Published in final edited form as:

J Aging Phys Act. ; 27(4): 482–488. doi:10.1123/japa.2018-0194.

The Effect of Structured Exercise on Sleep during the Corresponding Night among Trained Older Women

Charity B. Breneman,

Rural and Minority Health Research Center, Arnold School of Public Health, University of South Carolina, Columbia, SC.

Christopher E. Kline,

Dept. of Health & Physical Activity, School of Education, University of Pittsburgh, Pittsburgh, PA.

Delia West,

Dept. of Exercise Science, Arnold School of Public Health, University of South Carolina, Columbia, SC.

Xuemei Sui,

Dept. of Exercise Science, Arnold School of Public Health, University of South Carolina, Columbia, SC.

Xuewen Wang

Dept. of Exercise Science, Arnold School of Public Health, University of South Carolina, Columbia, SC.

Abstract

This study investigated the acute effect of exercise on sleep outcomes among healthy older women by comparing days with structured exercise versus days without structured exercise during four months of exercise training. Participants ($n = 51$) in this study had wrist-worn actigraphic sleep data available following at least three days with structured exercise and three days without structured exercise at mid- and end-intervention. The exercise intervention was treadmill walking. Multilevel models were used to examine whether structured exercise impacted sleep outcomes during the corresponding night. Overall, 1362 nights of data were included in analyses. In unadjusted and adjusted models, bedtimes were significantly earlier on evenings following an acute bout of structured exercise than evenings without structured exercise. No other sleep parameters differed between exercise and non-exercise days. Understanding the effects of exercise on sleep in this understudied population may help to improve their overall sleep quality.

Keywords

exercise training; aging; sleep behaviors

Introduction

There are noticeable age-related trends in sleep duration and quality in which older adults spend a greater amount of time in bed (TIB) as compared to younger individuals (Thomas, Lichstein, Taylor, Riedel, & Bush, 2014), but have declines in several metrics of sleep quality (SQ) that indicate lighter and more fragmented sleep as one ages (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004). Despite these changes in sleep architecture with age, the timing and quality of sleep are influenced by health behaviors during waking time (Irish et al., 2014). Regular exercise, a component of physical activity (PA), is one waking health behavior that is perceived in the general population to promote better sleep during the corresponding night (Urponen, Vuori, Hasan, & Partinen, 1988) and is a common sleep hygiene recommendation (Irish, Kline, Gunn, Buysse, & Hall, 2015).

However, recent evidence examining the day-to-day relationship between sleep and PA is mixed. Some studies support the perception that PA/exercise promotes better sleep (Dzierzewski et al., 2014; Kishida & Elavsky, 2016). Specifically, studies find that greater PA counts measured by accelerometers and more time spent in moderate-to-vigorous PA (MVPA) during the day were significantly associated with more total sleep time (TST) measured via actigraphy and higher self-reported SQ during the corresponding night (Dzierzewski et al., 2014; Kishida & Elavsky, 2016). Others find no significant associations or negative effects of PA on sleep among adults (Irish et al., 2014; Lambiase, Gabriel, Kuller, & Matthews, 2013; Mitchell et al., 2016).

The abovementioned studies have strengths for investigating the daily relationship between exercise and sleep, however, their limitations should be considered. Several of the studies reported low PA levels in their free-living samples of middle-aged to older adults; therefore, slight variations in either of these behaviors may not have been sufficient enough for detecting the daily (acute) effect of PA/exercise on sleep (Dzierzewski et al., 2014; Irish et al., 2014; Lambiase et al., 2013; Mitchell et al., 2016). In particular, one study noted that about 55.5% of the middle-aged women in their sample self-reported their daily exercise as light with another 6.9% self-reporting no participation in exercise during the 14–35-day observational period (Irish et al., 2014). Thus, the differences in PA levels between days may be minimal, resulting in little observable impact on sleep parameters. A clearer picture of the acute impact of PA on sleep may be found in individuals who participate in a structured exercise training regimen that creates a greater variation between days with and without structured exercise.

However, to date, only a few studies have examined the acute effects of exercise on sleep during an exercise training intervention among adults (Baron, Reid, & Zee, 2013; King et al., 2008; Melancon, Lorrain, & Dionne, 2015). Among these few studies, there are some prominent limitations which preclude clear conclusions about the acute effect of exercise on sleep among older women. The available studies have small sample sizes ($n < 25$ participants) and minimal numbers of sleep assessments. Since there is significant night-to-night variability in sleep (Dillon et al., 2014; Knutson, Rathouz, Yan, Liu, & Lauderdale, 2007; van Hilten et al., 1993), assessing only two nights, one following a day of exercise and the other a day without exercise, may be insufficient to capture the acute effect of exercise

on sleep. Multiple assessments of sleep following days with structured exercise and no structured exercise are needed to examine the acute effect of exercise on sleep beyond the nightly variations.

