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A 45-Minute Vigorous Exercise Bout Increases Metabolic Rate for 14 Hours

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Running Title: Exercise increases 24-h EE

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ABSTRACT

Introduction: The magnitude and duration of the elevation in resting energy expenditure following vigorous exercise have not been measured in a metabolic chamber. This study investigated the effects of inserting a 45-min vigorous cycling bout into the daily schedule versus a controlled resting day on 24-h energy expenditure in a metabolic chamber. **Methods**: Ten male subjects (ages 22 to 33 yrs) completed two separate 24-h chamber visits (one rest and one exercise day) and energy balance was maintained for each visit condition. On the exercise day, subjects completed 45-min of cycling at 57% $Watts_{max}$ (mean±SD, 72.8±5.8% VO_{2max}) starting at 11:00 am. Activities of daily living were tightly controlled to ensure uniformity on both rest and exercise days. The area under the energy expenditure curve for exercise and rest days was calculated using the trapezoid rule in the EXPAND procedure in the Statistical Analysis Systems (SAS) and then contrasted. **Results**: The 45-min exercise bout resulted in a net energy expenditure of 519±60.9 kcal (P<0.001). For 14-h post-exercise, energy expenditure was increased 190±71.4 kcal compared to the rest day (P<0.001). **Conclusions**: In young male subjects, vigorous exercise for 45-min resulted in a significant elevation in post-exercise energy expenditure that persisted for 14-h. The 190 kcals expended post-exercise above resting levels, represented an additional 37% to the net energy expended during the 45-min cycling bout. The magnitude and duration of increased energy expenditure following a 45-min bout of vigorous exercise may have implications for weight loss and management.

Keywords: Exercise, energy expenditure, whole body calorimetry, metabolic chamber, resting metabolic rate

INTRODUCTION

Paragraph 1 Measurement of the various components of energy expenditure including the resting metabolic rate (RMR) has improved our understanding of energy balance as it relates to human obesity. Accurate assessment of RMR requires sophisticated methodologies including direct and indirect calorimetry. Use of open circuit indirect calorimetry Douglas bag systems and metabolic carts is most commonly employed when measuring RMR, but measurement time is typically limited to 15-30 minutes and then extrapolated to 24-h time periods. Whole room indirect calorimeters (i.e. metabolic chambers) allow extended measurement of energy expenditure with tight control of energy intake and the daily schedule.

Paragraph 2 Studies using Douglas bag systems and metabolic carts have shown that 15 to 30 minutes of moderate-to-vigorous exercise causes a small increase in RMR that persists for a short time following exercise (25). One study of 10 male triathletes, for example, showed that three separate cycling bouts of 20, 30, and 60 minutes duration and 75%, 50%, and 50% maximum aerobic capacity, respectively, resulted in 12 to 30 net calories expended over 20 to 33 minutes post-exercise (25). Others report an extended increase in post-exercise energy expenditure after just 20 minutes of cycling at 70% maximum aerobic capacity (3), and differences between studies may be related to control of subject energy intake and daily activities. Several investigators emphasize that elevations in post-exercise energy expenditure depend on the degree of homeostatic disturbance, and that RMR is elevated especially following high intensity, long duration exercise (6, 23). For example, rates for post-exercise energy expenditure were elevated for 0.3 h, 3.3 h, and 10.5 h in six males cycling for 80 minutes at 29%, 50%, and 75% of maximum aerobic capacity (4). Methods using indirect calorimetry have suggested that the magnitude of the elevation in energy expenditure post exercise is dependent on the intensity of the exercise (15), thus resolving the issue of the duration and magnitude of the increase in energy expenditure following exercise bouts is important when considering the potential impact on total 24-h energy expenditure.

