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Individual responses to encapsulated caffeine and caffeine chewing gum on strength and power in strength-trained males

Hamed Teimouri-Korani[a], Mohammad Hemmatinafar[b], Mark ET Willems[c], Rasoul Rezaei[b] and Babak Imanian[b]

[a]Shahid Beheshti University, Department of Biological Sciences in Sports, Faculty of Sport Sciences and Health, Tehran, Iran; [b]Shiraz University, Department of Sport Sciences, Faculty of Education and Psychology, Shiraz, Iran; [c]University of Chichester, Institute of Applied Sciences, Chichester, UK

ABSTRACT

Background: Liquid-dissolved and encapsulated powder are two popular ways to consume caffeine for performance-enhancing effects. Caffeine in other delivery methods, such as chewing gums, orally dissolvable strips, gels, mouthwashes, energy drinks, and nasal sprays, is believed to be absorbed more quickly into the bloodstream. Inter-individual responses to caffeine's enhancing effects are recognized. The present study examined the inter-individual responses to the acute effects of encapsulated caffeine and caffeinated chewing gum on the lower-body isokinetic and isometric strength and power in strength-trained males.

Method: A randomized, cross-over, placebo-controlled study was conducted with 15 strength-trained males (age: 25 ± 4 years, height: 176 ± 7 cm, weight: 75 ± 11 kg, habitual caffeine intake: 66 ± 15 $mg{\cdot}day^{-1}$). Participants were randomly assigned to three conditions: i) caffeinated chewing gum (CG), ii) caffeine capsule (CC), and iii) starch capsule as a placebo (PLA). Participants consumed approximately 3 to 4.5 $mg{\cdot}kg^{-1}$ of caffeine 60 minutes before testing. The washout period between conditions was one week. Participants performed the Sargent jump test, followed by a 5-minute active recovery (walking). Subsequently, isokinetic strength and power (60°/s and 180°/s) and isometric strength (45° and 60°) parameters were measured for knee extensor and flexor muscles. Data were analyzed using one-way repeated measures ANOVA and Bonferroni post hoc tests, with significance set at $p \leq 0.05$. Responders to the caffeine conditions were identified using the smallest worthwhile change (SWC) analysis.

Results: In knee extensors, 1) average peak torque and power at 60°/s were higher in CC ($p = 0.045$; + 11.2% and $p = 0.038$; + 14.1%) and CG ($p = 0.044$; + 7.3% and $p = 0.015$; + 11.4%) compared to PLA with a co-response rate of 60% and 66%, 2) maximum voluntary isometric contraction at 45° (MVIC-45°) was higher in CC compared to PLA ($p = 0.031$; + 10.1%), and 3) MVIC-60° was higher in CG

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CONTACT Mohammad Hemmatinafar m.hemmatinafar@shirazu.ac.ir Department of Sport Science, Faculty of Education and Psychology, Shiraz University, Chamran Blvd., Pardis of Eram, Shiraz, 84334-71946 Iran

compared to PLA ($p = 0.037$; + 10.1%) with a co-response rate of 60%. In knee flexors, 1) time to peak torque at 60°/s was higher in CG compared to PLA ($p = 0.011$; + 18.2%) with a co-response rate of 46%, 2) average rate of force development at 60°/s was higher in CC ($p = 0.007$; + 24.1%) and CG ($p = 0.050$; + 20.6%) compared to PLA with a co-response rate of 53%, and 3) average power at 180°/s was higher in CC compared to PLA ($p = 0.033$; + 18%) with a co-response rate of 46%. However, there were no differences between other strength indicators in the knee extensors and flexors between the different conditions. Vertical jump height (VJH) was higher in CC ($p = 0.001$; + 5.5%) and CG ($p = 0.001$; + 6.) compared to PLA, with a co-response rate of 53%.

Conclusion: Caffeine supplementation in CC and CG forms significantly enhanced lower-body strength, power, and vertical jump height in strength-trained males, with over ~50% of participants exceeding the SWC thresholds across key performance metrics. CC showed slightly higher responder rates for strength parameters, while CG excelled in time-dependent measures, supporting their use as effective and flexible ergogenic aids.

1. Introduction

Caffeine and its effects on athletes' performance have been a longstanding topic of interest [1]. Numerous studies have provided observations on the beneficial impact of caffeine on a variety of exercise performance tasks in competitive athletes [2–6]. The consumption of caffeine facilitates signal transmission in the sympathetic nervous system [7]. Upon swift absorption through the digestive tract, caffeine permeates cell membranes, swiftly entering the body's cells and tissues [8]. The liver metabolizes caffeine (1,3,7-trimethyl xanthine), yielding metabolites such as paraxanthine (84%), theobromine (12%), and theophylline (4%) [9]. Paraxanthine, the primary metabolite in humans, increases plasma glycerol and free fatty acids during the lipolysis process [10,11]. Some of the mechanical actions that have been proposed to explain caffeine ergogenic effects are enhanced mobilization of free fatty acid and associated glycogen-sparing [12], adenosine receptor antagonism [13,14], enhanced catecholamine secretion [12,15,16], enhanced neuromuscular transmission [13,17,18], and enhanced calcium ion (Ca^{2+}) release from the sarcoplasmic reticulum [19,20]. Additionally, it improves the activation of motor units and the process of excitation-contraction coupling [21,22], leading to an increase in force production [18].

The predominant methods for caffeine supplementation include capsules and liquid-dissolved powders. However, there is a growing interest in exploring alternative caffeine delivery methods, such as chewing gum, orally dissolvable strips, gels, mouthwashes, energy drinks, and nasal sprays, due to their faster absorption rates into the bloodstream [23]. Caffeine in the form of chewing gum offers a distinct advantage by enhancing the rate of caffeine transfer to the blood through absorption via the buccal mucosa, which is richly vascularized [24,25]. Caffeine from chewing gum is absorbed through two primary pathways: directly through the oral cavity's buccal mucosa or via intestinal absorption after swallowing caffeine-containing saliva [24–26]. One of the key benefits of chewing gum during

exercise is its reduced digestive demands, promoting more efficient caffeine absorption than other forms, such as capsules or coffee, where gastrointestinal blood flow may be limited [23]. Previous studies indicate that while both capsules and chewing gum provide similar bioavailability, significant caffeine absorption from gum occurs within just 5 minutes, compared to the 45–60 minutes required for complete absorption from capsules [24,27–30]. This faster absorption makes caffeine chewing gum particularly advantageous in scenarios requiring a rapid and dynamic response [31].

Beyond its faster absorption, caffeine chewing gum has demonstrated significant ergogenic effects in enhancing sports performance and muscular strength. Studies have shown that caffeine gum can improve vertical jump height, isokinetic strength, and lower body power [32]. For instance, a meta-analysis study on caffeine ingestion on isokinetic muscular strength demonstrated that acute caffeine ingestion might significantly increase isokinetic strength [33]. A major advantage of caffeine gum is its practicality for use immediately before or even during physical activity, offering a nearly instant performance boost – especially beneficial in sports demanding quick reactions or high-intensity efforts [34]. These findings highlight caffeine gum as a versatile and effective ergogenic aid, supporting improvements in strength, endurance, and cognitive performance [33].

In the past decade, numerous studies have explored the impact of caffeine on strength performance. Despite the wealth of research, inquiries persist regarding the efficacy of caffeine in enhancing endurance, power, and muscular strength activities [35]. Recent investigations have yielded novel insights, expanding our understanding of caffeine's ergogenic effects on isometric and isokinetic strength. These studies have corroborated the significant positive impact of caffeine consumption on isometric and isokinetic strength [36–40]. Additionally, it has been observed that caffeine consumption moderately influences maximum power and the development of torque force [41]. Nonetheless, some studies reported no discernible increase in caffeine's performance-enhancing effects on isometric or isokinetic strength [41–43]. In summation, current findings affirm that caffeine consumption augments isometric and isokinetic strength [44].

The Smallest Worthwhile Change (SWC) analysis can be used for understanding the individual-level responses to interventions, particularly in sports performance and nutrition research [45]. It provides a quantitative threshold to distinguish meaningful improvements in performance metrics beyond natural variability [46]. Recent studies have highlighted the utility of SWC in identifying the effectiveness of caffeine supplementation in various forms, including capsules and chewing gum, for enhancing athletic performance [33,34]. By focusing on individual variability, SWC allows for a more nuanced evaluation of ergogenic effects, revealing that factors such as delivery method and time-dependent absorption can significantly influence outcomes [24,32]. This approach is particularly relevant in comparing the short-term effects of caffeine on strength and power metrics, providing robust evidence to support its role as an ergogenic aid [34]. Based on previous findings and recommendations from Guest et al. [34] and Grgic et al. [44], there is a need to investigate the effects of caffeine in capsules and chewing gum. This study leverages SWC analysis to examine the individual responses to caffeine capsules and chewing gum, offering insights into their effectiveness in enhancing lower-body strength, power, and functional performance in strength-trained males.

