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The Effect of Moderate-Intensity Exercise on Nightly Variability in Objectively Measured Sleep Parameters among Older Women

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Abstract

Objective/Background: Exercise training has been demonstrated to beneficially influence mean-level measures of sleep; however, few studies have examined the impact of an exercise intervention on night-to-night variability in sleep. This study investigated whether four months of moderate-intensity exercise impacted night-to-night variability in sleep among older women.

Methods: Participants (n=49) were randomized to one of two moderate-intensity walking programs with different doses of energy expenditure: low-dose (n = 23: 8 kcal/kg of body weight per week) or high-dose (n = 26: 14 kcal/kg of body weight per week). Sleep parameters were assessed objectively via actigraphy at baseline, mid- (2-month), and post-intervention (4-month). Nightly variability in each of the sleep parameters was calculated using the 7-day standard deviations (*SD*) and a coefficient of variation (*SD*/mean x 100%). Cardiorespiratory fitness (VO_{2peak}) was measured at baseline and post-intervention using a graded treadmill test.

Results: Both measures of nightly variability demonstrated a borderline to significant lower amount of night-to-night variability in wake time after sleep onset (WASO) and number of awakenings at post-intervention in comparison to baseline ($p \leq 0.05$). Higher VO_{2peak} levels at baseline were associated with less time in bed and lower total sleep time variability throughout the exercise intervention ($p < 0.05$).

Conclusion: Overall, participation in moderate-intensity exercise was observed to reduce the amount of nightly variability for WASO and number of awakenings over time in older women.

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Keywords

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Sleep is a modifiable behavior that commonly fluctuates from night to night within the same individual and varies across the lifespan (Dillon et al., 2014). These nightly variations are present in several sleep parameters, including time in bed (TIB), total sleep time (TST), sleep onset latency (SOL), and wake time after sleep onset (WASO) (Dillon et al., 2014; Knutson, Rathouz, Yan, Liu, & Lauderdale, 2007). Furthermore, the magnitude of the nightly variability in sleep differs by sex with females being more likely to demonstrate greater night-to-night variability in self-reported number of nighttime awakenings and SOL as compared to males (Dillon et al., 2014). This possibly indicates that sleep among females may be more susceptible to disruptions caused by environmental or hormonal changes (Dillon et al., 2014; Moline, Broch, Zak, & Gross, 2003). Also, sleep-related difficulties become more prevalent after menopause as evident by approximately 35–60% of postmenopausal women self-reporting sleep disturbances as compared to 16–42% of premenopausal women (National Institutes of Health, 2005). Specifically, insomnia is a prevalent sleep disorder among postmenopausal women and is commonly accompanied by elevated night-to-night variability in sleep patterns (Buysse et al., 2010; Krystal, Edinger, Wohlgemuth, & Marsh, 1998; Moline et al., 2003). Taken together, older women are particularly vulnerable to sleep disturbances and disorders that may result in significant night-to-night variability.

Recently, researchers have taken interest in examining how night-to-night fluctuations in sleep parameters may influence health. Emerging evidence demonstrates the clear clinical significance of this dimension of sleep; highly variable sleeping patterns are associated with several negative health outcomes, including higher concentrations of circulating pro-inflammatory markers, obesity, greater morbidity, and poorer self-reported health status (Bei, Wiley, Trinder, & Manber, 2015; Knutson et al., 2007; Okun et al., 2011; Patel et al., 2014). Additionally, there is evidence suggesting that the associations between night-to-night variability and poorer perceived health are independent of mean-level sleep measures (Lemola, Ledermann, & Friedman, 2013). Although the literature has yet to define what is considered an acceptable or normal amount of nightly variability, these findings suggest that studying nightly variability in sleep parameters may provide new insight to the relationship between sleep and health in addition to what has already been demonstrated at the mean-level.

There is evidence that nightly variability in sleep can be modified with behavioral intervention. For example, cognitive-behavioral therapy for insomnia (Edinger & Means, 2005; Espie, Inglis, & Harvey, 2001) has been found to significantly reduce night-to-night variability in self-reported TST, TIB, WASO, and sleep efficiency (SE) post-treatment (Edinger, Hoelscher, Marsh, Lipper, & Ionescu-Pioggia, 1992). A recent study demonstrated significant reductions in sleep variability for actigraphic measures of WASO and SE following an intervention that included both exercise and sleep hygiene education (Baron, Reid, Malkani, Kang, & Zee, 2017). This suggests that exercise may be a strategy to reduce

nightly variability in sleep. However, the traditional approach in the literature has investigated how exercise produces mean-level changes in sleep. Specifically, among studies that measured sleep objectively via wrist actigraphy, TST, SE, WASO, and activity counts were demonstrated to improve significantly among older women randomized to the exercise group (Baron, Reid, & Zee, 2013; Payne, Held, Thorpe, & Shaw, 2008). Taken together, these interventional studies demonstrate that exercise training has beneficial effects on mean-level measures of sleep; however, additional studies are needed to determine how an exercise intervention influences night-to-night variability in sleep.

