Ergogenic Effects of Very Low to Moderate Doses of Caffeine on Vertical Jump Performance

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Although the ergogenic effects of 3–6 mg/kg caffeine are widely accepted, the efficacy of low doses of caffeine has been discussed. However, it is unclear whether the ergogenic effects of caffeine on jump performance are dose responsive in a wide range of doses. This study aimed to examine the effect of very low (1 mg/kg) to moderate doses of caffeine, including commonly utilized ergogenic doses (i.e., 3 and 6 mg/kg), on vertical jump performance. A total of 32 well-trained collegiate sprinters and jumpers performed countermovement jumps and squat jumps three times each in a double-blind, counterbalanced, randomized, crossover design. Participants ingested a placebo or 1, 3, or 6 mg/kg caffeine 60 min before jumping. Compared with the placebo, 6 mg/kg caffeine significantly enhanced countermovement jump (p < .001) and squat jump (p = .012) heights; furthermore, 1 and 3 mg/kg of caffeine also significantly increased countermovement jump height (1 mg/kg: p = .002, 3 mg/kg: p < .001) but not squat jump height (1 mg/kg: p = .436, 3 mg/kg: p = .054). There were no significant differences among all caffeine doses in both jumps (all p > .05). In conclusion, even at a dose as low as 1 mg/kg, caffeine improved vertical jump performance in a dose-independent manner. This study provides new insight into the applicability and feasibility of 1 mg/kg caffeine as a safe and effective ergogenic strategy for jump performance.

Keywords: ergogenic aid, countermovement jump, squat jump, athlete

Caffeine (1,3,7-trimethylxanthine) is one of the most consumed substances in various competitive sports worldwide as an ergogenic aid. According to doping analyses, urinary caffeine concentrations in national and world competitions have increased each year in some sports, such as track and field, weightlifting, and rowing (Aguilar-Navarro et al., 2019). Indeed, various associations have reported the efficacy of 3–6 mg/kg caffeine supplementation as an acute ergogenic aid to sports performance (Guest et al., 2021; Maughan et al., 2018). On the other hand, the effects of low-dose (i.e., ≤3 mg/kg) caffeine have been discussed (Grigic, 2022, 2023; Spriet, 2014). The advantage of low-dose caffeine supplementation is increased safety compared with that of higher doses (Spriet, 2014). A higher dose of caffeine ingestion sometimes induces side effects (e.g., tachycardia, anxiety, headache, and insomnia), and the risk of such adverse effects increases in a dose-dependent manner (de Souza et al., 2022; Guest et al., 2021; Pallarés et al., 2013). Thus, a lower caffeine dose, which would be not only effective but also safe as an ergogenic aid, is desirable for many athletes.

Interestingly, the latest meta-analysis reported that the minimum ergogenic dose of caffeine that enhanced muscle strength was 0.9 mg/kg (Grigic, 2022). However, whether the ergogenic effects of caffeine are dose dependent is still controversial despite being an important aspect for determining the effectiveness of lower doses of caffeine supplementation. Some studies have reported that the effects of caffeine are dose dependent (Del Coso et al., 2012; Warren et al., 2010), but others have not confirmed these effects (Carvalho et al., 2022; Warren et al., 2010) during various types of athletic movements. Focusing on jump performance, although caffeine provides ergogenic effects on vertical jump performance (Grigic, 2023; Grigic et al., 2018; Salinero et al., 2019), only one study (Elis et al., 2019) compared the effects of multiple doses, including nearly minimum ergogenic dose for strength performance (Grigic, 2022), on vertical jump performance in athletes. However, the previous study (Ellis et al., 2019) compared the effects of low doses of caffeine within a limited range (i.e., 1, 2, and 3 mg/kg). Therefore, the effects of a wide range of caffeine doses, within previously recommended doses and lower doses, on vertical jump performance in athletes are unclear. Jumping is one of the critical components in many sports, and vertical jump height is associated with sprint, strength, and ball game performance (Armason et al., 2004; Kale et al., 2009; Loturco et al., 2015; Wisloff et al., 2004). Thus, exploring the ergogenic effects of caffeine on vertical jump performance would advance applications to other related aspects of sports performance. Overall, a comparative study assessing a wide range of caffeine doses is needed to elucidate caffeine’s ergogenic effects on jump performance.

