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Temporal relationships between physical activity and sleep in older women

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Abstract

Purpose—To examine the temporal and bidirectional relationship between accelerometer-derived physical activity estimates and actigraphy-assessed sleep characteristics among older women.

Methods—A sub-group of participants [N=143, mean age= 73y] enrolled in the Healthy Women Study wore an ActiGraph accelerometer on their waist and an Actiwatch sleep monitor on their wrist concurrently for 7-consecutive days. Multi-level models examined whether ActiGraph-assessed daily activity counts ($ct \cdot min \cdot d^{-1}$) and moderate- to vigorous- intensity physical activity (MVPA; $min \cdot d^{-1}$) predicted Actiwatch-assessed sleep onset latency, total sleep time, sleep efficiency, and sleep fragmentation. Similar models were used to determine if nighttime sleep characteristics predicted physical activity the following day.

Results—In unadjusted models, greater daily activity counts (B=-.05, p=.005) and more minutes of MVPA (B=-.03, p=.01) were temporally associated with less total sleep time across the week. Greater sleep efficiency was associated with greater daily activity counts (B=.37, p=.01) and more minutes of MVPA (B=.64, p=.009) the following day. Less sleep fragmentation was also associated with greater daily activity counts and more MVPA the following day. Findings were similar after adjustment for age, education, BMI, depressive symptoms, arthritis, and accelerometer wear time.

Conclusions—Few studies have used objective measures to examine the temporal relationship between physical activity and sleep. Notably, these findings suggest that nightly variations in sleep efficiency influence physical activity the following day. Thus, improving overall sleep quality in addition to reducing nightly fluctuations in sleep may be important for encouraging a physically active lifestyle in older women.

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Keywords

accelerometer; Actiwatch; objective measurement; sleep efficiency; moderate to vigorous physical activity

Introduction

A robust finding in epidemiological studies is that persons who are more physically active have a lower frequency of sleep disorders and better ratings of sleep quality (6, 35). However, the directionality of the physical activity-sleep relationship remains unclear. While there is a general belief that physical activity is beneficial for sleep (30, 35), there is also evidence that poor sleep may be associated with lower levels of physical activity (3) and that this relationship could be bidirectional (8, 23). Furthermore, few studies have examined these relationships using objective measurement of both physical activity and sleep. Including objective measurement of physical activity and sleep in studies is important because reported physical activity (27) and sleep (34) behaviors often differ from more direct assessments.

Accelerometers worn around the waist have been used extensively to assess physical activity in free-living environments and can objectively determine the frequency, intensity, and duration of movement (17, 33). Similarly, actigraphy sleep monitors worn on the wrist are a valid measure of sleep in the natural environment (14) and can objectively assess sleep onset latency, sleep duration, sleep efficiency, and sleep fragmentation. Research protocols that incorporate wearing both of these devices concurrently over an extended period of time are needed to better understand how overall levels and intensities of physical activity during the day are temporally related to sleep characteristics at night, and conversely, whether sleep at night is related to physical activity the following day.

Examining the temporal relationships between physical activity and sleep specifically among older women is important because both the rates of sleep disturbances (11, 29) and prevalence of physical inactivity (1) increase as women age. Additionally, older women differ from males and other age groups in physical and socio-demographic characteristics that may influence both physical activity and sleep. Given that physical activity and sleep are overtly related with health and mortality (4, 12), a better understanding of the temporal relationships between physical activity and sleep, and the directionality of this relationship, has important public health implications.

The purpose of this study was to examine the temporal and bidirectional relationship between accelerometer-derived physical activity estimates and actigraphy-assessed sleep characteristics among older women. Specifically, we aimed to test the following hypotheses: 1) Greater levels of physical activity (average daily activity counts, and time spent in moderate to vigorous intensity physical activity, MVPA) would be associated cross-sectionally with more favorable sleep characteristics (shorter sleep onset latency, longer sleep time, greater sleep efficiency, less sleep fragmentation), 2) Greater physical activity during the day would be temporally associated with better sleep at night, and 3) Better sleep would be temporally associated with greater physical activity the following day. In exploratory fashion, we examined whether physical or socio-demographic characteristics moderated the relationships between physical activity and sleep in either, or both, directions.

