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Caffeine intake helps maintain 3-km cycling performance the morning following sleep restriction

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Caffeine Intake Helps Maintain 3-km Cycling Performance
the Morning Following Sleep Restriction

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JAMES MADISON UNIVERSITY

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Abstract

Introduction: Although a full understanding of the role of sleep is debated, it is widely accepted that sleep is important for recovery from heavy exercise. Recent research suggests that sleep restriction (SR) may negatively impact recovery and subsequent performance. It is unknown if caffeine supplementation mitigates this performance decrement. Our objective was to investigate the effect of caffeine supplementation on exercise performance following one night of SR in trained cyclists.

Methods: Subjects (n=10) completed a 3-km time trial (TT) and an exhaustive bout of exercise in the evening (EX1), then returned to repeat the TT the following morning (EX2). Exercise trials were separated by a full night of sleep (FULL) or a night of restricted sleep (SR). Perceived fatigue was also assessed prior to EX2. Caffeine (CAF) or placebo (PLA) treatments were given before the start of EX2. A randomly counterbalanced, double blind, placebo controlled design was used to compare the effects of four different treatment conditions: FULL/PLA, SR/PLA, FULL/CAF, SR/CAF.

Results: Data were analyzed using magnitude-based inferences to compare differences in EX2 performances only. Power output was ‘possibly’ greater ($0.9 \pm 3.6\%$) following SR/PLA compared to FULL/PLA. Power output was ‘likely’ higher ($5.5 \pm 4.8\%$) following SR/CAF compared with SR/PLA. Perceived fatigue was rank ordered as 1) SR/PLA, 2) SR/CAF, 3) FULL/PLA, 4) FULL/CAF. Specifically, CAF ‘very likely’ reduced perceived fatigue following SR compared to SR PLA, but remained ‘likely’ higher than FULL/CAF.

Conclusion: These data show that caffeine has the ability to mitigate performance decrements resulting from a single night of SR following heavy exercise. Caffeine also prevented increases in perceived fatigue following SR.

Keywords: sleep restriction, caffeine, cycling, recovery

Chapter 1

Introduction

Though a full understanding of the importance of sleep has yet to be clearly explained, sleep is required for optimal physiological function. Therefore, it is widely recommended that adults sleep 7 to 9 hours a night. However, much of the population falls short of these guidelines (18, 60). The most recent poll conducted by the National Sleep Foundation found that 40% of respondents acquired less than 6.9 hours of sleep on weekdays (1). Sleep loss can occur through sleep deprivation or sleep restriction. Sleep deprivation is the complete absence of sleep, while sleep restriction is interrupted sleep cycles; these interruptions can occur through delayed sleep, intermittent waking, or early awakening. The importance of sleep is believed to be related to a number of different factors. A commonly accepted theory revolves around energy conservation, as sleep reduces daily metabolic requirements and energy expenditure (15, 45). Also, despite early data to the contrary, recent work clearly indicates that cognitive function is compromised following sleep loss, suggesting the central nervous system is reliant on sleep for optimal functioning (20, 59, 62). Finally, there is compelling evidence that long-lasting immunological memory is built through short adaptive immune responses that occur during sleep (7). When adequate sleep is not achieved, the integrity of these systems is compromised.

Athletes in particular require sufficient sleep, so as to facilitate recovery from the physiological and psychological demands of heavy training and competition (3, 14, 35). Sleep is believed to be critical for athletes due to restoration of the immune system,

restoring the metabolic cost of the wakeful state, and enhancing memory, learning, and synaptic plasticity (19, 25). Furthermore, when sleep is curtailed during periods of heavy training, recovery is adversely affected and the potential for overtraining and maladaptation arises, suggesting the necessity of sleep as a mode of recovery for athletes (4). When sleep loss occurs acutely, restoration of neurocognition and the immune system is inhibited, and could be a factor leading to decreased performance (25). Thus, sleep loss in athletes has the potential to negatively affect the adaptive physiological and psychological recovery processes. Moreover, athletes are especially susceptible to sleep loss. Many athletes routinely perform consecutive days of high-intensity training bouts, and heavy training has been shown to lead to impaired sleep (28). Further, the psychological stress of multi-day competitions or target competitions can also lead to insufficient sleep. A survey examining sleep habits of 632 athletes before an important competition or game reported that 62.3% of them had experienced poor sleep in the nights before a sports event at least once in the previous twelve months. Some athletes reported lost sleep had no effect on their athletic performance, while others reported decrements in mood, alertness, and athletic performance (17). When their schedules interfere with their sleep, whether involving late bedtime or early arousal, the potential for short- and long-term consequences arises. The deleterious effects of sleep on recovery and physical performance are therefore of interest to both coaches and athletes.

Predictably, complete sleep deprivation has a negative impact on athletic performance varying from strength and anaerobic exercise to prolonged aerobic exercise (10, 38, 39, 43, 50, 52, 55). This could be at least partially related to the well documented changes in perceived exertion and mood states following sleep deprivation (38, 43, 51, 52).

Interestingly, the effects of sleep deprivation on physical performance are conflicting. With the exception of one study, it would seem that sleep deprivation ranging from 30 to 60 hours decreases muscular strength and endurance (57). Significant decreases in muscular strength and endurance were seen through decreased vertical jump, isokinetic knee extension and flexion peak torque, and peak isometric voluntary force (10, 52, 58). Conversely, data indicate that short-duration performances seem to be unaffected by sleep deprivation (50, 55, 57, 58), with the exception of a recent report that 15-m sprint time was significantly increased when subjects incurred 30 hours of sleep deprivation compared to a full night of sleep (52). While the literature currently agrees that sleep deprivation can substantially impair aerobic performance (3-20%), the mechanisms for these decrements arise have yet to be explained. It would seem that cardiovascular, metabolic and ventilatory changes occur as a result of sleep deprivation; however the effects of sleep on these parameters are equivocal. In certain conditions, heart rate, oxygen consumption, and ventilatory responses to exercise change with sleep deprivation, while in others these measures stay the same. (38, 39, 43, 50, 57). Discrepancies in protocol may lead to the conflicting evidence; especially in regards to hours of sleep deprivation and exercise conditions. Studies have examined the effects of sleep deprivation in various amounts exceeding 24 hours on performance outcomes which could include time to exhaustion, total work, total distance covered, and maximal exercise intensity (5, 29, 37, 38, 42, 43). So, it appears that sleep deprivation can lead to decreased athletic performance, most notably in prolonged exercise.

In addition to sleep deprivation, some data has been gathered on the effects of acute sleep restriction (i.e. a few hours of lost sleep) on performance. Sleep restriction seems to

have equivocal effects on muscular strength. Reilly and Piercy reported that various submaximal and maximal weight lifting tasks were negatively affected by sleep restriction, while others report that handgrip and maximal voluntary contraction of muscles may either decrease or remain unchanged, respectively (24, 48, 49, 54). The effect of sleep restriction on anaerobic performance remains equivocal. While two studies have shown that there is no change in anaerobic performance the morning following sleep restriction, a few have reported decreased mean and peak power in a Wingate test the morning or evening following sleep restriction (2, 24, 41, 55). Interestingly, all of the studies that demonstrated performance decrements utilized early awakening as their form of sleep restriction (2, 24, 56). Similarly to total deprivation, the decrements seen in performance following sleep restriction could be due to effects on RPE and mood states as opposed to physiological mechanisms (24, 42, 56). Less is known about the effects of sleep restriction on aerobic performances. While two studies showed sleep restriction did not affect incremental running and cycling test durations the next day, others have demonstrated that sleep restriction decreases performance in intermittent recovery and incremental cycling tests (40, 42, 44, 48). Despite conflicting reports, it is clear that sleep restriction in the form of early awakening is more disturbing to afternoon performance than delayed-bedtime restriction for both aerobic and anaerobic exercise (2, 40, 56). It is important to consider that the consequences of sleep restriction might vary due to individual differences such as gender, age, morningness-eveningness classification (e.g. chronotype), amount of sleep required, and sleep latency differences (9, 12, 26, 27). In light of the current literature, it would seem that the effects of sleep restriction have negative consequences on performance.

Virtually everything that is known about sleep restriction and exercise performance has been derived from subjects that refrained from heavy exercise leading up to the night of sleep restriction. It is logical to expect that sleep loss following demanding exercise may have a more pronounced effect on next-day exercise. In support of this idea, our laboratory recently found that one night of sleep restriction following heavy exercise impairs short-duration cycling performance the following day by approximately 4 percent (13). Because sleep disruption is inevitable and markedly detrimental to performance, it is worthwhile to examine potential strategies to attenuate performance losses. One possible strategy to minimize the effects of sleep restriction on performance is caffeine supplementation; as caffeine would seem to have the potential to mitigate the detrimental effects of sleep restriction through increased neurocognitive function and decreased perceived exertion (8). Extensive research has demonstrated the effectiveness of caffeine as an ergogenic aid for aerobic and anaerobic performance (22, 33, 34, 61). Additionally, our laboratory recently reported that caffeine can enhance 3-km cycling time trial performance, especially early in the day (8, 46). The extent to which caffeine may be able to compensate for the negative effects of sleep loss has not been examined. Considering the efficacy of caffeine as a CNS stimulant, it is plausible that caffeine could attenuate some of neurocognitive factors that might lead to performance impairments (16). Therefore, the purpose of this investigation is to test the hypothesis that caffeine supplementation will attenuate but not eliminate the negative impact that sleep restriction has on next-day performance.

Aims and Hypotheses

Aim 1: To determine if caffeine supplementation attenuates the negative effects of sleep restriction on 3-km cycling TT performance.

Hypothesis 1: Caffeine supplementation will attenuate but not completely offset the negative effects of sleep restriction on 3-km cycling TT performance.

Aim 2: To determine if caffeine supplementation attenuates the negative effects of sleep restriction on muscle work during 30 isokinetic leg extension repetitions.

