Effect of caffeine on maximal strength and power in élite male athletes

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Computerized testing of 20 élite male athletes was performed to determine the effect of $7 \, mg \, kg^{-1}$ caffeine on strength and power of the knee extensors and flexors. Subjects received counterbalanced administrations of either caffeine or a placebo on two separate occasions. Peak torque (T) was measured for knee extension (ET) and flexion (FT) at angular velocities of 30°, 150° and $300° \, s^{-1}$. Additionally, performance for the first 125 ms (TAE) and power (W) were recorded during $300° \, s^{-1}$. Testing sessions were held 1 week apart, at which time the placebo/caffeine administration was reversed. A 2 × 2 repeated measures analysis of variance supplemented with a Neuman-Keuls *post hoc* test showed the following – significant caffeine-related increases ($P < 0.05$) for ET at $30° \, s^{-1}$, ET at $300° \, s^{-1}$, and $ETAE$, and EW at $300° \, s^{-1}$. Dependent t-tests performed for pre- to post-test means showed significant changes for the caffeine group in ET at $30° \, s^{-1}$, FT at $30° \, s^{-1}$, FT at $150° \, s^{-1}$, ET at $300° \, s^{-1}$, FT at $300° \, s^{-1}$, E and $FTAE$, and EW at $300° \, s^{-1}$. No significant effects were found for the placebo trial in any variable. It was concluded that caffeine can favourably affect some strength parameters in highly resistance-trained males. However, differences in subject fibre type, motivation and caffeine sensitivity need to be elucidated.

Keywords: Power, torque, athletes, ergogenic aid

Ingestion of large doses of caffeine has been reported by some of the nation's most élite contemporary athletes for the purpose of attaining an 'edge' in terms of competitive performance. Questionable sources have claimed that one athlete had consumed caffeine capsules equivalent to 41 cups of coffee (approximately 4100 mg of caffeine) before and during competition[1], while yet another athlete had admitted to ingesting an excess of 900 mg of caffeine to obtain an ergogenic effect[2]. Such reports are not isolated. Indeed, for athletes who rely on strength and power such as weightlifters and those involved in track and field events, caffeine use has a long tradition[3]. In an attempt to reduce the abuse of caffeine intake by amateur athletes, the International Olympic Committee and the National Collegiate

Athletic Association in the USA now consider the excessive use of caffeine ($12 \, \mu g \, ml^{-1}$ urine) a violation of their standards[4].

Speculation that caffeine may affect muscle function is based on the drug's actions on isolated nerve and muscle tissue[5,6]. Caffeine affects muscle tissue by direct intramuscular calcium ion manipulation[7,8]. Further, animal studies have shown that in the presence of caffeine, fatigue patterns differ between type I fibres and type II fibres, yet smaller muscles may not be affected to the same extent as larger muscles[9].

As an ergogenic agent, caffeine may improve simple movement speed[10] and long-term endurance[11,12], but similar benefits have not been found for short, exhaustive forms of exercise[13]. Previous studies have failed to show that caffeine affects muscle functions such as strength and power.

In recent caffeine studies, 7 mg of caffeine per kilogram body weight ($mg \, kg^{-1}$) produced no significant effect on power or fatigue during cycle ergometry[14]. No significant differences in grip strength were found after subjects ingested 167, 324 and 500 mg of caffeine[15]. A dose of 500 mg caffeine produced no measurable differences in voluntary contractions, but resulted in significantly greater muscle tension with low-frequency electrical stimulation both before and after fatigue[16]. Furthermore, caffeine failed to produce any significant changes in isometric grip force production, motor unit activation, electromyographic signal or endurance[6]. Previous studies from this laboratory have found no significant changes in isokinetic strength after caffeine ingestion (300 and 600 mg) by untrained subjects[17]. Similarly, $5 \, mg \, kg^{-1}$ caffeine yielded no significant changes in isokinetic strength tests at angular velocities of 30°, 150° and $300° \, s^{-1}$ (Reference 18). However, the authors recommended extending the protocol of their study by using a larger dose of caffeine. Other recommendations include the use of resistance-trained subjects[17], controlling subject selection and the subject's nutritional state[19].

Based on previous findings and recommendations, the purpose of this study was to determine the effect of $7 \, mg \, kg^{-1}$ caffeine on dynamic voluntary maximal strength and power output in highly resistance-trained athletes with similar ($<100 \, mg \, day^{-1}$) caffeine intake.