Paragraph 3 Metabolic chambers have been used to investigate the effects of physical activity on substrate utilization (18, 19, 26), and 24-h energy expenditure (21, 24). However, few studies to date have analyzed the effects of physical activity on post-exercise net energy expenditure over a 24-h period. Dionne et al. (9) investigated the effect of moderate intensity exercise (50% VO_{2max} for 60 minutes) on 24-h energy expenditure and substrate utilization in 8 young healthy males, and reported no difference in 24-h energy expenditure or respiratory quotient (RQ) between control and exercise sessions. Subjects exercised in the middle of the afternoon outside of the chamber, and immediately ingested a milk shake that equaled the energy expended during exercise. These research design characteristics and the moderate intensity of the exercise bout may explain the reported results. Treuth et al. (29) reported an increase in 24-h energy expenditure when contrasting high- and low-intensity exercise bouts, but the research design did not include a rest day for determination of the magnitude and duration of post-exercise net energy expenditure.

Paragraph 4 This study investigated the effect of 45 minutes of *vigorous* cycling (57% $Watts_{max}$ or ~70% VO_{2max}) on post-exercise RMR as measured in a metabolic chamber, under tightly controlled conditions of daily living. The exercise session was conducted late morning and contrasted with a rest day to determine both the magnitude and duration of vigorous exercise on post-exercise energy expenditure.

METHODS

Paragraph 5 **Subjects.** Ten healthy male subjects (age range 22-33 years) were recruited via mass advertisement. Inclusion criteria included the following: subjects had to be non-smokers, in good physical condition and capable of cycling vigorously for 45 minutes, and with no adverse medical issues including anxiety within closed spaces. Written informed consent was obtained from each subject, and the experimental procedures were approved by the institutional review board of Appalachian State University.

Paragraph 6 **Baseline Testing.** Two weeks prior to the study, subjects came to the North Carolina Research Campus Human Performance Laboratory for baseline testing which included body composition and VO_{2max} testing, and a full orientation regarding study requirements. Body composition was measured via dual energy x-ray absorptiometry (DEXA) (GE Lunar iDXA; Milwaukee, WI). Resting metabolic rate (RMR) was calculated using a fat free mass (FFM) based equation [418 + (20.3FFM)] (2). This estimated RMR was used for calculating total dietary energy intake while in the metabolic chamber (1.4 X RMR), and then adjusted using measured data (see below). VO_{2max} was measured using the Cosmet Quark CPET metabolic cart (Rome, Italy) with the Lode cycle ergometer (Lode Excaliber Sport, Lode B.V.; Groningen, Netherlands) and a graded protocol with a 15 watt/min increase to exhaustion (28). Several criteria were used to determine VO_{2max} including a respiratory exchange ratio (RER) of 1.15 and higher, a plateau of oxygen consumption, and a maximal heart rate within 12 beats of the predicted maximum.

Paragraph 7 **Study Design.** Ten subjects completed two sessions in the chamber on non-consecutive days (Monday and Wednesday or Tuesday and Thursday of the same week). During the first session, subjects remained in a rested state and engaged in no exercise while following the schedule of events depicted on the "X" axis in Figure 1a. During the second session, the same schedule was followed except that subjects completed 45 minutes of exercise on a cycle ergometer at 57% $watts_{max}$. This order was followed to avoid the potential influence of the exercise session on energy expenditure during the subsequent session in the metabolic chamber. The duration of 45 minutes corresponds to the middle of the range suggested by the physical activity guidelines for Americans (30-60 min). Fifty seven percent $Watts_{max}$ corresponds to a vigorous intensity of approximately 70% VO_{2max}. Subjects were instructed to avoid exercise on the days before entering the chamber, and to consume foods from a specific food list that has been used in prior studies to achieve a carbohydrate intake of approximately 55% total energy (20). Subjects were also instructed to avoid any supplements, including caffeine, for the duration of the study.

Paragraph 8 At approximately 7:30 am subjects reported to the metabolic chamber in an overnight fasted state (no food or beverage other than water from 11:00 pm). At 8:00 am, subjects were sealed in the chamber and asked to stay in a seated position unless they needed to use the restroom or perform other necessary daily activities (e.g. washing hands, brushing teeth, etc.). Breakfast was served through an air lock passage at 9:00 am. On rest days, subjects remained in a seated position from breakfast until 12:30 pm when they were asked to get up and stretch for 2 minutes. On both rest and exercise days starting at 12:30 pm, subjects were asked to get up and stretch for 2 minutes every hour until 6:30 pm.

