Associations of muscle-strengthening and aerobic exercise with self-reported components of sleep health among a nationally representative sample of 47,564 US adults

Jason A Bennie[1*], Katrien De Cocker[1], and Mitch J Duncan[2,3]

[1]Physically Active Lifestyles Research Group (USQ PALs), Institute for Resilient Regions, University of Southern Queensland, Springfield, Queensland, Australia.
[2] School of Medicine & Public Health; Faculty of Health and Medicine, The University of Newcastle, University Drive, Callaghan NSW 2308, Australia
[3] Priority Research Centre for Physical Activity and Nutrition, The University of Newcastle, University Drive, Callaghan NSW 2308, Australia

*Corresponding author
Jason Bennie, PhD, Physically Active Lifestyles Research Group (USQ PALs), Institute for Resilient Regions, University of Southern Queensland, Education City, 37 Sinnathamby Boulevard, Springfield Central, QLD 4300, Australia.
Email: Jason.bennie@usq.edu.au
P: +61 (7) 3470 4136 (office).

ABSTRACT

Objectives: Evidence demonstrates that physical activity is favourably associated with indicators of sleep health. However, population-based studies rarely examine the relationship between different physical activity modalities (i.e., aerobic exercise vs. muscle-strengthening exercise) with components of sleep health**.**

Methods: Cross-sectional analyses were conducted on the US 2017 Behavioral Risk Factor Surveillance System. Validated items assessed self-reported moderate-to-vigorous-intensity aerobic physical activity (MVPA), muscle-strengthening exercise (MSE), sleep duration, difficulties and disorders. Poisson regression assessed prevalence ratios (PR) of five components of detrimental sleep health (short sleep; long sleep; poor quality sleep; observed snoring; and observed breathing stoppage) separately for adults 18-64 years and ≥65 years, across four categories of physical activity guideline adherence (met neither [reference]; MSE only; MVPA only; met both).

Results: The sample comprised 47,564 adults (mean age: 48.4 years; ±1.4; 51.6% female). Among those 18-64 years, except for short sleep (4-6 hours), for all other detrimental sleep health components, the lowest PRs were observed among those meeting both MVPA-MSE guidelines. Among those aged ≥65 years, for all five detrimental sleep health components, compared to the other physical activity categories, the lowest PRs were observed among those meeting both MVPA-MSE guidelines. All associations remained after adjusting for potential confounders (sex, education, income, smoking, alcohol, depression, hypertension, diabetes).

Conclusion: A physical activity routine that includes both MVPA and MSE is likely to be beneficial for better sleep health. Longitudinal studies are needed to establish the temporal relationships between MVPA/MSE guideline adherence and sleep health.

Key Words: Epidemiology; Prevention; Sleep Disorders; Physical Activity

INTRODUCTION

Good sleep is a key determinant of optimal health and wellbeing.[1] Systematic reviews and meta-analyses have shown that insufficient sleep duration, and poor sleep quality and efficiency (i.e. sleep latency, wake after sleep onset) are associated with increased risk of all-cause mortality and incident diabetes, hypertension, cardiovascular diseases, depression, and obesity.[1-5] In the US, it is estimated that ~33% of adults do not report the recommended sleep duration,[6] with a similar proportion reporting insomnia (defined as ≥3 awakenings per night).[3] Given a combination of a high prevalence and significant health burden, success in strategies to improve dimensions of sleep health are a public health priority.[7] Regular physical activity is a key modifiable lifestyle and non-pharmaceutical approach to enhance sleep health.[8] Most of the evidence on physical activity and dimensions of sleep health is based on studies assessing the effects of aerobic moderate-to-vigorous physical activity (MVPA; e.g. walking, cycling, running).[8] A recent umbrella review of nine meta-analyses and six systematic reviews (comprising 166 unique studies), indicated that there is strong evidence that regular aerobic MVPA has beneficial effects on multiple dimensions of sleep health, including total sleep time, sleep quality and sleep onset latency.[8]

