Cognitive task performance causes impaired maximum force production in human hand flexor muscles

Steven R. Bray*, Jeffrey D. Graham, Kathleen A. Martin Ginis, Audrey L. Hicks

McMaster University, Canada

ARTICLE INFO

Article history:
Received 12 April 2011
Accepted 8 October 2011
Available online xxx

Keywords:
Self-regulation
Muscle fatigue
Perceived exertion

ABSTRACT

The purpose of this study was to investigate effects of demanding cognitive task performance on intermittent maximum voluntary muscle contraction (MVC) force production. Participants performed either a modified Stroop or control task for 22 min. After the first min and at 3-min intervals thereafter, participants rated fatigue, perceived mental exertion and performed a 4-s MVC handgrip squeeze. A mixed ANOVA showed a significant interaction, $F(7,259) = 2.43, p<.02$, with a significant linear reduction in MVC force production over time in the cognitively depleting condition ($p<.01$) and no change for controls. Ratings of perceived mental exertion, $F(7,252) = 2.39, p<.05$, mirrored the force production results with a greater linear increase over time in the cognitive depletion condition ($p<.001$) compared to controls. Findings support current views that performance of cognitively demanding tasks diminishes central nervous system resources that govern self-regulation of physical tasks requiring maximal voluntary effort.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

People commonly experience muscle fatigue when they perform sustained tasks such as carrying a heavy suitcase or repetitive tasks such as shoveling snow. In these instances, muscle fatigue is manifested as an increase in the amount of perceived effort required to maintain task performance and is accompanied by physiological changes such as increases in heart rate, energy metabolism, and muscle motor unit recruitment (Bigland-Ritchie, 1981; Dalsgaard and Secher, 2007; Nybo, 2003). For example, holding a 30% submaximal isometric hand squeeze on a handgrip dynamometer causes elevations in heart rate, muscle activation, and perceived exertion over time and eventually task failure due to exhaustion despite the demands of the task remaining constant (Taylor and Gandevia, 2008). Performing intermittent maximum force contractions while maintaining a weak submaximal workload (e.g., 15% of maximum voluntary contraction; MVC) also causes increases in ratings of perceived exertion and decreased ability to generate maximum force over time (Søgaard et al., 2006).

Fatigue associated with sustained or intermittent motor task performance has been investigated extensively and is considered to consist of two components: peripheral fatigue that occurs at the level of the muscle tissue and central fatigue that occurs in the central nervous system at the spinal and supraspinal levels (cf. Gandevia, 2001). The origins and manifestations of central fatigue are not well understood (Åhsberg et al., 2000; Enoka and Stuart, 1992; Taylor and Gandevia, 2008). However, in a study of isometric exercise using transcranial motor cortex stimulation, Taylor et al. (2006) provided evidence that central fatigue emanates upstream of the pre-motor cortex in the prefrontal areas of the brain associated with emotion, cognition and volition.

The idea that central fatigue can be traced, in part, to cerebral cortical regions of the brain responsible for higher order executive control functions (e.g., anterior cingulate cortex; ACC) is consistent with perspectives in exercise physiology (Kayser, 2003) as well as psychology and neuroscience that hypothesize there is a brain-based energy resource that governs performance of tasks requiring cognitive, emotional, and physical effort regulation (Baumeister et al., 1994; Gailliot et al., 2007; Muraven and Baumeister, 2000). According to the limited strength or ego depletion model (Baumeister et al., 2007; Baumeister and Vohs, 2007), self-regulating effort on one task can diminish effortful performance on subsequent tasks, provided both tasks require some form of emotional, cognitive, or physical effort regulation. In support of this model, a recent meta-analysis by Hagger et al. (2010) showed that effort-induced resource depletion in one domain (e.g., emotion, cognition, or behavior) has strong, consistent, performance-deteriorating aftereffects on subsequent effortful tasks regardless of whether those tasks are in the same domain (e.g., emotion control–emotion control) or dissimilar domains (e.g.,

* Corresponding author at: Department of Kinesiology, McMaster University, 1280 Main St. West, Hamilton, Ontario, Canada L8S 4K1.
Tel.: +1 905 525 9140x26472; fax: +1 905 523 6011.
E-mail address: sbray@mcmaster.ca (S.R. Bray).

