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Walk to a Better Night of Sleep: Testing the Relationship Between Physical Activity and Sleep

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Abstract

Objectives: Many do not sleep well, particularly middle-aged and older adults. Physical activity (PA) shows promise for improving sleep, however, populations with clinical sleep disturbances have been a research focus. It remains unclear whether low-impact daily PA, like walking, can affect sleep in healthy adults.

Design: The current study was embedded within a 4-week randomized controlled trial to increase PA.

Setting: Participants from the greater Boston area were recruited to participate in a 4-week walking intervention on a rolling basis, between October 2015 and August 2016.

Participants: 59 participants (72% female) were enrolled in the study, with an average age of 49.43(±8.40).

Intervention: The 4-week intervention was aimed at increasing participants' daily steps as the primary outcome. The current, supplementary study examined relationships between monthly and daily PA and sleep.

Measurements: Steps and active minutes were measured daily using a Fitbit Zip. Self-reports of sleep quality and duration were assessed daily, along with before and after the intervention.

Results and Conclusions: Averaged across the month, daily active minutes were positively related to sleep quality, but not duration. Gender moderated this relationship; women who took more steps and were more active reported sleeping better than those less active. Within-persons, on days that participants were more active than average, they reported better sleep quality and duration in both genders. Results suggest that low-impact PA is positively related to sleep, more so

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in women than men. Findings also showed that PA plays a greater role in predicting sleep quality than duration.

INTRODUCTION

Although sleep is important to physical, cognitive, and psychological health, many Americans do not sleep well[1–3]. Between 50 and 70 million adults suffer from a sleep disorder, and 1 in 3 adults do not get enough sleep[4,5]. Over 9 million US adults over age 30 rely on pharmacological sleep aids to fall asleep each night, despite their link to dependence, cancer, death, and other negative health effects[6,7]. Middle aged and older adults are more likely to take pharmacological sleep aids, likely a result of declining sleep quality and duration associated with aging[8]. Numerous non-pharmacological alternatives exist for improving sleep; including cognitive behavior therapy, mindfulness meditation, and physical activity[9–11].

Physical activity (PA) is perhaps one of the most promising alternatives for improving sleep because it can lower the risk of health conditions and diseases through various mechanisms, including reductions in weight and inflammation, and increases in psychological well being[12]. Regular exercise has also been shown to increase sleep quality and duration, however, a debate remains in the literature about which types of physical activity are best for improving sleep[11]. High-impact exercise has been a focus of research, which may not be feasible for those most at risk for poor sleep. Further, most studies have examined the effects of PA on sleep in college students, or adults with certain ailments, health problems, or clinical sleep problems. While this prior work is important to understanding how to improve sleep in certain populations, a recent review highlighted the importance of examining behavioral strategies to improve sleep in healthy adults[13]. Such work could uncover strategies for improving sleep at the public health level. While many have examined PA and sleep longitudinally, only one study to our knowledge has examined how daily fluctuations in PA affect sleep.

Sleep Duration and Quality

The National Sleep Foundation recommends that adults aged 18-64 sleep between 7-9 hours per night, while adults aged 65 and older should sleep between 7 and 8 hours[14]. Many adults do not meet these recommendations; over 37% of US adults report sleeping less than 7 hours per night[15]. While there are individual differences in the amount of sleep one needs to function well, many Americans do not get enough sleep. This is worrisome, considering the effects sleep deprivation can have on daytime functioning. Insufficient sleep has been linked to difficulty focusing, which could lead to issues like motor vehicle crashes or industrial accidents. Driving while drowsy has been implicated in many motor vehicle accidents, causing almost 800 deaths in 2017[16]. Additionally, recent estimates have linked chronic sleep deprivation to over 7% of workplace accidents, costing approximately 31 billion dollars annually[17]. Thus, sleep deprivation is a considerable public health concern.

Beyond sleep duration, the quality of this time is important to consider. Though sleep quality is typically harder to gauge because it can be subjective, it has legitimate effects on cognition and health[3,18]. Sleep quality can be operationalized subjectively (how rested an individual feels the following day), or objectively (number of awakenings, time spent in deep sleep). Both quality and duration are important to consider when evaluating one's sleep patterns, and both contribute to the vitality of sleep to mental and physical health.

Physical Activity for Improving Sleep

A recent meta-analysis examined the impact of physical activity on sleep quality and duration[11]. Exercise was grouped into two categories: *acute* (sleep following one day of exercise), and *regular* (sleep following a week or more of structured exercise). Both types of exercise benefitted sleep duration, and some aspects of sleep other than duration; latency (the time it takes to fall asleep), and efficiency (the amount of time spent asleep while in bed). This review provides evidence that exercise, like bicycling, running, and swimming can improve subjective (self-report) and objective sleep[11]. Proposed mechanisms include changes in body temperature, heart rate, mood, along with secretions of brain derived neurotropic factor (BDNF) and growth hormone (GH), among others[19,20]. There is evidence that both average patterns of, and daily fluctuations in physical activity are important to sleep.

