kg^{-1}	0.04 (–0.05, 0.14)	+0.9 kg (–1.1, 2.9 kg)	0.97
	Placebo-control vs. 6 mg·kg^{-1}	0.06 (0.00, 0.14)	+1.4 kg (0.0, 2.9 kg)	0.99
Number of repetition in the lower-body muscle endurnace test	No-placebo control vs. 2 mg·kg^{-1}	0.55 (0.21, 0.92)*	+4.2 repetitions (1.9, 6.5 repetitions)*	0.76
	No-placebo control vs. 4 mg·kg^{-1}	0.52 (0.07, 0.97)*	+3.3 repetitions (0.6, 5.9 repetitions)*	0.46
	No-placebo control vs. 6 mg·kg^{-1}	0.46 (0.01, 0.92)*	+3.9 repetitions (0.4, 7.3 repetitions)*	0.51
	Placebo-control vs. 2 mg·kg^{-1}	0.67 (0.17, 1.21)*	+4.8 repetitions (1.4, 8.1 repetitions)*	0.36
	Placebo-control vs. 4 mg·kg^{-1}	0.68 (0.22, 1.17)*	+3.9 repetitions (1.5, 6.3 repetitions)*	0.48
	Placebo-control vs. 6 mg·kg^{-1}	0.56 (0.01, 1.16)*	+4.5 repetitions (0.1, 8.8 repetitions)*	0.08

1RM: one repetition maximum; CI: confidence interval; *: significant difference between the conditions

Table 2. Summary of the exercise performance data and the responses to the rating of perceived exertion and pain perception scales under the five employed conditions

Variable	Control condition		Caffeine intake condition (dose)		
	No-placebo	Placebo	2 mg·kg^{-1}	4 mg·kg^{-1}	6 mg·kg^{-1}
1RM barbell back squat (kg)	128.7 ± 23.8	129.2 ± 21.7	132.2 ± 22.7[a, b]	130.8 ± 22.8	130.7 ± 24.6
RPE for 1RM barbell back squat (6-20 scale)	16.4 ± 2.6	17.0 ± 2.0	17.0 ± 1.8	16.9 ± 1.8	16.4 ± 2.2
PP for 1RM barbell back squat (0-10 scale)	2.3 ± 2.2	2.3 ± 2.8	2.8 ± 2.8	2.2 ± 2.5	2.1 ± 2.5
1RM barbell bench press (kg)	106.2 ± 21.6	106.9 ± 21.9	106.3 ± 21.1	107.8 ± 20.7[a]	108.3 ± 22.5[a]
RPE for 1RM barbell bench press (6-20 scale)	16.3 ± 2.3	15.9 ± 2.8	15.3 ± 2.8	15.7 ± 2.6	15.9 ± 2.7
PP for 1RM barbell bench press (0-10 scale)	1.8 ± 2.4	1.4 ± 2.2	1.9 ± 2.5	1.8 ± 2.2	1.6 ± 1.9
Barbell back squat – repetitions to failure with 60% of 1RM (repetitions)	21.7 ± 6.2	21.1 ± 4.9	25.9 ± 8.4[a, b]	25.0 ± 6.1[a, b]	25.5 ± 9.5[a, b]
RPE for barbell back squat repetitions to failure (6-20 scale)	16.7 ± 2.6	16.9 ± 2.4	17.0 ± 2.3	17.1 ± 2.6	17.2 ± 2.4
PP for barbell back squat repetitions to failure (0-10 scale)	2.9 ± 2.7	3.2 ± 2.7	3.5 ± 3.1	3.5 ± 3.1	3.0 ± 3.0
Barbell bench press – repetitions to failure with 60% of 1RM (repetitions)	20.5 ± 3.9	20.5 ± 4.2	21.1 ± 3.8	21.2 ± 3.6	20.9 ± 4.0
RPE for barbell bench press repetitions to failure (6-20 scale)	16.8 ± 2.3	17.0 ± 2.4	16.6 ± 2.4	16.9 ± 2.4	17.0 ± 2.5
PP for barbell bench press repetitions to failure (0-10 scale)	2.4 ± 2.6	2.3 ± 2.7	2.5 ± 3.2	2.3 ± 2.2	2.3 ± 2.7

All data are presented as mean ± standard deviation, RPE: rating of perceived exertion, PP: pain perception, 1RM: one repetition maximum; [a]: significant difference as compared to no-placebo control [b]: significant difference as compared to placebo-control