0301-0511/– see front matter © 2011 Elsevier B.V. All rights reserved.

cognitive control–physical control/endurance) with a moderate to large effect size (Cohen’s $d = .62$).

The focus of the present study is on the association between cognitive effort exertion and effortful physical exercise task performance. Despite a rather abundant literature examining the effects of exercise on cognitive performance (see reviews by Brisswalter et al., 2002; Etnier et al., 1987; Temporowski, 2003), few studies have investigated the reciprocal association of cognitively effortful task aftereffects on exercise performance. However, research along these lines stands to be informative for understanding the psychobiological phenomenology of muscle fatigue at a basic level as well as having applied relevance to tasks requiring intense physical performance that may be accompanied by cognitive demands such as athletics, performing arts, workplace, and military training or combat.

Although little research has been conducted on the aftereffects of cognitive and emotional tasks on physical performance, the premise that muscular fatigue may be induced by mental exertion was proposed by Mosso (1915, pp. 240–290) who commented on observations of his and colleagues’ inability to perform physical exercise at their normal levels after delivering lectures or administering oral examinations. More recent empirical work by Bray et al. (2008) showed that people who performed a cognitively effortful task (modulated Stroop color word task) for a brief interval experienced significant decrements in submaximal (50% of maximum voluntary contraction) (MVC) handgrip squeezing endurance compared to controls. Findings also revealed participants who performed the Stroop task showed greater proportional EMG amplitude scores in the hand flexor muscles than controls suggesting that prior cognitive exertion contributed to central muscle fatigue by inhibiting descending neural activation of muscle motor units required to sustain the submaximal contraction.

Marcora et al. (2009) also carried out a study examining carry-over effects of cognitive task performance on physical performance. Results showed that participants’ performance (time to exhaustion) on an exercise test was reduced dramatically following a mentally demanding task (640 ± 316s) compared to a control task (754 ± 339s). Ratings of perceived exertion (RPE; Borg, 1998) during exercise were significantly higher following the mentally demanding task compared to a control task, suggesting that cognitive exertion directly led to perceptions of greater effort required to perform the exercise task. These findings are also consistent with an interpretation that cognitive effort exertion contributes to central muscle fatigue.

Further evidence of a link between cognitive effort and muscle fatigue comes from a study by Martin Ginis and Bray (2010). They had participants perform an effortful exercise task and plan an exercise circuit training session that they would perform at the end of the testing session. Participants who performed the modified Stroop task reduced the amount of work output generated on the cycling task and planned less exertion for their exercise session ($p = .04, d = .55$) compared to controls. These two findings are also indicative of central muscle fatigue induced by a cognitively effortful task.

In concert, the results of these studies suggest that cognitive effort expenditure has an impact on central fatigue determining performance of endurance exercises requiring submaximal isometric muscular activation or high-intensity cardiovascular workload. However, as noted above, several paradigms can be used to investigate fatigue in exercising muscle, which include sustained or incremental submaximal effort and intermittent maximal efforts (Gandevia, 2001; Taylor and Gandevia, 2008). The three studies reviewed above represent investigations of effects of cognitive exertion on submaximal or incremental exercise performance. Yet, to the best of our knowledge, no studies have examined the effects of cognitive task exertion on tasks requiring maximal exercise efforts.

Although no studies have investigated cognitive resource depletion effects on maximal exercise performance, a study by Segaard et al. (2006) provides a model that would be appropriate for examining such effects. In that study, the investigators had participants sustain an isometric contraction of the elbow flexors (15% of MVC) for a span of 43 min. Throughout the sustained contraction, participants performed MVCs at 3-min intervals. All participants were able to hold the 15% contraction for the full 43 min. However, results revealed a consistent linear deterioration in MVC torque scores over time to approximately 70% of initial pre-test values after 20 min and 60% of the pre-test MVCs at 43 min. EMG recordings of muscle activation in the biceps brachii and brachioradialis muscles showed decreasing activation over time as well, indicating decreased neural drive to the motor units of the active muscles.

