ACUTE LOW-DOSE CAFFEINE SUPPLEMENTATION INCREASES ELECTROMYOGRAPHIC FATIGUE THRESHOLD IN HEALTHY MEN

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ABSTRACT

Morse, JJ, Pallaska, G, Pierce, PR, Fields, TM, Galen, SS, and Malek, MH. Acute low-dose caffeine supplementation increases electromyographic fatigue threshold in healthy men. *J Strength Cond Res* 30(11): 3236–3241, 2016—The purpose of this study is to determine whether consumption of a single low-dose caffeine drink will delay the onset of the electromyographic fatigue threshold (EMG_{FT}) in the superficial quadriceps femoris muscles. We hypothesize that the EMG_{FT} values for the caffeine condition will be significantly higher than the EMG_{FT} values for the placebo condition. On separate occasions, 10 physically active men performed incremental single-leg knee-extensor ergometry 1 hour after caffeine (200 mg) or placebo consumption. The EMG_{FT} was determined for each participant for both conditions. The results indicated a significant increase for maximal power output (16%; $p = 0.004$) and EMG_{FT} (45%; $p = 0.004$) in the caffeine condition compared with placebo. These findings suggest that acute low-dose caffeine supplementation delays neuromuscular fatigue in the quadriceps femoris muscles.

KEY WORDS exercise physiology, muscular fatigue, single-leg knee-extensor ergometry, quadriceps femoris muscles

INTRODUCTION

Natural products such as coffee beans and tea leaves contain caffeine which are found in various beverages and in over-the-counter medications (17,40). Moreover, caffeine is a stimulant that is on the World Anti-Doping Agency (WADA) Monitoring Program, but not prohibited to athletes. Del Coso et al. (12) examined caffeine consumption among various endurance athletes and found that ~75% of the athletes consumed caffeine before or during their competition. Moreover, studies indicate that caffeine consumption increases tolerance for various modes of exercise such as endurance (11) and/or strength (6) workbouts. The use of caffeine as an ergogenic aid, therefore, resides in the potential to attenuate physiological and potentially cognitive fatigue.

The mechanism of action of caffeine on skeletal muscle function during exercise is equivocal and may, in part, be associated with the duration and mode of exercise (27). For example, studies have suggested that caffeine increases β-oxidation in skeletal muscle and therefore sparing glycogen utilization (27). An alternative mechanism of action for caffeine is related to attenuating the perceptions of exertions and pain (13). It has been suggested that caffeine may act as an antagonist on adenosine receptors in the brain (13). In a recent meta-analysis, Doherty and Smith (14) concluded that caffeine reduced rating of perceived exertion (RPE) by ~5.6% which corresponded to an ~11.2% increase in exercise tolerance. Another factor that needs to be considered in studies examining the role of caffeine in attenuating exercise is the amount of daily caffeine consumption of the participant. Bell and McLellan (7) examine caffeine ingestion in participants who were classified as caffeine users or nonusers. The investigators concluded that individuals who were naive to caffeine consumption had significantly improved exercise tolerance than individuals who were not naive to caffeine consumption (7). Similarly, Mumford et al. (31) reported that low-dose caffeine (~160 mg) increases performance during an 18-hole round of golf and reported less perception of fatigue when compared with the placebo condition.

The majority of studies examining the effects of caffeine consumption on human performance have mainly focused on endurance exercise. To this extent, exercise tolerance is assessed using the time-to-exhaustion criterion which requires participants to exercise at a constant workload intensity until voluntary exhaustion. In their meta-analyses,

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Ganio et al. (19) concluded that caffeine consumption did not significantly improve time-to-exhaustion exercise tolerance. Moreover, this lack of a significant finding was associated with numerous factors such as the participant's habitual exercise regimen and the duration between the caffeine intake and the start of the exercise test (19). In addition, it has been suggested that lower dose caffeine supplementation does not influence peripheral physiological responses such as heart rate and levels of lactate during whole-body exercise (37). Thus, it may be more optimal to examine fatigue at the level of the muscle rather than using an exercise associated with cardiorespiratory fitness.