The purpose of this study was to investigate the acute ergogenic effects of very low to moderate doses of caffeine on vertical jump performance within a wide range of caffeine doses, including the commonly utilized ergogenic doses. Namely, we examined the effects of a wide range of caffeine doses, from 1 mg/kg (a very low dose; approximately the minimum ergogenic dose to enhance muscle strength [Grigic, 2022]), 3 mg/kg, and 6 mg/kg (the lower and upper limits of the commonly recommended dose, respectively [Guest et al., 2021; Maughan et al., 2018]), on vertical jump performance. We hypothesized that caffeine would exert dose-dependent ergogenic effects on vertical jump performance.
Methods

Participants

Thirty-two well-trained male collegiate track-and-field athletes (26 sprinters and six jumpers) participated in this study (mean ± SD; age: 19.8 ± 1.3 years, height: 174.7 ± 5.2 cm, weight: 64.8 ± 5.4 kg, personal best World Athletics score in their main event: 992 ± 103 points). Most of the participants in this study would fall into the category of subelite athletes, defined in previous studies (Matsumura et al., 2023; Miller et al., 2021), according to their reconverted 100-m sprint time (10.89 ± 0.35 s) from the World Athletics score (Miller et al., 2021). Habitual caffeine intake was estimated with the questionnaire from a previous study (Bühler et al., 2014) when participants first visited the laboratory. If participants habitually consumed any caffeinated foods or beverages, participants also provided the product name, if possible, and the caffeine content of this product was researched. If the product name or the caffeine content in the product was unclear, the caffeine content was recorded from values in a list from a previous study (Paluska, 2003) providing the caffeine content of common foods and beverages. The median habitual caffeine intake was 32 (0–127) mg per day (including 14 participants with no caffeinated foods/beverages). All included participants had a minimum of 2 hr per day and 5 days per week of training (including resistance training) and could complete vertical jumps with maximal effort. Participants were excluded from this study if they reported (a) an injury making it difficult to perform jump actions, (b) a mental disorder or cardiovascular disease, (c) smoking within the past year, or (d) an allergy to caffeine. This study conformed to the Declaration of Helsinki and was approved by the Ethics Committee for Human Experiments at Ritsumeikan University (BKC-LSMH-2022-015). Written informed consent was obtained from all participants.

Experimental Design

This study utilized a double-blind, counterbalanced, randomized, crossover design. Participants visited the laboratory five times (once for a familiarization session and four times for experimental trials). In the familiarization session, participants practiced the vertical jumps after having their height and weight measured with body scales (WB-510; TANITA Co.). In the four experimental trials, participants ingested a placebo or 1, 3, or 6 mg/kg of anhydrous caffeine (Pure Caffeine; Myprotein) in capsule form. Maltitol (Place-plus; Placebo Seiyaku) was used as the placebo. In addition, the weight of supplements across all conditions was adjusted by adding maltitol to prevent any other differences among the numbers of trials (all p > .05).