Subjects

Twenty male, intercollegiate Division I varsity team members in the sport of American football, with a mean(s.d.) age of 21(1.2) years, weight of 101(15) kg and height of 187(9) cm served as subjects for this study. All of the athletes had been competitively recruited by the university and awarded full academic scholarships based on their élite performance and abilities in the sport. Informed consent forms were signed in accordance with university policy. The subjects completed questionnaires addressing weekly caffeine consumption and years of resistance-training experience. Subjects with either high caffeine consumption (>100 mg day^{-1}) or lacking sufficient <2 years) weight training experience were excluded from the study.

Experimental design

Testing sessions (pre- and post-test) were held on two separate occasions. At each session, data for knee flexion and extension were obtained using a Cybex II Dynamometer (Cybex Division of Lumex, Ronkonkoma, New York, USA) interfaced with a Cybex Data Reduction Computer. The dynamometer was gravity corrected and calibrated for range of motion (ROM) using an on-line electrogoniometer, and the lever arm of the apparatus was adjusted for consistent fit of the subject's dominant leg. The testing velocities, but not the number of repetitions, were consistent with that of Bond et al.[18] For each testing session, the subject performed three repetitions at an angular velocity of 30° s^{-1}, three repetitions at 150° s^{-1} and 15 repetitions at 300° s^{-1}, for a total of 21 repetitions. One repetition consisted of moving the leg from a 105° flexed position to full extension and back again. Table 1 presents the measured dependent variables and their abbreviations, the units, and the angular velocity of each variable.

For each of the three sets (three or 15 repetitions), data were collected for mean peak torque (T) for knee extension (ET) and flexion (FT). In addition to these measurements, extension (300 EW) and flexion power (300 FW); extension (300 ETAE) and flexion torque accelerated energy (300 FTAE) were recorded for the set of 15 repetitions at 300° s^{-1}. Torque accelerated energy (TAE), a unique feature of the testing apparatus, measures energy related to the range of motion during the first 125 ms of muscular contraction. As defined by the Cybex Corporation, TAE is a ROM-dependent product of torque and distance[20]

Table 1. Variable names, abbreviations, and units of measurement for each repetitive (Rep) trial at selected angular velocities (Vel)

Rep × Vel movement	Peak T (Nm)	TAE (Joules)	Power (Watts)
3 × 30° s^{-1} Knee extension	30ET	—	—
3 × 30° s^{-1} Knee flexion	30FT	—	—
3 × 150° s^{-1} Knee extension	150ET	—	—
3 × 150° s^{-1} Knee flexion	150FT	—	—
3 × 300° s^{-1} Knee extension	300ET	300ETAE	300EW
3 × 300° s^{-1} Knee flexion	300FT	300FTAE	300FW

and may be measured in Joules (J) or Newton–metres (Nm). An identical testing sequence was followed to avoid differences in fatigue, and 3-min rest periods were allowed between sets. Instructions for testing and encouragement to promote maximal effort were given before testing. Subjects were pre- and post-tested on two separate occasions with random caffeine and placebo crossover administration.

Drug administration

Experimental drug dosage consisted of 7 mg kg^{-1} of caffeine which had been individually prepared according to each subject's body weight. Placebo consisted of 225 mg of methylcellulose. Administration of caffeine and placebo followed a double-blind format with a random counterbalanced design. For the first testing session the subjects were given randomly 150 ml orange juice and identical gelatin capsules containing either the experimental dose or the placebo. At the second testing session the random order of drug/placebo administration was reversed. Immediately after the pre-test, the subjects were given one of the prescribed doses and asked to sit quietly for a minimum of 1 h (Reference 21) before the post-test.

Procedures

To reduce any acquired or residual caffeine tolerance, the subjects were given written information concerning foods with caffeine as an ingredient and advised to abstain from these products for 1 week before testing. As a precaution against dissimilarities in nutritional status[22, 23], the subjects' diets were identical (carbohydrate 50%, fat 30%, protein 20%) for 2 days before each testing session. Subjects were instructed to report to each testing session 8 h postprandial and to refrain from exercise for 48 h before testing. Testing was held at the same time of day (0700 hours) 1 week apart.