Methods

Study Design and Participants

The Healthy Women Study (HWS) is a prospective cohort study designed to assess cardiovascular risk factors across the menopausal transition. Detailed descriptions of the HWS have been published elsewhere (19). Briefly, between 1983 and 1984 premenopausal women (42 to 50 y) who did not have hypertension or diabetes were recruited. Eligible women (N=541) were assessed at baseline and approximately 2, 5, and 8 years post-menopause. An ancillary study was added to the HWS protocol in 2010-2011, which collected accelerometer-assessed physical activity data and actigraphy-assessed sleep data on a subset of women.

Participants in the ancillary study wore an ActiGraph accelerometer on their dominant hip and an Actiwatch sleep monitor on their non-dominant wrist for 7-consecutive days. Participants were instructed to wear both the ActiGraph and Actiwatch devices at all times during the day and night for a full week, except to remove the ActiGraph monitor when bathing or doing water activities. Participants recorded the time they went to bed each night and the time they woke up each morning. All participants provided written informed consent and the protocol was approved by the University of Pittsburgh institutional review board.

Measures

Physical Activity—Accelerometer data were collected using the ActiGraph GT1M accelerometer (Pensacola, Florida). The ActiGraph GT1M accelerometer is a small (3.8cm × 3.7cm × 1.8cm), uni-axial piezoelectric activity monitor that measures acceleration in the vertical plane. Data output from the ActiGraph are activity counts, which quantify the amplitude and frequency of detected accelerations. Activity counts are summed over an investigator-specified time interval (i.e., epoch). A 60-epoch was used for the present study. The reliability and validity of the ActiGraph GT1M accelerometer have been described previously (18, 22).

Data from the ActiGraph were downloaded and screened for daily wear time. Daily wear time was determined by removing any intervals of non-wear (≥20 minutes of no detected movement) and any periods of sleep, as indicated by the Actiwatch. Summary estimates were computed if daily wear time was at least 10 hours. Daily activity counts from the ActiGraph, expressed as counts per minute per day ($\text{ct}\cdot\text{min}^{-1}\cdot\text{d}^{-1}$), were calculated using summed daily counts detected over daily wear time periods. Time spend per day ($\text{min}\cdot\text{d}^{-1}$) in MVPA was computed by summing the time spent above a threshold value ($>760\ \text{ct}\cdot\text{min}^{-1}$) proposed by Matthews et al. (18). The MVPA cutoff value of 760 $\text{ct}\cdot\text{min}^{-1}$ represents an intensity of 3METs (metabolic equivalent), which is comparable to a brisk walk.

Sleep—The Actiwatch-64m (Mini Mitter Division of Respironics Inc.) contains speed and motion-sensitive sensors and has been previously validated as an objective measurement of sleep (14). Data from the Actiwatch was downloaded and analyzed using Actiware software with a 60 second epoch. Bedtime and wake time from the sleep diary were used to define rest intervals for calculation of sleep-wake variables. Actiwatch variables considered here were sleep onset latency (bedtime to sleep start), sleep time (within the bedtime and wakeup time), sleep efficiency (total sleep time/time in bed × 100%), and fragmentation index. The fragmentation index is a measure of sleep restlessness, with higher values indicative of worse sleep continuity.

Covariates—Age was assessed via phone screen. Height and weight were measured with a stadiometer and calibrated balance beam scale, respectively. BMI was calculated as kilograms/meters squared. Socio-demographic characteristics and medical history, including medication use, were assessed via questionnaire. Education was obtained by the participant reporting their highest grade level completed, categorized into 3 groups (high school degree or less, some college/vocational training, college or higher) for analysis. Depressive symptoms were assessed via the Beck Depression Inventory (BDI) (2). The BDI consists of 21 items that are rated on a 4-point likert scale, with higher scores indicative of more depressive symptoms. One question on the BDI pertaining to sleep was removed for analyses. Arthritis was determined by the participant checking a box indicating ever having arthritis. We defined hypertension as the participant indicating ever having high blood pressure in addition to currently taking blood pressure medication. Hypertension was not, however, included as a covariate in the final analyses because it was strongly associated with both BMI and depressive symptoms and was not associated with any physical activity or sleep variables. Race and type 2 diabetes mellitus were considered as potential covariates, but were not included in the final analyses because over 90% of the sample was White and less than 7% of the sample had type 2 diabetes mellitus.