Hypothesis 2: Caffeine supplementation will attenuate but not completely offset the negative effects of sleep restriction on muscle work during 30 isokinetic leg extension repetitions.

Aim 3: To determine if caffeine supplementation attenuates the negative effects of sleep restriction on mood states.

Hypothesis 3: Caffeine supplementation will attenuate but not completely offset the negative effects of sleep restriction on mood states.

Significance

Sleep plays an important role in psychological and physiological recovery from exercise. Despite a resounding belief from athletes and coaches that sleep is critical to recovery and performance, the role sleep plays in enhancing recovery and promoting performance is still ambiguous. Little has been done to determine the effects of sleep restriction on recovery from heavy exercise and subsequent performance. Sleep restriction appears to negatively affect performance in athletes, especially when sleep restriction occurs in the form of early awakening. This seems to be due to negative impacts on cognitive functioning and mood states, however there may be underlying physiological mechanisms as well. Furthermore, potential strategies to mitigate performance decrements observed following sleep restriction have yet to be tested. Considering the prevalence of sleep loss in athletic populations, it is important to investigate the effects sleep restriction has on recovery from exercise as well as potential ways to ameliorate resulting decrements. The current study has the potential to determine if caffeine supplementation can serve as a method to improve 3km cycling time trial performance following heavy exercise and sleep restriction.

Chapter Two

Methods

Subjects

Eight to fifteen male and female recreational cyclists from James Madison University will participate in this study. All subjects must perform a minimum of 30 minutes of cycling, one to two days per week, for at least three months prior to the study, and possess a maximum oxygen consumption (VO_{2max}) of ≥ 40 ml/min/kg to qualify for participation. Additionally, participants will score ≤ 7 on the Pittsburg Sleep Quality Index (PSQI) to ensure they have “normal” sleeping habits (11). Participants will be informed of the experimental protocol, risks, and benefits before providing written consent. The study will has been approved by the James Madison Institutional Review Board.

Preliminary Testing

Following height and weight measurements, participants will perform an incremental exercise test to exhaustion on a cycle ergometer (Velotron, Racermate, Inc., Seattle, WA, USA) to determine VO_{2max} and maximum power in watts (W_{max}). The participants will warm up for five minutes at a self-selected workload, then begin the test at a workload between 100 and 175 W. The workload will increase every 2 minutes in 50 W increments until volitional fatigue or inability to maintain a cadence of 50 RPM or higher for more than 10 seconds. Expired air will be collected throughout the test and oxygen consumption (VO_2) will be assessed using the Moxus Modular Metabolic System (AEI Technologies, Pittsburgh, PA, USA). VO_{2max} will be determined by the highest 30-s mean VO_2 .

Experimental Design

Participants will complete a familiarization phase followed by four experimental phases, each separated by five to seven days. The familiarization and experimental phases will consist of two exercise sessions performed on consecutive days (EX1 and EX2). EX1 will consist of baseline performance testing followed by an exercise protocol designed to elicit fatigue. EX2 will be performed the following morning to assess recovery from the exercise protocol, and will only include the performance testing. EX1 and EX2 during the experimental phases will be separated by a night of full sleep (FULL) or a night of restricted sleep (SR). Sleep will be assigned to each participant in a randomized, crossover design. Participants will be informed of their designated sleep condition following the exercise protocol on EX1 and not before, to prevent reactive behavior changes leading up to the experimental trials.

Familiarization Phase

The familiarization phase will consist of EX1 and EX2 trials (as described below) without controls for sleep, diet, and physical activity. The participants will complete the trials at predetermined intensities to confirm they can complete the protocol, familiarize themselves with the equipment, and reduce learning-related improvements in performance during the experimental trials.

Experimental Trial 1 (EX1)

Participants will arrive at the Human Performance Lab between 3:00 and 5:00pm, having abstained from alcohol, tobacco, or caffeine for 24 hours. Additionally, they will

arrive fasted for ≥ 2 hours. Upon arrival, participants will be equipped with a heart rate (HR) monitor (Polar; Lake Success, NY, USA) to wear, and then rest in a reclined position for five minutes. At the cessation of the five minute period, resting HR will be recorded. Participants will then warm up for 20 minutes (10 minutes at 50% W_{max} followed by 10 minutes at 60% W_{max}) on the aforementioned cycle ergometer, during which metabolic measurements will be assessed, as described below. Following the 20 minute warm-up, participants will begin a computer simulated 3-km cycling time trial. Participants will be encouraged to give a maximal effort before the time trial. Following the time trial, participants will cool down on the bicycle ergometer at a self-selected intensity between 50-100W for 10 minutes. The cool-down intensity will be matched in subsequent trials. Following the cool-down, participants will perform three warm-up and 30 maximal single-leg extensions at 120°/second on an isokinetic dynamometer (Biodex Multi-Joint System - PRO, Biodex Medical Systems, Inc., Shirley, NY, USA). Upon completion of leg extensions, participants will perform a 60-minute sprint interval session, previously used in our laboratory (13). Intervals will alternate between 2 minutes at 95% W_{max} and 2 minutes at 50% W_{max} . If participants cannot maintain a cadence of ≥ 50 rpm at 95% W_{max} , power output will be reduced by 10% for following sprints.

Experimental Trial 2 (EX2)

Participants will begin EX2 between 7:00am and 9:00am the following morning. Participants will eat a standardized breakfast (detailed below) 2 hours prior to EX2. Caffeine/placebo capsules will be ingested 1 hour prior to EX2. Resting HR will be

recorded after 5 minutes of rest at the start of EX2. Following rest, participants will complete an assessment of transient mood states (POMS-2, Multi-Health System; North Tonawanda, NY, USA). Participants will then repeat the warm up and time trial protocol from EX1 and cool down on the cycle ergometer at their previously selected intensity. Following the cool-down, participants will perform the same leg-extension protocol from EX1.

Sleep Protocol

Participants will undergo the four experimental trials with 5-7 days between the end of one trial and beginning of another. Participants will be instructed to initiate sleep between 10:00 pm and 12:00 am for all FULL and SR trials, replicating the same onset time in all experimental phases. For FULL, participants will be instructed to set their wake-up time for 8 hours following sleep onset. After waking up, participants will report to the laboratory for EX2. For SR, participants will be instructed to set their wake-up time 3.5 hours following sleep onset. After waking up, participants will immediately report to the laboratory whereupon an investigator will accompany them to ensure wakefulness until testing begins. The start time of EX2 will remain constant throughout the experimental phases. The Sleep Cycle smartphone application (Northcube, AB, Göteborg, Sweden) will be used to evaluate the two nights preceding EX1 and the night before EX2. Participants will place the smart phone on their mattress in accordance with manufacturer recommendations and sleep data will be estimated based on motion detection. In addition to Sleep Cycle, sleep data will be acquired through the use of an Actigraph Accelerometer (Pensacola, FL, USA) worn on the non-dominant wrist.

Caffeine/Placebo Capsules:

A randomly counterbalanced, double blind, placebo controlled design will be utilized to compare the effects of four different treatment conditions. Participants will receive 6mg/kg body weight in capsule form containing either rice flour (PLA) or anhydrous caffeine. Capsules will be ingested 1 hour before each EX2 trial. The four treatment conditions will be: 1. FULL with caffeine capsule (FULL/CAF), 2. FULL with placebo capsule (FULL/PLA), 3. SR with caffeine capsule (SR/CAF), and 4. SR with placebo capsule (SR/PLA).

Dependent Measures*3-km Time Trial Performance*

3-km time trial performances will be performed on the Velotron cycle ergometer in all EX trials. Time to completion and average power output will be used as the primary performance measures.

Blood Lactate and Glucose

Blood lactate and glucose will be taken at minute 18 of the 20 minute warm-up preceding the 3-km time trial in all EX trials. A finger-stick blood draw will be performed and blood will be analyzed in a YSI 2300 Stat Plus Analyzer (YSI Incorporated; Yellow Springs, OH, USA).

Muscle Function

Total work and fatigue index will be determined using the Biodex dynamometer mentioned above at 120°/second during all EX trials.

Oxygen Consumption, Ventilation, & Respiratory Exchange Ratio (VO₂, VE, & RER)

VO₂, VE, and RER will be measured using a Moxus metabolic cart during the last 5 minutes of the 20 minute warm-up preceding the 3-km time trial in all EX trials. Values obtained in minutes 17-20 will be averaged and recorded.

Heart Rate & Rate of Perceived Exertion (HR & RPE)

During all EX trials, HR and RPE will be obtained at minute 20 of the 20 minute warm-up preceding the 3-km time trial.

Dietary and Exercise Controls

Participants will record all food and beverage intake for 24 hours before EX1 and continue recording until sleep onset that night. After the first EX phase, copies of food and beverage logs will be provided to the participants to replicate diet habits for the remaining phases. Participants will begin all EX trials after a ≥ 2 hour fast. Within one hour of completing EX1, participants will consume a meal replacement protein shake (Ensure Original Nutrition Shake, Abbott Laboratories). Participants will also be asked to abstain from consuming any other macronutrients within two hours of ending EX1. For all conditions, participants will be instructed to consume a standardized breakfast 2 hours before beginning EX2. The standardized breakfast will consist of orange juice, cereal, and

yogurt equaling approximately 400 calories. Participants will also be instructed to record all physical activity for 72 hours prior to EX1 in all phases, and keep physical activity habits for all phases. Additionally, they will be instructed to avoid physical activity the day of EX1 and between EX1 and EX2.

Statistics

Total time to completion and mean power output (Watts) during the 3-km time trial will be used as the performance measures. Data will be log transformed to reduce the effects of non-uniformity. Magnitude-based inferences will be derived about the data using methods previously described by Hopkins and colleagues (32). A previously determined “smallest worthwhile change” in performance will be used as a threshold value for a condition effect (EX1 time trial vs. EX2 time trial). The smallest worthwhile change in performance is defined as $0.3 \times$ the within subject variability of select groups of elite cyclists across repeated time trials ($CV = 1.5\%$ for time and estimated 4.5% for power) (31). For all other variables that will be analyzed, the threshold value for a substantial treatment effect will be defined as $0.2 \times$ within-subject standard deviation, under resting conditions.