Emerging clinical evidence suggests that muscle-strengthening exercise (MSE: e.g. resistance/strength training) may also improve various dimensions of sleep health. A 2018 systematic review of 13 randomized controlled trials (RCT),[9] and another more recent RCT[10], showed that compared to no exercise, MSE improved various dimensions of sleep health (i.e., sleep quality, latency, sleep disturbance), with the largest benefits observed on sleep quality.[9] However, since the available evidence on the associations between MSE and dimensions of sleep health is based on studies that recruited small and non-representative samples, it is unknown how these findings translate to large population-based samples.[10]

Moreover, while current evidence suggests that MSE may benefit some components of sleep health, it remains unclear if engaging in MSE in addition to MVPA confers additional benefits to overall sleep health.[9] Engaging in both aerobic MVPA and MSE has been shown to provide additional health benefits, including a reduced risk of all-cause and cancer mortality,[11-13] improved cardiometabolic,[14,15] and mental health,[16-19] compared to only engaging in one physical activity modality. However, to our knowledge, the independent and/or mutual associations between aerobic MVPA and MSE with components of sleep health at the population-level have not been previously examined. Developing an understanding of the association between different modes of physical activity and components of sleep health is important because such information could be used to inform future large-scale public health interventions designed to enhance sleep health.

This study aims to examine the cross-sectional associations between different groupings of adherence to the aerobic MVPA/MSE guidelines and components of sleep health among a large sample of community-dwelling adults.

METHODS

Participants: Data were drawn from the 2017 Behavioral Risk Factor Surveillance System (BRFSS 2017). Comprehensive descriptions of the background and methods utilised in the BRFSS are available elsewhere.[20] In brief, started in 1984, the BRFSS is an annual survey that collects state-specific data among US adults regarding their health-related risk behaviors, chronic health conditions, and use of preventive services. Each BRFSS survey is approved by the National Center for Health Statistics Research Ethics Review Board. In the BRFSS 2017, data were collected via landline and mobile/cell phone interviews from respondents from all

50 US states, the District of Columbia, Guam, and Puerto Rico. The median response rate was 47.2% (range: 34%-61%).

Data inclusion/exclusion

The BRFSS 2017 interviews comprised a range of items, including (but not limited to) information on demographics, health behaviors and chronic disease status. Participants were provided with the option of completing optional modules. In the current study, we included those who undertook the 'Sleep Disorder Module'. From the 450,016 adults who were originally interviewed, participants were excluded if they did not both complete the Sleep Disorder Module (n=400,651; 87% of the original sample), and did not respond to the physical activity items (n=2,257). The final sample in the present study was 47,564 (participant flow diagram is shown in Figure 1).

Exposure variables – Physical activity

An overview of the development and design of the BRFSS survey to assess physical activity is available elsewhere.[21] These items have shown to have acceptable reliability and validity, [21] and are routinely used in physical activity surveillance.[22-24]

Aerobic MVPA

Aerobic MVPA was assessed by asking "*During the past month, other than your regular job, did you participate in any physical activities or exercises such as running, callisthenics, golf, gardening, or walking for exercise*?". Physical activities were coded as 'non-aerobic' or 'aerobic' using a pre-defined list of 56 activities.[22] Examples of non-aerobic activities included bowling, golf, gardening and painting/papering, while aerobic activities included jogging, walking, tennis and soccer.[22] To count toward meeting the MVPA guideline, an activity had to be 'aerobic'. Using standardised scoring protocols, for estimating the intensity, the cut-point

for vigorous-intensity was defined as ≥60% of a respondent's estimated aerobic capacity, based on sex and age.[22] Moderate-intensity activities were categorized as aerobic physical activity of ≥3.0 metabolic equivalents,[25] and less than the respondent's vigorous-intensity cut-point. These items have adequate concurrent validity (Cohen's k= 0.17–0.22) (using accelerometry as the standard) and test-retest relatability (Cohen's k= 0.67-0.84).[26]

Muscle-strengthening exercise

MSE was assessed by asking "*During the past month, how many times per week or per month did you do physical activities or exercises to strengthen your muscles? Do not count aerobic activities like walking, running, or bicycling. Count activities using your own bodyweight like yoga, sit-ups or push-ups and those using weight machines, free weights, or elastic bands*". This item has evidence of convergent validity (against all-cause mortality)[13] and adequate test-retest reliability (Cohen's k= 0.85–0.92).[27] Using a previous scoring protocol,[28] for those reporting their MSE frequency as times per month, this number was divided by four to provide estimates of the weekly MSE frequency.