Though it is well-documented that exercise is beneficial to health and cognition, only about 20% of US adults meet the recommended weekly PA guidelines (150 minutes of moderate intensity aerobic activity and 2 days of muscle-strengthening)[21]. Middle aged and older adults are less likely to meet these recommendations than younger adults[22]. To determine successful strategies to increase PA, it is important to understand why so few adults engage in it regularly. People may not believe they have enough time to exercise, or that they can engage in moderate or vigorous PA due to health conditions or physical restrictions. For these reasons, many recent initiatives; such as Walk Boston (www.walkboston.org) and Walkable Communities (www.walkable.org) have begun to encourage daily walking. Walking is a low-impact activity that is easy to track, safe for all age groups, and easy to encourage throughout the day. Health benefits like weight reduction, cardiovascular health improvements, and improved psychological well-being have been associated with increased walking[23].

Recently, researchers have begun to investigate the impact of walking on sleep quality and duration. The majority of experimental studies, however, have examined this effect with regard to specialized populations, like those with insomnia, nursing home residents, women transitioning through menopause, and individuals with depression, cancer, and Alzheimer's disease[24–28]. Collectively, results suggest that walking can improve sleep quality, depressive symptoms, and sleep efficiency, while decreasing nighttime wakefulness and next day fatigue, in certain populations and situations.

Only two studies to our knowledge have examined how daily fluctuations in PA affect sleep, and have inconsistent findings. One study found that middle aged, overweight women slept longer following a day with more activity, measured by Actigraphy[29]. Another found no evidence for within-person associations between physical activity and sleep in healthy, physically active adults[30]. Taken together, these conflicting results warrant further investigation into the ways in which physical activity and sleep are related to one another. These two health behaviors likely compete for time; the time one is able to devote to sleep may come at the expense of time for exercise, and vice versa [31].

Prior work has shown that certain attributes of PA (e.g., duration, time of day, intensity) have differing effects on sleep[32,33]. It remains unknown whether *daily steps* are related to nightly sleep duration or quality. Measuring PA by counting daily steps has recently gained much public interest, likely a result of the influx of commercial devices that encourage users to increase their walking. Daily steps have become a meaningful metric to the millions of people who track their daily activity, and may provide an easy, straightforward way for one to observe how their activity and sleep are related. If the number of steps one takes per day can predict how well they will sleep at night, recommendations could be created to promote better sleep at the population level.

The current study examined whether PA (daily steps and active minutes, measured by a Fitbit Zip) was related to sleep quality and duration in middle-aged adults. Participants in this supplementary study were from the month-long Boston Roybal Center for Active Lifestyle Interventions (RALI Boston) Step Counting Study, described more thoroughly in the method section[34]. We first examined whether there were differences in sleep between the participants enrolled in the two different conditions. We predicted that, regardless of condition, more active individuals would report better sleep quality, and longer sleep durations than those less active. Finally, we hypothesized that on days in which participants were more physically active than average, they would report sleeping better and longer than less active days. We examined whether the predicted relationships were moderated by age, gender, or condition.

Participants and Method

Individuals were recruited via flyers, community events, and online advertisements, and were eligible if they were at least 35 years old, healthy enough to walk briskly, worked full-time (35+ hours per week), had access to an internet-connected computer or smartphone, and self-reported walking less than 60 minutes per day. Participants were randomly assigned to one of two groups, the intervention or control group. An *a priori* power analysis indicated that 32 participants per condition was required with an estimated effect size of d = .63, with 80% power at $p = .05$. A total of 59 participants (72% female) were enrolled in the study, with an average age of 49.43(±8.40). Tables 1 and 2 include descriptive statistics for participants, and correlations between variables of interest. All participants completed informed consent before beginning the study, and the University Institutional Review Board approved all procedures.

Measures

Physical Activity (PA) was measured with the Fitbit Zip, which shows good agreement with Actigraphy[35,36]. While the Fitbit measures many aspects of PA, the focus of the current study was steps taken per day and minutes spent active. Daily active minutes were calculated by summing the number of minutes spent in light, moderate, and vigorous activity each day.

These were recorded by the Fitbit and reported through Fitabase software. Of note, Fitbit only records active minutes in bouts of 10 minutes or longer. While both daily steps and active minutes are related measures, they pick up on different aspects of the activity. Active minutes capture longer bouts of physical activity, while steps are recorded continuously. Daily data were used to examine within-person relationships between PA and sleep, and monthly PA and sleep averages were calculated for between-person analyses. ***Mean daily steps*** ranged from 2,269 - 18,314, with an average of 7,258.64 (±3,026.13). ***Mean daily active minutes*** ranged from 86.30 – 343.18 minutes per day, with an average of 184.10 (±49.85).