Analytic Plan

Variables were examined for normality and small cell sizes. Non-normally distributed variables (average daily activity counts, MVPA, sleep onset latency, sleep time, sleep efficiency, sleep fragmentation, depressive symptoms) were log transformed for analyses. An alpha level of 0.05 was used for all analyses.

Cross-sectional analysis—Weekly averages of physical activity and sleep variables were calculated. Depending on the distribution of the variables, either Pearson or Spearman correlation coefficients were used to assess the bivariate relationships between covariates (age, education, BMI, depressive symptoms, arthritis) and weekly averages for daily activity counts ($\mathrm{ct \cdot min \cdot d^{-1}}$) and minutes of MVPA ($\mathrm{min \cdot d^{-1}}$). Similarly, Pearson or Spearman correlation coefficients were used to assess the bivariate relationships between covariates and weekly averages for sleep onset latency, sleep time, sleep efficiency, and sleep fragmentation. The unadjusted associations between average weekly physical activity estimates and average weekly sleep characteristics were assessed via Pearson correlations. Linear regression models were constructed to assess the relationship between physical activity and sleep while adjusting for covariates.

Temporal analyses—Multilevel models with a restricted maximum likelihood estimation method and an autoregressive correlation matrix were used to assess the temporal relationships between physical activity and sleep with physical activity/sleep nested within subjects. In analyses to assess whether physical activity on one day predicted sleep that night, physical activity was the predictor variable and sleep the outcome. Separate models were used to test the unadjusted relationship between each physical activity variable and each sleep variable. To assess whether sleep at night predicted PA the following day, similar analyses were performed with sleep as the predictor and the next day physical activity as the outcome. We then repeated each analysis adjusting for subject-level covariates (age, education, BMI, depressive symptoms, arthritis) and daily accelerometer wear time in all models. We also considered time of year (e.g. season) and sleep medication use as covariates. In exploratory fashion we examined whether physical (BMI, arthritis) or socio-demographic (education, depressive symptoms) variables, moderated any of these relationships. Moderation was tested via cross-product interaction terms between each moderator variable and each physical activity/sleep predictor variable entered separately as a final step in fully adjusted models.

In analyses predicting sleep from physical activity, we further considered the possibility that daytime physical activity may have a different relationship with sleep variables then physical activity performed in the evening. To test this hypothesis we repeated the analyses with physical activity as the predictor and sleep as the outcome including only daytime physical activity (between 9am and 6pm) or only evening physical activity (between 6pm and 10pm) estimates as predictor variables. All analyses were performed using SAS version 9.3 software.

Results

Data from 144 participants who wore both the ActiGraph accelerometer and Actiwatch were included for analyses. Participants had a mean of 6.1±1.0 days of valid accelerometer data and a mean of 6.7±.7 nights of Actiwatch data. Additionally, 141 participants (98% of sample) wore both the accelerometer and the Actiwatch for a minimum of 4 days. Participants were mostly White, well educated, and overweight (Table 1). Accelerometer-assessed physical activity and actigraphy-assessed sleep characteristics of the participants are presented in Table 2. Participants engaged in a median of 60.9 minutes of MVPA per day and had a median sleep efficiency of 85.5% per night over the week. When assessing the within-person variability in physical activity and sleep during the week, women had a median range of 59 minutes of MVPA and a median range of 12% sleep efficiency.

Cross-sectional analysis—When examining the association between covariates and average weekly physical activity, greater BMI was associated with lower average daily activity counts (r=-.22, p=.008) and less MVPA (r=-.23, p=.007). Similarly, having arthritis was associated with lower average daily activity counts (ρ=-.19, p=.02) and less MVPA (ρ=-.20, p=.02). Analyses examining the correlations between covariates and average weekly sleep characteristics indicated that higher education was associated with less sleep fragmentation (ρ=-.23, p=.005) and greater depressive symptoms were associated with greater sleep onset latency (r=.22, p=.01) and lower sleep efficiency (r=-.26, p=.002).