The results of Segaard et al. (2006) suggest that sustained physical effort regulation of a weak submaximal contraction gradually depleted central nervous system energy, which compromised the ability to generate maximal contractions over time. These results support the ego depletion/wound strength model because prolonged physical effort regulation led to depleted maximal effort production. The results also provide a foundation for hypotheses that sustained cognitive effort regulation, which should also deplete central nervous system energy, should compromise maximum strength output and voluntary muscle activation over time as well.

The purpose of the present study was to investigate the effects of cognitive effort depletion on maximum muscular force production. To this end, we had participants engage in either a cognitively demanding or control task throughout which they performed intermittent maximum (100% MVC) hand squeezes. It was hypothesized that cognitive effort ratings would be greater and increase faster over time in the group performing the cognitively demanding task compared to controls; however, in line with recent work by Vohs et al. (2011) we expected that more generalized sensations of subjective fatigue would not differ significantly between groups despite the occurrence of self-control depletion. We also expected there would be a more dramatic decrease in maximal muscle force production with an accompanying deceleration in muscle activation in the experimental group compared to controls.

2. Methods

2.1. Participants

Participants were 38 undergraduates who self-reported as being sedentary (exercising <2 occasions per week) and not partaking in employment that required physical labor. The sample consisted of women ($n = 23$) and men ($n = 15$) aged 18–36 ($M_{\text{age}} = 21.47 ± 3.16$) who were stratified by gender and randomized using a random number generator to either an experimental ($n = 21$) or control group ($n = 17$).

2.2. Measures

2.2.1. Isometric handgrip force generation

A handgrip dynamometer (model MLT003/D; ADInstruments, Colorado Springs, CO) with a digital PC interface (Powerlab ML870; ADInstruments) was used to monitor and record muscle force generation (in Newtons: N) during maximal voluntary handgrip contractions (MVC). The sampling frequency of the force signal throughout the study was 4 kHz. Drawing from procedures described by Segaard et al. (2006), participants performed a pre-test consisting of 5, brief (4-s duration) MVCs, each separated by a 1-min rest interval. Then, at 1-min (after pre-test) and at seven 3-min intervals thereafter, participants completed a single MVC, each lasting 4 s in duration. The force produced during a 1-s window straddling the peak force value generated during each MVC squeeze was used for analyses. All contractions were performed while sitting at a table, with the forearm outstretched at 90° elbow flexion and parallel to the sagittal plane in a static, neutral posture (i.e., positioned halfway between pronation and supination) with the elbow and base of the hand situated on a forearm/hand tracing superimposed on the flat surface of the table. In order to standardize force production across a broad range of raw force production values (i.e., some people had much higher force production than others),
raw force production scores (N) were converted to proportional force scores (%) by dividing handgrip squeeze force production scores at each of the eight in-trial test squeezes by a baseline force production score derived from the average of the 5 pre-test maximal squeezes. The 5 pre-test MVC scores had a high degree of consistency with an intraclass correlation (ICC) of .98, indicating our baseline force production score had good reliability.

2.2.2. Muscle activation (EMG)

Surface EMG activity of the hand flexors was monitored continuously during the experiment, however, only muscle activation during the 1-s peak force recordings for each MVC were analyzed. After cleansing and abrading the surface of the forearm with an alcohol swab, a disposable recording electrode (Ag–AgCl, 10 mm diameter) was secured to the forearm over the belly of the flexor muscle group (flexor digitorum profundus). The reference electrode was placed approximately 4 cm distal to the stigmatic electrode on the forearm surface in the tendinous region. A ground electrode was placed on the medial epicondyle of the humerus at the elbow. The EMG signals were amplified, digitized and continuously streamed using a Powerlab ML870 data acquisition system (ADInstruments, Colorado Springs, CO) to a PC at a sampling rate of 4 kHz and band pass filtered at 10Hz to 1 kHz. The EMG signal was saved, rectified and integrated using Chart 5™ software (ADInstruments, Colorado Springs, CO).