Sleep was measured before and after the intervention via the Pittsburgh Sleep Quality Index (PSQI) [37]. Of our participants, 41 had complete PSQI data at both timepoints. In the current study, we examined the PSQI global score, and raw scores for the duration and efficiency subscales. Daily sleep quality was measured with a single question, chosen because it was easily conceptualized, straightforward, and reduced participant burden. The question asked; *On a scale of 0-10, where 0 is the worst possible sleep and 10 is the best possible sleep, please rate the quality of your sleep last night.*

Daily sleep duration was measured via the questions; *What time did you go to bed last night?* and *What time did you wake up this morning?* ***Mean daily sleep quality*** across the month ranged from 2.94 to 9.14, with a mean score of 6.34 (±1.34). ***Mean daily sleep duration*** across the month ranged from 5.75 to 9.50 hours, with a mean of 7.68 (±0.85). Tables 1 and 2 include descriptive statistics and correlations between covariates, PA, and sleep variables.

Procedures

Participants were part of a randomized controlled trial, the RALI Boston Step Counting Study [32]. Before the 4-week study began, participants were asked to wear and monitor their steps on the Fitbit for one week to provide a baseline step count. The **Intervention Group** was asked to take 2,000 more steps per day than they had taken in the baseline week. For each of the following weeks, step goals in the intervention group increased in 2,000 step increments. To help this group meet their increasing step goals, they received additional materials about when, where, and how to increase their walking. They created daily schedules to plan when they could add steps (when), received customized maps weekly with routes around their home and work (where), and were sent tips weekly for adding steps throughout the day (how). The **Control Group** was given the Fitbit but were not given weekly step goals, nor were they provided with the additional resources for increasing their walking. Both groups received nightly emails with a link to a survey, including the sleep questions, and were called weekly to assess any potential problems with the Fitbit. More detailed information about the intervention and primary results for this study are reported in the original manuscript[32].

Data Analysis

Questionnaire data were collected nightly over four weeks via online surveys programmed in Qualtrics Survey Software. Physical activity data were collected daily with the Fitbit Zip, and aggregated via Fitabase (www.fitabase.com). Data were analyzed with SPSS software (IBM), and Statistical Analysis Software (SAS) was used for multilevel analyses. Analyses were conducted between person (i.e. Do those who are more active sleep better than those who are less active?) and within person (i.e. Do individuals sleep better on days they are more active than usual?).

Between-person relationships of mean daily physical activity and sleep.

We used repeated measures ANOVAs to test whether global PSQI scores, or the duration or efficiency subscales, changed from pre to post test, and whether this relationship differed by condition. We next examined whether mean daily physical activity (PA; steps or active minutes) was related to mean daily sleep (quality or duration). We examined these relationships using multiple regression models: Predicted mean daily sleep = $\beta_0 + \beta_1$(Mean daily PA) + β_2 (Age) + β_3 (Gender) + β_4 (Condition). We also examined whether age, gender, or condition moderated these relationships. Only significant interactions are reported.

Within-person associations between daily physical activity and sleep.

We investigated whether participants reported sleeping better on days in which they accumulated more PA than average. These hypotheses were tested using SAS with multilevel models:

Level 1: Daily $\text{sleep}_{ij} = \beta_{0j} + \beta_{1j}$ (Daily PA_{i}) + r_{ij}

Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01}$ (Age_j) + γ_{02} (Gender_j) + γ_{03} (Condition_j) + γ_{04} (average PA_j) + u_{0j}

RESULTS

Between-person relationships of mean daily physical activity and sleep.

While there were no significant differences between groups for most demographics, the intervention group was significantly younger than the control group (46.3 vs. 52.5 years old). Multilevel models revealed the intervention was associated with a significant increase in steps (27.77% increase from baseline) compared to the control group (3.60% decrease), $F(4,1260) = 3.61$, $p = .006$. A 2 (Condition) by 2 (Time) repeated measures ANOVA revealed no significant main effect of time in global PSQI scores from pre (M=5.37, SD=3.31) to post (M=5.04, SD=3.28) test, $F(1,37)=0.84$, $p=.37$, and no significant time by condition interaction, $F(1,37)=0.55$, $p=.46$. There was also no significant main effect of time in sleep duration from pre (M=6.91, SD=1.13) to post (M=6.81, SD=1.11) test, $F(1,37)=0.61$, $p=.44$, nor was there a significant time by condition interaction, $F(1,37)=1.18$, $p=.29$. There was neither a significant main effect of time in sleep efficiency from pre (M=87.89, SD=13.28) to post (M=90.03, SD=13.29) test, $F(1,37)=0.95$, $p=.34$, nor was there a significant time by condition interaction, $F(1,37)=0.15$, $p=.70$.