Average weekly ActiGraph-derived physical activity estimates were not associated with any average weekly Actiwatch-assessed sleep characteristics (data not shown). The results did not change when adjusting for age, education, BMI, depressive symptoms, arthritis, or sleep medication use.

Temporal analyses for physical activity predicting sleep—In unadjusted models greater daily activity counts (B=-.05, p=.005) and more minutes of MVPA (B=-.03, p=.01) were temporally associated with less sleep time. When adjusting for subject-level covariates and accelerometer wear time similar associations were observed for sleep time (Table 3). For each 1% increase in daily activity or minutes of MVPA, sleep time decreased by .04% and .02%, respectively. In more meaningful terms, a 10% increase in daily activity or minutes of MVPA would be associated with a .4% and .2% decrease in sleep time, respectively. Adjusting for time of year and sleep medication use did not change the results. Daily physical activity counts did not predict any other sleep characteristics. When examining the influence of daytime (8am to 6pm) vs. evening (6pm to 10pm) physical activity on sleep, daytime activity counts (B=-.04, p=.01) and evening MVPA (B=-.02, p=.02) were associated with shorter sleep time. Results were similar when adjusting for subject-level covariates. Neither daytime nor evening physical activity was associated with sleep onset latency, efficiency, or fragmentation.

In exploratory analyses to identify potential modifiers of the relationship between physical activity predicting sleep, only education significant modified the relationship between physical activity and sleep efficiency (interaction p<.02). Greater daily activity counts were associated with lower sleep efficiency only among less educated women (B=-.05, p=.07) compared to women with some college (B=.003, p=.86) or a college degree (B=.002, p=.85). The results for MVPA (interaction p=.05) showed a similar pattern.

Temporal analyses for sleep predicting physical activity the following day—In unadjusted models greater sleep efficiency was temporally associated with greater daily activity counts (B=.37, p=.01) and more minutes of MVPA (B=.64, p=.009) the following day. Similarly, less sleep fragmentation was associated with greater daily activity counts (B=-.06, p=.02) and more minutes of MVPA (B=-.11, p=.02) the following day. When adjusting for subject-level covariate sand accelerometer wear time similar associations were observed between sleep and physical activity (Table 4). A 1% increase in sleep efficiency was associated with a .32% increase in daily activity counts and .54% increase in minutes of MVPA. Thus, a 10% increase in sleep efficiency would be associated with a 3.2% increase in daily activity counts and a 5.4% increase in minutes of MVPA. Adjusting for time of year and sleep medication use did not change the results. Sleep onset latency and sleep time were not associated with physical activity the following day. No physical or socio-demographic variables significantly modified the relationship between sleep predicting physical activity.

Discussion

Few studies have examined the relationship between physical activity and sleep using objective measurements of both physical activity and sleep. Moreover, we are among the first to assess the temporal and bidirectional relationships between physical activity and sleep in older women. Our results suggest that greater sleep efficiency and lower fragmentation are associated with greater physical activity the following day, perhaps because women feel more energetic. Additionally, physically activity during the day was associated with less sleep at night, although this was trivial in terms of clinical significance. Interestingly, ActiGraph-derived physical activity estimates were not related cross-sectionally with Actiwatch-assessed sleep characteristics in older women.

Only a few studies have investigated the temporal and bidirectional relationships between physical activity and sleep. One study in children found that greater physical activity during the day was temporally associated with worse actigraphy-assessed sleep (less duration, lower efficiency, greater fragmentation) at night and better sleep was associated with lower physical activity the following day (23). Although these finding are contradictory to the prevailing cross-sectional literature demonstrating a positive relationship between physical activity and sleep, assessment of the temporal relationships between physical activity and sleep in children are likely to be affected by parent determined bedtimes and school start times. In healthy adults, Youngstedt et al. (36) concluded that self-reported physical activity was not temporally associated with either subjective or actigraphy-assessed sleep. However, this study did not examine whether sleep was also temporally associated with physically activity. Our results showing no association between daily variations in physical activity and measures of sleep quality in older women are similar to the findings of Youngstedt et al. (36). Physical activity during the day was, however, associated with less sleep time at night, although this finding was trivial given that an increase of 1 hour in MVPA each day would be needed to reduce sleep time by an average of 15 minutes. Furthermore, we demonstrated for the first time that greater sleep efficiency and lower sleep fragmentation were temporally associated with greater levels of physical activity the following day among older women.