Physical activity guideline adherence classification

Based on meeting or not meeting the global guidelines,[29] and consistent with previous studies,[15,19,30] four mutually exclusive physical activity categories were created: (i) 'Meet neither' (aerobic MVPA = 0-149 min/week & MSE <2 session/week); (ii) 'MSE only' (MSE ≥2 sessions/week & aerobic MVPA = 0-149 min/week); (iii) 'aerobic MVPA only' (aerobic MVPA ≥150 min/week & MSE <2 sessions/week); or (iv) 'Meet both' (aerobic MVPA ≥150 min/week & MSE ≥2 sessions/week).

<u>Outcome variables – Sleep health components</u>

A comprehensive overview of the BRFSS 2017 Sleep Disorder Module has been described elsewhere.[20] In brief, designed in consultation with leading sleep science academics, these items were developed to be able to accurately screen and detect sleep disorders in population-based studies.[31]

Sleep duration

Sleep duration was assessed by asking "*On average, how many hours of sleep do you get in a 24-hour period?*" and reported in whole hours. Reported sleep duration <4 hours (n= 333, 0.7% of the analytical sample) and >12 hours (n= 146, 0.3% of the analytical sample) were omitted to limit the influence of extreme sleep durations. Based on the 2015 National Sleep Foundation's adult age-specific sleep duration recommendations,[7] for adults aged 18-64 years, three categories were created: (i) 'shorter than recommended sleep' (short sleep) (4-6 hours); (ii) 'recommended sleep' (7-9 hours); and (iii) 'longer than recommended sleep' (long sleep) (10-12 hours). For adults aged ≥65 years, three categories were created: (i) 'short sleep' (4-6 hours); (ii) 'recommended sleep' (7-8 hours); and (iii) 'long sleep' (9-12 hours).[7]

Sleeping difficulties

Sleeping difficulties were assessed by asking *"Over the last 2 weeks, how many days have you had trouble falling asleep or staying asleep or sleeping too much?*". Similar with scoring protocols from previous studies,[27,32] the sample was dichotomised as: (i) 'good sleep quality' (<6 days in the last two weeks); and (ii) 'poor sleep quality' (≥6 days in the last two weeks).

Observed snoring and observed stopped breathing during sleep

Observed snoring was assessed by asking: "*Have you ever been told that you snore loudly?*". Observed breathing difficulties during sleep was assessed by asking: *"Has anyone ever*

observed that you stop breathing during your sleep?". For both these items, three response options were initially provided: (i) "yes"; (ii) "no"; or (iii) "don't know/unsure." In the current study, these options were then collapsed to "yes" and "no" (with "don't know/unsure" being excluded from the analysis).

Potential confounders

All potential confounders were chosen a priori, with previous literature showing that each is associated with engagement in aerobic MVPA-MSE [30] and poor sleep health.[32,33] Sociodemographic (sex, age, income, education, race/ethnicity) data and lifestyle characteristics (self-rated health [5 point-scale: '1' 'Excellent' to '5' 'Poor'], heavy alcohol consumption [>7 drinks/week for women, >14 drinks/week for men], smoking) were assessed using standardised questionnaire items.[20] Body mass index (BMI) was calculated from self-reported height (meters) and weight (kilograms) using the formula: BMI = kg/m^2. In addition, since poor mental health can negatively impact on both physical activity[17,30] and sleep,[32] we also adjusted for a proxy assessment of depression, classified as a previous clinical diagnosis for depression. Last, we adjusted for the self-reported presence ('yes', 'no' to each comorbidity) of the following comorbidities: arthritis/rheumatoid arthritis, hypertension, asthma, diabetes, high cholesterol, myocardial infarction, coronary heart disease, stroke, chronic obstructive pulmonary disease, kidney disease, and cancer (non-skin).