Publically available spreadsheets will be used to the likelihood of the true treatment effect (of the population) reaching the substantial change threshold (30). The percent likelihoods will be classified as: $<1\%$ almost certainly no chance, $1-5\%$ = very unlikely, $5-25\%$ = unlikely, $25-75\%$ = possible, $75-95\%$ = likely, $95-99\%$ = very likely, $>99\%$ almost certain. Clinical inference criteria will be used to classify the effects of all conditions on performance. If the percent chance of the effect reaching the substantial change threshold

is <25% and the effect is clear, it will be classified as 'trivial'. If the percent chance of the effect reaching the substantial change threshold for benefit exceeds 25%, but the chance for harm is >0.5%, the effect will be considered "unclear". An exception to the 0.5% chance of harm criterion will be made if the benefit/harm odds ratio is >66, in which the case of the effect will be interpreted as "clear".

Following individual condition analysis, treatment comparisons (FULL/CAF vs FULL/PLA vs SR/CAF vs SR/PLA) outcomes will be assessed using the previously mentioned spreadsheets (30). The classification system described above will apply, but mechanistic criteria will be used. If 90% confidence intervals include values that exceed the substantial change threshold for both a positive and negative effect, the effect will be considered 'unclear'.

Chapter 3
Manuscript

**Caffeine Intake Helps Maintain 3-km Cycling Performance the Morning Following
Sleep Restriction**

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Abstract

Introduction: Although a full understanding of the role of sleep is debated, it is widely accepted that sleep is important for recovery from heavy exercise. Recent research suggests that sleep restriction (SR) may negatively impact recovery and subsequent performance. It is unknown if caffeine supplementation mitigates this performance decrement. Our objective was to investigate the effect of caffeine supplementation on exercise performance following one night of SR in trained cyclists.

Methods: Subjects (n=10) completed a 3-km time trial (TT) and an exhaustive bout of exercise in the evening (EX1), then returned to repeat the TT the following morning (EX2). Exercise trials were separated by a full night of sleep (FULL) or a night of restricted sleep (SR). Perceived fatigue was also assessed prior to EX2. Caffeine (CAF) or placebo (PLA) treatments were given before the start of EX2. A randomly counterbalanced, double blind, placebo controlled design was used to compare the effects of four different treatment conditions: FULL/PLA, SR/PLA, FULL/CAF, and SR/CAF.

Results: Data were analyzed using magnitude-based inferences to compare differences in EX2 performances only. Power output was ‘possibly’ greater ($0.9 \pm 3.6\%$) following SR/PLA compared to FULL/PLA. Power output was ‘likely’ higher ($5.5 \pm 4.8\%$) following SR/CAF compared with SR/PLA. Perceived fatigue was rank ordered as 1) SR/PLA, 2) SR/CAF, 3) FULL/PLA, 4) FULL/CAF. Specifically, CAF ‘very likely’ reduced perceived fatigue following SR compared to SR PLA, but remained ‘likely’ higher than FULL/CAF.

Conclusion: These data show that caffeine has the ability to mitigate performance decrements resulting from a single night of SR following heavy exercise. Caffeine also prevented increases in perceived fatigue following SR.

Introduction

A full understanding of the precise physiological role of sleep has yet to be fully elucidated, but it is clear that sleep is required for optimal function. It is widely recommended that adults sleep 7 to 9 hours a night. Despite this recommendation, much of the population falls short of these guidelines (18, 60). The importance of sleep is believed to be related to energy conservation and optimal central nervous and immune system function (7, 15, 20, 45, 59, 62). Proper sleep may be critical to recovery for athletes due to maintenance of the immune system, restoring the metabolic cost of the wakeful state, preventing overtraining, and enhancing memory, learning, and synaptic plasticity (4, 19, 25). In addition, athletes are particularly susceptible to sleep loss due to heavy training and psychological stress of competitions (17, 28). Therefore, it is advantageous for both coaches and athletes to understand the effects of sleep on recovery and physical performance.

Complete sleep deprivation (SDEP; i.e. >24 hrs sleep loss) reportedly has negative impacts on athletic endeavors, ranging in duration from short sprints and Wingate tests (90s) to endurance trials lasting approximately 35 to 100 minutes. However, there is still some debate regarding the mechanisms which underlie these performance decrements (38, 43, 52, 55, 57). The detrimental effects of SDEP on performance have been at least partially attributed to changes in perceived exertion and mood states following SDEP, but the direct mechanisms have yet to be fully determined (38, 43, 51, 52). Although athletes may occasionally experience SDEP, it is presumably more common for athletes to experience acute sleep restriction (SR; abbreviated sleep duration) as a result of late bedtime, intermittent awakening, or early awakening. It would

seem that SR can negatively impact peak and mean muscular power, especially when performance is in the afternoon (2, 24, 41, 55). The effects of SR on longer performances such as cycling and running time to exhaustion as well as shuttle running are unequivocal. Early research indicated that SR had no effect on these performances. However, more recent data suggest that SR in the form of early awakening as opposed to delayed bedtime can inhibit performance in the afternoon suggesting the type of SR as well as the time of performance are key factors when investigating the implications of SR (40, 42, 44, 48).

Prior studies on SR and exercise performance had subjects refrain from heavy exercise leading up to the night of SR. Our laboratory recently found that one night of SR following heavy exercise impairs short-duration cycling performance by approximately 4% (13). Because SR is inevitable and in some cases, detrimental to performance, it is worthwhile to examine potential strategies to attenuate performance detriments following SR. One potential strategy is caffeine supplementation. Extensive research has demonstrated the effectiveness of caffeine as an ergogenic aid for performance through increased neurocognitive function and decreased perceived exertion (22, 33, 34, 61). Specifically, Souissi et al recently investigated the effects of caffeine on physical and cognitive performance following 36 hours of SDEP. Caffeine ingestion following SDEP improved mood states, cognitive function, squat jump and Wingate performance (53). While this data presents a strong case for caffeine mitigating the performance losses seen following SDEP, it is important to note that the tests were performed in the afternoon, sleep loss occurred through total SDEP, and subjects were fully rested leading into the study. Thus, it is important to investigate the role of caffeine in attenuating the

detrimental performance following sleep restriction. Therefore, the purpose of the present investigation is to test the hypothesis that caffeine supplementation will attenuate but not fully compensate for the negative impact that SR has on next-day performance.

Methods

Subjects

Ten male (n=8) and female (n=2) recreational cyclists from James Madison University participated in this study. All subjects performed a minimum of 30 minutes of cycling, one to two days per week, for at least three months prior to the study, and possessed a maximum oxygen consumption (VO_{2max}) of ≥ 40 ml/min/kg. Demographic information of the participants is highlighted in Table 1. Additionally, participants scored ≤ 7 on the Pittsburg Sleep Quality Index (PSQI) to ensure they had “normal” sleeping habits (11). Participants were informed of the experimental protocol, risks, and benefits before providing written consent. The study was approved by the James Madison Institutional Review Board

Preliminary Testing

Following height and weight measurements, participants performed an incremental exercise test to exhaustion on a cycle ergometer (Velotron, Racermate, Inc., Seattle, WA, USA) to determine VO_{2max} and maximum power in watts (W_{max}). The participants warmed up for five minutes at a self-selected workload, then began the test at a workload between 100 and 175 W based on self-reported training workloads. The workload increased every 2 minutes in 50 W increments until volitional fatigue or inability to maintain a cadence of 50 RPM or higher for more than 10 seconds. Breath samples were collected throughout the test and oxygen consumption was assessed using the Moxus Modular Metabolic System (AEI Technologies, Pittsburgh, PA, USA). VO_{2max} was determined by the highest 30-s mean oxygen uptake value.

Experimental Design

Participants completed a familiarization phase followed by four experimental phases, each separated by five to seven days. The familiarization and experimental phases consisted of two exercise sessions performed on consecutive days (EX1 and EX2). EX1 consisted of baseline performance testing followed by an exercise protocol designed to elicit fatigue. EX2 was performed the following morning to assess recovery from the exercise protocol, and only included the performance testing. EX1 and EX2 during the experimental phases were separated by a night of full sleep (FULL) or a night of restricted sleep (SR). Sleep condition was assigned to each participant in a randomized, crossover design. Participants were informed of their designated sleep condition following the exercise protocol on EX1 and not before, to prevent reactive behavior changes leading up to the experimental trials. A schematic of the experimental design can be found in Figure 1.

Familiarization Phase

The familiarization phase consisted of EX1 and EX2 trials (as described below), however sleep, diet, and physical activity were not controlled. These trials were performed at predetermined intensities calculated from W_{\max} to confirm they could complete the protocol, familiarize themselves with the equipment, and reduce learning-related improvements in performance during the experimental trials. Appropriate intensities for the various components of the experimental trials are defined below.

Experimental Trial 1 (EX1)

Participants arrived at the Human Performance Lab between 3:00 and 5:00pm, having not consumed alcohol, tobacco, or caffeine for 24 hours. Additionally, they arrived

having fasted from food for ≥ 2 hours. Upon arrival, participants were equipped with a heart rate (HR) monitor (Polar; Lake Success, NY, USA) to wear, and then rested in a reclined position for five minutes. At the cessation of the five minute period, resting HR was recorded and weight was measured. Participants warmed up for 20 minutes (10 minutes at 50% W_{max} followed by 10 minutes at 60% W_{max}) on the aforementioned cycle ergometer, during which metabolic measurements were assessed, as described below. Following the 20 minute warm-up, participants began a computer simulated 3-km cycling time trial. Participants were encouraged to give a maximal effort before the time trial. Following the time trial, participants cooled down on the bicycle ergometer at a self-selected intensity between 50-100W for 10 minutes. The cool-down intensity was matched in subsequent trials. Following the cool-down, participants performed three warm-up and 30 maximal single-leg extensions at 120°/second on an isokinetic dynamometer (Biodex Multi-Joint System - PRO, Biodex Medical Systems, Inc., Shirley, NY, USA). Upon completion of leg extensions, participants performed a 60-minute sprint interval session, previously used in our laboratory (13). Intervals alternated between 2 minutes at 95% W_{max} and 2 minutes at 50% W_{max} . If participants could not maintain a cadence of ≥ 50 rpm at 95% W_{max} , power output was reduced by 10% for following sprints. Upon leaving the laboratory, participants were instructed to continue refraining from the consumption of alcohol, tobacco, or caffeine.