Surface electromyography (EMG) is a noninvasive method of examining motor unit activation in small (biceps brachii) or large (quadriceps femoris) muscles under different exercise paradigms (3,4,43). The electromyographic fatigue threshold (EMG_{FT}) is theoretically the highest exercise intensity in which a participant can maintain indefinitely without an increase in EMG amplitude in the working muscles (8). Although this mathematical model has been used for multijoint exercise such as treadmill running (23) and cycle ergometry (8), it has been suggested that using a single-joint exercise may be optimal for understanding motor unit activation (29). A number of studies have used the single-leg knee-extensor ergometry mode of exercise to better understand motor unit activation (15,18). This exercise paradigm engages the quadriceps femoris muscles with little to no engagement of other muscles of the lower limb (33). Moreover, Rud and Hallén (36) found that single-leg knee-extensor ergometry required a higher oxygen demand than cycle ergometry. Thus, the EMG_{FT} presents a unique opportunity to examine the effects of various perturbations on motor unit activation.

Although numerous studies have examined the effects of caffeine during continuous exercise, to date, no studies have examined the effects of caffeine on the estimation of the EMG_{FT} for single-leg knee-extensor ergometry. The purpose of this study, therefore, is to determine whether consumption of a single low-dose caffeine drink will delay the onset of neuromuscular fatigue in the superficial quadriceps femoris muscles. We hypothesize that the EMG_{FT} values for the caffeine condition will be significantly higher than the EMG_{FT} values for the placebo condition.

Methods

Experimental Approach to the Problem

Each participant visited the laboratory on 3 separate occasions during a 3-week period. The initial visit included consent and orientation to the single-leg knee-extensor ergometry, whereas the 2 other visits were the testing sessions which required the participant to consume either the placebo or caffeine in a random order. In addition, during the testing sessions, each participant had EMG electrodes placed on their superficial quadriceps femoris muscles to determine the EMG_{FT}.

Subjects

Ten healthy college-aged men (mean ± *SEM*, age = 23.0 ± 0.4 years; weight = 80.6 ± 3.5 kg) were recruited from the university student population. Overall, the participants maintained an active lifestyle most days of the week involving activities ranging from running, biking, and/or weight lifting. The participants were asked to refrain from exercise 24 hours before the testing session. Although there were no dietary restrictions, each participant was asked to refrain from caffeine consumption 24 hours before the testing session. We did not have participants complete a 7-day caffeine consumption log because we did not want them to alter their daily caffeine intake as they became aware of how much caffeine they consumed daily. All participants, however, indicated that they consumed more than 200 mg dose operationally defined as equivalent to 2 cups of 8 fl. Oz. of coffee. Furthermore, the testing sessions for each participant were performed at relatively the same time (±1 hour) for each session. All procedures were approved by the University Institutional Review Board for Human Subjects, and each participant signed an informed consent before testing.

Placebo and Caffeine Drink

For visits 2 and 3, we used a double-blinded randomized placebo-controlled crossover approach. Thus, the participant was asked to consume either an 8 oz. bottle of water with dissolved crystal light (placebo) or an 8 oz. bottle of water with dissolved crystal light and Vivarin (200 mg caffeine). After consumption of the placebo or caffeine drink, participants rested in the laboratory for 1 hour before performing the incremental single-leg knee-extensor ergometry. This interval was used to be consistent with our previous studies on acute caffeine consumption (5,40). Moreover, it has been shown that plasma caffeine concentration increases 1 hour after consumption in a dose-related manner (21).

Incremental Single-Leg Knee Extensor

The single-leg knee-extensor ergometry has been used previously in our laboratory (15) and exclusively focuses the exercise demand on the quadriceps femoris muscles. Briefly, each participant was semirecumbent in an adjustable chair with a special ankle boot placed on the nondominant leg and connected by a bar to the ergometer. The dominant leg was on a platform attached to the knee-extensor device. Contractions of the quadriceps muscles caused the lower part of the leg to extend through an angle of ~90°–~10°. Therefore, the lower leg traveled with an arc-shaped trajectory of approximately 80° in an alternating manner. The momentum of the ergometer returned the relaxed leg passively to the start position and, as a result, the quadriceps muscle was functionally isolated. After a period of stabilization at rest, participants began kicking at 5 W for 2 minutes. The power output was then increased by 5 W every 2 minutes throughout the test until participants reached volitional fatigue. The cadence during the exercise workout was maintained at 70 revolutions per minute (15).