Paragraph 9 Lunch was served at 1:30 pm, and dinner was served at 7:00 pm. Subjects were asked to remain in the seated position until 8:00 pm, at which point they were able to relax and lay down but not go to sleep. Bed time was at 10:30 pm, and subjects were asked to lie down even if they were not sleeping. Subjects were wakened at 6:30 am and were allowed to move about the chamber and gather their belongings. At 7:15 am subjects exited the chamber.

Paragraph 10 Upon arrival on the exercise day, subjects were oriented to the cycle ergometer and instructed how to adjust wattage and report heart rate from the heart rate monitor (Polar Heart Rate Monitor, Kempele, Finland) during the test. The cycle ergometer was adjusted to fit the leg length of the subject. At 10:40 am, subjects prepared for exercise (e.g. stretch, change clothes, arrange room with towels and music, etc.). Subjects mounted the cycle ergometer, and started pedaling at 11:00 am. The cycling protocol consisted of 2 minutes at 50% of the workload (57% $Watts_{max}$), 2 minutes at 75% of the workload, 41 minutes at 100% of the workload, and another 2 minutes at 50% of the workload. Oxygen consumption and energy expenditure were measured continuously during the exercise bout, with heart rate recorded every 5 minutes. Immediately following exercise, subjects sat down for 40 minutes until 12:30 pm. At 12:30 pm subjects were allowed to clean themselves and change clothes, and then stayed in the seated position until lunch at 1:30 pm.

Paragraph 11 **Description of Metabolic Chamber.** Studies were conducted in the newly constructed metabolic chamber located at the UNC Chapel Hill Nutrition Research Institute (UNC NRI), Kannapolis, NC. The chamber was modeled after the chambers at the National Institute of Diabetes and Digestive and Kidney Diseases, Bethesda, MD (7). The UNC NRI metabolic chamber is an open-circuit, pull-type, whole room indirect calorimeter built with walk-in cooler panels. The metabolic chamber has a floor space of 10’11” X 8’0.5”, a height of 7’10”, and an air volume of 18,346 L when fully furnished. The room is equipped with a twin bed, bedside table, chair, toilet, mirror, sink, multi-media laptop, telephone, intercom, nurse call button, specimen refrigerator, iris ports for blood draws, and two air locks that serve as food and specimen passes. There is sufficient space to include a bike or treadmill inside the chamber. The metabolic chamber has 3 windows, 2 looking outside and 1 looking into the observation room.

Paragraph 12 An air conditioning system mixes the air in the chamber, maintaining a pre-set temperature and a relative humidity of less than 70%. For this particular study the average temperature maintained in the chamber was 23.1 ± 0.30ºC, and the average chamber relative humidity was 54.6 ± 1.5%. Fresh, conditioned air is passively drawn into the chamber from an adjacent buffer zone. Mixed, expired air is drawn out of the metabolic chamber by a small fan placed at the outlet of the chamber through a centralized sampling apparatus designed with evenly spaced sectors to ensure equal sampling throughout the chamber. The flow is set manually and kept at a constant rate, typically 60 L/min (capacity is 120 L/min). On rest day, the flow rate was kept at 60 L/min for lean individuals and 100 L/min for individuals with weights ≥130 kg. On exercise day, the flow rate was maintained at 120 L/min to account for ambient CO_2 build-up during exercise. These flow rates were chosen based on pilot data to assess the capacity of the chamber to handle increased CO_2 loads.

Paragraph 13 Before measurements, a small sample of air was cooled to 1°C and dried, drawn by a diaphragm pump, and filtered. The CO_2 and O_2 analyzers are differential and their full scale readings were set for 0-1%. The metabolic chamber has a passive infrared motion sensor to measure spontaneous physical activity. Oxygen consumption, CO_2 production, energy expenditure, respiratory quotient, and percent activity were recorded each minute. The lag time is constant at the start of exercise and at the end of exercise. Advanced noise suppression and trend identification techniques allow for accurate measurement and time discrimination of the exercise plateau as seen by the gas analyzers. Results are then aligned with the start of the exercise time. The Weir equation for EE (kcal/min) = (3.941*VO_2) + (1.106*VCO_2) was used for conversion of VO_2 (L/min) and VCO_2 (L/min) to kcal.