Taken together, these lines of evidence suggest that there are sleep adaptations following exercise training, as well as day-to-day relationships between sleep and exercise. Thus, there is reason to speculate that training status may impact the effect of an acute bout of exercise on sleep among older women. Only with multiple measures of sleep over the course of an exercise training intervention will the acute effect of exercise on sleep among older adults be elucidated. Therefore, the purpose of this study was to investigate the acute effect of exercise on sleep outcomes among healthy older women by comparing days with structured exercise versus days without structured exercise, and to investigate whether training status impacts the acute effect of exercise by comparing mid-intervention versus end-intervention sleep during four months of exercise training. Objective sleep outcomes via actigraphy have been identified in the literature to change significantly following an acute bout of aerobic exercise in postmenopausal women; specifically, wake after sleep onset (WASO), number of awakenings, and activity counts (Wang & Youngstedt, 2014). Therefore, we hypothesized that these sleep outcomes were most likely to be impacted by an acute bout of exercise among postmenopausal women in an exercise training program.

Methods

Study Population

The Women's Energy Expenditure in Walking Programs (WEWALK) study was a randomized clinical trial examining the effect of two moderate-intensity walking programs on total daily energy expenditure and its components (resting metabolic rate, thermic effect of food, and non-exercise activity thermogenesis) (Wang, Bowyer, Porter, Breneman, & Custer, 2017). Inclusion criteria included female gender, older age (60 – 75 years), a BMI between 18 and 30 kg/m², physically inactive (did not exercise more than 20 min three times per week), weight stable for the previous three months (+/- 3%), non-smoking, and no physical/mental limitations interfering with their ability to walk on a treadmill or to adhere to an exercise intervention. The research protocol for the WEWALK study was approved by the institutional review board, and informed consent was obtained from all participants. A total of 72 women completed the WEWALK study.

Exercise Intervention

Participants were randomly assigned to either a lower-dose exercise group (8 kilocalories (kcal) per kilogram of body weight per week) or a higher-dose exercise group (14 kcal/kg of body weight per week). For each exercise group, the amount of energy expended each week was based on previous exercise trials among sedentary older women (Frank et al., 2005; Littman et al., 2007; Morss, et al., 2004). Both exercise groups walked three times per week on a treadmill for four months under supervision in a research facility. Sessions occurred Monday through Friday between 6:30 am and 7:30 pm; participants were free to choose the specific time of their session within three time slots (morning: 6:30 am to 9:30 am; mid-day: 11:30 am to 1:30 pm; afternoon/evening: 4:30 pm to 7:30pm). Weekly energy expenditure

was individualized and based on the participant's body weight and assigned exercise dosage (8 kcal/kg vs. 14 kcal/kg).

In order to reduce the risk of injury in this physically inactive sample, both groups began training at an intensity of 40% of the participant's heart rate reserve (HRR), which was calculated using their maximum heart rate obtained during a baseline graded exercise test. The training intensity then increased every two weeks by 5% until the target training intensity (50% of HRR) was reached by week five. Weekly caloric expenditure began at four kcal/kg body weight during the first week of the intervention for both groups and then increased in weekly increments (lower-dose: one kcal/kg body weight per week; higher-dose: 2 kcal/kg body weight per week for the first month and then 1 kcal/kg body weight per week for the second month) until the assigned exercise dosage was reached by week five in the lower-dose group and week eight in the higher-dose group. Training intensity was monitored continuously throughout each session via heart rate monitors (FT1; Polar, Lake Success, NY, USA) in which heart rate was recorded every five min. Adherence to the exercise prescription (weekly energy expenditure goal of 8 kcal/kg or 14 kcal/kg of body weight) was monitored by calculating the amount of energy expended during each exercise session using the standard American College of Sports Medicine formula: $\{0.1 \times (\text{speed [miles per hour]} \times 26.8) + 1.8 \times (\text{speed [mph]} \times 26.8) \times \text{grade (\%)} + 3.5\} \times \text{weight (kg)} / 1000 \times 5 \text{ (L/min)} \times \text{time (min)}$ (American College of Sports Medicine, 2010).

At mid-intervention, participants in both exercise groups were at their target exercise intensity and energy expenditure dose, which were then maintained until the end. The only difference between the groups in their exercise prescription was the duration of each session, which varied from 35 to 40 min in the lower-dose group to 55 to 60 min in the higher-dose group. The acute effects of exercise were evaluated at mid-intervention and at end-intervention to determine any influence of training status on sleep.