2. Methodology

2.1. Participants

Fifteen healthy males (aged 19–31 years) with approximately five years of strength training experience and a minimum of three exercise sessions per week volunteered for this study. The anthropometric details of the participants are presented in Table 1. To ensure adherence to caffeine restriction, participants were given a detailed list of typical food and drink products containing caffeine and instructed to avoid them throughout the study. Participants abstained from supplements, medications, tobacco, alcohol, and caffeinated beverages for 72 hours before the start of data collection and throughout the experiment. Additionally, a three-day dietary recall was collected before each intervention session to verify compliance with dietary restrictions and confirm the absence of unintentional caffeine consumption. The habitual caffeine intake was quantified using the Center for Science in the Public Interest website (www.cspinet.org; accessed July 1997) [47], confirming that all participants were low caffeine consumers (66 ± 15 mg·day^{-1}). The present study complied with the Declaration of Helsinki and received approval from the Human Research Ethics Committee of Shiraz University (approval code: IR.US.PSYEDU.REC.1402.003). Participants were in the same training camp and followed a supervised identical exercise training program. Participants were instructed to abstain from strenuous exercise 48 hours before the testing sessions.

2.2. Sample size and study design

The sample size was calculated using the G*Power analysis software [48], considering a 5% Type I error rate, 80% statistical power, and a 0.90 correlation. Drawing from data from a previous caffeine study, an effect size of 0.2 for peak torque in the isokinetic knee extension at 60° s^{-1} was established as plausible [32]. While the calculated sample size was 12 participants, we opted for a sample size of 15 to anticipate dropout and ensure the robustness of our findings.

The study used a randomized, cross-over, placebo-controlled design (see Figure 1). Due to the physical differences between the chewing gum and capsule forms, completely

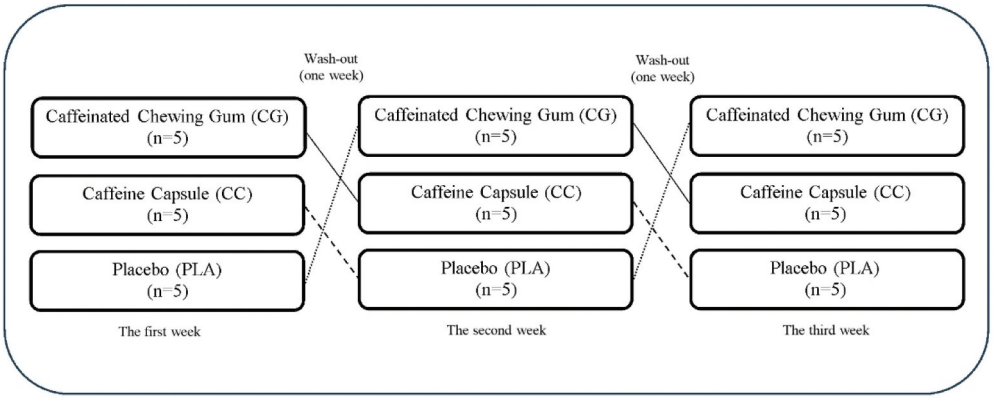

Figure 1. Cross-over, placebo-controlled study design in three conditions.

Table 1. Characteristics of participants ($n = 15$).

Characteristic	Mean ± SD
Age (year)	25 ± 4
Height (cm)	176 ± 7
Weight (kg)	75 ± 11

blinding participants was not feasible. However, to mitigate bias, researchers conducting performance assessments and data analyses remained blinded to the treatment conditions, helping to maintain objectivity in outcome measurements. Before the commencement of the study, participants underwent a familiarization session where they were introduced to all testing protocols and procedures, allowing them to become acquainted with the functional test and isokinetic testing device and its operation through physical practice. Age, height and body mass were recorded (Table 1). Additionally, participants completed i) a written informed consent form indicating comprehension of the implementation method, potential benefits, risks, and possible complications and ii) a caffeine consumption and intolerance questionnaire. Participants were provided with a list of dietary sources of caffeine and instructed to abstain from consuming these sources 72 hours before the exercise testing sessions. Participants were randomly assigned to one of three conditions: i) caffeinated chewing gum (CG, $n = 5$), ii) caffeine capsule (CC, $n = 5$), and iii) starch capsule as a placebo (PLA, $n = 5$). Participants received their assigned supplement according to the supplementation protocol (see below for details), followed by the administration of the Sargent jump test (see below for more information). Subsequently, after five minutes of active rest (walking), the isokinetic strengths and power of the knee extensor and flexor muscles were assessed at angular velocities of 60°/s and 180°/s, and isometric strengths of the knee extensor and flexor muscles were measured at knee angles of 45° and 60°. A one-week interval was designated as a washout period for each condition, with all tests conducted at each session (refer to Figure 2).

2.3. Caffeine supplementation and placebo

In the caffeinated chewing gum (CG) condition, participants chewed Military Energy Gum® (Ford Gum and Machine Co., Akron, NY, USA) containing 100 mg of caffeine for 10 minutes before the tests [2]. For the caffeine capsule (CC) condition, participants ingested pure caffeine anhydrous (Cat. No. C0750; Sigma-Aldrich; Steinheim; Germany) in 100 mg capsules with 200 milliliters of water 60 minutes before the tests [49]. In the placebo (PLA) condition, participants consumed a capsule filled with starch 60 minutes before the start of the tests. A laboratory employee provided the capsules in identical packages. The caffeine doses were administered depending on body mass. If body mass was less than 65 kg, participants consumed 200 mg of caffeine ($n = 2$). When body mass was more than 65 kg, participants consumed 300 mg of caffeine ($n = 13$) in the form of CG or CC [50]. So, all participants consumed caffeine with a dose of ~3 to 4.5 $mg \cdot kg^{-1}$. The active ingredient (200 or 300 mg caffeine) and placebo (starch) were packed in capsules that were identical in color, size, and weight. Participants received the same breakfast consisting of 250 kcal (45 g carbohydrates, 9 g protein, and 5 g fat) 90 minutes before the test sessions, with all three exercise testing sessions conducted at the same time of day (9:00 AM to 1:00

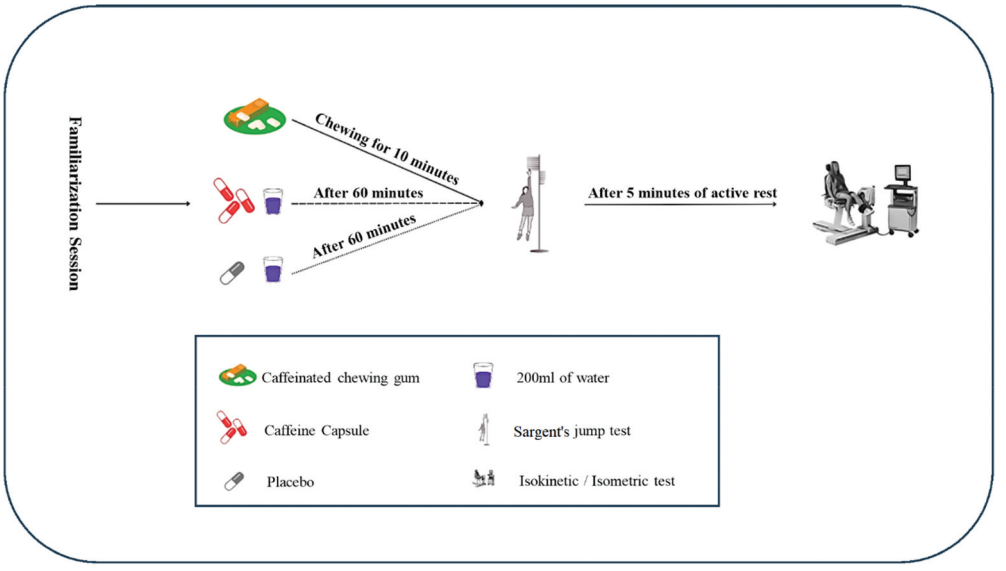

Figure 2. The protocol for taking supplements and performing tests.

PM). During the trials, participants had limited access to water. Participants were instructed to maintain their regular diet throughout the testing period, to avoid additional food an hour before testing, and to avoid strenuous exercise 48 hours before each trial.

2.4. Vertical jump height test

The Sargent Jump Test, also known as the Vertical Jump Test, is a widely used assessment to measure the explosive strength of the lower limbs. Developed by Dr. Dudley Allen Sargent in the early 20th century, this test evaluates an individual's ability to perform a vertical leap from a standstill position [51]. During the test, participants applied chalk to their fingertips, stood close to a wall, and reached up to mark it with the tip of their fingers (M1). They jumped as high as possible from a static position, marking the wall again (M2). Vertical Jump Height (VJH) was calculated as the distance between M1 and M2. The test was repeated three times, with a one-minute passive rest between attempts, and the highest jump was used for analysis [52].

The Sargent Jump Test is a reliable and valid measure of lower limb explosive power. It demonstrates strong test-retest reliability, with ICC = 0.828 for 4-year-olds and 0.739 for 5-year-olds [53]. Among young soccer players, it showed excellent reproducibility, with intra-evaluator ICC = 0.99 and inter-evaluator ICC = 1.0 [54]. The test's validity is confirmed by a high correlation ($r = 0.99$, $p = 0.001$) with the jump platform, the gold standard for explosive leg strength assessment [54]. This high correlation confirms that the Sargent Jump Test accurately reflects lower limb explosive power. Given these attributes, the use of the Sargent Jump Test in this study is well-justified, particularly where access to advanced equipment such as force plates is not available.