As was the case with the force generation data, in order to standardize the EMG data across individuals, raw EMG scores were converted to proportional scores (%) by dividing peak EMG scores at each of the eight in-trial MVCs by a baseline EMG score derived from the average of the 5 pre-test MVCs. Percentage scores based on the peak EMG scores (i.e., recorded in-trial EMG/average pre-test EMG × 100) were generated for each in-trial MVC.

2.3. Subjective fatigue

A 100 mm horizontal visual analogue scale (VAS; Gift, 1989) was used to assess subjective feelings of general fatigue. The VAS was anchored at the extreme points with the adjective descriptors “extremely tired” and “extremely energized.” Participants used a pencil to mark the VAS at a point on the scale corresponding to their perceived fatigue at that point in time. A standard metric ruler was used to convert the scale mark to a unit measure represented by millimeters with lower scores representing greater fatigue.

2.4. Ratings of perceived effort

A modified version of Borg’s CR-10 rating of perceived exertion (RPE) scale was used to assess participants’ perceived mental exertion. The original scale was modified in terms of the lead statement preceding the ratings which was “how much mental effort did you exert while performing the reading task”. Although Borg’s CR-10 scale has been used primarily to assess perceived exertion during cardiovascular exercise, it was originally developed to assess general perceptions of exertion (Borg, 1998) and has been used to assess perceived mental exertion on cognitively demanding tasks in several studies (e.g., Blackwood et al., 1998; Garcia et al., 2003; Larsby et al., 2005).

2.5. Experimental manipulations

Following the first in-trial MVC, and during the intervals between each successive MVC thereafter, participants completed either a modified incongruent Stroop color word task (high cognitive demand task) or a congruent color word task (low cognitive demand control task) for 2-min and 45-s discrete continuous blocks. For the modified incongruent Stroop word task (Wallace and Baumeister, 2002), participants read aloud from a list of printed words. The printed words and the ink color in which the words were printed were mismatched (e.g., the word “green” was printed in blue ink). Participants were required to say aloud the color of the ink in which the word was printed (e.g., for the word “green” printed in blue ink, they had to say “blue”). In addition, for words appearing in red ink, participants had to override the general instructions and say aloud the name of the printed word. The modified Stroop task has been used in several studies to induce self-control depletion (e.g., Bray et al., 2008; Martin Ginis and Bray, 2010; Wallace and Baumeister, 2002) with an average effect size of d = .40 (Hagger et al., 2010). For the congruent color word task (control), participants read aloud from a list of printed words. The printed words and the ink colors in which the words were printed were the same (e.g., the word “green” was printed in green ink).

2.6. Procedures

This study employed a single-blind randomized controlled design with stratification by gender. Upon arrival at the laboratory, participants were greeted, given a general description of the study procedures and provided informed consent. They completed a paper and pencil survey of their demographic information and then performed a set of five, 4-s MVC handgrip squeezes on a dynamometer, each separated by 1 min of rest. Following a standardized script, participants were given verbal instructions to “squeeze the handles as hard as possible for 4 seconds” prior to each MVC and verbal encouragement to “squeeze hard, hard, hard, hard, hard” during each 4-s trial to facilitate an all-out MVC for each handgrip squeeze. Following the baseline handgrip testing, participants were randomly assigned to either the cognitively demanding task (modified Stroop) or control conditions. They then performed either the modified Stroop task or control task for 45 s, after which they completed the subjective fatigue VAS, CR-10 RPE measure, and the first pre-trial 4-s MVC within a 15-s window. Following the first in-trial MVC, they completed 7, 3-min blocks of testing in which they performed either the modified Stroop task or control task for 2 min and 45 s followed by a 15-s interval during which they completed the subjective fatigue VAS, CR-10 RPE measure, and a 4-s MVC. As was the case for the pre-trial MVCs, participants were given verbal instructions to “squeeze the handles as hard as possible for 4 seconds” prior to each MVC and verbal encouragement to “squeeze hard, hard, hard, hard, hard” during each 4-s trial to facilitate an all-out MVC for each handgrip squeeze. Force production information/feedback for the MVC trials was not available to participants at any time during the experiment. Upon completion of the final MVC, they were debriefed and thanked for their participation in the study.