Measurements

Sleep parameters.—Sleep was measured objectively via actigraphy (GT3X+; Actigraph, Pensacola, FL, USA). All participants were instructed to wear an accelerometer on their non-dominant wrist continuously for up to 14 days at baseline, mid-intervention, and end-intervention. Daily sleep logs were kept by all participants in which bedtimes and arising times were recorded. The manufacturer's software (ActiLife version 6.11.2) was used to analyze the actigraphy data in 60-sec epochs. Sleep log data were entered manually into the program to determine TIB. A standardized approach was used to increase the reproducibility of values for TIB by estimating missing or adjusting inaccurate bed/awake times using a hierarchical ranking of inputs (i.e. sleep diary, light intensity, and activity counts) (Patel et al., 2015). Light intensity and activity counts were objectively measured by the GT3X+ and were used in the standardization of TIB. Each TIB interval was analyzed using the Cole-Kripke sleep scoring algorithm to quantify several sleep parameters: sleep onset latency (SOL; i.e., elapsed time from bedtime to initial sleep onset), WASO (i.e., total time in minutes that the algorithm scored as "awake" after sleep onset), TST, number of awakenings after sleep onset, and activity counts occurring within TIB (Cole, Kripke, Gruen, Mullaney, & Gillin, 1992).

Body mass index (BMI).—Height and weight were measured to the nearest 0.1 cm using a stadiometer and 0.1 kg using a digital scale, respectively. Two measurements were taken for both height and weight and averages of each were used to calculate BMI (kg/m^2) at baseline. Epidemiological evidence demonstrates that increased sleep fragmentation and poor sleep efficiency (SE; the percentage of time spent asleep while in bed) are related with obesity, and PA has been shown to be negatively associated with body weight (Bailey et al., 2014; U.S. Department of Health and Human Services, 2008; van den Berg et al., 2008). Therefore, BMI was calculated and included as a covariate in the analyses.

MVPA time.—The SenseWear mini armband (BodyMedia Inc., Pittsburgh, PA, USA) was worn by all participants at baseline to measure the amount of time spent in MVPA during the same time period as the GT3X+. There was also a subsample of women ($n = 44$) who wore the monitor at mid- and end-intervention. Of those 44 participants who wore the armband at all three time points, only 23 participants had three days of data with structured exercise and three days of data with no structured exercise at mid- and end-intervention. This multi-sensor device was worn on the upper left arm according to the manufacturer's instructions and participants were asked to continually wear the monitor day and night with the exception of during periods when the monitor may possibly get wet. Only days in which the monitor was worn for at least 23 hours were used to calculate the average daily time spent in MVPA at baseline for all participants and included as a covariate in the analyses ($M = 11.73$ days with sufficient wear time; $SD = 2.25$). Also, the criterion of at least 23 hours of wear time was used to determine if the amount of time spent in MVPA differed between days with structured exercise and days without structured exercise for the subsample of women ($M = 12.57$ days with sufficient wear time; $SD = 0.95$).

Statistical Analyses

This study included a subsample ($n = 51$) who had sleep data available following at least three days with structured exercise at a research facility and at least three days without such structured exercise at both mid- and end-intervention. The rationale for selecting three days of structured exercise and three days without structured exercise is based on research that demonstrated that there was no difference between actigraphic measures of central tendency for sleep variables obtained over a three-day aggregate in comparison to seven- or fourteen-day aggregates among older adults (Rowe et al., 2008). The number of observations available per participant at each time point ranged from 6 to 14 nights (total number including at both time points: 12 to 28 nights).

Baseline descriptive statistics were calculated and reported as means and standard deviations. Independent sample *t* tests and chi-square tests were used to identify baseline differences between randomized conditions (lower-dose vs. higher-dose). A multilevel statistical analysis was performed since the data were organized hierarchically where multiple nights of actigraphic sleep recordings were nested within 51 participants. This modeling approach allowed for the opportunity to determine whether structured exercise impacted sleep outcomes during the corresponding night. Both behavioral (i.e., bedtime, arising time, and TIB) and physiological (i.e., SOL, WASO, TST, number of awakenings, and activity counts) sleep parameters were investigated in this study. Separate multilevel

models with repeated measures were run with each sleep outcome as the dependent variable. The independent variable of interest was whether the preceding day included structured exercise (yes/no). Model 1 adjusted for time point (mid- vs. end-intervention), exercise dose (lower vs. higher), and mean baseline value of the respective sleep parameter, whereas Model 2 included Model 1 covariates plus adjustment for day of the week (weekday night [Sunday through Thursday] vs. weekend night [Friday and Saturday]), baseline BMI, and average baseline MVPA levels. An interaction term for ‘time point’ and ‘exercise/non-exercise day’ was added to all models to assess whether the acute effect of exercise on sleep varied as a function of training status.

Additionally, SOL, WASO, and activity counts after sleep onset were not normally distributed; therefore, the values were transformed (natural logarithm $[x+1]$, square root, and natural logarithm $[x]$, respectively) to achieve normality of distribution. Given the non-normal distribution of these variables, the Wilcoxon Rank Sum test was performed to identify baseline differences between randomized conditions (lower-dose vs. higher-dose). No other data transformations were needed for the remaining sleep parameters. Data were analyzed using PROC MIXED procedure in SAS software, Version 9.4 (SAS Institute, Cary, NC) and statistical significance was set at an alpha level of 0.05. Furthermore, dependent t tests were used to determine whether there was a significant difference in MVPA between days with and without structured exercise among the 23 participants with sufficient armband data.