2.5. Isokinetic and isometric strength tests

An isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY, USA) was used to measure the isokinetic strength of the knee extensor and flexor muscles (concentric phase, at an angular velocity of 60°/s and 180°/s, con/con ratio, dominant leg) with five consecutive repetitions in the direction of extension-flexion and 60 seconds of rest for recovery between each set. Gravity correction of the torque measurements was accomplished using the Biodex software package. For the tests, participants were stabilized with straps across the chest, above the knee, around the waist, and above the ankle. This arrangement secured the lower leg to the input shaft of the dynamometer. Furthermore, the estimated transverse rotational axis of the knee was visually aligned with the mechanical axis of the dynamometer. The range of motion of the knee joint during the test was set at 80°. Absolute peak torque (APT), relative peak torque (RPT), average peak torque (AvPT), time to peak torque (TPT), average rate of force development (AvRFD) (AvRFD was calculated using the APT/TPT equation), average power (AvPw) and total work (TW) were measured [55,56]. The angular velocities of 60°/s and 180°/s were chosen to enable a thorough evaluation of muscle performance parameters. 60°/s, as a lower velocity, assess maximal strength under controlled conditions, offering valuable insights into knee extensors' and flexors' peak torque production capabilities. This controlled assessment is crucial for understanding the effects of caffeine supplementation on maximal strength. On the other hand, 180°/s represents a higher velocity designed to evaluate dynamic muscle performance, reflecting the capacity for rapid force generation and power output in functional, sports-related movements. Together, these velocities provide a comprehensive analysis of strength and power, ensuring the study captures caffeine's potential ergogenic effects across different muscular performance profiles. These choices align with established protocols and previous research in isokinetic performance testing [33,57].

Maximum voluntary isometric contraction (MVIC) of the dominant leg was measured at 45° and 60° in away (extension) and toward (flexion) action, using the same device. The isometric testing consisted of 5 maximal efforts for 5 seconds at the knee angles of 45° and 60° [58]. The angles of 45° and 60° for MVIC testing were selected because they align with positions where the knee extensors and flexors produce near-peak torque due to optimal muscle length-tension relationships. These angles are commonly used in research to evaluate maximal voluntary contraction reliably, as they minimize joint strain while maximizing force output. Additionally, they reflect joint positions frequently used in functional and athletic movements, making them relevant for assessing the effects of caffeine supplementation on isometric strength [33,59].

2.6. Statistical analysis

Data were analyzed using the statistical package for social sciences (SPSS version 26, Chicago, IL, USA). The data distribution normality was determined using the Shapiro-Wilk test. One-way repeated measures ANOVA test was used to determine the main effect on isokinetic and isometric indicators and functional test results, and the Bonferroni post hoc test was used to determine pairwise differences. Also, the SWC was calculated as 0.2 times the within-subject standard deviation (SD) in PLA (SWC = 0.2 × SD), following established

methodologies for meaningful effect sizes in performance studies [46]. Participants whose individual performance changes exceeded the SWC threshold in the caffeine conditions (CC or CG) compared to PLA were classified as 'responders'. The partial eta squared ($pEta^2$) was calculated as an effect size measure for interaction and main effects. According to Cohen, $pEta^2 \geq 0.01$ indicates small effects, $pEta^2 \geq 0.059$ indicates medium effects, and pEta2 ≥ 0.138 indicates large effects [60]. The level of statistical significance was $p \leq 0.05$, and data are presented as mean ± SD. Figure production was also performed using GraphPad Prism (version 9.0.0, GraphPad Software, San Diego, CA, USA).

3. Results

Table 2 reports descriptive characteristics. Additionally, Table 3 lists the SWC results showing changes on an individual level.

3.1. Cohort observations: knee extensor isokinetic and isometric parameters

For the knee extensors, the main effect for AvPT-60°/s was significant ($F_{1.59} = 5.81$, $p = 0.013$, $pEta^2 = 0.294$), and the AvPT-60°/s was higher in CC ($p = 0.045$) and CG ($p = 0.044$) compared to PLA with no difference between CC and CG ($p = 0.721$) (Figure 3). There was a main effect for AvPw-60°/s ($F_{1.71} = 6.19$, $p = 0.009$, $pEta^2 = 0.307$) with higher AvPw-60°/s in CC ($p = 0.038$) and CG ($p = 0.015$) compared to PLA and no difference between CC and CG ($p = 1.000$) (Figure 3). There was a main effect for MVIC-45° ($F_{1.57} = 6.49$, $p = 0.009$, $pEta^2 = 0.317$) with an increase in MVIC-45° in CC compared to PLA ($p = 0.031$) but there were no differences between CC and CG ($p = 1.000$) and CG and PLA ($p = 0.071$) (Figure 3). The main effect for MVIC-60° was significant ($F_{1.53} = 4.27$, $p = 0.036$, $pEta^2 = 0.234$), with the MVIC-60° in CG compared to PLA ($p = 0.037$), but no differences between CC with CG ($p = 1.000$) and PLA ($p = 0.304$) (Figure 3). For the knee extensors, there were no differences for APT-60°/s ($F_{1.88} = 2.66$, $p = 0.091$, $pEta^2 = 0.160$), APT-180°/s ($F_{1.68} = 0.46$, $p = 0.601$, $pEta^2 = 0.032$), RPT-60°/s ($F_{1.86} = 2.22$, $p = 0.130$, $pEta^2 = 0.137$), RPT-180°/s ($F_{1.75} = 0.80$, $p = 0.444$, $pEta^2 = 0.054$), AvPT-180°/s ($F_{1.97} = 1.69$, $p = 0.203$, $pEta^2 = 0.108$), TPT-60°/s ($F_{1.93} = 0.50$, $p = 0.606$, $pEta^2 = 0.035$), TPT-180°/s ($F_{1.67} = 1.82$, $p = 0.188$, $pEta^2 = 0.115$), AvRFD-60°/s ($F_{1.93} = 0.52$, $p = 0.594$, $pEta^2 = 0.036$), AvRFD-180°/s ($F_{1.83} = 1.61$, $p = 0.218$, $pEta^2 = 0.104$), AvPw-180°/s ($F_{1.73} = 1.33$, $p = 0.278$, $pEta^2 = 0.087$), TW-60°/s ($F_{1.83} = 2.08$, $p = 0.149$, $pEta^2 = 0.129$), and TW-180°/s ($F_{1.64} = 0.92$, $p = 0.394$, $pEta^2 = 0.062$) (Figure 3). All of these results are listed in Table 4.

3.2. Knee flexor isokinetic and isometric parameters

For the knee flexors, the main effect for TPT-60°/s was significant ($F_{1.75} = 4.65$, $p = 0.023$, $pEta^2 = 0.250$), and the TPT-60°/s was higher in CG compared to PLA ($p = 0.011$). Still, there were no differences between CC with CG ($p = 1.000$) and PLA ($p = 0.124$) (Figure 4). Additionally, there was a main effect on AvRFD-60°/s ($F_{1.88} = 6.02$, $p = 0.008$, $pEta^2 = 0.301$), and the AvRFD-60°/s was higher in CC ($p = 0.007$) and CG ($p = 0.050$) compared to PLA; with, no difference between CC and CG ($p = 1.000$) (Figure 4). Furthermore, the main effect for AvPw-180°/s was significant ($F_{1.31} = 4.91$, $p = 0.031$, $pEta^2 = 0.260$), while the AvPw-180°/s was higher in CC compared to PLA ($p = 0.033$); nevertheless, there were no differences between CG with CC ($p = 0.565$) and PLA ($p = 0.075$) (Figure 4). However, the results

Table 2. Means and standard deviation (mean ± SD) of measured variables.