Statistical design

A 2 × 2 repeated measure analysis of variance was performed with the two levels of dose administration (caffeine and placebo) serving as the grouping factor and the two levels of testing (pre-test, post-test) serving as the trial factor[24]. A Neuman–Keuls post hoc test was used to ascertain the specific sites of significance. Probability level for significance was set at the $P < 0.05$ level. Additionally, to account for differences in gain score directions, within-group paired t tests were performed.

Results

As determined from the caffeine consumption questionnaire, the mean(s.d.) daily caffeine intake by the subjects was estimated at 72(25) mg. Subjects had been highly active in supervised resistance training for 5(1.8) years. Additionally, all of the subjects indicated that they had followed the directions of diet and caffeine intake as stipulated by the research.

Table 2. Knee extension and flexion, pre- and post-test peak torque means(s.d.) for placebo and caffeine trials at angular velocities of 30°, 150° and 300° s^{-1}

Variables (n = 20)	Mean(s.d.)
30ET pre-caffeine	292.4(59.2)
30ET post-caffeine	315.4(56.0)
30ET pre-placebo	297.3(54.8)
30ET post-placebo	285.1(51.1)
30FT pre-caffeine	196.5(29.5)
30FT post-caffeine	207.2(32.2)
30FT pre-placebo	201.7(33.9)
30FT post-placebo	203.3(34.2)
150ET pre-caffeine	244.5(36.6)
150ET post-caffeine	252.1(40.2)
150ET pre-placebo	236.6(38.0)
150ET post-placebo	199.2(35.0)
150FT pre-caffeine	158.9(22.8)
150FT post-caffeine	167.6(27.8)
150FT pre-placebo	157.6(27.7)
150FT post-placebo	159.1(21.0)
300ET pre-caffeine	155.1(36.5)
300ET post-caffeine	166.5(32.8)
300ET pre-placebo	158.7(27.4)
300ET post-placebo	156.0(24.4)
300FT pre-caffeine	119.1(17.1)
300FT post-caffeine	126.1(21.9)
300FT pre-placebo	119.8(16.8)
300FT post-placebo	212.3(14.3)

Table 3. Knee extension and flexion pre- and post-test torque accelerated energy (TAE in Joules) and power (W in Watts) means(s.d.) for placebo and caffeine trials at 300° s^{-1}

Variables (n = 20)	Mean(s.d.)
300ETAE pre-caffeine	6368.3(1397.5)
300ETAE post-caffeine	6905.5(1304.4)
300ETAE pre-placebo	6480.3(1113.5)
300ETAE post-placebo	6539.1(1016.4)
300FTAE pre-caffeine	4676.3(770.8)
300FTAE post-caffeine	5183.3(948.9)
300FTAE pre-placebo	4766.9(878.8)
300FTAE post-placebo	4923.1(715.9)
300EW pre-caffeine	598.9(134.4)
300EW post-caffeine	633.6(130.3)
300EW pre-placebo	621.2(133.5)
300EW post-placebo	597.3(105.1)
300FW pre-caffeine	452.7(80.8)
300FW post-caffeine	478.1(91.7)
300FW pre-placebo	462.5(82.3)
300FW post-placebo	454.2(67.6)

Table 2 and *Table 3* illustrate pre- and post-test means and standard deviations for all variables tested.

The 2 × 2 repeated measures analysis of variance combined with the *post hoc* procedure revealed significant ($P < 0.05$) between-group differences (*Table 4* and *Table 5*) for four of the ten variables: ET at 30° s^{-1}; ET at 300° s^{-1}; ETAE; and EW at 300° s^{-1}). Significant ($P \leq 0.05$) within-group (pre- to post-test) differences were noted in eight variables for the caffeine group: ET at 30° s^{-1}; FT at 30° s^{-1}; FT at 150° s^{-1}; ET at 300° s^{-1}; FT at 300° s^{-1}; ETAE; FTAE;

Table 4. Knee extension and flexion post-test peak torque (Nm) means(s.d.) and gain scores for placebo and caffeine trials at angular velocities of 30°, 150° and 300° s^{-1}