Statistical analysis

Analyses were conducted using the Complex Samples module of SPSS version 23. To allow for valid population estimates, weighting factors were included to correct for non-response and to account for clustering.[34] Descriptive statistics were used to describe the weighted

percentages (%) across all potential confounders, physical activity categories and potential detrimental sleep health components.

Generalized linear models with Poisson regression with robust error variance were used to calculate prevalence ratios (PR) assessing the associations separately with each detrimental sleep health component (outcome variables: 'short sleep'; 'long sleep'; 'poor sleep quality'; 'observed snoring'; 'observed stopped breathing during sleep') across physical activity categories (explanatory variable). Separate models were conducted for those aged 18-64 years and ≥65 years. For these analyses, the reference group was the most physically inactive ('meet neither guideline'). In population-based cross-sectional studies, presenting prevalence ratios (PRs) calculated via Poison regression is considered a more appropriate analytical approach than the usually used logistic regression reporting of odds ratios.[35,36]

To examine the impact of potential confounders, we conducted four generalized linear models for each detrimental sleep health component. These were: (i) 'Model 1' (unadjusted); (ii) 'Model 2' (adjusted for sex, age, education, income, race/ethnicity); (iii) 'Model 3' (adjusted for Model 2 + hazardous alcohol consumption, smoking, self-rated health, BMI, previous clinical diagnosis for depression, self-reported comorbidities; and (vi) 'Model 4' (adjusted for Model 3 + other detrimental sleep health components). Before running our final analytical models, we assessed the potential for collinearity between confounders using a test for variance inflation factor (VIF), with a VIF ≥2 indicating multicollinearity. The VIFs ranged from 1.08 to 1.78 representing no indication of multicollinearity.

Two sensitivity analyses were conducted to facilitate a more robust interpretation of the results. First, since sleep health components can vary by sex,[3,32] a sex-stratified analysis was

conducted. Second, given that poor mental health is a determinant of poor sleep health components,[3] we stratified the sample according to previous clinical diagnosis for depression ('yes' vs. 'no').

RESULTS

Sample description

The final sample in the analysis was 47,564 (18-80 years). Description of participant characteristics of those included in the analysis in comparison to the overall BRFSS sample shown in Appendix Table 1. Overall, when compared to the original BRFSS 2017 sample, the analytical sample in the present study had similar proportions across most sociodemographic/lifestyle characteristics and physical activity guideline adherence categories (Supplementary Table 1). In brief, over half the sample was female, mean age was 48.4 years (± 1.4), 12.1% were unemployed and 9.2% had a lower than high school education. Mean BMI was 28.1 kg/m^2 (± 0.5), 5% had 'poor' self-rated health, 17.2% were current smokers and 20.7% had a previous diagnosis of depression.

A total of 39.8% did not meet any physical activity guidelines, 9.6% met the MSE guideline only, 30.5% met the aerobic MVPA guideline only and 20% met both guidelines.

Detrimental sleep health components

For adults aged 18-64 years, 36.5% reported short sleep (4-6 hours), 60.8% reported recommended sleep (7-9 hours) and 2.8% reported long sleep (10-12 hours). For adults aged ≥65 years, 26.6% reported short sleep (4-6 hours), 63.1% reported recommended sleep (7-8 hours and 12.2% reported long sleep (9-12 hours). For the total sample, 22.6% reported

experiencing poor sleep quality, 40.6% observed snoring and 14% observed stopping breathing during sleep.

<< Insert Table 1 here >>

Adjusted analysis for the prevalence of detrimental sleep health components

The associations of physical activity categories (reference = meet neither guideline) with detrimental sleep health components('short sleep'; 'long sleep'; 'poor sleep quality'; 'observed snoring'; 'observed stopped breathing during sleep'), are presented separately, for adults aged 18-64 years (Table 2) and ≥65 years (Table 3), respectively. Across both age categories, associations remained similar after adjusting for sociodemographic/lifestyle characteristics, BMI, comorbidities and other detrimental sleep health components.