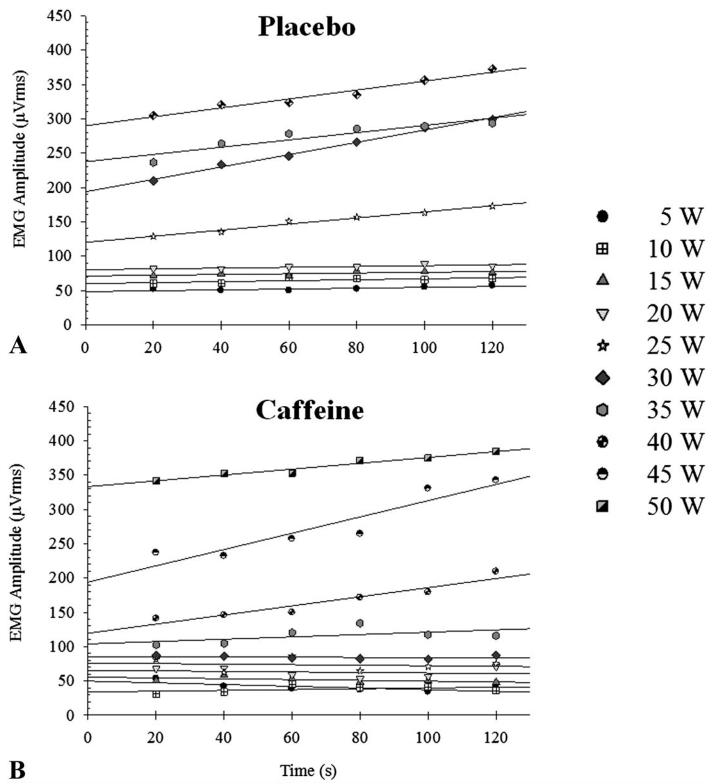

Figure 1. Example of the incremental single-leg knee-extensor ergometry for the placebo and caffeine conditions for 1 participant. The EMG_{FT} was operationally defined as the average of the highest power output that resulted in a nonsignificant slope coefficient ($p > 0.05$) and the lowest power output that resulted in a significant ($p \leq 0.05$) positive slope coefficient. Thus, in panel (A), the highest power output with a nonsignificant slope was 20 W, whereas the lowest power output with a significant positive coefficient was 25 W; therefore, 22.5 (23 W) is the estimated EMG_{FT}. For panel (B), the estimated EMG_{FT} was $(30 + 35)/2 = 32.5$ (33 W). EMG = electromyography; EMG_{FT} = electromyographic fatigue threshold.

Termination of the exercise test was determined if the participant met the following criteria: (a) RPE of 8 or higher and (b) inability to maintain the targeted kicking cadence despite strong verbal encouragement (15).

Electromyography

Electrode Placement

Three separate bipolar (20 mm center to center) surface electrode (EL500-6; BIOPAC Systems, Inc., Santa Barbara, CA) arrangements were positioned over the longitudinal axes of the vastus lateralis, rectus femoris, and vastus medialis muscles. These sites were traced with a permanent marker for the subsequent visit to maintain the consistency of the electrode placement. The electrodes for the vastus lateralis were placed over the lateral portion of the muscle at approximately 2/3 from the anterior superior iliac spine to the lateral side of the patella (24). For the rectus femoris muscle, the electrodes were placed at 50% of the distance between the anterior superior iliac spine and the superior border of the patella (24). For the vastus medialis muscle, the electrodes were placed 80% of the distance between the medial gap of the knee joint and the anterior superior iliac spine (24). The reference electrode was placed over the iliac crest. The shaved skin at each electrode site was carefully abraded and cleaned with alcohol, and interelectrode impedance was kept below 2,000 ohms. The EMG signal from each electrode placement site was amplified (gain: ×1,000) using differential amplifiers (EMG 100B; BIOPAC Systems, Inc.).

Table 1. Results from the placebo and caffeine conditions for various physiological indices.*

Physiological outcomes	Placebo	Caffeine
Maximal power output (W)	38 ± 2	44 ± 3†
Electromyographic fatigue threshold (W)	20 ± 2	29 ± 2‡
Maximal heart rate ($b \cdot min^{-1}$)	147 ± 3	154 ± 3§
Maximal heart rate (% predicted; 220-age)	74.6 ± 1.7	78.5 ± 1.6§
Rating of perceived exertion (0–10 scale)	9 ± 0	9 ± 0

*Mean ± *SEM*.
†Significantly ($p = 0.002$) different between conditions.
‡Significantly ($p = 0.004$) different between conditions.
§Significantly ($p = 0.042$) different between conditions.