Results

Participant Characteristics

The final sample with complete actigraphy data included 51 participants. Table 1 provides a summary of their characteristics, categorized according to exercise dose. Most of the women were non-Hispanic white with at least some college education. On average, the participants were 64.5 years of age and had a BMI of 25.3 kg/m². The lower-dose exercise group had significantly earlier arising times compared to the higher-dose group. No other between-group differences were found in the remaining baseline sleep parameters or in participant characteristics. Adherence to the prescribed exercise dose, as assessed by actual weekly energy expended divided by prescribed dose (8 kcal/kg body weight versus 14 kcal/kg body weight), was an average of 102.6% and 99.4% in the lower- and higher-dose groups, respectively.

Acute Effects of Exercise on Sleep during the Corresponding Night

Table 2 provides the results from the multilevel models for all sleep parameters. Bedtime was approximately 9.6 min earlier following structured exercise days compared to days without structured exercise at both mid- and end-intervention time points ($p = 0.006$ [Model 1]). This difference decreased slightly, but remained significant, after additional covariate adjustment in Model 2 ($p = 0.04$). Additionally, arising times were approximately 9.0 min earlier after exercising the day before as compared to a day following no exercise ($p = 0.01$ [Model 1]). However, this finding became non-significant after further covariate adjustment in Model 2 ($p = 0.77$). There were no other significant differences found between days with

structured exercise versus days without structured exercise in the remaining behavioral or physiological sleep parameters.

Effects of Training Status

The interaction term between time point and exercise/non-exercise days was non-significant for all sleep parameters, suggesting the acute effect of exercise on sleep did not vary as a function of training status; therefore, this interaction term was not included in the final models.

MVPA - Subgroup Analysis (n=23)

There was a significant difference in the total amount of time spent in MVPA between days with structured exercise versus days without structured exercise ($p < 0.001$). This difference was also evident within each group: participants spent more time in MVPA on structured exercise days as compared to the days without structured exercise (lower-dose: 73.1 min vs. 44.1 min, $p < 0.001$; higher-dose: 87.7 min vs. 36.8 min, $p < 0.001$, respectively).

Discussion

This study is one of the few to follow older women longitudinally during an exercise training intervention to determine the acute effects of exercise on sleep. Overall, behavioral sleep parameters were observed to be significantly impacted by structured exercise in which bedtimes were significantly earlier on nights following a day with structured exercise versus a day without structured exercise. Arising times were also significantly earlier the morning following a day of structured exercise, though this association did not persist once we accounted for day of the week (weekdays vs. weekends), baseline BMI, and baseline MVPA levels.

Acute exercise was demonstrated in this study to impact behavioral sleep parameters. Within the context of everyday life, the sleep-wake cycle is influenced by conscious decisions made within the framework of internal and external cues (Daan, Beersma, & Borbely, 1984). These cues include personal habits, such as exercise, that may impact both the need for sleep and the circadian pacemaker (Beersma & Gordijn, 2006; Daan et al., 1984). The observation that bedtimes differed significantly in the current study between nights following exercise and those nights when there was no structured exercise is consistent with this. These changes in bedtimes are independent of how long women had been exercise training (i.e., they were evident at both mid- and end-intervention), and have not been previously examined in other studies investigating the acute relationship between sleep and exercise during an exercise intervention (Baron et al., 2013; King et al., 2008; Melancon et al., 2015).

We did not find an acute bout of exercise to significantly impact any of the physiological sleep parameters during the corresponding night. Specifically, older, previously inactive women participating in a training program had similar physiological sleep profiles on those days they exercised and those days they did not exercise. However, there is evidence suggesting that an acute bout of exercise affects the physiological parameters of sleep in untrained individuals. Following an acute bout of moderate-intensity aerobic exercise, inactive non-obese older women demonstrated significant improvements in SQ shown by

improved actigraphic measures of WASO, number of nighttime awakenings, and movement while asleep compared to sleep following a day without exercise (Wang and Youngstedt, 2014). In another study, a bout of moderate-intensity aerobic exercise was observed to improve polysomnographic (PSG) measures of TST, SOL, total wake time, and SE, as well as self-reported TST and SOL in a sample of physically inactive middle-aged adults with insomnia (Passos et al., 2010). Similarly, at baseline in the untrained state, the proportion of time spent in non-rapid eye movement (REM) sleep was significantly higher on the night following an acute bout of exercise as compared to the non-exercise control day in older community-dwelling males (Melancon et al., 2015). These individual studies indicate a significant impact of an isolated bout of exercise on physiological parameters of sleep prior to any exercise training among otherwise inactive middle- and older-aged adults. This contrasts with the current study, and may explain in part the inconsistent findings, in which we evaluated the effects of an acute exercise bout on sleep at mid- and end- intervention, rather than at baseline in an untrained, inactive state.