Because the intervention did not have a specific focus on improving sleep, and no differences in sleep emerged between conditions, conditions were collapsed for all subsequent analyses. Condition was included as a covariate in all analyses, however, was not a significant predictor in any analysis. Condition was also tested as a moderator in all analyses, however, was not a significant predictor in any analysis.

Controlling for age, gender, and condition, multiple linear regressions revealed that while there was not a significant main effect of mean daily steps on mean daily sleep quality, this relationship was moderated by gender, $b = 3.1\ E^{-4}$, $t(58) = 2.96$, $p < .01$ (Figure 1). There was a significant main effect of mean daily active minutes on mean daily sleep quality, $b = 0.008$, $t(58) = 2.14$, $p = 0.04$, and this relationship was also moderated by gender, $b = .02$, $t(58) = 2.30$, $p = .03$ (Figure 2). Neither age nor condition were not significant moderators in these relationships.

The main effect of mean daily steps on mean daily sleep duration was not significant, nor was there a significant main effect mean daily active minutes on mean daily sleep duration. These relationships were not moderated by gender, age, or condition. Table 3 includes results for all relationships between mean daily steps and mean daily sleep quantity and duration. Table 4 includes results for all relationships between mean daily active minutes and mean daily sleep quantity and duration.

These results partially support our first hypothesis; those who spent more time active, on average, across the month reported better sleep quality. This relationship was moderated by gender; women who took more steps and spent more time active reported sleeping better than those less active, while activity levels did not affect sleep quality for men. Mean daily sleep duration did not appear to be affected by mean daily PA.

Within-person associations between daily physical activity and sleep.

Multilevel models revealed that, controlling for age, gender, and condition, on days in which participants accumulated more daily steps than average, they reported significantly better sleep quality ($\gamma = 0.00003$, $p = .05$), and a longer sleep duration ($\gamma = 0.00003$, $p = .05$). On days in which participants accumulated more active minutes than average, they reported significantly better sleep quality ($\gamma = 0.002$, $p = .05$), and longer sleep durations ($\gamma = 0.001$, $p = .04$). Table 5 includes results for all within-person analyses of PA and sleep quality and duration. Results supported our second hypothesis; both measures of daily physical activity (steps and active time) were related to sleep quality and duration within-persons.

DISCUSSION

Collectively, our results suggest that monthly and daily physical activity (PA) and sleep are related. Those who were more active throughout the month reported better sleep quality compared to those less active, more so for women than men. We also found that on days when one is more active than average, they report sleeping better and longer than less active days.

The interaction between physical activity and gender is interesting; while Kredlow and colleagues[11] found that gender moderated the effects of acute exercise on some aspects of sleep, they did not find and evidence for a gender moderation between regular PA and sleep quality or duration in their meta-analysis. Another meta-analytic review, however, did find that the relationship between PA and sleep was stronger for women than men[38]. One recent study found that in older adults with sleep disturbances, walking was associated with sleep quality improvements in women but not men [39]. In terms of other gender differences in health behaviors, some have shown that women are more sensitive to their internal bodily state, which could account for the current findings[40]. Our results should be interpreted with caution, our sample was 72% female and results may have differed if more men were enrolled. In terms of other moderators, while others have found that older adults are less likely to experience sleep improvements following PA[11], we did not find evidence for this moderation in our study. Perhaps the age variation in our study was not large enough to observe these effects.

Our daily results add to the literature examining within-person fluctuations of daily PA and sleep[29], and expand on these findings by suggesting that subjective reports, specifically sleep quality, may be affected by daily fluctuations in PA. Our findings, along with those from Kishida & Elavsky [29], suggest that higher intensity, structured exercise is not always needed to improve sleep. Improvements in sleep quality and duration occur as steps and active minutes are increased. It is encouraging that daily steps, measured by a consumer fitness tracker, can provide meaningful predictions about sleep. Thus, recommendations for increasing daily steps could be a feasible way to improve sleep at the population level, as most Americans have a fitness tracker or smartphone with the capability of measuring steps. It is likely that additional behavioral supports, such as goal setting, are necessary to promote increases in physical activity with fitness technology, as recent research suggests that fitness trackers are not effective on their own[41,42].