Electromyographic Signal Acquisition and Processing

During the 2 exercise sessions, the raw EMG signals were digitized at 1,000 Hz and stored in a personal computer (Dell Inspiron E1705; Dell Inc., Round Rock, TX) for subsequent analysis. All signal processing was performed using custom programs written with LabVIEW programming software (version 2014; National Instruments, Austin, TX). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10–500 Hz and the amplitude (microvolts root mean square, μVrms) value was used to determine the EMG_{FT}.

Determination of Electromyographic Fatigue Threshold

For both placebo and caffeine conditions, the EMG amplitude was calculated from 10-second epochs in 20-second intervals for each 2-minute stage and then plotted vs. time (Figure 1). Thereafter, linear regression was performed to determine whether there was a significant increase in EMG amplitude across time for each power output. The EMG_{FT} was operationally defined as the average of the highest power output that resulted in a nonsignificant slope coefficient ($p > 0.05$) and the lowest power output that resulted in a significant ($p \leq 0.05$) positive slope coefficient.

Although we collected the EMG signal from all 3 superficial quadriceps femoris muscles, we estimated the EMG_{FT} from the rectus femoris muscle only. This was done purposefully because studies show that this muscle has the highest activation relative to the vastus lateralis and vastus medialis muscles (33). Moreover, Mahmutović et al. (28) reported no significant mean differences for the EMG_{FT} values across these 3 superficial quadriceps femoris muscles.

Statistical Analyses

All data presented in this investigation are mean ± *SEM*. As described in detail above, linear regression was used to determine the EMG_{FT}. The EMG_{FT} estimated from the placebo and caffeine conditions was compared using a paired samples *t*-test. All statistical significance was set at $p \leq 0.05$.

Results

Exercise and Electromyographic Fatigue Threshold Outcomes

As shown in Table 1, the mean maximal power output achieved for the single-leg knee-extensor was 15.8% greater when caffeine was consumed than placebo. Moreover, the mean EMG_{FT} was significantly (45%) greater during the caffeine condition compared with placebo. When the EMG_{FT} for the caffeine condition was normalized to the maximal power output for the placebo condition, there was a significant increase (51.0 ± 4.1% vs. 75.9 ± 4.2%; $p < 0.001$). We also found that there was a slight (~5%), but significant increase in the absolute and normalized heart rate responses.

Discussion

The main and unique finding of this study was that a single low dose of caffeine, consumed 1 hour before exercise, increased EMG_{FT} compared with placebo. Although we used an absolute caffeine dose (200 mg), this corresponded to a relative dose of 2.5 ($SEM = 0.1$ mg·kg^{-1}) which is considered low relative to most studies examining the interaction of caffeine and exercise performance (14). Moreover, we found that participants were able to achieve a higher maximal power output in the caffeine condition than the placebo condition. To our knowledge, this is the first study to show that the EMG_{FT} may be influenced by acute caffeine supplementation.

The effect of acute caffeine supplementation for enhancing physical performance is equivocal. Beck et al. (5) reported that a single absolute dose (~201 mg) of caffeine taken 1 hour before the testing session did not significantly improve bilateral 1 repetition maximum (RM) leg extension or total volume of weight lifted during an endurance test with 80% of the 1RM. The investigators, however, found a significant increase in bench press 1RM with acute caffeine supplementation (5). Beck et al. concluded that acute caffeine usage improves upper-body strength, but not lower-body strength. Moreover, Graham-Paulson et al. (20) examined the effects of an acute dose of caffeine (~4 mg·kg^{-1}) on sprint performance in wheelchair rugby players and reported significantly faster sprint times in the caffeine condition compared with the control condition. Stadheim et al. (38) examined a single dose of caffeine (~6 mg·kg^{-1}) taken 75 minutes before performing an 8-km cross-country double-poling test. The investigators reported that the caffeine condition resulted in a significantly faster time to completion which corresponded to maintaining a higher speed and heart rate compared with the placebo condition (38). Stadheim et al. (2013) concluded that the increase in physical activity with caffeine usage may be, in part, due to reduced perception of effort or facilitation of motor unit recruitment.