Experimental Procedure

Participants arrived at the laboratory 75 min before the vertical jump tests and rested for 15 min. Subsequently, participants ingested caffeine or placebo capsules 60 min before the vertical jump tests; this timing is generally used for caffeine supplementation as an ergogenic aid (Guest et al., 2021). Following a rest, participants started the standardized warm-up (jogging, 10 body-weight squats, and jump practices) 10 min before the tests. Participants performed three countermovement jumps (CMJs) and three squat jumps (SJs) in one experimental trial with 1,250 Hz on the force platform (TF-4060-B; Tec Gihan Co.). Participants performed all jumps with their arms on their waist to prevent arm swinging. In the CMJ, participants maintained a standing position for at least 2 s on the force platform, dropped into the squat position, and immediately performed the vertical jump with their maximum effort (i.e., jump with countermovement). In the squat stance of the CMJ, we did not specify the depth of the squat position (i.e., knee angles) but told participants to drop down so that they could jump as high as possible. In the SJ, participants dropped into a squat position with their knees at 90°, kept this stance for at least 2 s, and jumped maximally without countermovement. If participants had any countermovement actions during the SJ as a result of the timely visual inspection of the force–time data, participants attempted to perform the SJ again. Between jumps, participants rested for 1 min. The order of jump trials was randomly determined (by the Research Randomizer; www.randomizer.org/) in each condition. Immediately after jump tests, participants underwent blood microsampling using the same method as in our previous study (Matsumura et al., 2023). Of note, the blood of two participants was not collected in this study.

Participants reported side effects of caffeine immediately after the blood microsampling (0 hr) and 24 hr later. Participants were asked eight yes/no questions based on a previous study (Pallarés et al., 2013) at each time point on the following side effects: muscle soreness, increased urine output, tachycardia and heart palpitations, anxiety or nervousness, headache, gastrointestinal problems, insomnia (only at 24 hr), increased vigor/activeness, and perception of performance improvement (only at 0 hr). Furthermore, to confirm the effectiveness of blinding, participants were asked to indicate their belief regarding which supplement they had taken in each trial (caffeine, placebo, or uncertain) before and after jump tests (Saunders et al., 2017).

Data Analyses

Participants’ blood samples were centrifuged and stored at –80°C immediately after sampling. Plasma caffeine concentration was analyzed by enzyme-linked immunosorbent assay (Caffeine ELISA Kit; Abnova Co.). The enzyme-linked immunosorbent assay was run according to the manufacturer’s instructions, and samples were run in duplicate.

Jump performance was determined using unfiltered force–time data (Street et al., 2001). Vertical jump heights were calculated from the vertical velocity of jumping takeoff following a previous study (Yamashita et al., 2020). Briefly, the vertical jump velocity (V) was calculated with the following equation:

\[ V = \frac{1}{m} \int_{t_i}^{t_o} (F - mg) dt, \]

where \( m, t_i, t_o, F, \) and \( g \) represent the body mass, time to start the jump motion, time to end the jump motion, vertical ground reaction force, and acceleration due to gravity, respectively.
force, and gravitational acceleration (i.e., 9.806 m/s), respectively. The body mass (m) was obtained from the 0.3 s average of the ground reaction force in the standing position. The start and the end of the jump motions were identified as the ground reaction force that changed by >1% of the body mass from the static stance and that reached <1% of the body mass, respectively. Subsequently, the jump height (H) was calculated by:

\[ H = \frac{V^2}{2g}. \]

The peak force and mean rate of force development (RFD) during jump motions were obtained from the force data. The peak force was defined as the highest ground reaction force during the jump motion. The mean RFD was calculated by dividing the change in minimum to maximum force in the eccentric phase by its duration (Barker et al., 2018). In addition, the eccentric utilization ratio, an indicator of stretch-shortening cycle performance, was calculated by dividing CMJ height by SJ height (McGuigan et al., 2006). This is a suitable index to evaluate the effective utilization of the eccentric phase in the CMJ (McGuigan et al., 2006; Van Hooren & Zolotarjova, 2017). Jump performance in each condition was reported as the mean of three trials for each type of jump.

**Statistics**

All data are expressed as the median (interquartile range). Because the Shapiro–Wilk test indicated that not all variables of jump performance were normally distributed, all values except for plasma caffeine concentration were log10 transformed for comparative analyses. Comparisons of all variables related to jump performance (i.e., the jump height, peak force and mean RFD in the CMJ and SJ, and the eccentric utilization ratio) were performed with one-way repeated-measures analysis of variance. Subsequently, the differences in CMJ height among the caffeine doses (all \( p>.05 \)) could not be applied to the plasma caffeine concentration because the data included zero; thus, we carried out nonparametric analyses of only plasma caffeine concentration. Comparisons of the side-effect incidence and the effectiveness of blinding (correctly recognized or not) among conditions were performed with Cochran’s \( Q \) test. Cohen’s \( d \), a measure of effect size, was calculated using the pooled standard deviation to determine the magnitude of the difference in measured variables among conditions. This effect size was interpreted as very small (\( d<0.2 \)), small (\( 0.2 \leq d<0.5 \)), medium (\( 0.5 \leq d<0.8 \)), or large (\( 0.8 \leq d; \) Sawilowsky, 2009).