One interesting question that remains is whether sleep quality or duration is more important. Few have examined this question, and some suggest sleep quality may be more closely tied to health, affect, and feelings of fatigue than sleep duration[43]. Another study found that sleep latency (time it takes to fall asleep) was more closely linked to risk of diabetes than sleep duration[44]. While both sleep quality and duration are important to health and cognitive functioning, our results suggest that PA is more consistently related to sleep quality than duration. While sleep quality and duration seem inherently related, they were not significantly correlated in our sample ($r = 0.07$, $p = .62$). Sleep quality may be an easier target for intervention, as sleep duration is likely tied to one's schedule or other responsibilities and therefore more difficult to change. Future research should also examine whether sleep quality or duration is more important for daily functioning, or whether both are equally important.

The study makes several contributions. This is one of the first studies to examine the relationship between daily steps, active minutes, sleep quality, and duration over 4 weeks. While others have examined the relationship between PA and sleep in young adults or older adults from special populations[45–47], few have probed these behaviors in a healthy sample of adults. While previous research has provided many important insights, the focus on structured PA left it unclear whether daily PA behaviors such as steps and active minutes predict nightly sleep.

It remains especially important to examine these relationships in healthy populations and age groups disposed to poor sleep, such as middle-aged and older adults. Midlife likely is an important time to promote healthy sleeping habits, as this is when sleep quality and duration both typically decrease[48].

Limitations

While this study presents some new and interesting results, limitations should be noted. First, our use of regression models for the between-person analyses does not allow for causal interpretation of our results. Due to the nature of recruitment, volunteer bias may have played a role in our findings. Because we specifically sought out those who 'believed they didn't have enough time to exercise', participants may have been already motivated to increase their PA or may not have had enough time to devote to sleep. Considering the high activity levels of our participants' (7,260 steps and 184 active minutes per day, on average), it is also possible that participants were more motivated to be active from the consistent contact and feedback from researchers and the Fitbit than the actual intervention. Contextual factors like mood, energy, work environment, or other familial or sociodemographic differences could have impacted the amount of time participants had to sleep, or how they reported their sleep. Certain aspects of the daily PA, like time of day or intensity of exercise could have also affected sleep differently[31]. Future work should examine how these factors play a role in the relationship between physical activity and sleep.

For proprietary reasons, Fitbit does not disclose the algorithms by which they calculate activity intensity or step data, so it is unclear how steps or active minutes were classified. While this limitation should be noted, all participants had their activity classified by the same algorithms, so these differences should not have affected the between and within person analyses drastically. The Fitbit used in the current study has been previously validated against research-grade devices, and correlations were strongest for step counts[49,50].

The Fitbit Zip did not allow for the objective measurement of sleep, and our reliance on subjective assessments could have affected our results. Because the questions asked about sleep on the previous night, participants may have forgotten or misremembered bed or wake times. Further, the question used in our study asked what time participants went to bed, rather than the time they fell asleep. Inclusion of other variables, such as sleep latency, would have provided a better picture of participants' sleep quality. Thus, our results should be interpreted with caution, and future studies should use more objective measures such as an activity monitor that measures sleep, or polysomnography, could have provided a better picture of participants' sleep. Many new activity monitors can measure sleep duration, efficiency, and the amount of time spent in specific sleep stages. These devices would allow for more accurate measurement and analysis of the relationships between PA and sleep. These monitors would likely also provide reports of sedentary time, another important variable to consider when examining daily activity and sleep.

Conclusion

The current study suggests that PA and sleep were related in multiple ways. The more active one is over a month, the better they report sleeping. Women who were more active reported sleeping better than less active women, but this relationship was not found for men, or with sleep duration. On days in which participants took more steps and spent more time active than average, they reported better sleep quality and longer sleep durations. The fact that both between and within-person analyses were significant suggests that average patterns of, and daily fluctuations in PA affect sleep. The results extend our knowledge by suggesting that metrics such as step counts and daily active time can predict sleep quality and sometimes duration in a healthy population of middle aged and older adults, and that this relationship is stronger for women. Future studies should explore further the role of gender as a moderator in the physical activity and sleep relationship. Also, future work should clarify the mechanisms whereby physical activity can improve sleep, and whether these mechanisms differ between men and women.

Our study has implications for future PA interventions for improving sleep; low-impact PA like walking may be enough, and gender differences should be examined. It is also important to consider how sleep is measured. It remains unknown whether subjective reports of how well one feels they've slept are similarly important as objective measures. Also, distinctions between quality and duration of sleep are unclear. Sleep quality may be more malleable than sleep duration, which is often dependent on one's schedule or other obligations. Future work should examine multiple PA metrics, like time spent in different activity intensities and sedentary time. Interventions that aim to improve both physical activity and sleep habits simultaneously in midlife may be important for buffering or preventing age-related declines in health and cognition.