	Variables	PLA ($n = 15$)	CC ($n = 15$)	CG ($n = 15$)
Extensors	APT-60°/s (Nm)	224.05 ± 37.69	236.56 ± 40.98	232.32 ± 38.76
	APT-180°/s (Nm)	156.72 ± 28.24	157.22 ± 26.47	159.42 ± 24.31
	RPT-60°/s (%)	299.32 ± 32.98	313.66 ± 36.87	310.84 ± 38.82
	RPT-180°/s (%)	209.51 ± 28.96	208.51 ± 23.21	213.52 ± 24.31
	AvPT-60°/s (Nm)	197.12 ± 31.51	219.24 ± 41.96	211.54 ± 38.47
	AvPT-180°/s (Nm)	135.89 ± 28.75	141.22 ± 23.18	141.79 ± 22.29
	TPT-60°/s (ms)	519.33 ± 158.63	528.66 ± 173.65	486.00 ± 158.05
	TPT-180°/s (ms)	248.00 ± 45.54	236.00 ± 40.14	226.00 ± 36.41
	AvRFD-60°/s (N/s)	0.47 ± 0.18	0.49 ± 0.17	0.52 ± 0.18
	AvRFD-180°/s (N/s)	0.65 ± 0.15	0.68 ± 0.17	0.71 ± 0.13
	AvPw-60°/s (watts)	130.64 ± 24.26	149.13 ± 32.71	145.56 ± 27.62
	AvPw-180°/s (watts)	223.34 ± 60.01	237.54 ± 55.20	239.10 ± 50.45
	TW-60°/s (Nm)	974.15 ± 120.00	1043.18 ± 103.50	1035.36 ± 122.49
	TW-180°/s (Nm)	825.37 ± 190.00	852.12 ± 159.44	862.94 ± 131.30
	MVIC-45° (Nm)	161.23 ± 37.04	177.60 ± 38.42	175.14 ± 36.46
	MVIC-60° (Nm)	216.27 ± 46.04	233.16 ± 40.17	238.22 ± 37.30
Flexors	APT-60°/s (Nm)	135.52 ± 24.11	143.72 ± 18.76	140.49 ± 15.95
	APT-180°/s (Nm)	95.92 ± 10.62	102.74 ± 16.45	99.96 ± 9.47
	RPT-60°/s (%)	182.66 ± 34.01	192.21 ± 26.43	189.62 ± 26.49
	RPT-180°/s (%)	128.63 ± 17.28	136.72 ± 23.89	134.35 ± 17.57
	AvPT-60°/s (Nm)	125.75 ± 25.11	137.94 ± 20.83	130.96 ± 15.22
	AvPT-180°/s (Nm)	88.21 ± 14.43	97.95 ± 17.29	93.32 ± 11.15
	TPT-60°/s (ms)	419.33 ± 107.00	438.66 ± 150.11	496.00 ± 130.70
	TPT-180°/s (ms)	230.56 ± 65.30	203.33 ± 32.87	204.00 ± 47.47
	AvRFD-60°/s (N/s)	0.29 ± 0.11	0.36 ± 0.11	0.35 ± 0.08
	AvRFD-180°/s (N/s)	0.45 ± 0.15	0.52 ± 0.13	0.51 ± 0.12
	AvPw-60°/s (watts)	94.13 ± 21.78	105.71 ± 18.85	100.72 ± 13.00
	AvPw-180°/s (watts)	153.02 ± 43.53	180.69 ± 46.69	167.77 ± 34.99
	TW-60°/s (Nm)	748.94 ± 132.80	794.84 ± 127.30	780.06 ± 120.22
	TW-180°/s (Nm)	547.47 ± 89.04	607.08 ± 121.89	591.54 ± 73.82
	MVIC-45° (Nm)	144.90 ± 21.60	149.13 ± 19.07	145.82 ± 23.00
	MVIC-60° (Nm)	142.24 ± 21.27	152.06 ± 25.67	144.51 ± 18.15
	VJH (cm)	39.40 ± 5.53	41.60 ± 5.42	41.80 ± 5.88

PLA: Placebo, CC: Caffeine Capsule, CG: Caffeinated Chewing Gum, APT: Absolute Peak Torque, RPT: Relative Peak Torque, AvPT: Average Peak Torque, TPT: Time to Peak Torque, AvRFD: Average Rate of Force Development, AvPw: Average Power, TW: Total Work, MVIC: Maximum Voluntary Isometric Contraction, VJH: Vertical Jump Height, Nm: Newton meter, ms: millisecond, N/s: Newton per second, cm: centimeter.

demonstrated that there were no differences in APT-60°/s ($F_{1.35} = 1.97$, $p = 0.174$, $pEta^2 = 0.124$), APT-180°/s ($F_{1.22} = 2.88$, $p = 0.101$, $pEta^2 = 0.171$), RPT-60°/s ($F_{1.49} = 1.69$, $p = 0.211$, $pEta^2 = 0.108$), RPT-180°/s ($F_{1.24} = 2.25$, $p = 0.148$, $pEta^2 = 0.139$), AvPT-60°/s ($F_{1.50} = 3.18$, $p = 0.074$, $pEta^2 = 0.185$), AvPT-180°/s ($F_{1.53} = 3.50$, $p = 0.069$, $pEta^2 = 0.200$), TPT-180°/s ($F_{1.64} = 1.53$, $p = 0.236$, $pEta^2 = 0.099$), AvRFD-180°/s ($F_{1.99} = 1.32$, $p = 0.282$, $pEta^2 = 0.087$), AvPw-60°/s ($F_{1.64} = 3.61$, $p = 0.051$, $pEta^2 = 0.205$), TW-60°/s ($F_{1.49} = 0.95$, $p = 0.376$, $pEta^2 = 0.064$), TW-180°/s ($F_{1.19} = 2.41$, $p = 0.108$, $pEta^2 = 0.147$), MVIC-45° ($F_{1.95} = 0.33$, $p = 0.716$, $pEta^2 = 0.023$), and MVIC-60° ($F_{1.85} = 3.01$, $p = 0.070$, $pEta^2 = 0.177$) (Figure 4). All of these results are reported in Table 4.

3.3. Vertical jump height

Statistical data analysis showed that the main effect in VJH was significant ($F_{1.68} = 18.55$, $p = 0.001$, $pEta^2 = 0.570$). The results of the Bonferroni test indicated that VJH was higher in CC ($p = 0.001$) and CG ($p = 0.001$) compared to PLA; however, there were no differences between CC and CG ($p = 1.000$) (Figure 5) (Table 4).

Table 3. Individual-level performance changes based on SWC analysis across CC, CG, and PLA conditions.

	Variables	SWC (0.2 × SD_{PLA})	Responders CC (n)	Responders CG (n)	Co-responders CC and CG (n)	Responders CC (%)	Responders CG (%)	Co-responders CC and CG (%)
Extensors	APT-60°/s (Nm)	7.53	8	8	6	53%	53%	40%
	APT-180°/s (Nm)	5.64	3	6	2	20%	40%	13%
	RPT-60°/s (%)	6.59	9	9	7	60%	60%	46%
	RPT-180°/s (%)	5.79	8	6	5	53%	40%	33%
	AvPT-60°/s (Nm)	6.30	12	10	9	80%	66%	60%
	AvPT-180°/s (Nm)	5.75	7	5	3	46%	33%	20%
	TPT-60°/s (ms)	31.72	8	6	5	53%	40%	33%
	TPT-180°/s (ms)	9.10	6	4	2	40%	26%	13%
	AvRFD-60°/s (N/s)	0.03	9	9	7	60%	60%	46%
	AvRFD-180°/s (N/s)	0.03	8	8	6	53%	53%	40%
	AvPw-60°/s (watts)	4.85	12	12	10	80%	80%	66%
	AvPw-180°/s (watts)	12.00	7	9	4	46%	60%	26%
	TW-60°/s (Nm)	24.00	10	8	5	66%	53%	33%
	TW-180°/s (Nm)	38.00	6	9	5	40%	60%	33%
	MVIC-45° (Nm)	7.40	12	9	9	80%	60%	60%
	MVIC-60° (Nm)	9.20	12	10	9	80%	66%	60%
Flexors	APT-60°/s (Nm)	4.82	8	7	6	53%	46%	40%
	APT-180°/s (Nm)	2.12	9	8	6	60%	53%	40%
	RPT-60°/s (%)	6.80	7	7	5	46%	46%	33%
	RPT-180°/s (%)	3.45	8	8	5	53%	53%	33%
	AvPT-60°/s (Nm)	5.02	9	9	8	60%	60%	53%
	AvPT-180°/s (Nm)	2.88	10	9	8	66%	60%	53%
	TPT-60°/s (ms)	21.40	6	11	7	40%	73%	46%
	TPT-180°/s (ms)	13.06	3	5	1	20%	33%	6%
	AvRFD-60°/s (N/s)	0.02	10	10	7	66%	66%	46%
	AvRFD-180°/s (N/s)	0.03	6	8	4	40%	53%	26%
	AvPw-60°/s (watts)	4.35	8	8	7	53%	53%	46%
	AvPw-180°/s (watts)	8.70	8	9	7	53%	60%	46%
	TW-60°/s (Nm)	26.56	7	8	6	46%	53%	40%
	TW-180°/s (Nm)	17.80	10	8	8	66%	53%	53%
	MVIC-45° (Nm)	4.32	6	5	4	40%	33%	26%
	MVIC-60° (Nm)	4.25	13	6	6	86%	40%	40%
	VJH (cm)	1.10	11	10	8	73%	66%	53%

SWC: Smallest Worthwhile Change, PLA: Placebo, CC: Caffeine Capsule, CG: Caffeinated Chewing Gum, APT: Absolute Peak Torque, RPT: Relative Peak Torque, AvPT: Average Peak Torque, TPT: Time to Peak Torque, AvRFD: Average Rate of Force Development, AvPw: Average Power, TW: Total Work, MVIC: Maximum Voluntary Isometric Contraction, VJH: Vertical Jump Height, Nm: Newton meter, ms: millisecond, N/s: Newton per second, cm: centimeter.