Additionally, the effects of exercise on sleep may be modulated/mediated by several factors including individual characteristics and exercise habits. Cardiorespiratory fitness (CRF) is one individual characteristic identified in several reviews and meta-analyses to impact sleep (Buman & King, 2010; Chennaoui et al., 2015; Uchida et al., 2012; Youngstedt, O'Connor, & Dishman, 1997). However, the literature has only examined mean-level associations and has yet to identify whether CRF is associated with night-to-night variability.

Therefore, the main purpose of this study was to examine whether four months of moderate-intensity exercise impacted night-to-night variability in objectively measured sleep among healthy, physically inactive older women. We predicted that chronic exercise would significantly reduce night-to-night variability in sleep in both groups given recent evidence demonstrating significant reductions in sleep variability for actigraphic measures following a non-pharmacologic intervention with an exercise component (Baron et al., 2017). A secondary purpose of this study was to examine the relationship between baseline CRF and changes in CRF with night-to-night variability. We predicted that those participants with higher baseline CRF or those with greater improvement in CRF would experience less night-to-night variability throughout the intervention.

Methods

Study Population

Data for the present analyses were obtained from the WEWALK study which was a clinical exercise trial examining the effects of two walking programs with different energy expenditures on non-exercise activity thermogenesis in physically inactive older women (N = 72) (ClinicalTrials.gov identifier: NCT01722136) (Wang, Bowyer, Porter, Breneman, & Custer, 2017). A subsample of females enrolled in the WEWALK study who had at least seven consecutive days of actigraphic sleep recordings at baseline, mid-intervention (2-month), and post-intervention (4-month) (n = 53) was considered for the present analyses. If the change to/from Daylight Saving Time was included in the 7 days of actigraphy at any of the time points, the participant was excluded from these analyses due to the potential impact time change may have on sleep variability (n = 4). This resulted in a total of 49 participants from the WEWALK study being included in these analyses. In comparison to those who were excluded (n=23) due to incomplete data, the subsample of women included in the present analyses had higher nightly variability in WASO ($p < 0.01$); there were no differences in any of the demographic or baseline measures of fitness, BMI, mean-level sleep parameters, or other night-to-night variability sleep parameters.

Participants of the WEWALK study were female, aged 60–75 years, non-smokers, weight stable (±3%) for the previous three months, physically inactive (did not engage in structured exercise more than three times per week), had a body mass index (BMI) ≥ 18 and ≤ 30 kg/m^2, and were free from cardiovascular disease, diabetes, or any other condition that might prevent them from adhering to the study protocol. Since sleep was not a primary outcome of interest of the WEWALK study, sleep disorders were not specifically screened in the study. The study protocol was approved by the University of South Carolina Institutional Review Board and all participants signed an informed consent form.

Study Intervention

Participants in the WEWALK study were randomized to one of two moderate-intensity walking programs with different doses of energy expenditure: low-dose (8 kcal/kg of body weight per week) or high-dose (14 kcal/kg of body weight per week). The exercise training period for both groups was four months and each training session occurred in a research facility under supervision. Participants in both groups walked three to four times per week on treadmills. The two different doses were achieved by varying the weekly duration of exercise in order for the participants to reach their energy expenditure goals according to body size and exercise dosage (8 kcal/kg versus 14 kcal/kg). Weekly energy expenditure was determined by multiplying the participant's weight by their assigned dosage and was closely monitored throughout the intervention.

Due to the physically inactive state of the participants at baseline, both groups began their training at an intensity of 40% of their heart rate reserve which was obtained during a baseline CRF test (see below). The intensity increased in both groups by 5% every two weeks from 40% to a target level of 50–55% of the participant's heart rate reserve. Both exercise groups began at a weekly caloric expenditure of 4 kcal/kg body weight during the first week of the intervention and then progressed until the assigned exercise dosage was reached by week five in the low-dose group and week eight in the high-dose group.

Measurements

Sleep parameters.—Sleep parameters were assessed objectively by wrist actigraphy (GT3X+; Actigraph, Pensacola, FL, USA). Participants wore the monitors on the non-dominant wrist for up to 14 days of continual wear at baseline, mid-intervention, and post-intervention. The first seven consecutive days of actigraphy data at baseline, mid-, and post-intervention, respectively, were used in this study in order to standardize the number of days among participants with complete data. This was done in order to reduce the amount of additional variability that may occur due to reasons other than normal night-to-night variability (e.g., variability due to longer data collection time [7+ days], variability due to varying number of weekend days across individuals, etc.). Additionally, the participants were asked to keep daily logs in which bedtimes and arising times were recorded.