Paragraph 14 The analyzers were calibrated weekly utilizing standard gas mixtures (zero gas is ~21% O_2, balance nitrogen; span gas is ~20% CO_2, ~1% O_2, balance nitrogen). The chamber was validated using a series of propane burn tests. Five propane burns were conducted at a flow rate of 60 L/min. The CO_2 recovery was 97.6% ± 0.6% (SD) and the O2 recovery was 99.1% ± 0.4%. Monthly propane tests were conducted to verify the accuracy of the chamber.

Paragraph 15 Prior to conducting trials in the chamber, we tested the reproducibility of the 24-h EE measurement. Ten subjects (including 8 from the exercise portion of the study) completed two non-consecutive sessions in the metabolic chamber (either Monday and Wednesday or Tuesday and Thursday of the same week). Subjects were fed the same three meals during both sessions in the chamber, and urine was collected for measurement of nitrogen. The average 24 hour EE difference between the two chamber sessions was 66.5 ± 74.2 kcal/day, corresponding to a 2.5 ± 2.3% difference between days. For the 8 subjects completing 4 separate days in the chamber, the average coefficient of variation for the three rest days was 2.3%.

Paragraph 16 **Design of Metabolic Diets.** Diets during chamber days were designed to provide approximately 35% fat, 55% carbohydrates, and 15% protein. The same foods were served at all chamber visits, with the exception of the snacks provided on exercise day to achieve energy balance. Calories were assigned to each subject based on calculated RMR X 1.4. To calculate the amount of calories to provide, we took into account that 93% of energy content is metabolizable (27). Menus were designed and analyzed with Esha Food Processor SQL Software (Esha Research Inc., Salem, OR). Meals were delivered at designated times, and picked up 30 minutes later. Subjects were asked to consume all foods provided. Food intake was documented and on the rare occasion that a subject did not eat all of the food provided, the food was weighed back and the nutrients removed from the final nutrient analysis. To ensure energy balance conditions, 3 and 7 hour predictions of 24-h EE from the chamber software were utilized to modify the baseline menu. On the exercise day, snacks with the same nutrient composition as the base menu were provided to account for additional calories burned during exercise. Exercise EE was calculated, and approximately ½ of the calories needed to achieve energy balance were added to lunch. The final calories needed for energy balance was determined with the 7 hour prediction. Based on this prediction, the balance of the needed calories was provided at dinner.

Paragraph 17 **Statistical Analysis.** Two energy expenditure curves, one for the exercise day and one for the rest day, were generated for each subject with the x axis representing time (minutes), and y axis representing energy expenditure (kilocalories). In order to determine the total energy expenditure for each activity period (pre-exercise, exercise preparation, exercise, immediate post exercise, dress, from dress to sleep, sleep), the area under the energy expenditure curve for each activity period was calculated by using the trapezoid rule in the EXPAND procedure in SAS (version 9.1.3; SAS Institute, Inc., Cary, NC). Paired t-test on log transformed area was performed to compare the energy expenditure of each activity period in the exercise day with the corresponding period in the rest day.

The total energy expenditure for each hour was also calculated using the area under curve method as described above. Paired t-test on log transformed area was performed to compare energy expenditure of each hour in the exercise day with the corresponding hour in the rest day.

Shapiro-Wilk test in the UNIVARIATE procedure in SAS was used for normality check. Benjamini-Hochberg method for *False Discovery Rate* (FDR) correction in the MULTTEST procedure in SAS was used for multiple testing corrections.

RESULTS

Paragraph 18 Subject characteristics for the 10 subjects completing the study are summarized in Table 1. The young adult males in this study varied widely in BMI, body composition, and aerobic fitness, and all successfully completed the total 47-minute cycle ergometry exercise in the metabolic chamber.