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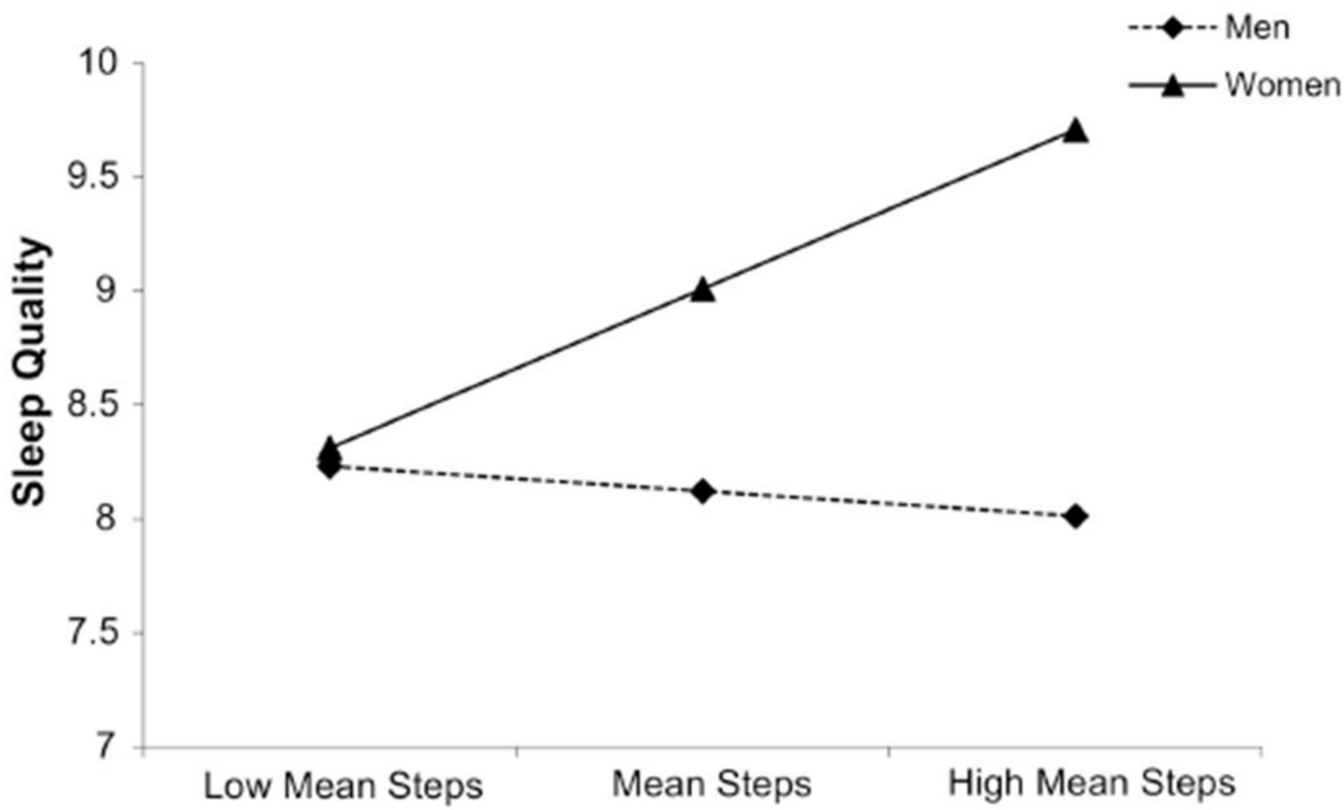

Figure 1. Relationship of mean daily steps and sleep quality across the month by gender

Between-person relationship between mean daily steps (low = − 1 SD, mean, high = +1SD) and mean sleep quality across the month by gender, controlling for age and condition.