Software provided by the manufacturer (ActiLife version 6.11.2) was used to analyze the actigraphy data in 60-second epochs and the times recorded on the sleep logs were manually entered into the program to quantify TIB. The GT3X+ provides objective measures of activity counts as well as information on the environment via an ambient light sensor. A

standardized approach developed by Patel and colleagues (2015) was used to define TIB. Missing entries on logs and inaccurate recordings of bed/awake times were estimated or adjusted, respectively, based on the hierarchical ranking of inputs (i.e., sleep logs, light intensity, and activity counts) in order to improve the reproducibility of the values. The Cole-Kripke algorithm was used to determine when each participant was asleep or awake (Cole, Kripke, Gruen, Mullaney, & Gillin, 1992). The software provides estimates of SOL (duration from specified bedtime to when the algorithm scored sleep onset), TST (total length of TIB specified by the algorithm as "asleep"), WASO (number of minutes scored as "awake" after sleep onset), frequency of awakenings during the sleep period, and activity counts during TIB.

CRF.—CRF was measured in all participants at baseline and post-intervention using a graded treadmill test. The test involved an incremental protocol in which participants walked at a self-selected, comfortable but challenging speed that remained constant throughout the test with the incline increasing by 2% every two minutes. Volume of oxygen consumption (VO_2) was monitored continuously with a metabolic cart (True Max 2400; ParvoMedics, Sandy, UT, USA) and heart rate was recorded with a standard 12-lead ECG (Q-Stress ®; Cardiac Science, Bothell, WA, USA). Peak oxygen consumption (VO_{2peak}) was determined by the highest 30-second averaged VO_2 value during the test. Change in VO_{2peak} was calculated by subtracting the baseline value from post-intervention measure. Because CRF has been identified in several reviews and meta-analyses as a potential moderating/mediating factor of sleep (Buman & King, 2010; Chennaoui, Arnal, Sauvet, & Leger, 2015; Uchida et al., 2012), both baseline VO_{2peak} and change in VO_{2peak} were used as covariates.

Statistical Analyses

Baseline descriptive statistics, including individual means and standard deviations (*SD*), were calculated. Group differences in baseline characteristics between those randomized to the low-dose versus high-dose exercise prescriptions were tested using t-tests or chi-square tests, as appropriate. Means and *SD*s over the first 7 consecutive days for each of the sleep parameters were calculated at each time point (baseline, mid-, and post-intervention). The primary measure of nightly variability for each of the sleep parameters was the 7-day *SD*. A secondary measure of variability, the coefficient of variation (CV), was computed for each sleep outcome by dividing the 7-day *SD* by the mean (*SD*/mean x 100%) for each individual. (Buman, Hekler, Bliwise, & King, 2010; Knutson et al., 2007; Rowe et al., 2008). Since *SD* is a measure of how much the data points deviate from the mean, it is possible that higher individual-level means will occur with higher variability when using the *SD*; thus, the CV is a more conservative measure of intra-individual variability than the 7-day *SD* because it references the mean (Buman et al., 2010). Therefore, both measures of variability were examined for comparison purposes and any differences were noted. Higher values in either of these measures of nightly variability indicated greater intra-individual variability. Additionally, neither measure of variability was normally distributed; therefore, the values were transformed using the natural logarithm function to achieve normality of distribution. No data transformations were needed for the mean-level measures of any sleep parameter assessed.

Separate models were run for each sleep parameter with the corresponding 7-day *SD* or the CV as the dependent variable. Similar but separate models were run using the mean for each sleep outcome as the dependent variable to determine if mean-level changes also occurred in that parameter. A repeated measures analysis was conducted using a mixed effects model to test the main effect of time while adjusting for group, baseline VO_{2peak} levels, and changes in VO_{2peak} as covariates. The resulting beta coefficients for time, baseline VO_{2peak} levels, and changes in VO_{2peak} were interpreted in order to assess whether changes occurred across time in response to the 4-month intervention and also to determine the relation of CRF with nightly variability. To further examine the changes over time, 2-month and 4-month values were compared to baseline. Tukey-Kramer procedure was used to account for multiple comparisons. A group x time effect was tested and found to be nonsignificant for all of the variability and mean-level sleep parameters and, therefore, this interaction term was excluded from the analyses. Statistical significance was set at $p < 0.05$ and all analyses were performed in SAS 9.4 (SAS Institute Inc., Cary, NC).

Results

Participant Characteristics

The sample consisted of 49 women with complete baseline, mid-, and post-intervention data for sleep (low-dose: $n = 23$; high-dose: $n = 26$). Table 1 presents the means and *SD*s of the baseline demographic characteristics of the sample. Overall, the women were predominantly non-Hispanic white with a college education. On average, they were 64.5 years of age with a VO_{2peak} of 19.8 ml/kg/min and a body mass index of 25.5 kg/m^2. As shown in Table 2, the low-dose group had significantly higher variability in WASO at baseline as quantified by the CV. No other baseline differences were noted.