Moreover, to test for bias in the trial order, a one-way repeated-measures analysis of variance was used to compare jump performances among the trials, as mentioned in the Experimental Design section. The statistical significance threshold was set at \( p<.05 \). All statistical analyses were carried out using IBM SPSS software (version 28).

**Results**

**Jump Height**

There was a significant main effect of condition on CMJ height (\( p<.001, \eta^2_p = .32 \)). Compared with the placebo (36.0 [33.8–40.2] cm), 1 mg/kg (37.6 [35.5–41.0] cm, \( p=.002, d=0.31; 95\% \text{ confidence interval [CI]} [0.13, 0.49] \), 3 mg/kg (37.9 [36.5–41.1] cm, \( p<.001, d=0.40; 95\% \text{ CI} [0.20, 0.59] \), and 6 mg/kg caffeine (38.4 [36.0–42.8] cm, \( p<.001, d=0.52; 95\% \text{ CI} [0.28, 0.75] \) significantly increased CMJ height (Figure 1a). There were no other significant differences in CMJ height among the caffeine doses (all \( p>.05 \)).

There was a significant main effect of condition on SJ height (\( p=.006, \eta^2_p = .14 \)). Compared with the placebo (36.7 [33.3–39.5] cm), 6 mg/kg caffeine (38.3 [34.7–41.1] cm, \( p=.012, d=0.35; 95\% \text{ CI} [0.12, 0.58] \) significantly increased jump height (Figure 1b). However, 1 mg/kg (36.9 [35.1–40.0] cm, \( p=.436, d=0.19; 95\% \text{ CI} [–0.02, 0.40] \) and 3 mg/kg caffeine (37.3 [34.2–40.3] cm, \( p=.054, d=0.17; 95\% \text{ CI} [0.04, 0.30] \) did not significantly change the jump height from that with the placebo.

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**Figure 1** — The effects of 1, 3, and 6 mg/kg caffeine on vertical jump heights in the CMJ (a) and SJ (b) as well as the eccentric utilization ratio (c). Significant differences versus the placebo condition are shown as 
\( *p<.05, **p<.01, \) and 
\( ***p<.001 \). Values are presented as the median (IQR). Each participant’s result is presented in the plot (black circles). CMJ = countermovement jump; SJ = squat jump; IQR = interquartile range.

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\( *p<.05, **p<.01, \) and 
\( ***p<.001 \). Values are presented as the median (IQR). Each participant’s result is presented in the plot (black circles). CMJ = countermovement jump; SJ = squat jump; IQR = interquartile range.
Table 1 Plasma Caffeine Concentration Immediately After Jump Tests and Variables of Jump Performances Between Conditions

<table>
<thead>
<tr>
<th></th>
<th>Placebo</th>
<th>1 mg/kg</th>
<th>3 mg/kg</th>
<th>6 mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma caffeine concentration (μM)</td>
<td>0.2 (0.0–0.8)</td>
<td>8.8 (7.0–11.2)**</td>
<td>23.0 (21.1–26.5)<strong>,</strong></td>
<td>42.3 (39.8–46.2)<strong>,</strong>,**</td>
</tr>
<tr>
<td>n = 32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ Peak force (N)</td>
<td>1,543 (1,440–1,699)</td>
<td>1,565 (1,435–1,735)</td>
<td>1,562 (1,449–1,704)</td>
<td>1,565 (1,475–1,741)**</td>
</tr>
<tr>
<td></td>
<td>3,907 (3,608–4,671)</td>
<td>4,007 (3,720–5,171)</td>
<td>4,093 (3,533–5,292)</td>
<td>4,401 (3,658–5,200)</td>
</tr>
<tr>
<td>SJ Peak force (N)</td>
<td>1,478 (1,374–1,626)</td>
<td>1,488 (1,422–1,620)</td>
<td>1,487 (1,401–1,603)</td>
<td>1,474 (1,395–1,663)</td>
</tr>
<tr>
<td></td>
<td>2,651 (2,027–2,852)</td>
<td>2,474 (2,033–2,882)</td>
<td>2,540 (2,091–2,993)</td>
<td>2,610 (2,385–3,151)</td>
</tr>
</tbody>
</table>