Variables (n = 20)	Placebo mean(s.d.)	Gain score	Caffeine mean(s.d.)	Gain score
Extension (30ET) 3 × 30° s^{-1}	285.1(51.1)	−12.2	315.4(56.0)	22.6*†
Flexion (30FT) 3 × 30° s^{-1}	203.3(34.2)	1.6	207.2(32.2)	10.7†
Extension (150ET) 3 × 150° s^{-1}	237.7(34.1)	1.0	252.1(40.2)	7.4
Flexion (150FT) 3 × 150° s^{-1}	159.1(21.0)	1.6	167.6(27.8)	8.6†
Extension (300ET) 3 × 150° s^{-1}	156.0(24.4)	−2.8	166.5(32.8)	11.4*†
Flexion (300FT) 3 × 150° s^{-1}	121.3(14.3)	1.5	126.1(21.9)	7.0†

* $P \leq 0.05$ between group significance
† $P \leq 0.05$ within group significance

Table 5. Knee extension and flexion post-test TAE (J) and power (Watts) means(s.d.) and gain scores for placebo and caffeine trials at 300° s^{-1}

Variables (n = 20)	Placebo mean(s.d.)	Gain score	Caffeine mean(s.d.)	Gain score
Extension (300ETAE) 3 × 300° s^{-1} (Joules)	6539(1060)	58.7	6905(1304)	537.1*†
Flexion (300FTAE) 3 × 300° s^{-1} (Joules)	4923(716)	156.1	5183(950)	508.0†
Extension (300EW) 3 × 300° s^{-1} (Watts)	597(105)	−22.9	633.6(130)	34.8*†
Flexion (300FW) 3 × 300° s^{-1} (Watts)	454(67)	−8.3	478(91)	25.4

* $P \leq 0.05$ between group significance
† $P \leq 0.05$ within group significance

and EW at 300° s^{-1}. No significant changes occurred in any of the placebo trials.

Discussion

Studies have demonstrated that, under certain conditions, caffeine may enhance muscle force production and endurance[16, 25]. To date, no studies have reported increases in voluntary strength and/or power resulting from caffeine. The results of our study are more consistent with caffeine studies conducted in vitro[25, 26] than those done in vivo[6, 16–18]. Our data show significant ($P \leq 0.05$) caffeine-related strength and power increases and possible reductions in post-test strength loss in some variables.

Studies *in vitro* have demonstrated that absorption of caffeine by the muscle tissue[5] potentiates isometric twitch tension in stimulated isolated muscle tissue[9, 25] after both rest and fatigue[25]. The effects of caffeine on muscle tissue were attributed to: (1) rapid release of calcium ions from the sarcoplasmic reticulum (SR)[8]; (2) decrease in the rate of calcium ion uptake[7]; (3) increase in the calcium ion permeability of the sarcolemma[27]; (4) loss of membrane integrity by rapid dilation of SR tubules[28]; (5) increased intracellular

cyclic adenosine 5' monophosphate (AMP) levels[29]. Contractures present after caffeine treatment are absent in calcium ion-depleted muscle tissue[30]. Perhaps the most noted difference between in vitro and in vivo studies is that caffeine doses found to be effective in vitro are generally of greater relative magnitude than those obtained in oral, in vivo, administration.

Much of the disagreement in caffeine-related investigations results from differences in experimental protocol[19]. In an attempt to explain our results, several variations from preceding investigations must be addressed. Following the recommendations by previous authors[18], whose equipment and protocol we followed closely, a larger dose of caffeine ($7\,mg\,kg^{-1}$) was used in this study. Likewise, Williams and associates[6,14] used similar doses of caffeine on two separate occasions but failed to find significant changes in isometric strength, time to fatigue, or power. In contrast to our study, they studied pedalling at maximal velocities for 15 s on a cycle ergometer under moderate load[14].

The caffeine-related effects found in our study may be due to the nature and background of our subjects with respect to resistance training and athletic competition. With the exception of one study that used aerobically trained subjects, no other study revealed the training background of their subjects. Given the resistance-type protocol used in assessing strength and power, our subjects' extensive involvement and acquaintance with resistive training may have enhanced the ability to exert maximal effort in each trial.

Caffeine reduces the ability of the SR to store and accumulate calcium ions, and depresses calcium ion release by inhibiting reaccumulation[9]. In animal studies, fatigue patterns of type I muscle fibres are more dramatically affected by caffeine than in type II fibres, presumably because of the sparser SR common to type I fibres[9]. This phenomenon has not been investigated in human caffeine studies[22].