Our findings are similar to those studies that also examined the effect of an acute bout of exercise on sleep during an exercise training intervention among older individuals with sleep complaints or insomnia. For example, King and colleagues (2008) did not observe any significant difference in any PSG sleep parameters following one day of structured exercise compared to one day without structured exercise at the midpoint or end of a 12-month training intervention. Additionally, Baron et al. (2013) used multilevel modeling to analyze whether exercise duration of an acute bout of exercise was a predictor of sleep during the corresponding night. They also did not observe a significant association between exercise duration and actigraphic measures of SOL, TST, WASO, or SE during the corresponding night among older women with insomnia.

We further investigated whether training status affected the acute effect of exercise by comparing mid-intervention versus end-intervention sleep. The interaction between time point in the exercise intervention (mid- vs. end-intervention) and exercise/non-exercise condition was not significant. This conflicts with the findings of Melancon and colleagues (2015), who assessed the acute effect of a bout of exercise before and after four months of exercise training among community-dwelling older males. They found a significant interaction between exercise (exercise vs. non-exercise days) and training (baseline vs. post-training) for percent time spent in non-REM stage 2 sleep, which may indicate a possible training effect. The discrepancies between our findings may be due to the participants of our study reaching their exercise dose by mid-intervention which was then maintained for the remaining two months of the exercise intervention; therefore, no changes occurred in the exercise dose between mid- and end- intervention. Coupled with the study findings among untrained individuals, it may be that the chronic effect of training versus no training, rather than the duration of being in an exercise intervention, has a greater impact on the acute effect of exercise on sleep.

Meta-analyses have not examined whether ‘training status’ was an effect modifier of the effect of acute exercise on sleep; however, meta-analyses have examined the moderating effects of proxy measures of training status, such as fitness and baseline PA levels (Kredlow, Capozzoli, Hearon, Calkins, & Otto, 2015; Kubitz, Landers, Petruzzello, & Han, 1996;

Youngstedt, O'Connor, & Dishman, 1997). Kubitz et al. (1996) observed that the effect of acute exercise on REM sleep and Stage 4 non-REM sleep was greater among less fit individuals compared to the fit. Although we did not measure the effect of an acute bout of exercise on sleep at baseline when our participants were physically inactive, we did observe no significant effect on the physiological sleep parameters at the end-of-intervention even with significant fitness gains in both exercise groups ($p < 0.001$) (Wang, Bowyer, Porter, Breneman, & Custer, 2017). This may indicate smaller effects of an acute bout of exercise on sleep with higher fitness or at the end of an intervention. However, other meta-analyses have provided conflicting findings. Low fitness status (defined as “low or average fitness”, no regular exercise, or having a peak oxygen uptake <50 [men] or <40 ml/kg/min [women]) or low baseline PA (defined as sedentary or not exercising more than 30 min three times per week) were not associated with differential sleep responses to acute exercise when compared to higher fitness status or higher baseline PA (Kredlow et al., 2015; Youngstedt et al., 1997). These categories were created based on the inclusion of studies that predominantly had samples of young to middle-aged adults and would result in our study sample being classified as “unfit” even at the end of our intervention given that their average fitness levels were 22.2 ml/kg/min.

The strengths of this study include the use of actigraphy to objectively measure sleep over multiple nights in the home environment, which allowed for comparison between several nights following days with structured exercise versus days of no structured exercise. Additionally, the structure of the data was organized hierarchically where multiple nights of actigraphic sleep recordings were nested within each participant, which allowed for the acute effect of exercise on sleep to be examined longitudinally. Also, structured exercise in a supervised facility was the main exposure and the overall adherence to the exercise dose in the study was high for both groups, which contrasts with other studies which were unsupervised and/or had lower adherence (85% adherence) in comparison to ours (Baron et al., 2013; King et al., 2008; Mitchell et al., 2016).

In addition to the study strengths, there are limitations that should be considered. One limitation includes the restricted generalizability of the results to healthy, trained older women willing to participate in a university-based exercise training intervention. Furthermore, there is evidence of sex differences in sleep and the type of physical activity preferred between men and women (Mong & Cusmano, 2016; van Uffelen, Khan, & Burton, 2017), which we were unable to examine given that our study only included females. Also, the effect of exercise on sleep may be different among individuals with sleep complaints or disorders; however, because sleep was not the primary aim of the WEWALK study, this was not assessed. Another limitation of this study is the inability to investigate or compare the effects of an acute bout of exercise in the untrained state versus mid- or end-intervention. Furthermore, we could not account for time of day in which the acute bout of exercise occurred; it is possible that the acute effect of exercise may depend upon the time of day in which the exercise occurred (Kredlow et al., 2015; Kubitz et al., 1996; Youngstedt et al., 1997). An additional limitation is that we could only categorize exercise days based on whether structured exercise occurred in our facility; we have no information on whether individuals engaged in additional exercise congruent with their exercise prescription outside of the center-based structured sessions, and therefore, we might have inadvertently classified

these as non-exercise days. However, based on the available information, more time was spent in MVPA on structured exercise days compared to days without structured exercise.