Note. Values are presented as the median (IQR). CMJ = countermovement jump; SJ = squat jump; RFD = rate of force development; IQR = interquartile range. **Significant (p < .01) difference versus the placebo condition. ***Significant (p < .001) difference versus the placebo condition. ^^^Significant (p < .001) difference versus the 1 mg/kg caffeine condition. +++Significant (p < .001) difference versus the 3 mg/kg caffeine condition.

Table 2 The Percentage of Participants Who Reported Side Effects Immediately (0 hr) and 24 hr After Jumps (24 hr)

<table>
<thead>
<tr>
<th>Side effects (n = 32)</th>
<th>Placebo</th>
<th>1 mg/kg</th>
<th>3 mg/kg</th>
<th>6 mg/kg</th>
<th>0 hr</th>
<th>24 hr</th>
<th>0 hr</th>
<th>24 hr</th>
<th>0 hr</th>
<th>24 hr</th>
<th>0 hr</th>
<th>24 hr</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 hr</td>
<td>24 hr</td>
<td>0 hr</td>
<td>24 hr</td>
<td>0 hr</td>
<td>24 hr</td>
<td>0 hr</td>
<td>24 hr</td>
<td>0 hr</td>
<td>24 hr</td>
<td>0 hr</td>
<td>24 hr</td>
<td></td>
</tr>
<tr>
<td>Muscle soreness</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>13</td>
<td>.284</td>
<td>.101</td>
<td></td>
</tr>
<tr>
<td>Increased urine output</td>
<td>25</td>
<td>3</td>
<td>22</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>16</td>
<td>16</td>
<td>.239</td>
<td>.241</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tachycardia and heart palpitations</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>.572</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anxiety or nervousness</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.000</td>
<td>.392</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headache</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>.572</td>
<td>.896</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gastrointestinal problems</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>.392</td>
<td>.572</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insomnia</td>
<td>—</td>
<td>3</td>
<td>—</td>
<td>6</td>
<td>—</td>
<td>0</td>
<td>—</td>
<td>6</td>
<td>—</td>
<td>.468</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased vigor/activeness</td>
<td>6</td>
<td>3</td>
<td>13</td>
<td>3</td>
<td>22</td>
<td>3</td>
<td>16</td>
<td>3</td>
<td>.315</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perception of performance improvement</td>
<td>19</td>
<td>—</td>
<td>31</td>
<td>—</td>
<td>41</td>
<td>—</td>
<td>28</td>
<td>—</td>
<td>.244</td>
<td>—</td>
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</tbody>
</table>

Note. p values show the results of Cochran’s Q test for each item at each time point.
utilized ergogenic doses (i.e., 3 and 6 mg/kg). Very low to moderate doses of caffeine enhanced vertical jump performance, but the increase in jump height was not statistically different among caffeine doses, contrary to our hypothesis. To the best of our knowledge, this study is the first to show the ergogenic effect of 1 mg/kg caffeine on CMJ performance. Although a recent meta-analysis showed that low doses of caffeine improved jump performance (Grgic, 2023), few of the included studies examined the effects of very low doses of caffeine. Only one included study examined the effect of 1 mg/kg caffeine on CMJ performance (Ellis et al., 2019); a significant effect was not found, even though the caffeine condition had mean jump heights 1.3 cm higher than the placebo condition, which might be attributed to the smaller sample size \((n = 15); \text{less than half of the present study}\). Interestingly, even 0.9 mg/kg caffeine has an ergogenic effect on strength performance (Grgic, 2022). Consistent with these findings, this study also indicates that a very low dose of caffeine has an ergogenic effect on jump performance.