Experimental Trial 2 (EX2)

Participants began EX2 between 7:00am and 9:00am the following morning. Participants ate a standardized breakfast (detailed below) 2 hours prior to EX2. Caffeine/placebo capsules were ingested 1 hour prior to EX2. Resting HR was recorded

after 5 minutes of rest at the start of EX2. Following rest, participants completed an assessment of transient mood states (POMS-2, Multi-Health System; North Tonawanda, NY, USA). Participants then repeated the warm up and time trial protocol from EX1. Participants cooled down on the cycle ergometer at their previously selected intensity. Following the cool-down, participants performed the same leg-extension protocol from EX1.

Sleep Protocol

Participants were instructed to initiate sleep between 10:00 pm and 12:00 am for all FULL and SR trials, and replicated the same onset time in all experimental phases. For FULL, participants were instructed to set their wake-up time for 8 hours following sleep onset. After waking up, participants reported to the laboratory for EX2. For SR, participants were instructed to set their wake-up time 3.5 hours following sleep onset. After waking up, participants immediately reported to the laboratory whereupon an investigator accompanied them to ensure wakefulness until testing began. The start time of EX2 remained constant throughout the experimental phases. The Sleep Cycle smartphone application (Northcube, AB, Göteborg, Sweden) was used as to confirm adherence for the two nights preceding EX1 and the night before EX2. Participants placed the smart phone on their mattress in accordance with manufacturer recommendations and sleep data was estimated based on motion detection. In addition to Sleep Cycle, sleep data was acquired through the use of an accelerometer (ActiGraph GT3X+, ActiGraph Corp, Pensacola, FL, USA) worn on the non-dominant wrist. Sleep amounts acquired by participants can be found in Table 2.

Caffeine/Placebo Capsules:

A randomly counterbalanced, double blind, placebo controlled design was utilized to compare the effects of four different treatment conditions. No treatments were administered during the familiarization trials. During the experimental trials participants were given 6mg/kg body weight in capsule form containing either rice flour (PLA) or anhydrous caffeine (CAF). Capsules were ingested 1 hour before each EX2 trial. The four treatment conditions were: 1. FULL with caffeine capsule (FULL/CAF), 2. FULL with placebo capsule (FULL/PLA), 3. SR with caffeine capsule (SR/CAF), and 4. SR with placebo capsule (SR/PLA).

Dependent Measures*3-km Time Trial Performance*

3-km time trial performances were performed on the Velotron cycle ergometer in all EX trials. Time to completion and average power output were used as the primary performance measures.

*Responses to Fixed-Load Exercise*Oxygen Consumption, Ventilation, & Respiratory Exchange Ratio (VO₂, VE, and RER)

VO₂, VE, and RER were measured using a Moxus metabolic cart during the last 5 minutes of the 20 minute fixed-load phase preceding the 3-km time trial in all experimental trials. Values obtained in minutes 17-20 were averaged and recorded.

Heart Rate & Rate of Perceived Exertion (HR & RPE)

During all experimental trials, HR and RPE were obtained at minute 20 of the 20 minute fixed-load phase preceding the 3-km time trial.

Muscle Function

Total work, peak torque, and fatigue index over 30 maximal leg extensions were determined using the Biodex dynamometer mentioned above at 120°/second during all EX trials. Total work was the sum of work done in Joules (J) over the course of the 30 maximal leg extensions. Fatigue index was calculated for the 30 maximal leg extensions as a percent change using the formula

$$\left[\frac{\text{Peak Torque 5 strongest repetitions} - \text{Peak Torque 5 weakest repetitions}}{\text{Peak Torque 5 strongest repetitions}} \right] \times 100$$

Dietary and Exercise Controls

Participants recorded all food and beverage intake for 24 hours before EX1 and continued recording until sleep onset that night. After the first EX phase, copies of food and beverage logs were provided to the participants to replicate diet habits for the remaining phases. Participants began all EX trials after a ≥ 2 hour fast. Within one hour of completing EX1, participants consumed a meal replacement protein shake. Participants were asked to abstain from consuming any other macronutrients within two hours of ending EX1. For all conditions, participants were instructed to consume a standardized breakfast 2 hours before beginning EX2. The standardized breakfast consisted of orange juice, cereal, and yogurt equaling approximately 400 calories. Participants were also instructed to record all physical activity for 72 hours prior to EX1 in all phases, and keep physical activity habits for all phases. Additionally, they were instructed to avoid physical activity the day of EX1 and between EX1 and EX2.

Statistics

Total time to completion (min) and mean power output (Watts) were used as the main performance measures, while isokinetic testing was used to assess muscle function. Data was log transformed to reduce the effects of non-uniformity. Magnitude-based inferences were derived about the data using methods previously described by Hopkins and colleagues (32). A previously determined “smallest worthwhile change” in performance was used as a threshold value for a between condition effect (EX2 time trial vs. EX2 time trial). The smallest worthwhile change in performance was defined as 0.3 x the within subject variability of select groups of elite cyclists across repeated time trials (CV = 1.5% for time and estimated 4.5% for power) (31). For all other variables that were analyzed, the threshold value for a substantial treatment effect was defined as 0.2 x within-subject standard deviation, under resting conditions.

Publically available spreadsheets were used to the likelihood of the true treatment effect (of the population) reaching the substantial change threshold (30). The percent likelihoods were classified as: <1% almost certainly no chance, 1-5% = very unlikely, 5-25% = unlikely, 25-75% = possible, 75-95% = likely, 95-99% = very likely, >99% almost certain. Clinical inference criteria were used to classify the effects of all conditions on performance. If the percent chance of the effect reaching the substantial change threshold was <25% and the effect is clear, it was classified as ‘trivial’. If the percent chance of the effect reaching the substantial change threshold for benefit exceeded 25%, but the chance for harm was >0.5%, the effect was considered “unclear”. An exception to the 0.5% chance of harm criterion was made if the benefit/harm odds ratio was >66, in which the case of the effect was interpreted as “clear”.

Following individual condition analysis, treatment comparisons (FULL/CAF vs FULL/PLA vs SR/CAF vs SR/PLA) outcomes were assessed using the previously mentioned spreadsheets (30). The classification system described above was applied, but mechanistic criteria was used. If 90% confidence intervals included values that exceeded the substantial change threshold for both a positive and negative effect, the effect was considered 'unclear'. All data are presented as means \pm SD.

Results

3-km Time Trial Performance

Statistics were performed on 3-km TT power output and mean values displayed in Figure 2. For reference, EX2 finishing times were as follows: FULL/PLA, 301.1 ± 32.2 sec; SR/PLA, 300.7 ± 33.2 sec; FULL/CAF, 296.9 ± 37.8 sec; SR/CAF, 294.8 ± 39 sec. Statistics were performed on EX2 power output, but for reference, finishing times were as follows: Time trial performance had a clear order effect such that they rode progressively slower chronologically. Therefore, EX1 3-km TT performances were aggregated and are only used as a reference point in comparison to EX2 performances in the four experimental conditions. Average time trial power output for EX1 was 273.7 ± 69.2 W (mean finishing time: 294.9 ± 32.8 sec). For all conditions except SR/CAF, average power output and finishing time were lower the following morning for EX2. All comparisons presented henceforth are from the EX2 (morning) trials. Power output was ‘possibly’ greater ($0.9 \pm 3.6\%$) following SR/PLA compared to FULL/PLA. Power output was ‘likely’ higher ($5.5 \pm 4.8\%$) following SR/CAF compared with SR/PLA. There were ‘unclear’ ($1.9 \pm 3.2\%$) differences in power output following SR/CAF compared to FULL/CAF. Power output was ‘very likely’ greater ($6.5 \pm 5.2\%$) following SR/CAF compared to FULL/PLA.

Muscle Function

Peak isokinetic torque, total work, and fatigue index data at $120 \text{ deg}\cdot\text{sec}^{-1}$ are displayed in Table 3. There were no differences in peak torque between any of the experimental conditions.

Total Work

There was a ‘likely trivial’ difference in total work ($-2.0 \pm 6.4\%$) between SR/PLA and FULL/PLA. However, total work was ‘possibly’ higher ($4.9 \pm 7\%$) following SR/CAF compared to SR/PLA. Finally, there was a ‘likely trivial’ difference ($3.5 \pm 3.6\%$) between FULL/CAF and SR/CAF.

Fatigue Index

There were no differences in fatigue index when comparing FULL/PLA to SR/CAF, SR/PLA to SR/CAF, and FULL/CAF to SR/CAF. However, fatigue index was ‘very likely’ higher ($18.1 \pm 11.5\%$) following FULL/PLA compared to SR/PLA.

Muscle Soreness

Sleep condition did not seem to affect muscle soreness in the placebo or caffeine treatments. Additionally, treatment did not seem to affect muscles soreness following a night of sleep restriction. Muscle soreness was only different when comparing SR/CAF to FULL/PLA. Surprisingly, muscle soreness was ‘most likely’ lower ($-42.7 \pm 14.4\%$) following SR/CAF ($20.8 \pm 10.9\text{mm}$) compared to FULL/PLA ($34.7 \pm 15\text{mm}$).

Responses to Fixed-Load Exercise

HR and RPE

There were no differences in fixed-load HR between FULL/PLA and SR/PLA or between SR/CAF and SR/PLA. Fixed-load HR was ‘possibly’ higher ($2.4 \pm 3.4\%$) following SR/CAF compared to FULL/CAF.