In summary, we observed significantly earlier bedtimes following days with structured exercise versus no structured exercise in healthy, trained older women. This behavioral change did not correspond with any improvements to physiological sleep parameters. Future exercise training studies should longitudinally measure sleep subjectively and objectively at multiple time points in the training period with one of those time points occurring within the first week of training, in order to better understand how training status impacts the acute effects of exercise on sleep. Furthermore, advancing the literature on exercise and sleep among older women is warranted given that they are an understudied population with demonstrated sleep issues for whom exercise might be beneficial if we better understood the effects of exercise on sleep.

Acknowledgments

The authors wish to thank Ryan R. Porter, Kimberly Bowyer, and Sabra Custer for their contributions in collecting the data for this study. This research was supported by NIH grant R00AG031297 (PI: Wang). Partial support for investigator effort was also provided by NIH grant K23HL118318 (PI: Kline).

References

- American College of Sports Medicine. (2010). ACSM's guidelines for exercise testing and prescription. Philadelphia, PA: Lippincott Williams & Wilkins.
- Bailey BW, Allen MD, LeCheminant JD, Tucker LA, Errico WK, Christensen WF, & Hill MD (2014). Objectively measured sleep patterns in young adult women and the relationship to adiposity. *American Journal of Health Promotion*, 29, 46–54. [PubMed: 24200246]
- Baron KG, Reid KJ, & Zee PC (2013). Exercise to improve sleep in insomnia: Exploration of the bidirectional effects. *Journal of Clinical Sleep Medicine*, 9, 819–824. [PubMed: 23946713]
- Beersma DGM, & Gordijn MCM (2006). Circadian control of the sleep-wake cycle. *Physiology & Behavior*, 90, 190–195. [PubMed: 17055008]
- Cole RJ, Kripke DF, Gruen W, Mullaney DJ, & Gillin JC (1992). Automatic sleep/wake identification from wrist activity. *Sleep*, 15, 461–469. [PubMed: 1455130]
- Daan S, Beersma DGM, & Borbely AA (1984). Timing of human sleep: Recovery process gated by a circadian pacemaker. *American Journal of Physiology*, 246, R161–R178. [PubMed: 6696142]
- Dillon HR, Lichstein KL, Dautovich ND, Taylor DJ, Riedel BW, & Bush AJ (2014). Variability in self-reported normal sleep across the adult age span. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 70, 46–56.
- Dzierzewski JM, Buman MP, Giacobbi PR Jr, Roberts BL, Aiken-Morgan AT, Marsiske M, & McCrae CS (2014). Exercise and sleep in community-dwelling older adults: Evidence for a reciprocal relationship. *Journal of Sleep Research*, 23, 61–68. [PubMed: 23980920]
- Frank LL, Sorensen BE, Yasui Y, Tworoger SS, Schwartz RS, Ulrich CM, ... McTiernan A (2005). Effects of exercise on metabolic risk variables in overweight postmenopausal women: a randomized clinical trial. *Obesity Research*, 13:615–25. [PubMed: 15833948]
- Irish LA, Kline CE, Gunn HE, Buysse DJ, & Hall MH (2015). The role of sleep hygiene in promoting public health: A review of empirical evidence. *Sleep Medicine Reviews*, 22, 23–36. [PubMed: 25454674]
- Irish LA, Kline CE, Rothenberger SD, Krafty RT, Buysse DJ, Kravitz HM, ... Hall MH (2014). A 24-hour approach to the study of health behaviors: Temporal relationships between waking health behaviors and sleep. *Annals of Behavioral Medicine*, 47, 189–197. [PubMed: 24043549]