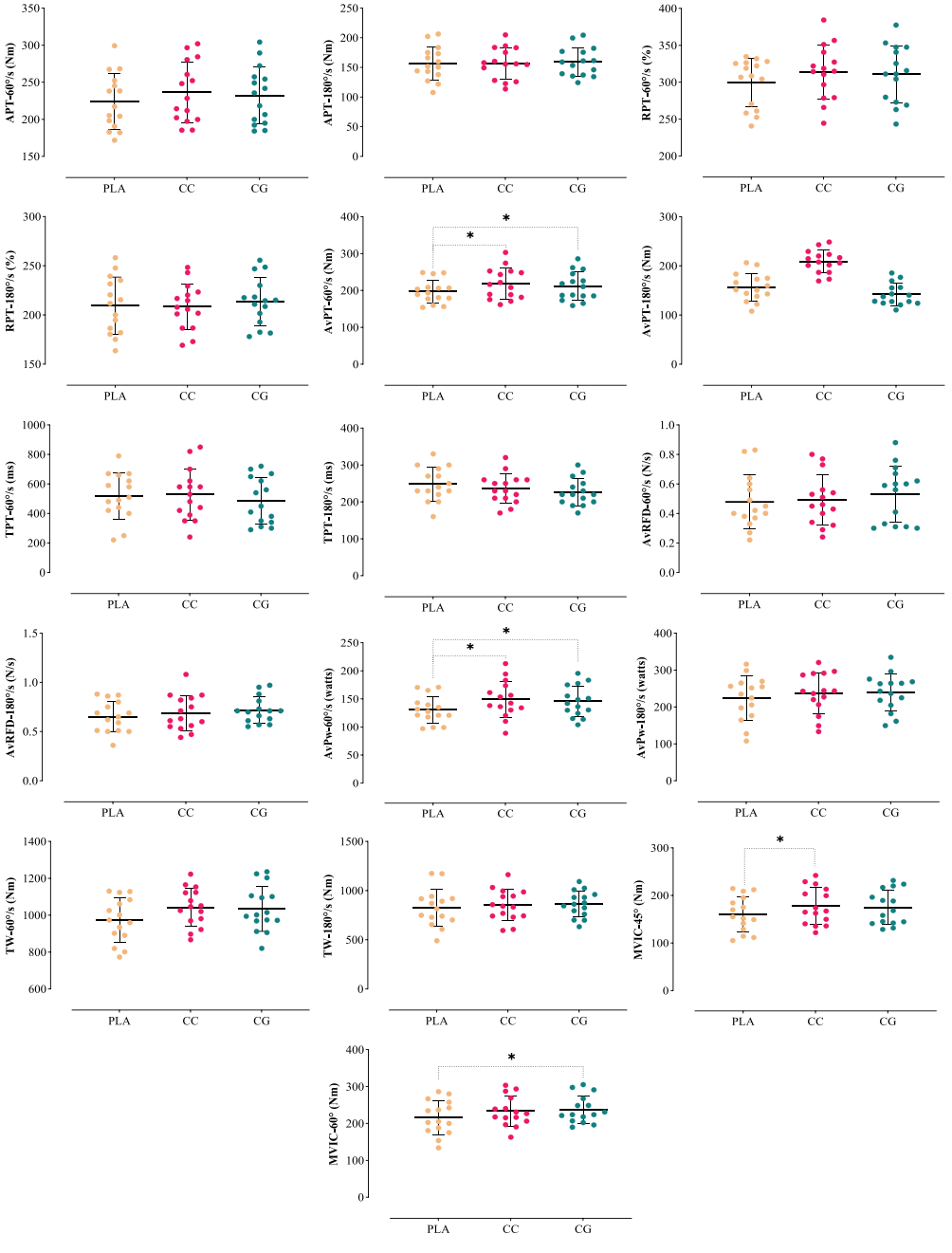

Figure 3. Individual responses and means and standard deviations of the knee extensor isokinetic and isometric parameters in the three conditions. PLA: placebo, CC: caffeine capsule, CG: caffeinated chewing gum. *: Significant difference compared to PLA

Table 4. Comparison of the variables data between three conditions.

			CC ($n = 15$)		CG ($n = 15$)	
Variables			PLA	CG	PLA	CC
Extensors	APT-60°/s (Nm)	MD	12.50	4.24	8.26	− 4.24
		Sig	0.182	1.000	0.367	1.000
		95%CI	− 4.16–29.17	− 10.21–18.69	− 5.40–21.93	− 18.69–10.21
	APT-180°/s (Nm)	MD	0.50	− 2.20	2.70	2.20
		Sig	1.000	1.000	1.000	1.000
		95%CI	− 5.73–6.73	− 11.56–7.15	− 5.75–11.16	− 7.15–11.56
	RPT-60°/s (%)	MD	14.34	2.82	11.52	− 2.82
		Sig	0.276	1.000	0.262	1.000
		95%CI	− 7.20–35.89	− 17.02–22.68	− 5.50–28.54	− 22.68–17.02
	RPT-180°/s (%)	MD	− 1.00	− 5.01	4.01	5.01
		Sig	1.000	0.895	1.000	0.895
		95%CI	− 10.01–8.01	− 17.63–7.60	− 8.10–16.12	− 7.60–17.63
	AvPT-60°/s (Nm)	MD	22.11	7.70	14.41	− 7.70
		Sig	0.045	0.721	0.044	0.721
		95%CI	0.40–43.82	− 9.36–24.76	0.36–28.46	− 24.76–9.36
	AvPT-180°/s (Nm)	MD	5.32	− 0.57	5.90	0.57
		Sig	0.415	1.000	0.341	1.000
		95%CI	− 3.88–14.53	− 10.69–9.54	− 3.60–15.40	− 9.54–10.69
	TPT-60°/s (ms)	MD	9.33	42.66	− 33.33	− 42.66
		Sig	1.000	1.000	1.000	1.000
		95%CI	− 118.45–137.12	− 83.71–169.04	− 143.89–77.22	− 169.04–83.71
	TPT-180°/s (ms)	MD	− 12.00	10.00	− 22.00	− 10.00
		Sig	0.994	0.830	0.368	0.830
		95%CI	− 44.39–20.39	− 14.01–34.01	− 58.38–14.38	− 34.01–14.01
	AvRFD-60°/s (N/s)	MD	0.01	− 0.03	0.05	0.03
		Sig	1.000	1.000	0.905	1.000
		95%CI	− 0.13–0.16	− 0.17–0.10	− 0.07–0.17	− 0.10–0.17
	AvRFD-180°/s (N/s)	MD	0.03	− 0.03	0.06	0.03
		Sig	1.000	1.000	0.392	1.000
		95%CI	− 0.06–0.13	− 0.11–0.05	− 0.04–0.17	− 0.05–0.11
	AvPw-60°/s (watts)	MD	18.48	3.57	14.91	− 3.57
		Sig	0.038	1.000	0.015	1.000
		95%CI	0.92–36.05	− 11.67–18.82	2.76–27.05	− 18.82–11.67
	AvPw-180°/s (watts)	MD	14.20	− 1.56	15.76	1.56
		Sig	0.599	1.000	0.273	1.000
		95%CI	− 14.47–42.87	− 35.03–31.91	− 7.83–39.35	− 31.91–35.03
	TW-60°/s (Nm)	MD	69.02	7.82	61.20	− 7.82
		Sig	0.356	1.000	0.370	1.000
		95%CI	− 43.82–181.87	− 78.16–93.80	− 40.28–162.69	− 93.80–78.16
	TW-180°/s (Nm)	MD	26.75	− 10.81	37.56	10.81
		Sig	1.000	1.000	0.392	1.000
		95%CI	− 66.53–120.04	− 83.13–61.50	− 26.01–101.14	− 61.50–83.13
	MVIC-45° (Nm)	MD	16.37	2.46	13.90	− 2.46
		Sig	0.031	1.000	0.071	1.000
		95%CI	1.36–31.38	− 6.75–11.68	− 0.98–28.80	− 11.68–6.75
	MVIC-60° (Nm)	MD	16.88	− 5.06	21.94	5.06
		Sig	0.304	1.000	0.037	1.000
		95%CI	− 9.28–43.05	− 21.00–10.88	1.21–42.67	− 10.88–21.00

(*Continued*)

Table 4. (Continued).