There was no difference in RPE when comparing SR/PLA to FULL/PLA. RPE was ‘very likely’ lower ($-9.5 \pm 4.4\%$) following SR/CAF compared to SR/PLA. Additionally,

RPE was ‘very likely’ lower following SR/CAF compared to FULL/PLA. Sleep condition had a ‘very likely’ effect on RPE with the caffeine treatment. Interestingly, RPE was ‘very likely’ lower ($-7.4 \pm 4.8\%$) following SR/CAF compared to FULL/CAF.

VO₂, VE, and RER

Sleep condition had an ‘unclear’ effect on VO₂ during the placebo treatment ($1.4 \pm 4.9\%$). VO₂ was ‘likely’ lower ($-5.3 \pm 5.2\%$) following FULL/PLA compared to SR/CAF. There was a ‘possible’ effect of treatment ($3.8 \pm 6\%$) on morning performance. VO₂ was ‘possibly’ lower for SR/PLA compared to SR/CAF. Similarly, VO₂ was ‘possibly’ lower ($-2.0 \pm 3.4\%$) following FULL/CAF compared to SR/CAF.

There were ‘unclear’ ($0.3 \pm 4.2\%$) differences between SR/PLA and FULL/PLA. Ventilation was ‘likely’ elevated ($5.7 \pm 5.2\%$) following SR/CAF compared to SR/PLA. Also, ventilation was ‘possibly’ elevated ($1.5 \pm 3.3\%$) SR/CAF (77 ± 8.9 L/min) compared to FULL/CAF.

There were ‘unclear’ differences in RER for all comparisons except when comparing FULL/PLA to SR/CAF ($1.1 \pm 1.6\%$). RER was ‘possibly’ lower for the FULL/PLA than for SR/CAF.

Profile of Mood States

Total Mood Disturbance

Data for POMS total mood disturbance are displayed in Table 3. Total mood disturbance was ‘likely’ higher ($7.1 \pm 5.5\%$) following SR/PLA compared to FULL/PLA. Total mood disturbance was ‘possibly’ lower ($-2.0 \pm 3.8\%$) following SR/CAF compared

to SR/PLA and ‘very likely’ lower ($-7.5 \pm 3.9\%$) following FULL/CAF as compared to SR/CAF.

Fatigue-Inertia

Fatigue-inertia was ‘very likely’ ($11 \pm 7.4\%$; 92% likelihood) greater following SR/PLA compared to FULL/PLA. Fatigue-inertia was ‘very likely’ greater ($8.3 \pm 5.5\%$) following SR/PLA compared to SR/CAF. Additionally, fatigue-inertia was ‘likely’ greater ($6.2 \pm 8\%$) following SR/CAF compared to FULL/CAF.

Vigor-Activity

Vigor-activity was ‘possibly’ lower ($-7.3 \pm 7.6\%$) in SR/PLA compared to FULL/PLA. Conversely, vigor-activity was ‘likely’ greater ($18.3 \pm 16.8\%$) following SR/CAF (47.4 ± 10.2) compared to SR/PLA. Additionally, vigor-activity was ‘possibly’ lower ($-4.2 \pm 7.9\%$) following SR/CAF compared to FULL/CAF.

Discussion

This study was designed to investigate the effect of sleep restriction on next morning cycling time trial performance following heavy exercise. Specifically, the goal of this study was to explore whether caffeine can compensate for the performance decrements following sleep restriction recently reported by our laboratory (13). Interestingly, there were no differences in performance between FULL/PLA compared to SR/PLA as previously suggested, but these findings may have been confounded by a placebo effect (13, 47). Regardless, the most notable finding was that participants had ‘very likely’ increased power output (6.5%) following SR/CAF compared to FULL/PLA. While we anticipated that caffeine would attenuate performance decrements following sleep restriction, we did not expect to see performance exceeding that of a full night of sleep under any of the sleep restriction conditions. Although greater than expected, there was a ‘likely’ improvement in power output (5.5%) following SR/CAF compared to SR/PLA. No systematic differences in muscle function were observed. This is consistent with our recent report that even with impaired recovery (as evidenced by 3-km time trial performance), there were no differences in muscle function (13). The majority of cardiorespiratory variables taken during the fixed-load phase prior to the time trial in the SR/CAF condition were altered. Specifically, ventilation, VO_2 , and HR were ‘possibly’ and ‘likely’ elevated. Altogether, these data suggest that caffeine supplementation can benefit performance through increasing power output following both sleep restriction and a full night of sleep.

The effects of sleep restriction on recovery from exercise have been investigated in only a few studies. One observational study reported decreased sleep duration negatively impacted perceived recovery the following morning in elite soccer players that participated in night matches compared to day matches. While there were no specific performance measures, players reported lower perceived recovery following night matches and decreased sleep duration (21). Additional quantitative research supports the notion that sleep facilitates recovery. Previous findings showed a 4-5% decrease in cycling performance following heavy exercise and sleep restriction, presumably due to diminished muscle glycogen replenishment as well as reduced restoration of the immune and endocrine systems (13, 16, 47, 52). Despite such findings, the current study did not observe any difference in performance following heavy exercise and sleep restriction compared to a full night of sleep. Even with a full night of sleep it appears that the participants in this study had a difficult time recovering from the heavy exercise, whereas in our previous research and the study by Rae et al, the participants seemed to sufficiently recovery from previous exercise with a full night of sleep. What makes this finding even more surprising is that the negative psychological effects (mood disturbance, sleepiness, fatigue, etc.) of sleep restriction (49, 51), which have been used to explain impaired next-day performance, were present with SR compared to FULL. If the psychological alterations do contribute to performance impairment, they were not marked enough to influence performance in the current study. Due to the multifaceted nature of recovery, it is difficult to identify the reason for the inconsistent performance findings. One possible explanation for the current outcome is the nocebo effect, or worsening performance due to the expectation of negative

outcome (6). While our study was not designed to test the nocebo effect, it may be that subjects underperformed when they were confident that they were not receiving the caffeine treatment, as has been shown in previous literature. Six of our ten subjects were able to accurately identify when they received the placebo in the present study, which could be a reason they underperformed following placebo treatments. Furthermore, the participants in the current study certainly experienced the negative psychological effects of sleep restriction. It is well known that disrupted sleep causes disturbances in mood (49, 51). Total mood disturbance following sleep restriction was 7.1% greater than a full night of sleep in the placebo condition. Furthermore, an 11% increase in fatigue was observed in the sleep restriction condition compared to the full night of sleep under placebo treatment. Despite the greater mood disturbance following sleep restriction, it was not enough to impact performance compared to FULL/CAF.

While the results in the FULL/PLA condition were surprising, the outcomes following caffeine supplementation were more consistent with our hypothesis. Following sleep restriction, when participants received caffeine treatment, they had 5.5% greater power output than when they received placebo. This was enough of an increase to maintain 3-km TT performance from the previous evening. This increase in power output with caffeine following SR supports the well-established efficacy of caffeine as an ergogenic aid for short-duration cycling performance (22, 33, 34, 61) as well as Wingate performance following sleep deprivation (53). Previous research by Souissi et al. demonstrated that when Wingate performance was assessed 36 hours following SDEP, caffeine improved peak and mean power output compared to placebo. Additionally, when compared to the

placebo treatment following sleep restriction, caffeine supplementation resulted in similar peak and mean power output compared to a full night of sleep without caffeine (53). Along with altering performance, caffeine also moderately influenced psychological measures. After ingesting caffeine, participants had a modest but 'possible' 2% reduction in total mood disturbance in the sleep restriction condition compared to placebo. Although smaller in magnitude, these findings are in line with the literature, which documents decreased mood following sleep restriction, and furthermore, improved mood following caffeine supplementation despite a poor night of sleep. In a study evaluating caffeine supplementation following sleep deprivation, there was a 33% decrease in fatigue and a 55% increase in vigor as assessed by the POMS survey (53). Additionally, supplementation with 300 mg of caffeine decreased fatigue by 6% and increased vigor by 39% following 72 hours of sleep deprivation in Navy Seal trainees (36). The noted improvements in mood following caffeine supplementation supports previous knowledge that caffeine exerts its ergogenic properties through influence on the central nervous system and ratings of perceived exertion (34). Altogether, these findings suggest that caffeine ingestion is a worthwhile strategy to compensate for probable impairments in performance following a night of SR.

In addition to observed alterations in time trial performance and mood, cardiorespiratory variables during submaximal exercise (fixed-load phase) seemed to be affected by sleep condition and caffeine supplementation. This observation is contradictory to our previous study which lacked any sleep-related alterations in physiological responses to steady state exercise (13). The SR/CAF condition increased ventilation, VO_2 , and HR.

Considering there were modest changes in these variables in the SR/PLA or FULL/CAF conditions, we cannot attribute these findings to sleep restriction or caffeine supplementation alone. Sleep restriction and caffeine supplementation have been separately implicated with increasing levels of catecholamine levels, which could have secondary influences on these cardiorespiratory variables (23, 42, 57). Although these changes were present, it is important to note that cardiorespiratory variables were assessed during submaximal exercise, whereas time trial performance was by nature, higher in intensity.

Based on the current findings, there is uncertainty surrounding the effects of sleep restriction on recovery from heavy exercise. While some research suggests that sleep restriction impedes recovery compared to a full night of sleep, the present study did not. Regardless, there were performance decrements the following morning that were compensated for following supplementation with caffeine. This further strengthens the well-established role caffeine plays as an ergogenic aid. While there were mood disturbances following sleep restriction that were improved following caffeine supplementation, it is not likely that mood was the only factor contributing to decreased morning performance. Perhaps negative expectations, or a 'nocebo' effect, contributed to the poor time trial performance in the morning trials in the placebo treatment. These findings necessitate further research considering the conflicting results between recent work done in our lab and the current findings regarding the effects of sleep restriction on recovery from heavy exercise and next day performance. Specifically, more definitive mechanisms are needed to determine why sleep restriction impairs recovery and next day

performance. Finally, more research is warranted to determine the effects of time of day on performance and the efficacy of caffeine supplementation following sleep restriction.