The training intervention significantly increased VO_{2peak} levels in both groups with an average increase of 7.4% (1.43 ml/kg/min) in the low-dose group ($p = 0.01$) and 14.3% (2.86 ml/kg/min) in the high-dose group ($p < 0.01$). The increase in VO_{2peak} did not differ between the training groups ($p = 0.11$).

Change in Mean-Level Sleep Parameters—There was no significant group x time interaction for any of the sleep parameters at the mean-level or for either measure of variability. Table 3 provides the results from the mixed effects models examining mean-level changes for each of the sleep parameters over time. A significant time effect was observed for mean-level bedtimes ($p = 0.04$). Post-hoc comparisons revealed that bedtimes were significantly later at mid-intervention in comparison to post-intervention ($p = 0.04$). No other significant time differences were noted.

Change in Night-to-Night Variability in Sleep Parameters—Table 3 also provides the results from the mixed effects models examining the changes in nightly variability over time using the two indices of variability (7-day *SD* and CV) for each sleep parameter. A significant overall time effect was observed for the 7-day *SD* variability in WASO ($p = 0.02$). Specifically, the amount of night-to-night variability in WASO was significantly lower at mid- and post-intervention in comparison to baseline, but no difference between mid- and post-intervention values ($p = 0.67$). No significant overall time effects were observed for the

remaining sleep parameters. However, although the overall time effect was not significant (p = 0.12), the amount of night-to-night variability in the number of awakenings was significantly lower at post-intervention in comparison to baseline (p = 0.048).

When using CV as a measure of nightly variability, there were no significant overall time effects for any of the sleep parameters. However, borderline significant differences between baseline and post-intervention were observed for the amount of night-to-night variability in WASO and the number of awakenings (p = 0.05 and p =0.052, respectively). Specifically, the amount of night-to-night variability in WASO and the number of awakenings were lower at post-intervention in comparison to baseline.

CRF and Mean and Night-to-Night Variability in Sleep—There was a significant negative association between baseline VO_{2peak} and mean TIB (B = −3.97, p = 0.03), indicating that higher values of baseline VO_{2peak} were associated with a shorter amount of TIB throughout the exercise intervention. No other significant associations between baseline VO_{2peak} and mean-level sleep parameters were observed.

When using the 7-day *SD*, baseline VO_{2peak} was significantly and negatively associated with the amount of night-to-night variability for TST (B on log scale = −0.03, p = 0.03) and WASO (B on log scale = −0.03, p = 0.048). This indicates that higher baseline VO_{2peak} levels were associated with lower night-to-night variability in TST and WASO throughout the exercise intervention. When using the CV as a measure of sleep variability, baseline VO_{2peak} was significantly and negatively associated with the amount of night-to-night variability for TST (B on log scale = −0.03, p = 0.04); however, baseline VO_{2peak} was not associated with WASO CV (p = 0.65). Change in VO_{2peak} was not associated with night-to-night variability for any of the sleep parameters using either 7-day *SD* or CV approaches (p > 0.05).

Discussion

The purpose of this study was to examine whether four months of moderate-intensity exercise impacted night-to-night variability in sleep among healthy, physically inactive older women using objective measures of sleep. Our results revealed a significant overall time effect for WASO and a significant difference between post-intervention and baseline for number of awakenings when using 7-day *SD*, indicating that variability in these parameters decreased as women participated in moderate-intensity exercise. Additionally, greater fitness at baseline was associated with more consistent TST and less TIB, as demonstrated by the significant inverse association between baseline VO_{2peak} levels with nightly variability in TST and mean-level TIB.

The observed reduction in both indices of variability for WASO and number of awakenings post-intervention in our study may be an indication of a possible improvement in sleep quality. Although sleep quality was not assessed in this study, previous studies have found greater variability in objectively measured WASO, SE, and sleep fragmentation to be significantly associated with poorer self-reported sleep quality (Baron et al., 2017; Sánchez-Ortuño & Edinger, 2012). Additionally, significant correlations between reductions in the

amount of variability of SOL, WASO, and SE and improvements in self-reported sleep quality have been reported among individuals with comorbid insomnia who received cognitive-behavioral therapy (Sánchez-Ortuño & Edinger, 2012). Also, our results are consistent with the existing literature in which moderate-intensity aerobic exercise has been demonstrated to significantly reduce nightly variability in self-reported SOL (Buman et al., 2010) and actigraphic SE and WASO (Baron et al., 2017) post-intervention in older adults. Thus, these findings provide further evidence supporting exercise as a non-pharmacological approach to improving sleep quality via reductions in night-to-night variability for several physiological sleep parameters.