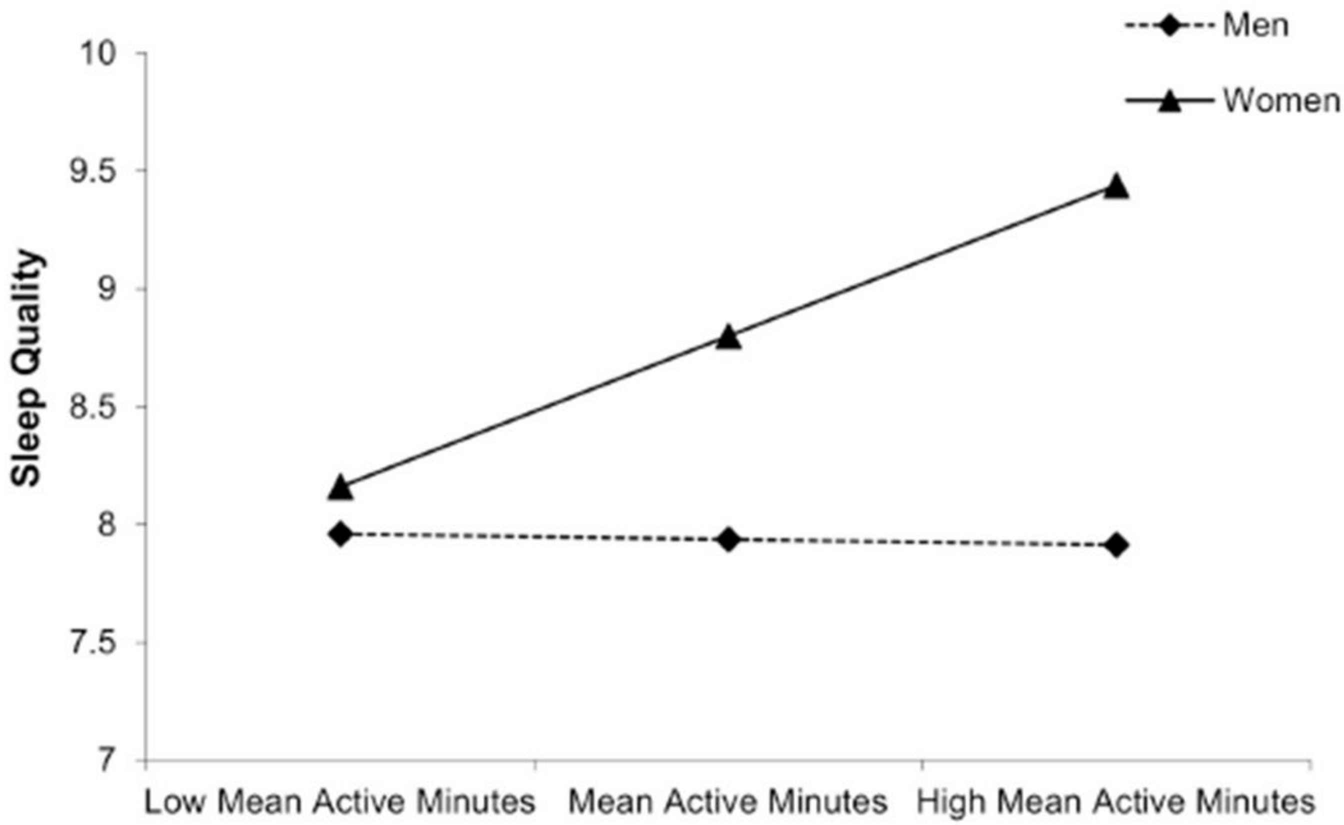

Figure 2. Relationship of mean daily active minutes and sleep quality across the month by gender

Between-person relationship between mean daily active minutes (low = − 1 SD, mean, high = +1SD) and mean sleep quality across the month by gender, controlling for age and condition.

Table 1

Descriptive statistics and correlations between covariates and pre- and post- sleep measures

	N	Mean (SD)	Condition	2	3	4	5	6	7	8
2. Age	59	49.64 (8.31)	−0.38**							
3. Gender (% female)	59	73%	−0.02	0.10						
4. Pre-PSQI Global	51	5.37 (3.31)	−0.03	−0.06	0.03					
5. Post-PSQI Global	47	5.04 (3.28)	0.08	−0.01	−0.03	0.84**				
6. Pre-PSQI Duration	51	6.91 (1.13)	0.04	−0.04	0.07	−0.65**	−0.57**			
7. Post-PSQI Duration	47	6.81 (1.10)	−0.21	−0.02	0.05	−0.41**	−0.49**	0.75**		
8. Pre-PSQI Efficiency	51	87.89 (13.28)	−0.14	0.24	−0.09	−0.78**	−0.70**	0.54**	0.29	
9. Post-PSQI Efficiency	47	90.03 (13.29)	−0.29*	0.15	−0.11	−0.59**	−0.75*	0.30	0.48**	0.69**

* $p < 0.05$ (2-tailed),

** $p < 0.01$ (2-tailed),

*** $p < 0.001$ (2-tailed).

Gender: 0 = male, 1 = female.

Condition; 0 = control, 1 = intervention.

Table 2

Descriptive statistics and correlations between covariates, physical activity, and sleep

	N	Mean (SD)	Condition	Age	Gender	Quality	Duration	Steps
Age	59	49.64 (8.31)	−0.36**					
Gender (% female)	59	73%	0.01	0.06				
Mean Daily Sleep Quality	59	6.34 (1.34)	−0.02	0.23	0.28*			
Mean Daily Sleep Duration	59	7.68 (0.85)	−0.04	−0.23	0.29*	0.07		
Mean Daily Steps	59	7258.64 (3026.13)	0.40**	−0.06	−0.12	0.18	−0.17	
Mean Daily Active Minutes	59	184.10 (49.85)	0.36**	0.08	−0.003	0.28*	−0.10	0.76**

* $p < 0.05$ (2-tailed),

** $p < 0.01$ (2-tailed),

*** $p < 0.001$ (2-tailed).

Gender: 0 = male, 1 = female.