Although the previous study compared the effects of low doses of caffeine within a limited range on vertical jump performance (Ellis et al., 2019), we adopted a broader range of caffeine doses, including 1–6 mg/kg, with a relatively larger sample size. Notably, no significant differences were observed among caffeine doses, suggesting that increased caffeine doses would provide no additional enhancement of jump performance. Generally, 3–6 mg/kg caffeine improves performance in various sports (Guest et al., 2021; Maughan et al., 2018) and vertical jumps (Grgic et al., 2018; Salinero et al., 2019). The recommended daily caffeine intake of the general population is up to 200 mg of caffeine per dose and 400 mg per day to address safety concerns (EFSA Panel on Dietetic Products, Nutrition & Allergies [NDA], 2015). Therefore, caffeine doses >3 mg/kg for many athletes may exceed the recommended caffeine intake per dose. Thus, lower caffeine doses are relatively favorable for safety. On the other hand, the incidence of side effects in the present study did not differ between ingesting either a placebo or very low to moderate doses of caffeine; this finding supports the safety of commonly utilized doses of caffeine. Importantly, the incidence of side effects increases in a dose-dependent manner with caffeine intake; even 3–6 mg/kg caffeine can induce adverse effects in some cases (Del Coso et al., 2012; de Souza et al., 2022; Pallarès et al., 2013). Thus, 1 mg/kg caffeine would suppress any potential safety concerns. Moreover, many athletes generally utilize commercial beverages, such as energy drinks or coffee (Guest et al., 2021), which usually contain ≤200 mg of caffeine (e.g., 70–200 mg in energy drinks of 16-oz serving [Higgins et al., 2010] and 100 mg in a 6-oz cup of brewed coffee [Paluska, 2003]). Athletes, thus, need to consume multiple cans or cups of these beverages for an ergogenic effect according to previously recommended caffeine doses. However, the American College of Sports Medicine recommends avoiding the consumption of energy drinks before/after strenuous activities or consuming multiple energy drinks at once to prevent potential adverse events (Higgins et al., 2018). Overall, our study suggests that lower doses of caffeine would be suitable in terms of both applicability/feasibility and safety for sports.

We did not find ergogenic effects of 1 and 3 mg/kg caffeine on the SJ, in contrast to the CMJ. In the present study, caffeine did not change the eccentric utilization ratio (Figure 1c); thus, caffeine did not specifically improve stretch-shortening cycle performance during the CMJ. Notably, to increase the vertical jump height, not only the enhancement of lower muscle strength but also the coordination of movement patterns is important (Bobbert & Van Soest, 1994). Although caffeine enhances muscle strength/power (Carvalho et al., 2022; Grgic, 2022; Grgic et al., 2018; Guest et al., 2021; Warren et al., 2010), the SJ had a shorter jump duration than the CMJ (Van Hooren & Zolotarova, 2017); thus, the jump motion in the SJ might not be fully controlled to increase the vertical jump height. On the other hand, despite the nonsignificant improvement in SJ height by 1 and 3 mg/kg caffeine, the very small effect size \((d = 0.19 \text{ and } 0.17, \text{respectively})\) was almost equivalent to the results of caffeine’s effects on vertical jump performance in several meta-analyses (Grgic et al., 2018; Salinero et al., 2019). In summary, the ergogenic effects of low-dose caffeine on SJ performance remain equivocal and require further clarification.