			CC ($n = 15$)		CG ($n = 15$)	
Variables			PLA	CG	PLA	CC
Flexors	APT-60°/s (Nm)	MD	8.20	3.23	4.97	− 3.23
		Sig	0.428	0.747	0.731	0.747
		95%CI	− 6.15–22.56	− 4.07–10.54	− 6.13–16.07	− 10.54–4.07
	APT-180°/s (Nm)	MD	6.82	2.78	4.04	− 2.78
		Sig	0.241	1.000	0.342	1.000
		95%CI	− 3.00–16.64	− 5.51–11.07	− 0.135–7.94	− 11.07–5.51
	RPT-60°/s (%)	MD	9.55	2.59	6.96	− 2.59
		Sig	0.502	1.000	0.666	1.000
		95%CI	− 8.28–27.38	− 7.52–12.70	− 7.84–21.76	− 12.70–7.52
	RPT-180°/s (%)	MD	8.09	2.37	5.72	− 2.37
		Sig	0.380	1.000	0.613	1.000
		95%CI	− 5.45–21.63	− 8.84–13.59	− 0.13–11.30	− 13.59–8.84
	AvPT-60°/s (Nm)	MD	12.19	6.98	5.21	− 6.98
		Sig	0.175	0.175	0.920	0.175
		95%CI	− 3.87–28.26	− 2.22–16.18	− 8.14–18.57	− 16.18–2.22
	AvPT-180°/s (Nm)	MD	9.74	4.63	5.10	− 4.63
		Sig	0.123	0.780	0.185	0.780
		95%CI	− 2.01–21.49	− 6.09–15.35	− 1.72–11.94	− 15.35–6.09
	TPT-60°/s (ms)	MD	19.33	− 57.33	76.66	57.33
		Sig	1.000	0.124	0.011	0.124
		95%CI	− 62.99–101.65	− 126.67–12.00	17.08–136.24	− 12.00–126.67
	TPT-180°/s (ms)	MD	− 27.23	− 0.66	− 26.65	0.66
		Sig	0.435	1.000	0.679	1.000
		95%CI	− 75.16–20.69	− 38.12–36.79	− 83.61–30.48	− 36.79–38.12
	AvRFD-60°/s (N/s)	MD	0.06	0.01	0.05	− 0.01
		Sig	0.007	1.000	0.050	1.000
		95%CI	0.01–0.11	− 0.05–0.07	0.00–0.11	− 0.07–0.05
	AvRFD-180°/s (N/s)	MD	0.07	0.00	0.06	0.00
		Sig	0.495	1.000	0.615	1.000
		95%CI	− 0.06–0.20	− 0.11–0.13	− 0.06–0.18	− 0.13–0.11
	AvPw-60°/s (watts)	MD	11.58	4.99	6.58	− 4.99
		Sig	0.130	0.564	0.362	0.564
		95%CI	− 2.59–25.75	− 4.80–14.79	− 4.24–17.41	− 14.79–4.80
	AvPw-180°/s (watts)	MD	27.67	12.92	14.75	− 12.92
		Sig	0.033	0.565	0.075	0.565
		95%CI	− 2.26–57.60	− 12.47–38.31	1.04–28.46	− 38.31–12.47
	TW-60°/s (Nm)	MD	45.89	14.77	31.12	− 14.77
		Sig	0.899	1.000	0.830	1.000
		95%CI	− 69.90–161.69	− 65.72–95.26	− 43.61–105.85	− 95.26–65.72
	TW-180°/s (Nm)	MD	59.61	15.54	44.06	− 15.54
		Sig	0.371	1.000	0.416	1.000
		95%CI	− 39.27–158.50	− 63.91–95.00	− 5.53–82.60	− 95.00–63.91
	MVIC-45° (Nm)	MD	4.22	3.31	0.91	− 3.31
		Sig	1.000	1.000	1.000	1.000
		95%CI	− 9.51–17.97	− 12.38–19.01	− 14.11–15.94	− 19.01–12.38
	MVIC-60° (Nm)	MD	9.82	7.54	2.27	− 7.54
		Sig	0.166	0.183	1.000	0.183
		95%CI	− 2.93–22.57	− 2.51–17.61	− 8.89–13.44	− 17.61–2.51
	VJH (cm)	MD	2.20	− 0.20	2.40	0.20
		Sig	0.001	1.000	0.001	1.000
		95%CI	1.23–3.16	− 1.60–1.20	1.25–3.55	− 1.20–1.60

PLA: Placebo, CC: Caffeine Capsule, CG: Caffeinated Chewing Gum, MD: Mean Difference, CI: Confidence Interval, APT: Absolute Peak Torque, RPT: Relative Peak Torque, AvPT: Average Peak Torque, TPT: Time to Peak Torque, AvRFD: Average Rate of Force Development, AvPw: Average Power, TW: Total Work, MVIC: Maximum Voluntary Isometric Contraction, VJH: Vertical Jump Height, Nm: Newton meter, ms: millisecond, N/s: Newton per second, cm: centimeter.

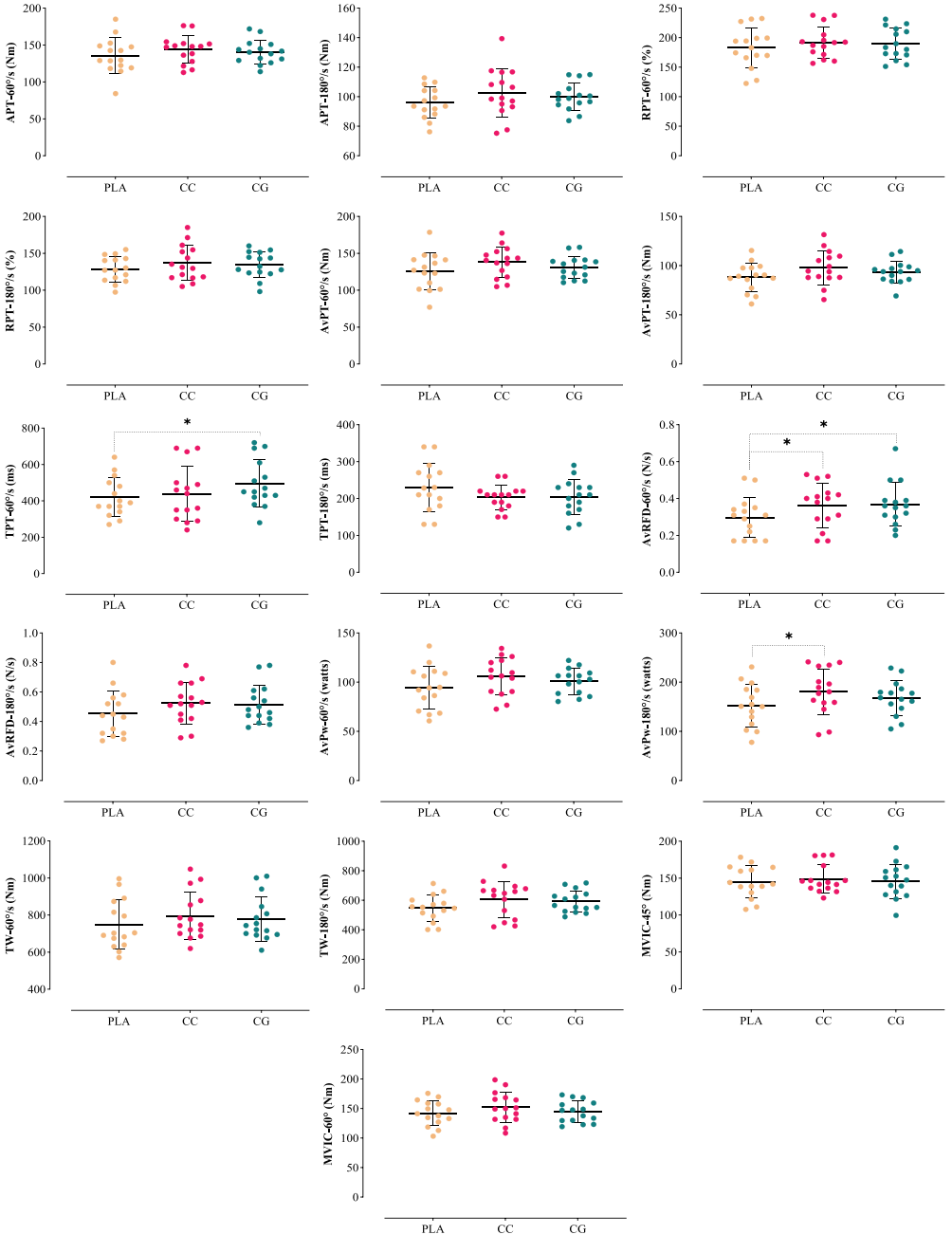

Figure 4. Individual responses and means and standard deviations of the knee flexor isokinetic and isometric parameters in the three conditions. PLA: placebo, CC: caffeine capsule, CG: caffeinated chewing gum. *: Significant difference compared to PLA.

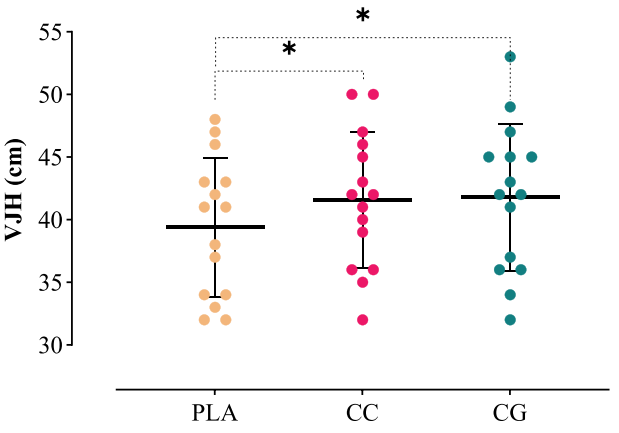

Figure 5. Individual responses and means and standard deviations of the vertical jump height (VJH) in the three conditions. PLA: placebo, CC: caffeine capsule, CG: caffeinated chewing gum. *: Significant difference compared to PLA.

3.4. Individual responses: smallest worthwhile change (SWC) analysis

The analysis of individual-level performance changes using the SWC approach provides detailed insights into the effectiveness of CC and CG supplementation compared to the PLA condition. This analysis emphasizes the extent of response variability among participants across key performance indicators for knee extensors, flexors, and VJH. Table 3 presents the analysis of individual-level performance changes using the SWC approach. Below is a summary of the findings:

3.5. Knee extensor parameters

The SWC analysis for knee extensor parameters revealed significant improvements with both CC and CG supplementation compared to the PLA condition. For AvPT-60°/s, 80% of participants in the CC condition and 66% in the CG condition showed improvements exceeding the SWC threshold, with a co-response rate of 60%. Similarly, AvPw-60°/s demonstrated an 80% responder rate in both CC and CG conditions, with 66% of participants benefiting from both. Additionally, MVIC-60° improved in 80% of participants in the CC condition and 66% in the CG condition, with a co-response rate of 60%. These results indicate that caffeine supplementation, regardless of form, effectively enhances isokinetic and isometric strength parameters of the knee extensors, with CC showing slightly higher responder rates.