Reductions in nightly variability for WASO and number of awakenings were seen in our study despite a lack of change in mean-level sleep parameters. This is consistent with another study that reported that the significant reductions in SOL were independent of mean-level changes in SOL (Buman et al., 2010). When also considering that sleep variability has been associated with multiple negative health outcomes above and beyond mean-level sleep (Bei et al., 2015; Knutson et al., 2007; Okun et al., 2011; Patel et al., 2014), reductions in nightly variability may be clinically meaningful given that sleep is a modifiable behavior and non-pharmacological approaches have been demonstrated to successfully reduce nightly variability. However, additional research is needed to examine whether changes in nightly variability are associated with changes in the negative health outcomes significantly associated with highly variable sleeping patterns, including cardiometabolic risk measures, circulating pro-inflammatory markers, obesity, morbidity, and poor self-reported health status (Baron et al. 2016; Bei et al., 2015; Knutson et al., 2007; Okun et al., 2011; Patel et al., 2014). Additionally, this indicates that nightly variability is an independent dimension of sleep that should be investigated in conjunction with individual means in order to fully understand the relationship between exercise and sleep.

The inverse association demonstrated in our study between baseline VO_{2peak} levels and nightly variability in TST has not been previously examined in the literature. Our study also demonstrated that high baseline VO_{2peak} levels were associated with less TIB throughout the exercise intervention. Several studies have evaluated the association between sleep and fitness by comparing mean-level sleep parameters between physically fit and unfit individuals (Lee & Lin, 2007; Porter & Horne, 1981; Strand et al., 2013). In these studies, young and middle-aged adults classified with high fitness were observed to have significantly greater slow wave sleep, better sleep quality, fewer insomnia symptoms, later bedtimes, shorter self-reported SOL, and shorter TST in comparison to unfit individuals. Our findings extend the existing literature on mean-level sleep by indicating that fitness is associated with more consistent sleep duration. However, changes in VO_{2peak} were not found in our study to be associated with more consistent sleep patterns or improvements to mean-level sleep parameters. The lack of an association may be due to an insufficient change in fitness levels post-intervention (average change in VO_{2peak} = 11.1% [2.2 ml/kg/min]) or could point toward the importance of innate fitness as opposed to acquired fitness.

Although there were similarities between both measures of variability (7-day *SD*s and CV), there were some associations observed when using the 7-day *SD*s that were not replicated using the CV. Specifically, the amount of night-to-night variability in WASO was

significantly lower at mid- and post-intervention in comparison to baseline when quantified using 7-day *SD*s. The difference between post-intervention and baseline was borderline significant when using CV while no significant difference was observed between mid-intervention and baseline. These differences are likely due to the CV being a more conservative measure of intra-individual variability since it takes into account the individual-level mean over the same time period as the *SD*. The literature predominantly assesses night-to-night variability via *SD*s more than CV or any other analytic method (Bei et al., 2015), which may be due to the ease of calculation and interpretability.

This study has several strengths. We studied older women, who are more likely to demonstrate greater night-to-night variability in self-reported sleep parameters as compared to males (Dillon et al., 2014), which makes this population ideal for studying night-to-night variability. The use of objective measures of sleep via actigraphy is another strength that allows for night-to-night variability to be estimated across multiple nights in the home environment. In addition, the length of observation includes weekend nights in the calculation of nightly variability which is notable since sleep patterns tend to change on the weekends (Hashizaki, Nakajima, & Kume, 2015).

There are limitations to this study. One involves its generalizability, as the results can only be generalized to healthy older women. Individuals with insomnia or other sleep disorders may have different responses to exercise than those who do not; however, this study was unable to address this question because sleep complaints and disorders were not assessed. Even though this was not measured, an examination of baseline sleep characteristics does demonstrate that these women may be considered good sleepers given that, on average, they obtained 7.36 hours of sleep per night and had a SOL of 5.27 minutes. Additionally, other variables not assessed in this study, might impact the sleep-exercise relationship, including light exposure, naps, and stress (Gerber et al., 2014; Tanaka et al., 2002; Youngstedt et al., 1997). The lack of a control group is another limitation of this study because we were unable to determine whether the observed changes in nightly variability and mean-level sleep parameters were the result of the exercise intervention or other factor(s). Lastly, we did not assess self-reported sleep parameters and, therefore, were unable to determine whether subjective indices of sleep improved in conjunction with the observed reductions in objectively measured nightly variability.

In summary, participation in moderate-intensity exercise training was observed to reduce the amount of nightly variability for WASO and number of awakenings over time in older women. The reductions in nightly variability of these sleep parameters suggest improved sleep quality; however, it is unknown if reducing variability in other sleep parameters might have a greater impact on sleep quality or whether the magnitude of variability reduction observed in this study has meaningful health implications. This study also demonstrated that higher VO_{2peak} at baseline was associated with more consistent sleep duration and shorter TIB throughout the exercise intervention, but further research is warranted in order to confirm this finding and to better understand the relationship between fitness and nightly sleep variability.

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References

Baron K, Reid K, Malkani R, Kang J, & Zee P (2017). Sleep variability among older adults with insomnia: Associations with sleep quality and cardiometabolic disease risk. Behavioral Sleep Medicine, 15, 144–157. [PubMed: 26745754]

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]

Bei B, Wiley JF, Trinder J, & Manber R (2016). Beyond the mean: A systematic review on the correlates of daily intraindividual variability of sleep/wake patterns. Sleep Medicine Reviews, 28, 104–120.