Assessing the temporal and bidirectional relationships between physical activity and sleep among older women has important implications for informing both clinical and public health practice. A majority of previous research examining the relationship between physical activity and sleep has hypothesized that physical activity is beneficial for sleep. Although cross-sectional studies consistently demonstrate a positive relationship between physical activity and sleep, studies including experimental manipulations of physical activity have demonstrated less consistent effects on sleep (35). For example, acute bouts of exercise and exercise interventions have produced positive effects on sleep in some (9, 13, 24, 28), but not all studies (7, 21, 35). Furthermore, previous studies assessing the temporal relationship between physical activity and sleep, including the present study, do not support the hypothesis that daily fluctuations in physical activity are positively related with measures of sleep. In fact, we observed that greater levels of physical activity during the day were associated with less sleep time at night, although this finding was negligible in terms of clinical significance. Perhaps, women who are busier and do more activity during the day have less time to sleep at night. Since we did not manipulate physical activity levels, the physical activity estimates represent normal daily routines. Thus, small fluctuations in daily activities may not be sufficient to benefit sleep.

Less work has examined the effects of sleep on physical activity. However, there is some evidence that experimentally induced sleep restriction results in lower physical activity levels the following days (25, 26). Similar to these studies, our results suggest that nightly variations in sleep efficiency influence physical activity the following day. Thus, normal fluctuations in sleep quality may have immediate effects on a person's willingness to be physically activity the following day. Women who are well-rested may feel more energetic and be more likely to engage in greater amounts and intensities of activities throughout the day. These findings are notable given the considerable within-person variability in sleep quality observed across a week and given that even small increases in physical activity can be beneficial for health (32). It has been recognized that individuals vary considerably in their night-to-night sleep (10, 31). However, few studies have examined the health impacts of these normal fluctuations in sleep. Examining the influence of nightly variations in sleep on physical activity patterns may be particularly pertinent in older women because older women are at high risk for inactivity (1) and females may have greater variability in sleep than males (31). Thus, considering both overall sleep quality and within-person variability in sleep may be important for encouraging a physical activity lifestyle in older women.

In exploratory fashion we considered whether physical or socio-demographic factors moderated the temporal relationships between physical activity and sleep in either, or both, directions. Results from these analyses suggest that education may play a moderating role in the relationship between physical activity during the day and sleep efficiency at night. Greater physical activity during the day was associated with significantly lower sleep efficiency primarily among the least educated women (i.e. ≤ high school). It is not presently known why greater levels of physical activity would be associated with lower sleep efficiency only among less educated women. One possibility is that less educated women accumulate the majority of their physical activity in non-leisure domains (i.e., occupational-, transportation-, or domestic- related activities), which could have different relationships with sleep than activities performed during leisure time. Although we were able to assess the overall amount of activity and the amount of time spent in MVPA, we do not know what specific activities or contexts these women participated in. A majority of previous studies have focused on the relationship between leisure time physical activity (e.g. structured exercise, sports) and sleep. However, we have recently demonstrated that the relationship between non-leisure time activities (e.g. household chores) and sleep is different for lower SES minority women compared to higher SES White women (15). Thus, future work is needed to clarify how different types of activities may be related to sleep and to determine the mechanisms whereby indicators of socioeconomic status may moderate these relationships.

Our study is unique in that we collected valid objective measures of both physical activity and sleep concurrently over an entire week in a sample of older women. Studies in the general population (16, 30) and among older women (5) have consistently demonstrated positive cross-sectional associations between physical activity and sleep. However, previous studies have relied upon subjective assessments of physical activity and/or sleep. Subjective reports of physical activity and sleep often differ from objective assessments and can be affected by cognition, memory, and respondent bias (20, 27, 34). While, it was surprising that we did not observe a cross-sectional relationship between accelerometer-derived physical activity estimates and actigraphy-assessed-sleep characteristics in the present study, these findings underscore the importance of integrating both subjective and objective measures of physical activity and sleep in research studies of women.