- King AC, Pruitt LA, Woo S, Castro CM, Ahn DK, Vitiello MV, ... Bliwise DL (2008). Effects of moderate-intensity exercise on polysomnography and subjective sleep quality in older adults with mild to moderate sleep complaints. *Journal of Gerontology*, 63A, 997–1004
- Kishida M, & Elavsky S (2016). An intensive longitudinal examination of daily physical activity and sleep in midlife women. *Sleep Health*, 2, 42–48. [PubMed: 29073452]
- Knutson KL, Rathouz PJ, Yan LL, Liu K, & Lauderdale DS (2007). Intra-individual daily and yearly variability in actigraphically recorded sleep measures: The CARDIA Study. *Sleep*, 30, 793–6. [PubMed: 17580601]
- Kredlow MA, Capozzoli MC, Hearon BA, Calkins AW, & Otto MW (2015). The effects of physical activity on sleep: A meta-analytic review. *Journal of Behavioral Medicine*, 38, 426–449.
- Kubitz KA, Landers DM, Petruzzello SJ, & Han M (1996). The effects of acute and chronic exercise on sleep: A meta-analytic review. *Sports Medicine*, 21, 277–291. [PubMed: 8726346]
- Lambiasi MJ, Gabriel KP, Kuller LH, & Matthews KA (2013). Temporal relationships between physical activity and sleep in older women. *Medicine & Science in Sports & Exercise*, 45, 2362–2368. [PubMed: 23739529]
- Littman AJ, Vitiello MV, Foster-Schubert K, Ulrich CM, Tworoger SS, Potter JD, ... McTiernan A (2007). Sleep, ghrelin, leptin and changes in body weight during a 1-year moderate-intensity physical activity intervention. *International Journal of Obesity (London)*, 31:466–75.
- Melancon MO, Lorrain D, & Dionne IJ (2015). Sleep depth and continuity before and after chronic exercise in older men: Electrophysiological evidence. *Physiology & Behavior*, 140, 203–208. [PubMed: 25540930]
- Mitchell JA, Godbole S, Moran K, Murray K, James P, Laden F, ... Glanz K (2016). No evidence of reciprocal associations between daily sleep and physical activity. *Medicine & Science in Sports & Exercise*, 48, 1950–1956. [PubMed: 27285490]
- Mong JA & Cusmano DM (2016). Sex differences in sleep: Impact of biological sex and sex steroids. *Philosophical Transactions of the Royal Society London B: Biological Sciences*, 371.
- Morss GA, Jordan AN, Skinner JS, Dunn AL, Church TS, Earnest CP, ... & Blair SN (2004). Dose-response to exercise in women aged 45–75 yr (DREW): Design and rationale. *Medicine & Science in Sports & Exercise*, 36: 336–344. [PubMed: 14767260]
- Ohayon MM, Carskadon MA, Guilleminault C, & Vitiello MV (2004). Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: Developing normative sleep values across the human lifespan. *Sleep*, 27, 1255–1273. [PubMed: 15586779]
- Passos GS, Poyares D, Santana MG, Garbuio SA, Tufik S, & Mello MT (2010). Effects of acute physical exercise on patients with chronic primary insomnia. *Journal of Clinical Sleep Medicine*, 6, 270–275. [PubMed: 20572421]
- Patel SR, Weng J, Rueschman M, Dudley KA, Loreda JS, Mossavar-Rahmani Y, ... Wang R (2015). Reproducibility of a standardized actigraphy scoring algorithm for sleep in a US Hispanic/Latino population. *Sleep*, 38, 1497–1503. [PubMed: 25845697]
- Rowe M, McCrae C, Campbell J, Horne C, Tiegs T, Lehman B, & Cheng J (2008). Actigraphy in older adults: Comparison of means and variability of three different aggregates of measurement. *Behavioral Sleep Medicine*, 6, 127–145. [PubMed: 18443950]
- Thomas SJ, Lichstein KL, Taylor DJ, Riedel BW, & Bush AJ (2014). Epidemiology of bedtime, arising time, and time in bed: Analysis of age, gender, and ethnicity. *Behavioral Sleep Medicine*, 12, 169–182. [PubMed: 23574553]
- Urponen H, Vuori I, Hasan J, & Partinen M (1988). Self-evaluations of factors promoting and disturbing sleep: An epidemiological survey in Finland. *Social Sciences and Medicine*, 26, 443–450.
- U.S. Department of Health and Human Services. 2008 Physical Activity Guidelines for Americans. Washington, DC: U.S. Department of Health and Human Services, 2008.
- van den Berg JF, Knivistingh Neven A, Tulen JH, Hofman A, Witteman JC, Miedema HM, & Tiemeier H (2008). Actigraphic sleep duration and fragmentation are related to obesity in the elderly: The Rotterdam Study. *International Journal of Obesity*, 32, 1083–1090. [PubMed: 18414418]

- van Hilten JJ, Braat EAM, van der Velde EA, Middelkoop HAM, Kerkhof GA, & Kamphuisen HAC (1993). Ambulatory activity monitoring during sleep: An evaluation of internight and intrasubject variability in healthy persons aged 50–98 years. *Sleep*, 16, 146–150. [PubMed: 8446834]
- van Uffelen JGZ, Khan A, & Burton NW (2017). Gender differences in physical activity motivators and context preferences: A population-based study in people in their sixties. *BMC Public Health*, 17: 624–634. [PubMed: 28676081]
- Wang X, Bowyer BP, Porter RR, Breneman CB, & Cutser SS (2017). Energy expenditure responses to exercise training in older women. *Physiological Reports*, 5, e13360. [PubMed: 28774950]
- Wang X, & Youngstedt SD (2014). Sleep quality improved following a single session of moderate-intensity aerobic exercise in older women: Results from a pilot study. *Journal of Sport and Health Science*, 3, 338–342. [PubMed: 25685605]
- Youngstedt SD, O'Connor PJ, & Dishman RK (1997). The effects of acute exercise on sleep: A quantitative synthesis. *Sleep*, 20, 203–214. [PubMed: 9178916]