Table 1. Subject Demographics

	Age (yrs)	VO_{2max} (ml•kg⁻¹•min⁻¹)	Peak Watts	Height (cm)	Body Mass (kg)
Subjects (n=10)	21.3 ± 2.9	60.7 ± 8.0	290 ± 47	174.6 ± 7.0	69.8 ± 7.6

Data are expressed as means ± SD. Peak Watts represents power output at final complete stage of VO_{2max} test

Table 2. Sleep Data

	Sleep Onset Time	Wake-Up Time	Sleep Duration (hrs)	Efficiency (%)
FULL/PLA	10:46 PM (9:35PM-12:38AM)	6:06 AM (5:25-7:00AM)	6:28 (5:28-7:09)	88 (70-93)
SR/PLA	10:57 PM (9:52PM-12:40AM)	2:27 AM (1:30-3:40AM)	3:00 (2:23-3:31)	85 (69-100)
SR/CAF	10:54 PM (9:57PM-12:38AM)	2:27 AM (1:30-3:31AM)	3:06 (2:16-3:57)	88 (68-96)
FULL/CAF	10:45 PM (9:37PM-12:40AM)	5:59 AM (4:55-6:50AM)	6:19 (5:37-7:16)	87 (75-96)

Data are expressed as means with ranges displayed below. FULL, full night of sleep; SR, sleep restriction; CAF, caffeine treatment; PLA, placebo treatment. Regardless of treatment, participants fasted from caffeine at least 24 hours before beginning the evening exercise session. Sleep efficiency is a measure of sleep quality ([time in bed - sleep latency - time awake/time in bed], with 85% being considered sufficient.

Table 3. Peak Torque, Total Work, and Fatigue Index

	Peak Torque 120 deg·sec⁻¹ (Nm)	Total Work (J)	Fatigue Index (%)
FULL/PLA	164 ± 35	6020 ± 1548	31.0 ± 4.1 ^b
SR/PLA	163 ± 29	5920 ± 1726	25.7 ± 5.0
SR/CAF	164 ± 36	6105 ± 1351 ^a	29.6 ± 6.4
FULL/CAF	166 ± 26	6366 ± 1552	32.9 ± 6.4

Data are expressed as means ± SD. To assess fatigue index, participants performed 30 isokinetic leg extensions on the Biodex at 120 deg·sec⁻¹. All values are representative of morning exercise sessions; **a**, ‘possibly’ higher than SR/PLA [53% LH]; **b**, ‘very likely’ higher than SR/PLA [97% LH].

Table 4. Profile of Mood States (POMS)

	Total Mood Disturbance	Fatigue-Inertia	Vigor-Activity
FULL/PLA	41 ± 5 ^{a,b}	42 ± 5.2	43.4 ± 10.1
SR/PLA	44 ± 6 ^c	46.9 ± 8 ^{e,f}	40.1 ± 9.1 ^h
SR/CAF	43 ± 6	42.8 ± 5.6 ^g	47.4 ± 10.2 ^{i,j}
FULL/CAF	40 ± 5 ^d	40.3 ± 5.2	49.5 ± 10.3

Data are expressed as means ± SD. Total mood disturbance was assessed using the POMS questionnaire, which investigates transient mood states; **a**, ‘likely’ lower than SR/PLA [95% LH]; **b**, ‘likely’ lower [83% LH] than SR/CAF; **c** ‘possibly’ greater [53% LH] than SR/CAF; **d** ‘very likely’ lower [98% LH] than SR/CAF; **e**, ‘very likely’ greater [92% LH] than FULL/PLA; **f**, ‘very likely’ greater [95% LH] than SR/CAF; **g**, ‘likely’ greater [79% LH] than FULL/CAF; **h**, ‘possibly’ lower [72% LH] than FULL/PLA; **i**, ‘likely’ greater [93% LH] compared to SR/PLA; **j**, ‘possibly’ lower [45% LH] than FULL/CAF

Table 5. Responses to Fixed-Load Exercise

	Steady State HR (bpm)	RPE	VO ₂ (mL/kg/min)	Ventilation (L/min)	RER
FULL/PLA	153 ± 14 ^a	12.5 ± 1.3 ^f	40.9 ± 3.1 ^b	72.5 ± 7.2 ^d	0.86 ± 0.04 ^e
SR/PLA	155 ± 19	12.7 ± 1.6 ^f	41.6 ± 4.9 ^c	73.0 ± 9.7 ^d	0.87 ± 0.04
SR/CAF	156 ± 15	11.8 ± 1.1	43.1 ± 4.1	77.0 ± 8.9	0.87 ± 0.05
FULL/CAF	152 ± 15 ^a	12.6 ± 1.3 ^f	42.1 ± 2.5 ^c	75.9 ± 9.2 ^e	0.85 ± 0.03

Data are expressed as means ± SD. **a**, ‘possibly’ lower than SR/CAF [FULL/CAF, 55% LH; FULL/PLA, 58% LH]; **b**, ‘likely’ lower than SR/CAF [86% LH]; **c**, ‘possibly’ lower than SR/CAF [SR/PLA, 70% LH; FULL/CAF, 50% LH]; **d**, ‘likely’ lower than SR/CAF [FULL/PLA, 94% LH; SR/PLA, 88% LH]; **e**, ‘possibly’ lower than SR/CAF [ventilation, 63% LH; RER, 61% LH]; **f**, ‘very likely’ higher than SR/CAF [FULL/PLA, 98% LH; SR/PLA, 99% LH; SR/CAF, 96% L

Figure 1. Experimental Design

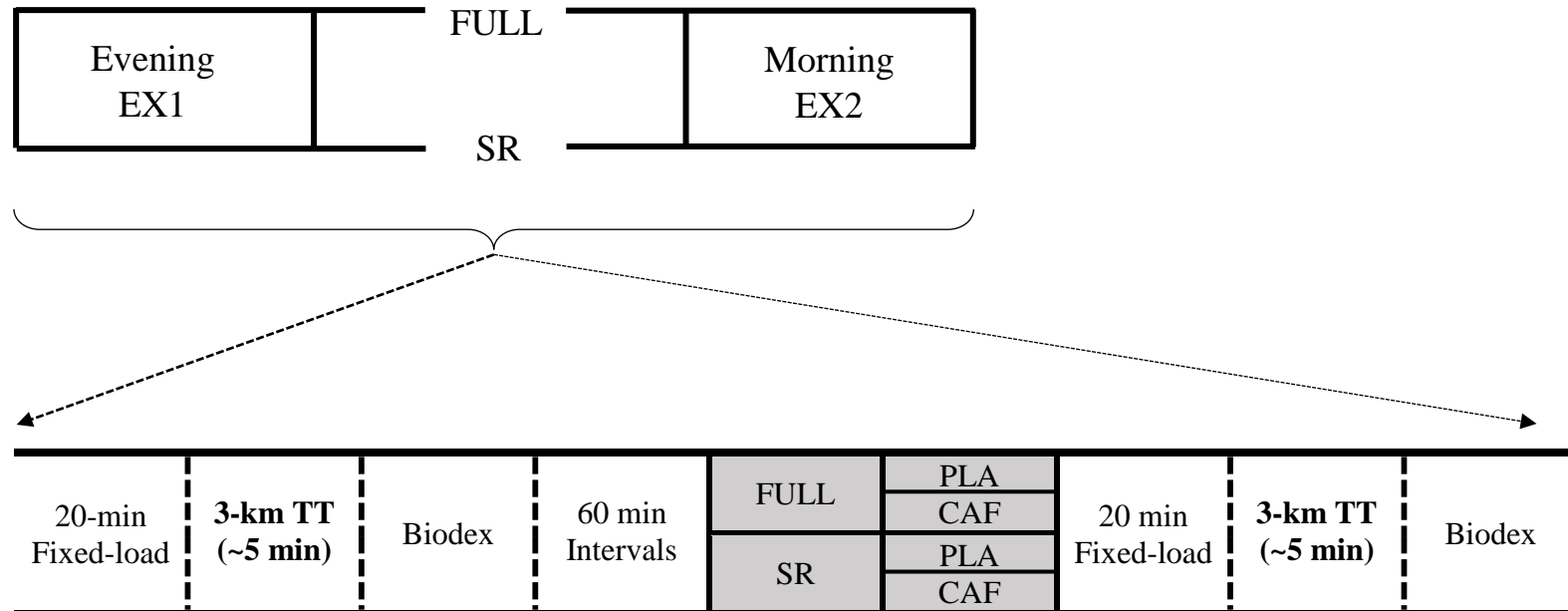


Figure 1. Experimental design and primary dependent measures. Sleep+, full night of sleep; Sleep-, night of sleep restriction; PLA, placebo treatment one hour before commencing EX2; CAF, caffeine treatment before commencing EX2.