In the CMJ, only 6 mg/kg caffeine increased the peak force but not the RFD. In contrast, a previous study reported a significant improvement in jump height in terms of both the peak force and RFD in response to caffeine (Bloms et al., 2016). However, vertical jump height only is determined by the velocity at the takeoff (Ruddock & Winter, 2016). Thus, increasing jump heights can be interpreted as caffeine supplementation enhancing the impulse by improving muscle activation, leading to higher velocity at takeoff. Even though the higher dose of caffeine enhances the peak force during the jump motion in the CMJ, this effect did not directly or markedly contribute to increases in jump heights.

In this study, the plasma caffeine concentration after jump tests was increased in a dose-dependent manner. This increase was almost the same as that previously reported; after ingesting 1, 3, and 6 mg/kg caffeine, the peak plasma caffeine concentrations are typically 5–10, 15–20, and 40–50 μM, respectively (Carrillo & Benitez, 2000; Graham & Spriet, 1995; Magkos & Kavouras, 2005; Spriet, 2014). Caffeine would affect central/peripheral factors, such as neural systems and skeletal muscle (Guest et al., 2021; Magkos & Kavouras, 2005; McLellan et al., 2016), resulting in enhanced jump performance in this study. Specifically, caffeine acts as an antagonist of adenosine receptors in the central nervous system, leading to increased motor unit activation (McLellan et al., 2016). Although the influence of very low doses of caffeine on the neural systems during jump performance is unclear, the result of our study suggests that caffeine may have such an effect dose independently within 1–6 mg/kg. However, this study did not evaluate the mechanism of increased jump performance for caffeine, so further research is warranted.

Although this study had a double-blind design, an average of 34% and 41% of participants correctly identified the conditions before and after jump tests, respectively. Correctly identifying the experimental condition could influence the results of the study; specifically, those who correctly identified the placebo both before and after trials could have decreased physical performance compared with a condition without any supplementation (Saunders et al., 2017). Thus, correct identification of the placebo condition may have led participants to overestimate the effects of caffeine. In this study, 13 participants correctly identified the placebo condition either before or after jumps (seven of them correctly identified the condition both before and after jumps). However, differences in jump heights were not found between those who correctly recognized the placebo condition and other participants in all conditions \((p > 0.05, \text{data not shown})\). In addition, there were no significant differences in the percentage of participants who correctly recognized the condition across conditions. These results suggest that the effectiveness of blinding did not decrease in any particular condition.

This study has several limitations. First, we did not assess a baseline plasma caffeine concentration due to the kit failure. Second, the influence of genetic factors that may affect the
ergonomic effects of caffeine, such as CYP1A2 and ADORA2A (Guest et al., 2021), was unclear. Third, only male athletes participated in this study, so this study did not find the effects of caffeine in female athletes. Finally, we did not measure the concentration of caffeine metabolites in plasma, such as paraxanthine and theophylline. These metabolites are potentially ergonomic (Magkos & Kavouras, 2005).

In conclusion, caffeine, even at 1 mg/kg, enhanced vertical jump performance in a dose-independent manner. One milligram per kilogram of caffeine is within the range found in common commercial beverages. Although commonly used ergonomic doses of caffeine are safe and effective, a very low dose of caffeine can be used to improve vertical jump performance as a safe and more applicable ergonomic aid.

Acknowledgments

The authors appreciate the time and effort of the volunteer participants. Author Contributions: Research design: Matsumura, Takamura, Tomoo, Shinohara, Nagano, Hashimoto. Experiments: Matsumura, Takamura, Fukuzawa, Nakagawa, Nonoyama, Tsukamoto, Shinohara, Nagano, Hashimoto. Experimental data analysis: Matsumura, Takamura. Interpretation of results: Matsumura, Takamura, Fukuzawa, Nakagawa, Nonoyama, Nagano, Hashimoto. Writing of the first manuscript: Matsumura. Manuscript editing and revision: Matsumura, Nonoyama, Tomoo, Tsukamoto, Shinohara, Iemitsu, Nagano, Isaka, Hashimoto. Approval of the final manuscript: All authors. Funding Sources: This study was supported by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Culture, Sports, Science, and Technology (grant no. 21H03384 to T.H.).

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