Few studies, however, have examined the effect of acute caffeine supplementation on the motor unit recruitment. Trevino et al. (40) reported that caffeine supplementation (5 or 10 mg·kg^{-1}) 1 hour before performing maximal isometric muscle action of the elbow flexors did not significantly increase the normalized EMG or mechanomyography amplitude in healthy college-aged men. Greer et al. (22) examined the frequency domain of the EMG signal which has been suggested to be associated with muscle fiber action potential conductive velocity (2). The investigators found no significant mean differences in the EMG frequency between the caffeine and placebo conditions during the Wingate test (22). Similarly, Williams et al. (42) reported no significant mean differences between the caffeine and placebo conditions for isometric maximum voluntary contraction and EMG frequency. Conversely, Behrens et al. (6) reported that caffeine consumption (8 mg·kg^{-1}) significantly increased peak torque for isometric, concentric, and eccentric muscle actions for quadriceps muscle, whereas muscle activation (by EMG) was significantly higher for isometric and eccentric muscle actions only compared with controls. Taken together, these studies indicate that the acute effect of caffeine consumption on motor unit recruitment is variable and may be exercise mode dependent.

In this study, we found that for 9 of 10 (90%) participants, there was an increase of at least 1 stage (5 W) in the caffeine condition relative to the placebo condition (Table 1). When the patterns of responses between the placebo vs. caffeine conditions were analyzed on a subject-by-subject basis, 4 of 10 participants increased their maximal power output by 5 W, whereas 5 of 10 participants increased their maximal power output by 10 W (i.e., 2 stages). There was, however, 1 participant who increased their maximal power output by 5 W in the placebo condition relative to the caffeine condition. For the estimation of the EMG_{FT}, we found that all participants increased their EMG_{FT} in the caffeine condition compared with the placebo condition which is equivalent to ~45% increase. Moreover, we found that absolute heart rate ($b \cdot min^{-1}$) at maximal exercise increased by ~4.8% in the caffeine condition compared with placebo. It should be noted, however, that in both the placebo and caffeine conditions, the participants did not reach their age-predicted (220-age) estimated maximal heart rate (Table 1). This is due, in part, to the exercise mode (single-leg knee-extensor ergometry) which specifically focused on the quadriceps femoris muscles and minimized the role of central factors (i.e., cardiovascular and respiratory) (1,29). Therefore, this mode of exercise has been used to examine the oxygen uptake demand of the quadriceps femoris muscles in various clinical populations which may otherwise prematurely fatigue during whole-body exercise such as treadmill walking or cycle ergometry (32,34,35).

The reduction of fatigue by caffeine consumption may be, in part, due to its lipophilic properties, therefore, allowing it to cross the blood-brain barrier and influence adenosine receptors in the brain (9,10,39). Studies examining the role of caffeine-induced fatigue reduction suggest that the potential mechanism of action resides in blocking specific adenosine receptors (A_1R and $A_{2A}R$) in the brain (9,10,39). Moreover, studies have suggested that caffeine consumption increases dopamine signaling by blocking the A_{2A} receptor but also through an unblocked dopamine receptor (16,30). The striatum region of the brain has been the focal point of caffeine because of its involvement in motor performance and influence by dopamine (for detailed review, see reference (26)). Using positron emission tomography scanning, Volkow et al. (41) reported that a single dose (300 mg) of caffeine administration, in 20 healthy individuals, increased dopamine receptors for the putamen and ventral striatum, but not the caudate striatum when compared with the placebo condition. Similarly, Kaasinen et al. (25) reported a comparable dopaminergic effect in the striatum in the sample. Taken together, these underlying physiological mechanisms of acute caffeine consumption on motor performance may potentially explain the increase in the EMG_{FT} observed in this study.

Practical Applications

An abundance of studies examining the effect of caffeine consumption have used moderate to high dosages which may potentially cause health issues. In this study, we used a single low dosage caffeine (~2.5 $mg \cdot kg^{-1}$) treatment to attenuate neuromuscular fatigue in the quadriceps femoris muscles. As a result, participants were able to significantly increase their fatigue threshold compared with the placebo condition. These findings suggest that an acute low dose of caffeine 1 hour before the workbout may have ergogenic effects for exercises using isolated continuous muscle action for the quadriceps femoris muscles.

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