Figure 2. 3-km Time Trial Performance Power Output

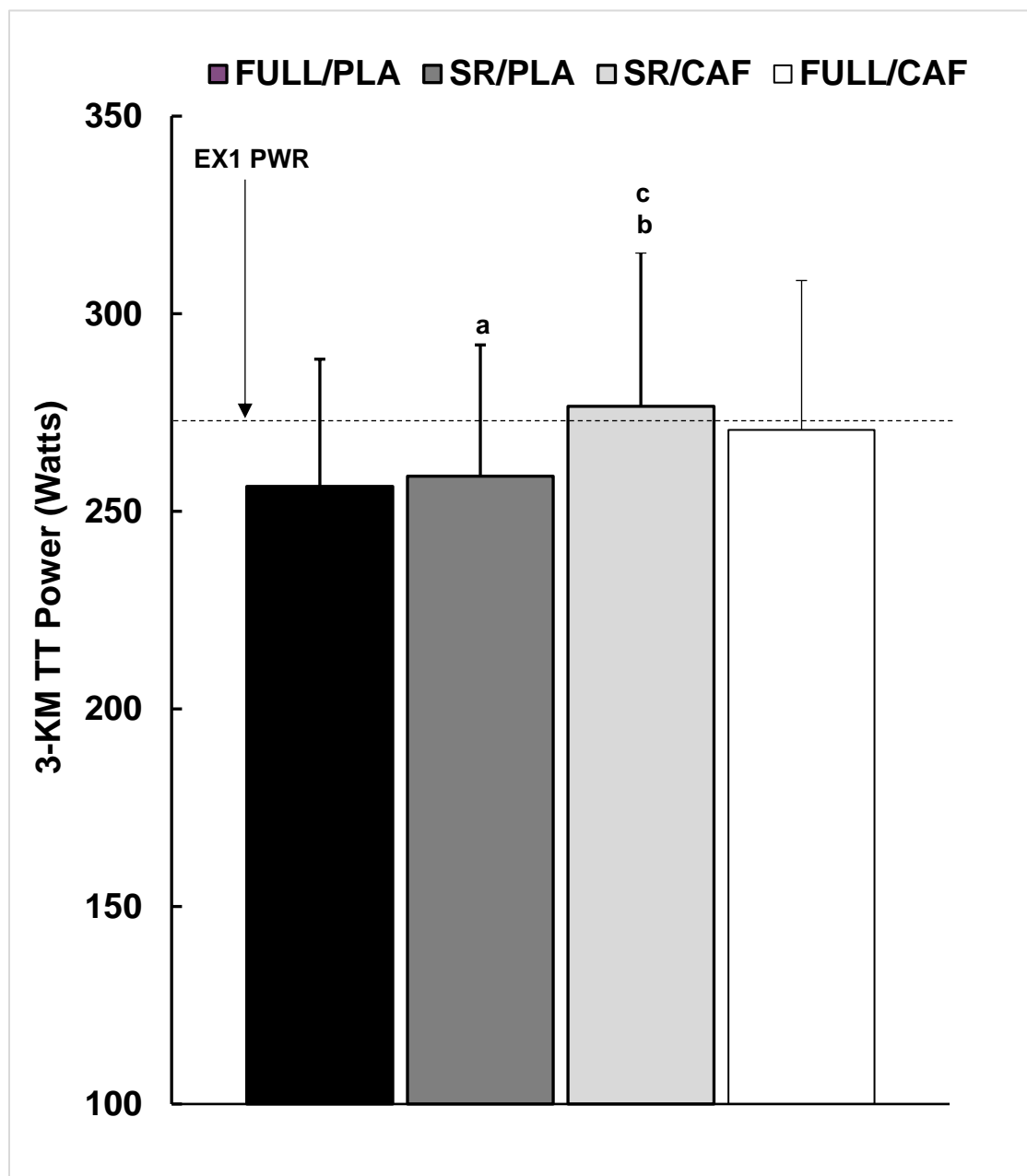


Figure 2. Mean power output in the morning following condition and treatment. SR/PLA, sleep restriction and placebo; SR/CAF, sleep restriction and caffeine; FULL/CAF, full night of sleep and caffeine; FULL/PLA, full night of sleep and placebo. The dashed horizontal line represents the average power output for the 3-km time trial in EX1, which was 273.7 ± 69.2 W; **a**, ‘possibly’ greater than FULL/PLA ($0.9 \pm 3.6\%$; 44% LH); **b**, ‘likely’ greater than SR/PLA ($5.5 \pm 4.8\%$; 94%); **c**, ‘very likely’ higher than FULL/PLA ($6.5 \pm 5.2\%$; 96% LH).

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Appendices

James Madison University

Department of Kinesiology

Consent for Investigative Procedure

I, _____, hereby agree on _____ (date) to participate in the research project conducted by Nicholas D. Luden, Ph.D. and Erin Horil from James Madison University titled *Performance Impairment Following Sleep Restriction - Is Caffeine the Antidote?*

The purpose of this study is to determine the effects caffeine has on performance following recovery from exercise following sleep restriction. Additionally, this study aims to determine the effects that caffeine has on performance following heavy exercise, compared to a full night of rest without caffeine.

Subject Responsibility

I understand that I will undergo the following testing:

This study consists of 11 separate visits performed, 10 of which will involve exercise on a resistance exercise device and 10 of which will involve exercise on a stationary bike (cardiovascular fitness test, two familiarization trials, and six exercise trials). All testing will occur in Godwin Hall, room 209, on the campus of James Madison University. You will also be asked about lifestyle behaviors such as smoking and physical activity and complete dietary and physical activity records. The total time commitment is estimated to be less than 16 hours over the course of 6 weeks.

Preliminary Trial (1 visit; 60 min):

After completing this consent form and the health history screening, if you meet the inclusion criteria for the study, researchers will measure your height and body weight.

You will then be asked to perform a maximal cardiovascular fitness test to determine your maximum oxygen consumption (VO_{2max}). You will be asked to ride a stationary bike at an initial workload that is 'fairly easy'. The workload will then be increased every two minutes until fatigue is reached, determined by either: 1) your request to stop due to fatigue, or 2) inability to maintain a cadence of ≥ 50 revolutions per minute. You will be verbally encouraged to continue to obtain an accurate measurement of VO_{2max} . To access oxygen consumption, you will need to breathe through a mouthpiece/breathing apparatus which collects expired air throughout the test (10-15 minutes).

Familiarization Phase (2 visits; total time of 180 min):

The familiarization phase will consist of two consecutive days of exercise trials. Procedures will be the same as the experimental trials detailed below. However, no blood samples will be obtained and you will not be assigned to sleep and caffeine conditions.

Experimental Phase**Exercise Trial 1 (4, 120 min each)**

You will be asked to arrive at the human performance lab between 3-5pm, not having consumed alcohol, tobacco or caffeine 24 hrs prior to testing.

Muscle Soreness – Upon arriving to the lab, you will be asked to rate your level of muscle soreness using a scale ranging from 0-100 (taken walking up stairs, walking down stairs and standing) and subjective ratings of energy and fatigue will be assessed using a short questionnaire.

3-km Cycling Time Trial – Immediately following the questionnaires, you will be prompted to perform a 20-min warm-up on a stationary cycle ergometer. During the warm-up, several measurements will be taken (detailed below). Following the warm-up, you will be prompted to transition into a 3-km computer-simulated time trial on the cycle ergometer. This will last approximately 4-7 minutes and you will be reminded to treat this like a competition.

Skeletal Muscle Function – 10 minutes following the 3-km cycling time trial, you will perform a muscle strength test where you will be asked to push as hard as possible against a shin pad for 30 consecutive leg extensions.

60-minute Sprint Interval – Immediately following completion of the skeletal muscle function testing, you will complete 60 min of sprint intervals. **You will only perform these intervals on Exercise Trial 1.** You will be asked to cycle at high intensities for 2-minute intervals, separated by 2 min of moderate intensity cycling. Intensity will be progressively decreased throughout to permit you to finish the 60-minute session.

Exercise Trial 2 (4, 60 min each)

You will be asked to arrive at the human performance lab between 7-9 am, not having consumed alcohol, tobacco, or caffeine 24 hrs prior to testing.

Muscle Soreness – Upon arriving to the lab, you will be asked to rate your level of muscle soreness using a scale ranging from 0-100 (taken while walking up stairs, walking down stairs, and standing) and subjective ratings of energy and fatigue will be assessed using a short questionnaire.

3-km Cycling Time Trial – You will then be asked perform a 20-min warm-up on a stationary cycle ergometer, then perform a 3-km computer-simulated time trial on the cycle ergometer. This will last approximately 4-7 minutes.

Skeletal Muscle Function – 10 minutes following the 3-km cycling time trial, you will again perform 30 consecutive leg extensions on the resistance exercise device as described above.

Measurements During 20-Minute Warm-Up

Heart Rate & Rate of Perceived Exertion (HR & RPE)

You will be fitted for a heart rate monitor so that we can measure your heart rate throughout the exercise trial. Additionally, you will be asked to rate your level of exertion on a scale from 6 to 20 at various points throughout your warm up.

Glucose & Lactate (GLU & LAC)

Finger-stick blood samples (1-2 drops of blood) will be obtained at min 10 and min 20 of the warm-up preceding the 3km time trial for measurement of blood sugar and lactic acid.

Oxygen Consumption, Ventilation, & Respiratory Exchange Ratio (VO_2 , VE & RER)

You will also be hooked up to a mouth-piece (and nose clip) in 2 x 5-minute increments during the warm-up for measurement of oxygen consumption and other measures of cardiorespiratory function.

Sleep Protocol:

Sleep will be measured, but not controlled, during the familiarization trials. During the experimental phases, you will be randomly assigned to a sleep and caffeine condition: a full night of sleep with placebo, a full night of sleep with caffeine, a night of sleep restriction with placebo, or a night of sleep restriction with caffeine. You will either be given a caffeine pill or placebo pill filled with rice flour, but you will not know which treatment you are receiving. You will not know your assigned sleep condition until completion of the first exercise trial. The sleep condition will be randomly selected for each exercise phase such that you may be assigned each sleep condition, or multiples of the same sleep/caffeine conditions. Following the first night of sleep assignment, you will be asked to record what you wore to sleep and replicate that on the second night of sleep assignment. You will also be asked to download a smartphone application, Sleep Cycle, which will detect movement during sleep, and wake up either 3.5 or 7.5 hrs following sleep onset, dependent upon sleep assignment for the night. Finally, you will wear an accelerometer to record movements while you sleep. Should you not comply with sleep protocols, you will be given another chance to complete the study seven days later. Failure to comply with sleep protocol a second time will result in removal from the study.

Caffeine Treatment:

Caffeine pills will be prepared for you individually. The caffeine treatment will consist of 6mg caffeine powder per kilogram body weight. Placebo pills will be filled with rice flour. You will be prompted to consume the treatment pill one hour before your visit for EX 2. You will not know the treatment you are receiving at any time during the study. At the conclusion of the study, you will be asked to guess which treatment you received for each condition.