3.6. Knee flexor parameters

The SWC analysis for knee flexor parameters indicated notable improvements in performance metrics with CC and CG supplementation compared to the PLA. For AvPT-60°/s, both CC and CG showed a 60% responder rate, with a co-response rate of 53%. Similarly, AvPw-180°/s improved in 66% of participants in the CC and 60% in the CG conditions, with 46% responding positively to both. TPT-60°/s demonstrated the most robust

response for CG, with 73% of participants exceeding the SWC threshold compared to 40% in CC. Additionally, the AvRFD-60°/s showed equal responder rates of 66% for both CC and CG, with 46% of participants benefiting from both. These results underscore the efficacy of caffeine supplementation in enhancing knee flexor performance, with CG providing slightly superior effects in time-dependent parameters like TPT-60°/s.

3.7. Vertical jump height (VJH)

VJH improvements were recorded for 73% of participants in the CC condition and 66% in the CG condition, with a co-response rate of 53%. This finding underlines the positive impact of caffeine supplementation on explosive power and functional performance.

4. Discussion

This study investigated the effects of short-term consumption of caffeine capsules compared to caffeinated chewing gum on strength-trained males' lower-body strength and power performance. In short, the results of the present study showed that in knee extensors, the AvPT-60°/s and AvPw-60°/s were higher in CC (+ 11.22% and + 14.15%) and CG (+ 7.32% and + 11.42%) compared to PLA, the MVIC-45° increased in CC (+ 10.15%) compared to PLA, and the MVIC-60° was substantially higher in CG (+ 10.15%) compared to PLA. Also, in knee flexors, the TPT-60°/s was higher in CG (+ 18.28%) compared to PLA, the AvRFD-60°/s was considerably higher in CC (+ 24.14%) and CG (+ 20.69%) compared to PLA, and the AvPw-180°/s was markedly higher in CC (+ 18.08%) compared to PLA. Eventually, the VJH was higher in CC (+ 5.58%) and CG (+ 6.09%) than in PLA. However, there were no differences in other strength parameters of the knee extensors and flexors in the different experimental conditions. Additionally, the SWC analysis showed that both CC and CG significantly improved performance, with over ~ 50% of participants surpassing SWC thresholds in key strength and power metrics. CC demonstrated higher responder rates for strength parameters, while CG excelled in time-dependent measures like TPT-60°/s. Both supplements effectively enhanced vertical jump height, supporting their ergogenic potential. This variability in individual responses may be influenced by genetic factors, such as Cytochrome P450 1A2 (CYP1A2) and Adenosine A2A receptor (ADORA2A) polymorphisms, which affect caffeine metabolism and sensitivity, as well as habitual caffeine consumption patterns. These insights highlight the potential benefits of incorporating genetic profiling and developing individualized caffeine dosing strategies in future research to optimize performance outcomes through targeted caffeine supplementation.

Some studies align with the present study's results [17,32,33,61–63]. For example, in the study of Venier et al., 19 resistance-trained men consumed, in randomized, counterbalanced order, caffeinated chewing gum (300 mg of caffeine) and completed isokinetic knee extension, and knee flexion at angular velocities of 60°/s and 180°/s. Caffeinated chewing gum enhanced knee extension peak torque and average power at 60°/s, knee extension average power at 180°/s and knee flexion peak torque at 60°/s and 180°/s [32]. Also, Behrens et al. investigated the effects of caffeine ingestion on MVIC and voluntary activation of the quadriceps during isometric, concentric, and eccentric contractions. They found that caffeine increased by 6% for the explosive voluntary strength of the triceps surae [17]. In addition, Scapec et al. in 2024 showed improvements in muscular endurance

(+8.3%), strength (+5.3%), or power (+1.0%) when caffeine was consumed in isolation or combination with paracetamol on 29 resistance-trained athletes [63]. On the other hand, some studies are inconsistent with the present study [31,41]. For example, Dittrich et al. showed that there was a reduction of MVIC after exercise for caffeinated chewing gum condition (300 mg of caffeine) in twelve trained male endurance runners [31]. It seems that the different protocols used make some comparisons difficult, and it can cause contradictory results. Additionally, Peterson et al., in a study conducted on healthy male students, found that consuming a caffeinated drink (6 mg per kg of body weight) during the isokinetic knee extension test at angular velocities of 60, 180, and 300°/s did not change peak torque values between caffeine and PLA conditions [41]. Contrary to the findings of Peterson et al., the present study observed that in knee extensors, the AvPT-60°/s was higher in CC (+11.22%) and CG (+7.32%) compared to PLA. Additionally, individual responses revealed that in the AvPT-60°/s, 80% of participants in the CC condition and 66% in the CG condition demonstrated performance improvements exceeding the SWC threshold compared to PLA, with a co-response rate of 60%, indicating that a significant proportion of participants benefited from both forms of caffeine supplementation. For knee flexors, the TPT-60°/s was significantly higher in the CG condition (+18.28%) compared to PLA, with 40% of participants in the CC condition and 73% in the CG condition showing substantial improvements relative to PLA. Despite this, it should be noted that the forms of caffeine consumed are different in these two studies. Additionally, the discrepancies between studies could be due to variations in caffeine delivery methods, dosages, and participant characteristics, such as training status or genetic polymorphisms (CYP1A2, ADORA2A). These factors likely influence individual variability in caffeine metabolism and ergogenic response, as supported by our study's SWC analysis. Future studies should incorporate standardized protocols and genetic profiling to clarify the effects of different caffeine forms on performance outcomes and address the apparent inconsistencies in the literature.

Notably, Grgic et al. [33] reported in a meta-analysis that short-term caffeine consumption significantly enhances isokinetic strength, particularly in the knee extensor muscles and at higher angular velocities. Their subgroup analysis revealed significant differences between caffeine and PLA conditions at 60°/s and 180°/s; no significant effect was observed at 30°/s. These findings align with previous meta-analyses by Warren et al. [64] and Grgic et al. [65], which also highlighted caffeine's pronounced impact on large muscle groups, such as the knee extensors, compared to smaller muscle groups like the elbow flexors. Warren et al. [64] suggested that this discrepancy might be due to a "ceiling effect" in smaller muscle groups, where motor units are already maximally recruited (up to **99%** during maximal voluntary contraction), leaving less room for improvement through increased central excitability and motor unit recruitment induced by caffeine. Moreover, the superior performance of CG in time-dependent measures, such as TPT-60°/s, may be attributed to its faster absorption rate through the buccal mucosa, leading to a quicker onset of caffeine's ergogenic effects [24]. Conversely, the higher responder rates observed with CC in strength parameters might reflect the more consistent and sustained release of caffeine through gastrointestinal absorption, which could benefit strength-based tasks requiring prolonged muscle activation. However, the study's methodological limitations must be acknowledged, as they may have influenced these outcomes. The absence

of a placebo chewing gum and incomplete participant blinding due to the distinct physical forms of CC and CG could introduce bias. Additionally, while the SWC analysis provided insights into individual variability, the study did not assess genetic polymorphisms (CYP1A2, ADORA2A) that might explain differential responses to caffeine.

Caffeine does appear to have some direct effects on muscle which may contribute to its ergogenicity. The most likely pathway that caffeine may benefit muscle contraction is through Ca^{2+} mobilization, which facilitates force production by each motor unit [64,66]. Fatigue caused by the gradual reduction of Ca^{2+} release may be attenuated after caffeine ingestion [67]. Similarly, caffeine may work, in part, in the periphery through increased sodium/potassium (Na^{+}/K^{+}) pump activity to potentially enhance the excitation-contraction coupling necessary for muscle contraction [68]. Caffeine appears to employ its effects at various locations in the body, but the most robust evidence suggests that the main target is the CNS, which is now widely accepted as the primary mechanism by which caffeine alters mental and physical performance [69]. Caffeine is believed to exert its effects on the CNS via the antagonism of adenosine receptors, leading to increases in neurotransmitter release, motor unit firing rates, and pain suppression [62,70]. In addition to increasing motor unit recruitment, it has been shown that caffeine consumption can reduce the perception of pain and may contribute to increased strength [71]. It is generally accepted that one of the mechanisms of action of caffeine on performance is its effects on adenosine receptors (central mechanisms) [71,72]. Caffeine is a competitive adenosine receptor antagonist and, therefore, after consumption, binds to adenosine A_1 and A_2a receptors, reducing the feeling of fatigue and ultimately leading to improved exercise performance [71]. Due to its analgesic properties, caffeine is used in various pain medications. Motl et al., in a study, reported a reduction in pain perception after caffeine consumption during long-term aerobic exercise [73]. Only one of the 10 studies was included in the meta-analysis of Grgic et al. [65], which examined the effects of caffeine on strength and its relationship with the amount of pain perception. Tallis and Yavuz [61] reported no effect of caffeine on pain perception. However, a significant increase in maximal knee extensor muscle torque was observed at both 3 and 6 mg/kg body weight caffeine doses. These results suggest that different mechanisms contribute to improved performance besides reducing pain perception. Also, laboratory studies using isolated muscle fibers commonly report that caffeine administration directly enhances skeletal muscle force production [74,75]. It is believed that the direct effects of caffeine on force production are due to the binding of caffeine to the ryanodine receptor 1 of skeletal muscle, which leads to an increase in the release of calcium ions from the sarcoplasmic reticulum [76,77]. It should be noted, however, that studies using isolated muscle fibers typically use doses of toxic caffeine in humans [76]. Also, according to the results of two studies [78,79] conducted on humans, the participants did resistance exercises to the point of exhaustion after consuming 3 or 6 mg of caffeine per kilogram of body weight. Several neurophysiological parameters were evaluated, and they showed that caffeine consumption improves the average torque and exercise volume by increasing the neuromotor force, thus confirming that caffeine exerts most of its effects on the nervous system. However, in most of the tests of this study, isokinetic and isometric strength indices increased, which can be attributed to the stimulating effects of caffeine on the central nervous system. However, it is obvious that future research is needed in this area before any definitive conclusions can be drawn.