Table 1**Baseline Participant Characteristics by Exercise Dose**

	Total (n=51)	Lower-Dose (n=24)	Higher-Dose (n=27)	p value
Age (years)	64.47 (3.74)	64.50 (4.21)	64.44 (3.34)	0.96
Race, % (#)				0.34
White	84.31 (43)	91.67 (22)	77.78 (21)	
Black	13.73 (7)	8.33 (2)	18.52 (5)	
Other	1.96 (1)	0.00 (0)	3.70 (1)	
Education, % (#) ^a				0.82
High School Graduate	15.69 (8)	12.50 (3)	18.52 (5)	
College 1 to 3 years	29.41 (15)	29.17 (7)	29.63 (8)	
College 4 years or more	54.90 (28)	58.33 (14)	51.85 (14)	
Household Income, % (#) ^a				0.91
<\$30,000	9.80 (5)	12.50 (3)	7.41 (2)	
\$30,000 – 49,999	15.69 (8)	16.67 (4)	14.81 (4)	
\$50,000 – 69,999	19.61 (10)	16.67 (4)	22.22 (6)	
\$70,000+	49.02 (25)	50.00 (12)	48.15 (13)	
BMI (kg/m ²)	25.38 (3.44)	25.91 (3.74)	24.91 (3.15)	0.30
MVPA (min per day)	40.80 (24.60)	37.80 (22.80)	43.80 (25.80)	0.38
Average Sleep Parameters				
Bedtime (h:min)	10:58 PM (1:00)	10:45 PM (1:04)	11:11 PM (0:55)	0.11
Arising Time (h:min)	6:58 AM (0:50)	6:40 AM (0:54)	7:13 AM (0:40)	0.02
TIB (min)	479.70 (45.46)	476.50 (42.96)	482.50 (48.21)	0.65
SOL (min)	5.35 (0.81)	5.28 (0.80)	5.41 (0.83)	0.83 ^b
WASO (min)	41.98 (17.93)	38.23 (14.37)	45.31 (20.28)	0.31 ^b
TST (min)	432.36 (43.05)	433.00 (43.86)	431.80 (43.14)	0.92
Number of Awakenings (#)	13.97 (4.34)	13.04 (3.77)	14.80 (4.71)	0.15
Activity Counts (#)	30,157.54 (12,985.48)	27,763.90 (10,259.90)	32,285.20 (14,871.70)	0.29 ^b

Note: BMI = body mass index; MVPA = moderate to vigorous physical activity; SOL = sleep onset latency; TIB = total time in bed; TST = total sleep time; WASO = wake after sleep onset. Values presented as mean (standard deviation) or as % (n), as appropriate. *P* values were obtained from chi-square and t-tests, with statistical significance defined at the alpha < 0.05 level.

^aIndicates missing values which results in some percentages not totaling up to 100%.

^bIndicates that a non-parametric test was used to evaluate differences between means due to the variable having a non-normal distribution.

Table 2
Objectively Measured Sleep Variables Estimated from Multilevel Models (n = 51)

Predictor Variable	Behavioral Sleep Parameters						Physiological Sleep Parameters								Activity Counts ^c	
	Bedtime		Arising Time		TIB		SOL ^a		WASO ^b		TST		Number of Awakenings			
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Exercise	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Non-exercise	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Exercise	-0.16 (0.06)**	-0.12 (0.06)*	-0.15 (0.06)*	-0.02 (0.06)	0.91 (4.43)	6.23 (4.44)	-0.004 (0.01)	-0.006 (0.01)	0.006 (0.08)	0.05 (0.08)	1.00 (4.04)	5.74 (4.04)	0.18 (0.27)	0.33 (0.28)	-0.01 (0.02)	0.003 (0.02)
Time Point																
Mid	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Post	-0.18 (0.13)	-0.17 (0.13)	-0.10 (0.12)	-0.08 (0.12)	4.68 (8.35)	5.52 (8.11)	0.02 (0.02)	0.02 (0.02)	0.10 (0.20)	0.11 (0.19)	3.74 (7.30)	4.49 (6.97)	-0.29 (0.63)	-0.27 (0.60)	0.04 (0.06)	0.05 (0.06)

Note: SOL = sleep onset latency; TIB = total time in bed; TST = total sleep time; WASO = wake after sleep onset. Unstandardized regression coefficients are presented along with standard errors. Model 1 variables included exercise condition (exercise, non-exercise), time point (mid-, post-intervention), exercise group (lower-dose, higher-dose), and mean baseline value of the respective sleep parameter. Model 2 variables included those from Model 1 plus day of the week (weekday night [Sunday through Thursday] versus weekend night [Friday and Saturday]), baseline BMI, and average baseline MVPA levels.

^aLog(x+1) transformation used for statistical analysis and variable reported on transformed scale.

^bSquare root transformation used for statistical analysis and variable reported on transformed scale.

^cLog(x) transformation used for statistical analysis and variable reported on transformed scale.

* $p < 0.05$

** $p < 0.01$