Athletes, those involved in anaerobic compared to those involved in aerobic sports, have differences in fibre-type ratios. Additionally, these athletes possess fibre types different from non-athletes[31]. If the animal models can be applied to humans, it is conceivable that the effects of caffeine may differ in fatigue patterns between those individuals with unbalanced fibre type ratios and those with balanced ratios. In examining our results, it appears that in certain tests a fatigue factor was more prominent in the placebo group than in the caffeine group. However, muscle fibre-type ratio was not examined in this study so one can only speculate on this phenomenon.

It has been documented that specific nutrients may inhibit the effects of caffeine[23]. Diet has been related to carbohydrates and aerobic activity but has not been investigated in anaerobic activity. By controlling the subject's diet for 2 days before testing, possible metabolic interferences may have been reduced. Other than regulating caffeine intake, no methods of diet control were mentioned in other similar investigations.

In conclusion this study shows that it is possible for caffeine ingestion to give rise to some changes in voluntary strength and power output. Furthermore, the experimental doses show that the effects of caffeine may be magnified and the experimental doses may be more indicative of those consumed by some athletes for the purpose of enhancing athletic performance. Although none of our subjects had any adverse reactions to the drug, we recommend that additional investigations exploring the effect of doses more common to abuse should also consider the health of the subjects. Some subjects reported that they felt as if they had performed better following caffeine. Perhaps the stimulating effects of caffeine serve to alter perceived exertion, not unlike results found for treadmill running[19]. Finally, the possibility that caffeine may delay muscular fatigue may be an area worth exploring.

We suggest with some caution that $7\,mg\,kg^{-1}$ of caffeine may enhance strength and power parameters in resistance-trained athletes. It should be noted that extreme levels of caffeine are not only illegal in sanctioned competition, but may present potential health risks during competition, such as exacerbated dehydration and fatigue[32], delirium, anxiety, memory impairment and hallucinations[33].

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Book reviews

Advances in Ergometry
N. Bachl, T. E. Graham and H. Lollgren, eds
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Every conference organizer feels the need to commemorate the event to which he has devoted so much effort by publishing the proceedings. On occasion, the result is an outstanding success – an example which comes to mind is the proceedings of the conference on the Marathon published as volume 301 of the Annals of the New York Academy of Sciences in 1977. More commonly, however, published conference proceedings are a failure, and there are several reasons for this. Keynote papers or reviews by the invited speakers are almost invariably identical to reviews published elsewhere. The abstracts of oral communications or poster sessions offer the opportunity to see some new material, but again, you can be sure that any data of substance will appear in one of the scientific journals.

What then is the value of conference proceedings, and does this volume offer anything of value to the reader? I see two main reasons for reading (as opposed to publishing) conference proceedings. One is speed of publication. Since the refereeing process for papers is considerably shortened, or perhaps omitted altogether, it is possible for the publication time to be shortened to no more than a few months rather than the 1–2 years which now seems to be normal for journals. Second, the less stringent refereeing of conference papers means that the reader can see data that would

otherwise remain unpublished. Keynote speakers often take the opportunity to introduce preliminary or inconclusive results and to speculate in a way that would not be considered acceptable by most journals and their referees. Much of the information that appears in abstract form in conference proceedings never appears as a full paper, and so would be lost to the scientific community.

This volume fails on the first count. We are not told the date of the conference (the Sixth International Seminar on Ergometry), but the publication date is 1991, and the most recent date that I could find in the reference lists is 1989, so I suspect that

N. Bachl T. E. Graham H. Löllgen (Eds.)

Advances in Ergometry

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publication has been a slow process. The review papers are generally disappointing. An outstanding exception to this is the review on lactate metabolism by Terry Graham – although this is not so different from other reviews by the same author, it deserves to be read by everyone working in this area of exercise physiology. This chapter, with its explicit criticism of the anaerobic threshold concept, sits oddly with the large part of the remainder which is concerned with the minutiae of the conduct and interpretation of this test.

Another redeeming feature of this book is the considerable amount of information from scientists working in Europe, and especially in Germany, who do not normally publish in English language journals. This reveals two things – first, many of us must be quite unaware of much of the work that is being done, and second, the converse is also true. Much effort is being devoted to investigating problems which I thought had been resolved many years ago. Although it is good to see established ideas challenged by repetition, and either confirmed or refuted, it is depressing not to see any acknowledgement of the large body of published data which exists. The difficulty of communication is also evident in the quality of the English translation, which makes some of the papers hard to follow.

In conclusion, then, it is difficult to know whether to recommend this book or not, but it is probably worth looking at for Terry Graham's review alone.

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