3. Results

Four separate 2 (experimental; control group) × 8 (11 min; 4 min; 7 min; 10 min; 13 min; 16 min; 19 min; 22 min) mixed ANOVAs were computed on the MVC force production, proportional EMG amplitude, RPE, and subjective fatigue data. For each analysis, data were screened for normality, homogeneity of variance, and sparcity and were found to meet assumptions of repeated measures ANOVA with the exception of the RPE data which revealed unequal variances and were subjected to Greenhouse–Geisser corrections.

The force production data showed no main effects for time, F(7, 252) = 1.20, p = .30, ηp2 = .03 or group, F(1, 36) = 1.60, p = .22, ηp2 = .04. However, there was a significant group × time interaction, F(7, 252) = 2.43, p = .02, ηp2 = .06. Post hoc examination of the separate within-group effects showed there was a linear reduction in MVC force production (relative to baseline) over time in the experimental condition (F(7, 140) = 2.46, p < .05, ηp2 = .11) but no change in force production over time in the control condition (F(7, 112) = 0.85, p = .55, ηp2 = .05). Further post hoc analyses (simple contrasts) of between-group differences at each time point revealed marginally significant (p < .07) trends between force scores at 16 and 19 min and a significant (p = .01) difference at 22 min. These results are displayed graphically in Fig. 1.

A 2 x 8 mixed ANOVA on the perceived mental exertion ratings data showed significant effects for both group, F(1, 36) = 8.92, p = .005, ηp2 = .20 and time, F(7, 252) = 24.57, p < .001, ηp2 = .41; which were superseded by a significant group × time interaction, F(7, 252) = 2.39, p < .05, ηp2 = .06. Post hoc univariate tests showed significantly higher levels of RPE in the Stroop depletion condition at each of the 8 in-trial intervals (p < .05). Also, there was a linear increase in perceived mental exertion for both groups over time but a larger effect in the experimental condition (F(7, 140) = 18.09, p < .001, ηp2 = .48) than the control group (F(7, 112) = 8.64, p < .001, ηp2 = .35). These results are displayed graphically in Fig. 2.

Fig. 1. Means (with standard error bars) of observed force production (relative to baseline MVC) at 3-min intervals over 22 min of modified Stroop or control task performance.
As a follow-up to these two primary hypothesis tests of group-level effects, we conducted additional analyses to investigate a possible association between changes in RPE and force production over time within individuals. Two analyses were conducted. First, we computed magnitude of change scores by subtracting the values for relative force production and RPE generated at time 1 from the values generated at time 8. In addition, we computed simple slopes (β) representing trajectories of change for each of RPE and relative force by regressing each individual’s scores for the 8 measurements on the linear function of time at each interval (i.e., 1–8). Pearson bivariate correlations between the RPE and relative force change scores were then computed. None of the correlations approached significance (r(38) < .29, p > .10) whether the sample was examined as whole or in separate groups.

Descriptive statistics of the EMG amplitude data are presented by group and over time in Table 1. A 2 × 8 mixed ANOVA on the muscle activation (EMG) data revealed no significant effects for time (F(7, 252) = 0.99, p = .44, η² = .03), group (F(1, 36) = 1.03, p = .32, η² = .03), or the time × group interaction (F(7, 252) = 1.32, p = .24, η² = .04).

Descriptive statistics of the subjective fatigue data are presented by group and over time in Table 1. A 2 × 8 mixed ANOVA on subjective fatigue scores showed a significant effect for time, F(7, 252) = 10.88, p < .001, η² = .23. However, neither the main effect for group F(1, 36) = 0.17, p = .68, η² = .01, nor the group × time interaction F(7, 252) = 1.07, p = .39, η² = .03 were significant. Thus, both groups reported small, linear increases in subjective fatigue throughout the experiment.