Dietary and Exercise Controls:

You will be asked to record all food and beverage intake for 24 hrs preceding the first exercise trial and the day of EX 2. After the initial exercise trial, you will be provided with copies of your dietary records and instructed to replicate their dietary habits for the second EX phase. You will be asked to report to all testing after a >2 hr fast. You will be asked to consume Ensure Active High Protein Shake within 1 hour of completing the first exercise trial. Additionally, you will be instructed to refrain from consuming anything other than water during the 2 hours following EX1. You will be asked to record of dietary intake following EX1, and replicate that seven days later after the second EX1 trial, and seven days after that for the third EX1 trial. For all conditions, you will be given a standardized breakfast to consume two hours before beginning EX2. You will also be instructed to record all physical activity 72 hrs prior to the first exercise trial in all phases and the day of EX 2. Additionally, you will be instructed to avoid physical activity between the first and second exercise trials, and to keep physical activity habits consistent between all exercise phases.

Risks/Benefits:

Skeletal Muscle Function

The risks of muscle function testing include soreness from exertion 24-48 hours post and potential lightheadedness or loss of consciousness if correct form is not utilized. You will be instructed in correct form and breathing techniques prior to testing.

Sleep Disruption

The consequences of a single night of sleep restriction comparable to this investigation have not been well documented but include impaired insulin sensitivity, increased sleepiness and fatigue, and reduced alertness and constant attentiveness. The latter have the *potential* to impact short-term academic performance, decision-making and tasks such as driving ability but these have not been documented.

Cardiovascular Exercise (3-km Time Trial, 60-min sprint interval session, and VO_{2max} test)

According to the American College of Sports Medicine's Guidelines for Exercise Testing and Prescription, the risk associated with heavy exercise for individuals categorized as "low risk" is very minimal, and physician supervision is not necessary. The conditions that the exercise sessions are to take place are likely safer than the typical exercise environments of the subjects. If you do not meet ACSM criteria for "low risk", you will not be allowed to participate in the study. In the unlikely event of cardiac or other complications during exercise, an emergency plan is in place. This includes immediate access to a phone to call emergency personnel. In addition, at least one of the listed investigators will be present during the exercise sessions, and all are CPR certified.

Caffeine Ingestion

The risks and side effects associated with caffeine supplementation include: rapid heart rate, elevated blood pressure, headache, nausea, vomiting, restlessness, agitation, and anxiety.

Blood Sampling

The risks of finger-stick blood sampling include possible mild bruising, and the risk of transfer of blood-borne pathogens, as well as possible risks of infection or skin irritation. These risks are considered to be minimal, and all safety precautions for handling blood samples will be followed according to OSHA protocols, including: investigators will wear latex gloves at all times during blood sampling and testing. A sharps container lined with a biohazard bag will be used for all sharp objects involved in the blood sampling; all other materials (i.e. gloves, gauze pads, etc.) used during the sampling will be put in a separate waste disposal unit lined with a biohazard bag. All investigators who will be involved in blood draws (and handling of blood) have been trained in these phlebotomy techniques, and completed JMU blood-borne pathogen training. A total of <10 milliliters of blood will be obtained throughout the course of the study, which is roughly 2% of the amount of blood typically obtained during blood donation (1 pint or 473 milliliters)

Performance incentive:

The top 5 3-km time trial performers will be entered into a drawing to win \$150. Individuals with the top 6-10 times will be entered into a drawing to win \$75. Times from both EX2 trials will be averaged to determine the top performers.

Confidentiality:

The results of this research will be presented at conferences and published in exercise science journals. The results of this project will be coded in such a way that your identity will not be attached to the final form of this study. The researcher retains the right to use and publish non-identifiable data. However, you can ask that your data be removed from the study at any point prior to presentation and publication. While individual responses are confidential, aggregate data will be presented representing averages or generalizations about the responses as a whole. All data will be stored in a secure location accessible only to the researcher. Final aggregate results will be made available to you upon request.

Participation & Withdrawal:

Your participation is entirely voluntary. You are free to choose not to participate. Should you choose to participate, you can withdraw at any time without consequences of any kind. Your right to withdraw includes the right to request that your blood samples be discarded at any time. To dispose of your samples, your samples will be rinsed down a chemical drain in our laboratory or will be disposed of in a biohazard container. Again, your sample will not be identifiable without the coding document that will be locked away in a filing cabinet.

Questions:

You may have questions or concerns during the time of your participation in this study, or after its completion. If you have any questions about the study, contact Nicholas D. Luden, Ph.D. at ludennd@jmu.edu or by phone at 540-568-4068.

Giving of Consent:

I have read this consent form and I understand what is being requested of me as a participant in this study. I freely consent to participate. I have been given satisfactory answers to my questions. The investigator provided me with a copy of this form. I certify that I am at least 18 years of age.

 Name of Participant (Printed)

 Name of Researcher(s) (Printed)

 Name of Participant (Signed)

 Name of Researcher(s) (Signed)

 Date

 Date

For questions about your rights as a research subject, you may contact the chair of JMU's Institutional Review Board (IRB). Dr. David Cockley, (540) 568-2834, cocklede@jmu.edu.

AHA/ACSM Health/Fitness Facility Pre-participation Screening QuestionnaireAssess your health status by marking all *true* statements**History**

You have had:

- a heart attack
 heart surgery
 cardiac catheterization
 coronary angioplasty (PTCA)
 pacemaker/implantable cardiac
 defibrillator/rhythm disturbance
 heart valve disease
 heart failure
 heart transplantation
 congenital heart disease

If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with a **medically qualified staff**.

Symptoms

- You experience chest discomfort with exertion
 You experience unreasonable breathlessness
 You experience dizziness, fainting, or blackouts
 You take heart medications

Other Health Issues

- You have diabetes
 You have asthma or other lung disease
 You have burning or cramping sensation in your lower legs when walking short distances
 You have musculoskeletal problems that limit your physical activity
 You have concerns about the safety of exercise
 You take prescription medication(s)

Cardiovascular risk factors

- You are a man older than 45 years
 You smoke, or quit smoking within the previous 6 months
 Your blood pressure is > 140/90 mmHg
 You do not know your blood pressure
 You take blood pressure medication
 Your blood cholesterol level is > 200 mg/dl
 You do not know your cholesterol level
 You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister)
 You are physically inactive (i.e. you get < 30 minutes of physical activity on at least 3 days of the week)
 You are > 20 pounds overweight

If you marked two or more of the statements in this section, you should consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with a **professionally qualified exercise staff** to guide your exercise program.

- None of the above

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided program or almost any facility that meets your exercise program needs.

The Pittsburgh Sleep Quality Index (PSQI)

Instructions: The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month. Please answer all questions. During the past month,

1. When have you usually gone to bed? _____
2. How long (in minutes) has it taken you to fall asleep each night? _____
3. When have you usually gotten up in the morning? _____
4. How many hours of actual sleep do you get at night? (This may be different than the number of hours you spend in bed) _____

5. During the past month, how often have you had trouble sleeping because you...	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times week (3)
a. Cannot get to sleep within 30 minutes				
b. Wake up in the middle of the night or early morning				
c. Have to get up to use the bathroom				
d. Cannot breathe comfortably				
e. Cough or snore loudly				
f. Feel too cold				
g. Feel too hot				
h. Have bad dreams				
i. Have pain				
j. Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):				
6. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?				
7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?				
8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?				
	Very good (0)	Fairly good (1)	Fairly bad (2)	Very bad (3)
9. During the past month, how would you rate your sleep quality overall?				

- Component 1 #9 Score C1 _____
- Component 2 #2 Score ($\leq 15\text{min}=0$; $16-30\text{ min}=1$; $31-60\text{ min}=2$, $>60\text{ min}=3$) + #5a Score (if sum is equal $0=0$; $1-2=1$; $3-4=2$; $5-6=3$) C2 _____
- Component 3 #4 Score ($>7=0$; $6-7=1$; $5-6=2$; $<5=3$) C3 _____
- Component 4 (total # of hours asleep)/(total # of hours in bed) x 100
 $>85\%=0$, $75\%-84\%=1$, $65\%-74\%=2$, $<65\%=3$ C4 _____
- Component 5 Sum of Scores #5b to #5j ($0=0$; $1-9=1$; $10-18=2$; $19-27=3$)..... C5 _____
- Component 6 #6 Score C6 _____

Component 7 #7 Score + #8 Score (0=0; 1-2=1; 3-4=2; 5-6=3)..... C7_____

Add the seven component scores together _____ **Global PSQI Score** _____

Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Journal of Psychiatric Research*, 28(2), 193-213.

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Daily Activity Records

Subject # _____

Date: _____

Date	Type of Exercise Performed	Duration of Exercise (minutes)	Intensity of Exercise (use scale below)

Intensity Scale

- 6
- 7 Very, very light
- 8
- 9 Very light
- 10
- 11 Fairly light
- 12
- 13 Somewhat hard
- 14
- 15 Hard
- 16
- 17 Very hard
- 18
- 19 Very, very hard
- 20

DIET RECORD

Subject number _____

Date _____

Day of

Week _____

Time	Food and/or Drink	Method of Preparation	Quantity Consumed	Brand Name

Adapted From: Lee RD, Nieman DC. *Nutritional Assessment*. 2nd ed. United States of America: Mosby; 1996.

Subject Prescreening Information

Age: _____ years

Height _____ Weight _____

Typical Exercise Habits over the Past 3-6 Months:

Average number of days of cycling per week _____

Average number of hours of cycling per week _____

Briefly describe your cycling habits over the past 3-6 months:

Average number of days of resistance exercise/weight lifting per week

Average number of days of resistance exercise/weight lifting per week

Briefly describe your resistance training habits over the past 3-6 months:

Do you have a muscle or joint injury/condition that precludes the completion of the cycling or muscle function protocol? If yes, please explain.

Are you allergic to wheat?

Do you have gluten intolerance?

Are you allergic to latex?

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