Paragraph 19 Table 2 reports average workload, heart rate, oxygen consumption, and energy expenditure data for all subjects during the exercise bout. The relative heart rate and oxygen consumption data indicate that this exercise bout set at 57% $Watts_{max}$ was at a vigorous level, as defined by the American College of Sports Medicine (1). Energy expenditure during the exercise bout was 6.1-fold greater than the corresponding energy expenditure on the rest day.

Paragraph 20 Table 3 summarizes the energy and macronutrient intakes and energy expenditure data over 24-h on rest and exercise days. A significantly higher energy intake occurred on the exercise compared to rest day, with a mean increase of 659±104 kcal/day (P<0.001). The percent of energy consumed as carbohydrate and fat was slightly different on the exercise day; however, this difference corresponds to less than 0.6%. Total energy expenditure was greater on the exercise versus rest day by 750±121 kcal/day (P<0.001). On the rest day, energy intake was slightly below energy expenditure, with a mean difference of 38.0±89.3 kcal/day. On the exercise day, energy intake was also slightly below energy expenditure by 129±123 kcal/day.

Paragraph 21 Figure 1 contrasts energy expenditure for the exercise and rest days. The exercise bout resulted in a net energy expenditure of 519±60.9 kcal (contrast in area under the curve, P<0.001). Hour by hour analysis showed that energy expenditure was significantly elevated on the exercise day for 14.2 hours post exercise, corresponding to an increase of 190 ± 71.4 kcal compared to the rest day. This increase in resting energy expenditure included 3.5 hours of the early sleep period, accounting for 32.0±39.3 kcal (P=0.030).

Paragraph 22 Immediately after exercise, subjects sat quietly for 40 minutes, and the net energy expenditure during this period was 15.4±12.8 kcal (P=0.001). Subjects next were allowed to change clothes and clean themselves with a towel, and the net increase in energy expenditure during this period was 19.3±16.0 kcal (P=0.004). From this point in time to bedtime (a total of 9.7 h), net increase in energy expenditure was 144±49.9 kcal (P<0.001). Pre-exercise periods did not differ between rest and exercise days, and subject movement recorded with the metabolic chamber infrared monitor was not different between exercise and rest days during this 9.7-h time period (data not shown, P=0.83).

DISCUSSION

Paragraph 23 This study found that in healthy young male subjects, vigorous exercise (57% $Watts_{max}$ or 73% VO_{2max}) for 45 min starting at 11:00 am resulted in 519 calories expended above the rest day. Post-energy expenditure was significantly elevated for 14.2 hours compared to rest day, corresponding to an additional 190±71.4 kcal that included 3.5 hours and 32.0±39.3 kcal during the early sleep period. Energy intake and expenditure were tightly matched on both the rest and exercise days to ensure zero energy balance under both conditions, and the daily activities of living were controlled.

Paragraph 24 Most previous studies evaluating the effect of single exercise bouts on post-exercise energy expenditure have utilized Douglas bag and metabolic cart systems, with widely varying results (6, 10, 11, 13, 17, 22, 30). This variation is related to multiple factors including non-continuous measurement of energy expenditure, the use of pre-exercise RMR as the criteria for normal levels (6, 11, 22), and the lack of tight control of daily activities of living. Despite these limitations, previous studies emphasize the importance of exercise intensity to produce sizeable increases in post-exercise energy expenditure (6). For example, Phelain et al. (23) found that when subjects burned the same amount of calories either through high intensity exercise or low intensity exercise, energy expenditure remained elevated at 3-h post-exercise only for the high intensity condition. The magnitude of post-exercise energy expenditure is greatest when the body experiences significant physiologic stress during prolonged and high intensity exercise (4).

Paragraph 25 Post-exercise energy expenditure was significantly elevated for 14.2 hours when compared to the rest day, adding 37% or 190 ± 71.4 kcal to the net energy expenditure of the 45-min cycling bout. The duration of increase in post-exercise energy expenditure is comparable to Bahr et al. (3) who assessed the effect of high intensity exercise on excess post-exercise oxygen consumption (EPOC) under tightly controlled conditions. In this study, subjects rested or exercised early in the morning, and then remained supine in bed for 24 hours while fed three meals. Using Douglas Bag methods, oxygen consumption remained elevated after 12-h following 40 minutes of exercise at 69% VO_{2max}. Our magnitude of increase in post-exercise energy expenditure (37%), however, is substantially above the 14% reported by Bahr et al. (3).