Buman MP, Hekler EB, Bliwise DL, & King AC (2010). Exercise effects on night-to-night fluctuations in self-rated sleep among older adults with sleep complaints. Journal of Sleep Research, 20, 28–37.

Buman MP, & King AC (2010). Exercise as a treatment to enhance sleep. American Journal of Lifestyle Medicine, 4, 500–514.

Buysse D, Cheng Y, Germain A, Moul D, Franzen P, Fletcher M, et al. (2010). Night-to-night sleep variability in older adults with and without chronic insomnia. Sleep Medicine, 11, 56–64. [PubMed: 19962939]

Chennaoui M, Arnal PJ, Sauvet F, & Leger D (2015). Sleep and exercise: A reciprocal issue? Sleep Medicine Reviews, 20, 59–72. [PubMed: 25127157]

Cole R, Kripke D, Gruen W, Mullaney D, & Gillin J (1992). Automatic sleep/wake identification from wrist activity. Sleep, 15, 461–469. [PubMed: 1455130]

Dillon H, Lichstein K, Dautovich N, Taylor D, Riedel B, & Bush A (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.

Edinger J, Hoelscher T, Marsh G, Lipper S, & Ionescu-Pioggia M (1992). A cognitive-behavioral therapy for sleep-maintenance insomnia in older adults. Psychology and Aging, 7, 282–289. [PubMed: 1610517]

Edinger J, & Means M (2005). Cognitive–behavioral therapy for primary insomnia. Clinical Psychology Review, 25, 539–558. [PubMed: 15951083]

Espie C, Inglis S, & Harvey L (2001). Predicting clinically significant response to cognitive behavior therapy for chronic insomnia in general medical practice: Analyses of outcome data at 12 months posttreatment. Journal of Consulting and Clinical Psychology, 69, 58–66. [PubMed: 11302278]

Gerber M, Brand S, Herrmann C, Colledge F, Holsboer-Trachsler E, & Pühse U (2014). Increased objectively assessed vigorous-intensity exercise is associated with reduced stress, increased mental health and good objective and subjective sleep in young adults. Physiology & Behavior, 135, 17–24. [PubMed: 24905432]

Hashizaki M, Nakajima H, & Kume K (2015). Monitoring of weekly sleep pattern variations at home with a contactless biomotion sensor. Sensors, 15, 18950–18964. [PubMed: 26247948]

Knutson K, Rathouz P, Yan L, Liu K, & Lauderdale D (2007). Intra-individual daily and yearly variability in actigraphically recorded sleep measures: The CARDIA study. Sleep, 30, 793–6. [PubMed: 17580601]

Krystal A, Edinger J, Wohlgemuth W, & Marsh G (1998). Sleep in peri-menopausal and post-menopausal women. Sleep Medicine Reviews, 2, 243–53. [PubMed: 15310495]

Lee AJY, & Lin WH (2007). Association between sleep quality and physical fitness in female young adults. Journal of Sports Medicine and Physical Fitness, 47, 462–467. [PubMed: 18091688]

Lemola S, Ledermann T, & Friedman EM (2013). Variability of sleep duration is related to subjective sleep quality and subjective well-being: An actigraphy study. PLoS One, 8, e71292. [PubMed: 23967186]

Moline ML, Broch L, Zak R, & Gross V (2003). Sleep in women across the life cyle from adulthood through menopause. Sleep Medicine Reviews, 7, 155–177. [PubMed: 12628216]

National Institutes of Health. (2005). National Institutes of Health State-of-the-Science Conference statement: Management of menopause-related symptoms. Annals of internal Medicine, 142, 1003–1013. [PubMed: 15968015]

Okun ML, Reynolds CF, Buysse DJ, Monk TH, Mazumdar S, Begley A, et al. (2011). Sleep variability, health-related practices, and inflammatory markers in a community dwelling sample of older adults. Psychosomatic Medicine, 73, 142–150. [PubMed: 21097658]

Patel S, Hayes A, Blackwell T, Evans D, Ancoli-Israel S, Wing Y, et al. (2014). The association between sleep patterns and obesity in older adults. International Journal of Obesity, 38, 1159–1164. [PubMed: 24458262]

Patel SR, Weng J, Rueschman M, Dudley KA, Loredo JS, Mossavar-Rahmani Y, et al. (2015). Reproducibility of a standardized actigraphy scoring algorithm for sleep in a US Hispanic/Latino Population. Sleep, 38, 1497–1503. [PubMed: 25845697]

Payne JK, Held J, Thorpe J, & Shaw H (2008). Effects of exercise on biomarkers, fatigue, sleep disturbances, and depressive symptoms in older women with breast cancer receiving hormonal therapy. Oncology Nursing Forum, 35, 635–642. [PubMed: 18591167]