The results of this study demonstrated that VJH improved by + 5.58% in the CC condition and + 6.09% in the CG condition compared to PLA. Additionally, individual response analysis revealed that 73% of participants in the CC condition and 66% in the CG condition experienced significant improvements in VJH relative to PLA. There are some studies in line with the results of the present study [2,3,32]. For example, a study showed that the explosive power of the lower body muscles of female table tennis players (Sargent's jump test) increased with coffee mouth rinsing and caffeinated chewing gum conditions compared to placebo [2]. However, some studies are inconsistent with the present study. For example, Farmani et al. showed that 300 mg of caffeinated chewing gum has no significant effect on Sargent's jump height of male table tennis players [4]. It seems that the nature of sports is the cause of this contradiction between the results of these studies. As mentioned before, caffeine appears to have direct effects on muscle contraction. The proposed pathway is through the mobility of Ca^{2+}, which facilitates the production of force by each motor unit [34]. Caffeine binds to A1 and A2 adenosine receptors and reduces the effect on the parasympathetic system. The synthesis of neurotransmitters such as dopamine and catecholamines [80] at the peripheral level improves the activity of the sodium-potassium pump (Na^{+} - K^{+}) and increases the bioavailability of Ca^{2+} in the myoplasm [81]. Therefore, it is possible that one or a combination of the mentioned factors can cause more and more muscular contraction and, thus, more power by increasing actin binding to myosin. In addition, previous studies have shown that the isokinetic strength of knee extensors [82,83] and knee flexors [84,85] significantly correlates with jumping ability. In the present study, the AvPT-60°/s and AvPw-60°/s in the knee extensors were considerably higher in CC (+ 11.22% and + 14.15%) and CG (+ 7.32% and + 11.42%) compared to PLA. In the knee flexors, the TPT-60°/s was higher in CG compared to PLA, and the AvPw-180°/s was markedly higher in CC compared to PLA, which may improve vertical jump performance. It should be noted that the present study only examined the knee extensors and flexors. However, jumping ability is also influenced by the strength of other leg muscles and contraction modes (eccentric force production) [86]. Therefore, increased jumping ability in CC and CG conditions may also be due to the improvement of other leg muscles' eccentric and concentric strength parameters (hip extensors and plantar flexors). According to the present study, the AvRFD-60°/s improvement in knee flexors may also improve jumping performance. RFD is a parameter that shows how fast an athlete can produce peak force and is calculated with a force-time curve [87]. On the other hand, previous studies have also demonstrated that increased RFD improves jumping ability [88–91]. The improvement in VJH observed in both CC and CG conditions can likely be attributed to the increased AvRFD-60°/s of knee flexors compared to the PLA condition. The individual response analysis further demonstrated that for most measured variables related to knee extensors and flexors, more than 50% of participants in both the CC and CG conditions showed significant improvements beyond the SWC threshold for the placebo. This finding not only reinforces the enhancement in VJH but also highlights the potential ergogenic benefits of both caffeine delivery methods. However, it is essential to consider that individual variability in caffeine response, influenced by genetic polymorphisms (CYP1A2 and ADORA2A) and habitual caffeine consumption, could affect the range of performance outcomes observed.

The findings from the SWC analysis provide compelling evidence of the individual-level variability in response to caffeine supplementation in capsule and chewing gum forms.

For knee extensor parameters, both CC and CG effectively improved AvPT-60°/s and AvPw-60°/s, with 80% of participants exceeding the SWC threshold for these variables in the CC condition and 66% in CG, demonstrating the robust impact of caffeine on lower-body strength. Similarly, knee flexor metrics such as TPT-60°/s and AvRFD-60°/s revealed notable enhancements, particularly with CG supplementation, where 73% of participants exceeded the SWC for TPT-60°/s compared to 40% in CC. VJH improvements further reinforced the efficacy of caffeine, with 73% of participants in CC and 66% in CG showing significant enhancements. These results highlight not only the benefits of caffeine supplementation on strength and power but also underscore the importance of individual response variability, which may be influenced by factors such as genetics, caffeine metabolism and habitual consumption. The data also suggest that while CC tends to produce slightly higher responder rates for strength variables, CG offers a potential advantage in time-sensitive performance metrics. This distinction provides valuable insights for tailoring caffeine supplementation strategies to specific athletic needs.

Genetic variants affect the way we absorb, metabolize, and utilize and excrete nutrients, and gene-diet interactions that affect metabolic pathways relevant to health and performance are now widely recognized [92]. In the field of nutrigenomics, caffeine is the most widely researched compound with several randomized controlled trials investigating the modifying effects of genetic variation on exercise performance [93–96]. Numerous studies have investigated the effect of supplemental caffeine on exercise performance, but there is considerable inter-individual variability in the magnitude of these effects [97–99] or in the lack of an effect [100,101], when compared to placebo. Due to infrequent reporting of individual data, it is difficult to determine the extent to which variation in responses may be occurring. The performance of some individuals is often in stark contrast to the average findings reported, which may conclude beneficial, detrimental, or no effect of caffeine on performance. For example, Roelands et al. [101] reported no ergogenic effect of caffeine in a study involving trained male cyclists. The authors concluded that inter-individual differences in response to caffeine might be responsible for the lack of overall performance improvement, as 50% of subjects improved while 50% worsened, in the caffeine compared to the placebo trial. These inter-individual differences appear to be partly due to variations in genes such as CYP1A2 and possibly ADORA2A, which are associated with caffeine metabolism, sensitivity, and response [102]. Over 95% of caffeine is metabolized by the CYP1A2 enzyme, which is encoded by the CYP1A2 gene and is involved in the demethylation of caffeine into the primary metabolites paraxanthine, theophylline and theobromine [103]. The ADORA2A gene is a key genetic modifier influencing the effects of caffeine on performance. The adenosine A2A receptor, encoded by the ADORA2A gene, is critical in regulating myocardial oxygen demand and enhancing coronary circulation through vasodilation [104,105]. The results of the Smallest Worthwhile Change (SWC) analysis revealed substantial individual variability in response to both forms of caffeine supplementation, with more than 50% of participants surpassing performance thresholds. This variability is consistent with existing evidence suggesting that genetic polymorphisms, particularly in CYP1A2 and ADORA2A, significantly affect caffeine metabolism and performance outcomes [102].

This study had several limitations that should be acknowledged. Firstly, we did not measure plasma caffeine levels after ingesting caffeine capsules (CC) and caffeinated chewing gum (CG). This could have provided valuable insights into caffeine absorption

rates and their relationship with performance outcomes. Additionally, the study exclusively involved strength-trained males, limiting the generalizability of the findings to other populations, including female athletes and individuals with different training backgrounds. The use of the Sargent's Jump Test to assess lower-body explosive power, while practical and standardized, may have been influenced by factors such as motivation and familiarization, and more advanced methods like countermovement jump testing with a force plate could offer greater precision. Methodologically, the absence of a placebo chewing gum and incomplete participant blinding due to the distinct physical forms of the interventions are notable limitations. These factors could have influenced the study outcomes, highlighting the need for future research to incorporate a placebo gum and improved blinding techniques to enhance methodological rigor and the validity of results.

5. Conclusion

This study demonstrates that caffeine supplementation, in both capsule and chewing gum forms, is an effective ergogenic aid for enhancing lower-body strength and power performance in strength-trained males. CC showed higher responder rates for strength parameters, while CG provided distinct benefits in time-dependent measures such as TPT-60°/s, highlighting the potential to tailor caffeine delivery methods based on specific performance goals. The findings also emphasize the importance of considering individual response variability, potentially influenced by genetic factors. These insights support the practical use of both CC and CG as effective strategies for strength-trained athletes. Overall, the study contributes to the growing evidence of caffeine's central and peripheral effects on athletic performance and underscores the need for personalized supplementation approaches in future research.

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ORCID

Mohammad Hemmatinafar http://orcid.org/0000-0001-7585-7592
Mark ET Willems http://orcid.org/0000-0003-4385-8739

Consent for publication

Informed consent was obtained from all individual participants included in the study.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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