Paragraph 26 Investigators have utilized metabolic chambers to measure the influence of exercise on fuel substrates and total 24-h energy expenditure (18, 19, 26), but only one other chamber study has measured the effect of a single exercise bout on resting energy expenditure (9). Dionne et al. (9) reported no effect of a mid-afternoon, 60-min moderate intensity exercise bout (50% VO_{2max}) on 24-h energy expenditure in young adult males compared to a rest day under energy balance conditions. The authors attributed the absence of post-exercise changes in energy expenditure to the ingestion of a snack immediately following the 60-min exercise bout (9). This snack contained the same amount of energy and macronutrients oxidized during the exercise bout, and the authors speculated that the snack ingestion caused an accelerated replenishment of glycogen stores and recovery of energy balance. Our results argue against this rationale. The higher exercise intensity in our study caused a greater homeostatic disturbance and more than likely explains the contrast in the magnitude and duration of post-exercise energy expenditure.

Paragraph 27 The prolonged increase in RMR post-exercise observed in the current study could have been caused by a number of contributing factors including enhanced energy flux. Subjects in our study were maintained in energy balance during both the exercise and rest days, resulting in an added energy intake of 659 kcal on the exercise day. The increased energy intake balanced against energy expenditure (energy flux) has been shown in several studies to contribute to the elevated 24-h energy expenditure on exercise days or in trained individuals (5,8,12). Other potential factors include homeostatic disturbance from vigorous exercise, as theorized by Bahr et al. (4), increased circulation of stress hormones and sympathetic tone (14), and recovery from decreased muscle glycogen levels (14).

Paragraph 28 Our data support that vigorous cycling (~70% VO_{2max}) has a significant effect on 24-h energy expenditure under conditions when energy intake is balanced with energy expenditure. The magnitude (190 kcal) and duration (14.2 h) of net energy expenditure following 47 min cycling at 73% VO_{2max} are greater than previously reported in most studies conducted outside a metabolic chamber. The 24-h net energy expenditure difference between exercise and rest days was 750 kcal, a meaningful quantity over time if two or three such exercise bouts are inserted into the weekly schedule and energy intake is controlled (3, 4, 6).

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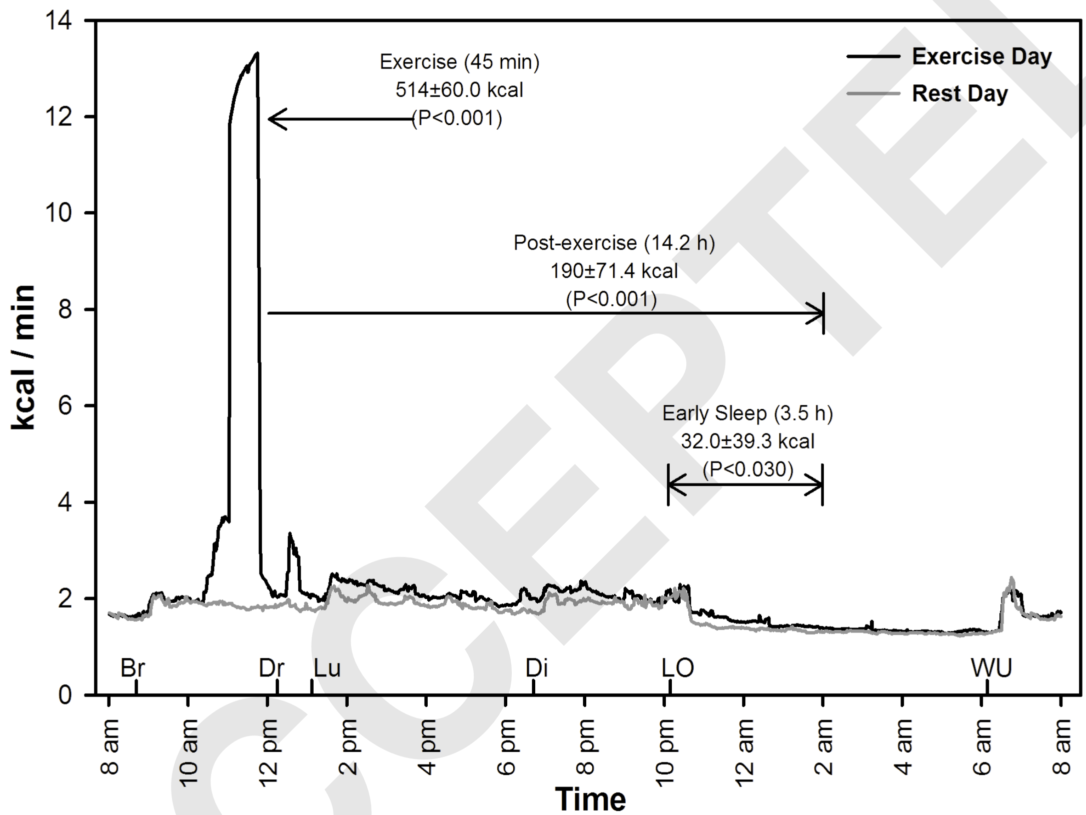
FIGURE LEGENDS