Porter JM, & Horne JA (1981). Exercise and sleep behavior: A questionnaire approach. Ergonomics, 24, 511–521. [PubMed: 7333268]

Rowe M, McCrae C, Campbell J, Horne C, Tiegs T, Lehman B, et al. (2008). Actigraphy in older adults: Comparison of means and variability of three different aggregates of measurement. Behavioral Sleep Medicine, 6, 127–145. [PubMed: 18443950]

Sanchez-Ortuno M, & Edinger J (2012). Internight sleep variability: its clinical significance and responsiveness to treatment in primary and comorbid insomnia. Journal of Sleep Research, 21, 527–534. [PubMed: 22463493]

Strand L, Laugsand L, Wisløff U, Nes B, Vatten L, & Janszky I (2013). Insomnia symptoms and cardiorespiratory fitness in healthy individuals: The Nord-Trøndelag Health Study (HUNT). Sleep, 36, 99–108. [PubMed: 23288976]

Tanaka H, Taira K, Arakawa A, Urasaki C, Yamamoto Y, Okuma H, et al. (2002). Short naps and exercise improve sleep quality and mental health in the elderly. Psychiatry and Clinical Neurosciences, 56, 233–234. [PubMed: 12047572]

Uchida S, Shioda K, Morita Y, Kubota C, Ganeko M, & Takeda N (2012). Exercise effects on sleep physiology. Frontiers in Neurology, 3, 48–52. [PubMed: 22485106]

Wang X, Bowyer BP, Porter RR, Breneman CB, & Custer SS (2017). Energy expenditure responses to exercise training in older women. Physiological Reports, 5, e13360. [PubMed: 28774950]

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 Demographic Characteristics

	Total (n=49)	Low-Dose (n=23)	High-Dose (n=26)	p-value
Age (years)	64.53 (3.83)	64.52 (4.37)	64.54 (3.37)	0.99
Race, % (#)				0.34
White	83.67 (41)	91.30 (21)	76.92 (20)	
Black	14.29 (7)	8.70 (2)	19.23 (5)	
Other	2.04 (1)	0.00 (0)	3.85 (1)	
Education, % (#)[a]				0.80
High School Graduate	16.33 (8)	13.04 (3)	19.23 (5)	
College 1 to 3 years	28.57 (14)	26.09 (6)	30.77 (8)	
College 4 years or more	53.06 (26)	56.52 (13)	50.00 (13)	
Household Income, % (#)[a]				0.97
<$30,000	8.16 (4)	8.70 (2)	7.69 (2)	
$30,000 – 49,999	16.33 (8)	17.39 (4)	15.38 (4)	
$50,000 – 69,999	20.41 (10)	17.39 (4)	23.08 (6)	
$70,000+	46.94 (23)	47.83 (11)	46.15 (12)	
BMI (kg/m^2)	25.48 (3.57)	26.34 (3.93)	24.72 (3.11)	0.11
VO_{2peak} (ml/kg/min)	19.76 (3.74)	19.43 (3.25)	20.05 (4.18)	0.57
CES-D	5.00 (5.01)	5.17 (5.46)	4.85 (4.68)	0.82

Note. BMI = body mass index; CES-D = Center for Epidemiologic Studies Depression score; VO_{2peak} = peak oxygen consumption. Values presented are means (standard deviations) unless otherwise stated. P-values were obtained from chi-square and t-tests, with statistical significance defined at the alpha < 0.05 level.

[a]Indicates missing values which results in some percentages not totaling up to 100%.