4. Discussion

The purpose of the present study was to investigate the effects of cognitive effort depletion on maximum muscle force production over time. We expected that cognitive effort depletion would be greater in the group performing the cognitively demanding Stroop task compared to controls. We also expected there would be decreases in maximal muscle force production over a 22-min span involving 8 intermittent MVC handgrips and accompanying deterioration in muscle motor unit activation in the experimental group compared to controls.

As predicted, participants in the experimental group reported higher ratings of perceived mental exertion after 1 min of modified Stroop task performance and a prominent linear increase in ratings of perceived mental exertion over 21 additional min of performing this cognitively demanding task. Participants in the control condition also reported increasing levels of mental exertion over the course of the experiment, but to a lesser extent. This manipulation created the desired conditions for us to test hypotheses regarding muscular force production and muscle unit activation for a maximum isometric handgrip squeezing task throughout the background cognitive effort expenditure task.

As predicted, results revealed a significant condition × time interaction in the force generation data. That is, there was a linear decrease in force production in the group that performed the cognitively demanding task that fell from approximately 100% of pre-test force production in the first two test intervals to less than 95% at 22 min. Conversely, there was no change in force production over time in the control group, with force production remaining above 100% of the pre-test values throughout all intervals of the testing window. As far as we are aware, this is the first study to show this effect. This evidence supports our theorizing that expenditure of cognitive effort depletes central nervous system resources that are utilized during maximum voluntary muscular effort production. The idea that cognitive effort exertion is resource-dependent is not new and aligns with earlier theorizing in cognitive neuroscience (Hockey, 1997; Kahneman, 1973). However, the view that cognitive, emotional, and behavioral effort control draw upon a common pool of resources is a relatively novel perspective that has gained considerable attention in recent years (cf. Hagger et al., 2010). The current findings are consistent with this perspective and previous results showing cognitive effort exertion has spillover effects on submaximal muscular and cardiovascular exercise endurance (e.g., Bray et al., 2008; Marcora et al., 2009; Martin Ginis and Bray, 2010; Muraven et al., 1998). The current findings are unique in that they illustrate spillover effects of cognitive effort exertion on maximal voluntary muscle force production as well.

It was also of interest to observe this pattern of results in the presence of data showing that general feelings of subjective fatigue experienced by participants did not differ by experimental condition. Self-reported fatigue ratings were low-moderate and increased marginally in both groups over the course of the experiment, but consistent with recent findings by Vohs et al. (2011), muscle fatigue or depletion effects occurred independently of subjective fatigue.

Although we are not aware of any research that has examined the effects of cognitive effort exertion on maximal muscular force production, past research has investigated the effects of prolonged submaximal physical effort on maximal force production. Indeed, our findings are consistent with Søegaard et al. (2006), who tested maximum muscle force production interspersed with a sustained weak (i.e., 15% of MVC) submaximal physical effort task. It is interesting that RPE in both studies started off about 2/10 on the RPE scale and rose at a similar trajectory to ~5/10 by min 22, suggesting the manipulations were consistent in the amount of perceived effort required to sustain the background task. We should note however, that the effects in Søegaard et al.’s study were much stronger; showing ~30% drop in MVC force production over 22 min whereas the effects observed in the present data represent about a 5% deterioration over the same amount of time. It is reasonable to suggest the difference in effects across the two studies is attributable to peripheral muscle fatigue factors (e.g., lactic acidosis) that may have contributed to Søegaard et al.’s effects given the submaximal effort task manipulation and maximal effort criterion tasks involved the same muscle groups. Of course, our cognitive manipulation did not involve direct or purposeful activation of the forearm skeletal musculature to perform the Stroop task, which leads us to suggest that the effects observed in the present study were independent of factors associated with peripheral muscle fatigue. However, it should be noted that Stroop task performance has been associated with activation of the trapezius muscle in past research (Larsson et al., 1995; Laursen et al., 2002; Lundberg et al., 2002; MacDonell and Keir, 2005; Waersted and Westgaard, 1996).

and while those effects have not been consistent across studies or shown to generalize to other muscle groups (MacDonell and Keir, 2005; Waersted, 2000), it is possible that Stroop task performance may have led to unmeasured activation of the forearm muscle fibres in the present study and led to some degree of peripheral muscle fatigue as well.