Figure 1: Average 24-h energy expenditure on rest day and exercise day. 45-min of cycling resulted in 519±60.9 kcal of energy expended above rest day ($P<0.001$), while 190±71.4 kcal were expended above levels on the rest day for 14.2-h post-exercise ($P<0.001$). Net energy expenditure difference from the start of sleep to hour 18 post-exercise was 32.0±39.3 kcal ($P=0.030$).

Figure 1



Exercise (45 min)
514±60.0 kcal
(P<0.001)
Post-exercise (14.2 h)
190±71.4 kcal
(P<0.001)
Early Sleep (3.5 h)
32.0±39.3 kcal
(P<0.030)
Exercise Day
Rest Day
kcal / min
14
12
10
8
6
4
2
0
Br
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8 am
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8 pm
10 pm
12 am
2 am
4 am
6 am
8 am
Time

Table 1 Subject characteristics (N=10)

	Mean ± SD	Minimum	Maximum
Age (yrs)	25.4 ± 3.4	22	33
Height (cm)	180 ± 8.02	166	193
Weight (kg)	90.3 ± 27.9	62.6	148
BMI (kg/m^2)	27.9 ± 6.9	20.1	39.8
Body fat (%)	21.9 ± 11.4	9.4	39.4
VO_2max ($ml \cdot kg^{-1} min^{-1}$)	43.5 ± 12.8	22.9	62.5
HR_{max} (beats/min)	188 ± 10.6	166	200

Table 2 Performance data during the 47-minute cycling bout in the metabolic chamber.

Measure	Mean ± SD
Workload (Watts)	156 ± 25.9
Heart rate (beats/min)	163 ± 16.4
Heart rate (% maximal)	86.7±5.9
VO_2 (L/min)	2.64 ± 0.26
VO_2 ($mL \cdot kg^{-1} min^{-1}$)	31.4 ± 8.6
VO_2 (% maximal)	72.8±5.8
Energy expenditure (kcal/min)	12.8 ± 1.3

Table 3 Energy intake and expenditure data (mean±SD)

	Rest Day	Exercise Day	p-value
Energy Intake Data			
Energy intake (kcal/day)	2400 ± 448	3058±462	<0.0001
Carbohydrate (% of energy)	49.7 ± 1.4	50.3 ± 1.1	0.0002
Fat (% of energy)	33.3 ± 1.2	32.8 ± 0.9	0.0005
Protein (% of energy)	16.9 ± 0.7	16.9 ± 0.6	0.31
Energy Expenditure Data			
Energy expended (kcal/day)	2438 ± 475	3188 ± 559	<0.0001
Respiratory quotient	0.83 ± 0.01	0.84 ± 0.01	0.004