Condition; 0 = control, 1 = intervention.

Table 3

Between-person relationships between mean daily steps and sleep across the month

	M1: Mean Daily Sleep Quality			M2: Mean Daily Sleep Quality			M1: Mean Daily Sleep Duration			M2: Mean Daily Sleep Duration		
Outcome	**B**	**SE**	**β**	**B**	**SE**	**β**	**B**	**SE**	**β**	**B**	**SE**	**β**
Mean Daily Steps	1.1 E^{-4}	6.1 E^{-5}	0.25	−3.5 E^{-5}	7.5 E^{-5}	−0.08	−3.02 E^{-5}	3.8 E^{-5}	−0.11	−1.94 E^{-5}	0.80	−0.07
Age	0.03	0.02	0.21	0.04	0.02	0.24	−0.03*	0.01	−0.29	−0.03*	0.01	−0.30
Gender	0.89*	0.37	0.30	0.86*	0.35	0.29	0.56*	0.24	0.29	0.56*	0.24	0.30
Condition	−0.13	0.39	−0.05	−0.26	0.36	−0.10	−0.17	0.25	−0.10	−0.16	0.25	−0.10
Mean Daily Steps*Gender				3.1 E^{-4}**	1.1 E^{-4}	0.49				−2.32 E^{-5}	7.2 E^{-5}	−0.06
Adjusted R^2		0.12			0.23			0.11			.010	

Results from separate analyses controlling for age, gender, condition, and testing for a mean steps*gender interaction.

Mean steps were centered in analyses with significant interactions. Steps*age and steps*condition interactions were not significant.

* $p < 0.05$(2-tailed),

** $p < 0.01$(2-tailed),

*** $p < 0.001$(2-tailed).

Adjusted R^2 are multivariate, considering all variables and interactions in each model.

Table 4

Between-person relationships between mean daily active minutes and sleep across the month

	M1: Mean Daily Sleep Quality			M2: Mean Daily Sleep Quality			M1: Mean Daily Sleep Duration			M2: Mean Daily Sleep Duration		
Outcome	**B**	**SE**	**β**	**B**	**SE**	**β**	**B**	**SE**	**β**	**B**	**SE**	**β**
Mean Daily Active Minutes	0.008*	0.004	0.29	−0.002	0.005	−0.06	−0.001	0.002	−0.03	−0.001	0.004	−0.07
Age	0.03	0.02	0.17	0.03	0.02	0.21	−0.03*	0.14	−0.30	−0.03*	0.14	−0.29
Gender	0.81*	0.37	0.27	0.83*	0.35	0.28	0.58*	0.24	0.31	0.58*	0.24	0.31
Condition	−0.19	0.38	−0.07	−0.17	0.37	−0.06	−0.23	0.25	−0.14	−0.23	0.25	−0.14
Mean Daily Active Mins*Gender				0.02*	0.007	0.44				0.001	0.004	0.05
Adjusted R^2		0.14			0.20			0.10			0.09	

Results from separate analyses controlling for age, gender, condition, and testing for an active minutes*gender interaction.

Active minutes were centered in analyses with significant interactions.

Active*age and active*condition interactions were not significant.

* $p < 0.05$(2-tailed),

** $p < 0.01$(2-tailed),

*** $p < 0.001$(2-tailed).

Adjusted R^2 are multivariate, considering all variables and interactions in each model.

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Table 5

Within-person relationship between daily physical activity and sleep

	Sleep Quality		Sleep Duration	
Outcome	**γ**	**SE**	**γ**	**SE**
Daily Steps	0.00003 *	0.00002	0.00003 *	0.00001
Mean Daily Steps	0.00009	0.00006	−0.00005	0.00004
Age	0.03	0.02	−0.03 *	0.01
Gender	0.97 *	0.37	0.54 *	0.22
Condition	−0.28	0.36	−0.28	0.02
	Sleep Quality		**Sleep Duration**	
Outcome	**γ**	**SE**	**γ**	**SE**
Daily Active Minutes	0.002 *	0.0008	0.001 *	0.0007
Mean Daily Active Minutes	0.007	0.004	−0.001	0.002
Age	0.03	0.02	−0.03 *	0.01
Gender	0.90 *	0.36	0.58 *	0.22
Condition	−0.33	0.36	−0.35	0.22

* $p < 0.05$ (2-tailed),

** $p < 0.01$ (2-tailed),

*** $p < 0.001$ (2-tailed).