The study had several limitations. The sample was primarily White older women. Thus, the findings may not generalize to other age, gender, or racial groups. Further, we did not assess sleep stage. Previous work has shown that exercise can affect sleep stages, including slow wave sleep and rapid eye movement sleep (6, 35). Sleep stage may also affect how rested women feel and could also affect physical activity the following day. Lastly, we assessed temporal relationships between physical activity and sleep, which cannot determine causality.

Conclusions

The present study assessed the temporal and bidirectional relationships between physical activity and sleep using accelerometer and actigraphy data collected concurrently over a 24-hour period across an entire week. Our findings in older women suggest that greater sleep efficiency and lower fragmentation are associated with greater levels of physical activity the following day. Thus, improving sleep quality and sleep consistency may be one way to encourage a physically active lifestyle among older women. Future work is needed to better comprehend the temporality and directionality of the physical activity-sleep relationship. Furthermore, it will be important to identify the mechanisms whereby socioeconomic status may moderate these relationships.

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Table 1

Characteristics of the participants (N=144)

Age, mean (SD), y	73.3 (1.7)
BMI, mean (SD), kg/m^2	27.6 (5.1)
Race, n (%)	
White	132 (91.7)
Black/Other	12 (8.3)
Education, n (%)	
High school or less	32 (22.2)
Some college	33 (22.9)
4 year degree or higher	78 (54.9)
Chronic disease (yes), n (%)	
Arthritis	80 (55.6)
High blood pressure	58 (40.3)
Diabetes	9 (6.3)
Sleep medication (yes), n (%)	23 (16.0)
BDI, median (IQR)	5.5 (5.0)

BMI = body mass index
BDI = beck depression inventory
IQR = interquartile range

Table 2

Physical activity and sleep characteristics of the participants

	Weekly average[a], median (IQR)	Range within week[b], median (IQR)
Physical activity (accelerometer)		
Daily activity counts, $ct \cdot min^{-1} \cdot d^{-1}$	188.9 (93.4)	135.3 (111.3)
MVPA, min	60.9 (45.4)	59.0 (54.4)
Sleep (actigraphy)		
Onset latency, min	10.1 (11.0)	24.0 (28.5)
Total sleep time, min	399.1 (74.7)	134.0 (95.0)
Efficiency, %	85.5 (6.7)	12.0 (10.6)
Fragmentation index	27.5 (14.6)	27.3 (20.0)

[a] Physical activity/sleep values averaged across total number of valid days/nights

[b] Range of physical activity/sleep values within each participant; range = highest value measured during the week – lowest value measured during the week

SD = standard deviation
IQR = inter quartile range
MVPA = moderate to vigorous physical activity; minutes above 760 counts/min

Table 3
Multilevel models for physical activity predicting sleep

Physical Activity	Onset latency, min	Sleep time, min	Efficiency, %	Fragmentation index
Daily activity counts, ct·min^{-1}·d^{-1}	-.04 (.08)	-.04 (.02) **	-.007 (.009)	-.008 (.04)
MVPA, min	-.05 (.05)	-.02 (.01) *	-.004 (.006)	.004 (.03)

Data are regression coefficient (standard error). Physical activity and sleep variables are log transformed. Physical activity variables were entered separately.

Covariates: age, education, BMI, depressive symptoms, arthritis, accelerometer wear time

BMI = body mass index

MVPA = moderate to vigorous physical activity

* $p<.05$,

** $p<.01$

Table 4

Multilevel models for sleep predicting physical activity the following day

Physical Activity	Onset latency, min	Sleep time, min	Efficiency, %	Fragmentation index
Daily activity counts, $ct{\cdot}min^{-1}{\cdot}d^{-1}$	-.01 (.01)	.10 (.07)	.32 (.14) *	-.06 (.03) *
MVPA, min	.006 (.02)	.02 (.12)	.54 (.24) *	-.10 (.04) *

Data are regression coefficient (standard error). Physical activity and sleep variables are log transformed. Sleep variables were entered separately.

Covariates: age, education, BMI, depressive symptoms, arthritis, accelerometer wear time

BMI = body mass index

MVPA = moderate to vigorous physical activity

[*] $p<.05$