Table 2

Baseline Sleep Characteristics

	Total (n=49)	Low-Dose (n=23)	High-Dose (n=26)	p-value
Average Sleep Parameters				
Bedtime (h:min)	10:54 PM	10:50 PM	10:57 PM	0.73
Arising time (h:min)	7:03 AM	6:55 AM	7:10 AM	0.34
TIB (min)	489.62 (47.43)	485.30 (44.37)	493.50 (50.54)	0.55
TST (min)	441.36 (42.52)	440.0 (41.30)	442.60 (44.35)	0.84
SOL (min)	5.27 (0.95)	5.08 (0.90)	5.44 (0.98)	0.19
Activity counts (#)	30,989.65 (15,210.13)	29,001.80 (13,256.60)	32,748.10 (16,813.30)	0.40
WASO (min)	42.99 (20.92)	40.18 (19.12)	45.48 (22.47)	0.38
Number of awakenings (#)	14.20 (4.53)	13.51 (4.14)	14.80 (4.84)	0.32
Night-to-Night Variability (7-day *SD*)				
Bedtime (min)	57.20 (36.85)	63.37 (41.42)	51.73 (32.10)	0.27
Arising time (min)	50.89 (27.11)	54.88 (32.41)	47.35 (21.42)	0.34
TIB (min)	69.07 (45.26)	77.35 (51.49)	61.74 (38.48)	0.23
TST (min)	63.31 (37.34)	68.78 (44.06)	58.48 (30.29)	0.34
SOL (min)	1.36 (1.09)	1.19 (0.93)	1.50 (1.21)	0.31
Activity counts (#)	13,423.87 (10321.29)	14,350.40 (11,817.70)	12,604.20 (8,952.60)	0.56
WASO (min)	18.57 (9.96)	19.35 (9.70)	17.87 (10.32)	0.61
Number of awakenings (#)	4.52 (1.70)	4.45 (1.79)	4.58 (1.65)	0.79
Night-to-Night Variability (CV)				
Bedtime	4.16 (2.69)	4.64 (3.12)	3.73 (2.21)	0.24
Arising time	11.79 (5.38)	12.79 (6.25)	10.90 (4.42)	0.22
TIB	14.12 (9.03)	15.81 (9.79)	12.62 (8.20)	0.22
TST	14.47 (8.59)	15.63 (9.58)	13.44 (7.66)	0.38
SOL	25.47 (18.90)	24.73 (21.64)	26.12 (16.51)	0.80
Activity counts	42.45 (18.23)	47.80 (19.85)	37.72 (15.54)	0.05
WASO	45.95 (16.85)	51.49 (17.22)	41.04 (15.20)	0.03
Number of awakenings	34.10 (13.90)	34.48 (13.32)	33.77 (14.64)	0.86

Note. CV = coefficient of variation; SOL = sleep onset latency; TIB = total time in bed; TST = total sleep time; WASO = wake after sleep onset. Values presented are *M* (*SD*). P-values were obtained from t-tests, with statistical significance defined at the alpha < 0.05 level.

Table 3

Mixed Effects Models Examining Changes in Nightly Variability (7-day SD and CV) and Means for each Sleep Parameter Over Time

		7-Day *SD*		CV		Mean-level	
Sleep Parameter	**Time Point**	***B* (*SE*)[a]**	**p-value**	***B* (*SE*)[a]**	**p-value**	***B* (*SE*)**	**p-value**
TIB	Baseline	Ref		Ref		Ref	
	Mid	0.05 (0.08)	0.57	0.07 (0.09)	0.20	−11.00 (6.71)	0.11
	Post	0.09 (0.07)	0.26	0.10 (0.07)	0.39	−2.71 (6.80)	0.69
Bedtime	Baseline	Ref		Ref		Ref	
	Mid	−0.11 (0.08)	0.15	−0.11 (0.08)	0.14	0.08 (0.10)	0.40
	Post	0.08 (0.08)	0.32	0.08 (0.08)	0.29	−0.11 (0.10)[b]	0.28
Arising time	Baseline	Ref		Ref		Ref	
	Mid	0.01 (0.08)	0.86	0.03 (0.08)	0.69	−0.09 (0.10)	0.33
	Post	−0.01 (0.08)	0.90	0.02 (0.08)	0.85	−0.15 (0.10)	0.15
TST	Baseline	Ref		Ref		Ref	
	Mid	0.002 (0.07)	0.98	0.03 (0.07)	0.73	−8.12 (5.37)	0.13
	Post	0.04 (0.07)	0.58	0.05 (0.07)	0.51	−0.46 (5.37)	0.93
SOL	Baseline	Ref		Ref		Ref	
	Mid	0.21 (0.15)	0.16	0.15 (0.14)	0.29	0.28 (0.18)	0.12
	Post	0.12 (0.15)	0.41	0.06 (0.14)	0.68	0.31 (0.18)	0.08
Activity counts	Baseline	Ref		Ref		Ref	
	Mid	−0.17 (0.09)	0.07	−0.09 (0.08)	0.26	−3487.23 (1780.88)	0.06
	Post	−0.16 (0.09)	0.07	−0.10 (0.07)	0.16	−2541.32 (1762.61)	0.16
WASO	Baseline	Ref		Ref		Ref	
	Mid	−0.14 (0.07)	**0.049**	−0.09 (0.07)	0.20	−3.16 (2.40)	0.19
	Post	−0.18 (0.07)	**0.01**	−0.13 (0.07)	0.050	−2.57 (2.35)	0.28
Number of awakenings	Baseline	Ref		Ref		Ref	
	Mid	−0.02 (0.07)	0.77	−0.04 (0.06)	0.51	0.47 (0.54)	0.39
	Post	−0.14 (0.07)	**0.048**	−0.13 (0.06)	0.052	0.05 (0.51)	0.92

Note. The models for each sleep parameter were adjusted for exercise group, baseline VO_{2peak}, and changes in VO_{2peak} from baseline to post-intervention. *B* = unstandardized regression coefficients; CV = coefficient of variation; SOL = sleep onset latency; TIB = total time in bed; TST = total sleep time; WASO = wake after sleep onset.

[a] Unstandardized regression coefficients presented on the log scale.

[b] Represents a significant time effect ($p = 0.04$, mid vs. post-intervention).