The central nervous system resource or energy perspective can account for the present findings and those derived from studies of submaximal effort exertion, however, that perspective lacks concrete specification of structural or mechanistic processes that mediate the effects of cognitive effort expenditure on muscular effort production. Based on recent work involving fMRI, we contend that the anterior cingulate cortex (ACC) area of the prefrontal cortex plays a major role in controlling these effects. For example, several studies show increased activation of the ACC during performance of the Stroop task (Gruber et al., 2002; Milham et al., 2002; Peterson et al., 1999) as well as during prolonged submaximal handgrip squeezing (Lui et al., 2003; van Duinen et al., 2007). Nonetheless, a question that remains unanswered, is what physiological (e.g., neurochemical, neuroelectrical) mechanisms are affected by ACC activation during effortful or centrally fatiguing tasks. Gailliot (2008) suggests and provides evidence that conscious effort control depletes blood glucose concentrations (Gailliot and Baumeister, 2007; Gailliot et al., 2007). Thus, increases in cerebral metabolism linked to ACC activation may rapidly consume fuel stores required for maximal effort expenditure and regulation over time. Researchers in exercise science have also suggested ammonia accumulation and HT-5 neurotransmitter activation are implicated in central fatigue attributable to muscular effort endurance tasks as these substances that are by-products of metabolic processes that occur in muscle during exercise can cross the blood–brain barrier (Dalsgaard and Secher, 2007; Davis, 1995; Enoka and Stuart, 1992; McKenna and Hargreaves, 2008). To gain an understanding of mechanisms underlying spillover effects leading from cognitive effort expenditure to declines in maximal or submaximal muscular performance, future research should seek to uncover and isolate physiological processes that emanate from and operate within central nervous system structures during effort regulation.

Our findings did not reveal the hypothesized decline in muscle activation over the course of the experiment (see Table 1). Indeed, the values obtained for proportional EMG remained constant at approximately 100% of the baseline values. These findings serve to indicate that participants in both groups were using close to the maximum number of available motor units during each MVC throughout the experiment. This finding does not support the idea that there is a centrally mediated reduction in neural drive following cognitive depletion, which has been seen in previous work (e.g., Bray et al., 2008) and raises questions about the generalizability of that finding or alternative explanations such as reduced activation in co-contracting or antagonist muscles of the forearm. However, the current findings and those observed in previous work differ in that a submaximal endurance task was used in the Bray et al. study while we used an intermittent MVC protocol. Furthermore, the proportional EMG values used to represent muscle activation in the present study are based on an unverifiable assumption that the maximum available motor units were activated during the baseline MVC squeezes. The inclusion of twitch interpolation or transcranial motor cortex stimulation techniques should be considered in future extensions of the current work to better gauge the proportion of available motor units recruited during each intermittent MVC.

As noted earlier, the findings may have important implications in physical performance contexts that require maximal investments of effort. One implication of these findings is that people may be consciously aware of being in a cognitively depleted state while performing tasks that require high cognitive loads such as information processing or decision making, yet expect their performance capabilities to be unaffected. Thus, manual laborers, competitive athletes, or combat soldiers who are often placed in cognitively demanding situations involving complex decision making or information processing may find themselves with diminished abilities to perform physically demanding feats that are also required. Such circumstances may lead to sub-par performances or require response adaptations in situations that may place individuals at risk for injury.

5. Conclusions

The present study provides evidence that prolonged performance of a cognitively effortful task is associated with a linear decline in maximal voluntary muscular force generation in a handgrip squeezing task over time. This finding is the first to implicate the expenditure of cognitive resources in the deterioration of maximal voluntary exercise effort. The findings align with data from a study involving prolonged submaximal physical effort regulation (Segaard et al., 2006), but stand alone in terms of attempting to isolate non-muscular (i.e., cognitive effort expenditure) influences on muscle fatigue. Importantly, there was a progressive decline in MVC force production that mirrored linearly increasing ratings of perceived mental exertion over time. Thus, the effects of cognitive effort expenditure or regulation on muscle fatigue were not immediately observable, but rather emerged over time.

References