<< Insert Table 2 here >>

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As shown in Table 2, for adults aged 18-64 years, in the fully adjusted model (Model 4), compared to those who did not meet either guideline, all categories of physical activity guideline adherence were associated with significantly lower adjusted prevalence ratios (APRs) for each detrimental sleep health component. Specifically, the APRs for most of the detrimental sleep health components tended to be lowest among those meeting both guidelines (range: 0.41-0.87), followed by MVPA only (range: 0.49-0.90) and MSE only (range: 0.58-0.89). Across all the physically active groups, compared to 'short sleep' (range: 0.85-0.89), lower APRs were observed among for 'long sleep' (range: 0.41-0.58), and somewhat similar for 'poor sleep quality' (range: 0.70-0.79) 'observed snoring' (range: 0.76-0.90) and 'observed stopped breathing during sleep' (range: 0.64-0.81).

For adults aged ≥65 years (Table 3), in the fully adjusted model (Model 4), meeting the MSE guideline only was not associated with lower APRs for any of the detrimental sleep health components. The APRs for detrimental sleep health components tended to be lower among those meeting both guidelines (range: 0.66-0.86), compared to MVPA only (range: 0.71-0.93). Marginally lower APRs were observed for 'long sleep' (range: 0.64-0.77), compared to 'short sleep' (range: 0.71-0.79). Across the remaining detrimental sleep health components, the lowest APRs were for 'poor quality sleep' (range: 0.66-0.71), followed 'observed stopped breathing during sleep' (range: 0.72-0.80) and 'observed snoring' (range: 0.86-0.93).

Sensitivity analyses

The stratified analysis for the 18-64 years sample is shown in Supplementary Table 2, and the ≥65 years sample is shown in Supplementary Table 3. In brief, across both age groups, the APRs of the association between the physical activity guideline adherence categories and detrimental sleep health components were generally similar for both males and females. When stratified by previous diagnosis of depression (yes vs no), across both age groups, the overall trend of the APRs was similar within both groups.

DISCUSSION

This is the first study to examine the associations between different combinations of aerobic MVPA and MSE guideline adherence with a set of established detrimental sleep health components among a large sample of adults. The key finding was that among those aged 18-64 years and ≥65 years, with few exceptions, compared to other physical activity groups, meeting both MVPA-MSE guidelines was associated with lowest APRs for most of the assessed detrimental sleep health components. These preliminary cross-sectional observations need to be replicated in well-controlled longitudinal studies with representative samples that

include regular/standardised assessments of aerobic MVPA/MSE/sleep health components. However, the current study suggests that a physical activity routine that includes both aerobic MVPA and MSE is likely to be associated with better sleep health.

At present, most of the epidemiological evidence for the associations between physical activity and sleep heath is based on studies of aerobic MVPA.[8] The current study is important because it provides an initial insight into the potential beneficial role of both MSE and combined MVPA-MSE on detrimental sleep health components among a large population-based sample. Consistently, our data suggest that compared to the other physical activity categories, meeting both the MVPA-MSE guidelines generally had the most favourable associations with components of sleep health. The key findings of the present study are supportive of the extensive literature on the benefits of physical activity on sleep health components (8). A recent synthesis of findings from over 150 studies identified that regular aerobic activity positively influences sleep health in multiple ways, including reducing the length of time it takes to go to sleep/daytime sleepiness and increasing the time in deep sleep (8). While less is known about the positive effects of MSE on sleep health components, a recent systematic review of 13 clinical exercise studies showed that this exercise mode enhanced sleep quality, sleep latency, sleep efficiency, mid-sleep disturbance, and daytime dysfunction (9). It might also be possible that favourable associations between combined MVPA-MSE and sleep health components is due to an increased energy expenditure from engaging in both physical activity modes, compared to one mode alone. This may result in an increased perception of acute physical fatigue, which is likely to enhance various sleep health components.

It is not possible within the context of the present study to establish the physiological mechanisms to explain these outcomes, and the mechanisms specifically linking MSE to

improved sleep are also unclear.[9] However, clinical exercise studies have shown that compared to engaging in either activity alone, combining aerobic MVPA and MSE has more favourable effects on cardiometabolic biomarkers,[37-40] and indicators of mental health, such as perceptions of energy and fatigue and mental agility.[16] Further, both aerobic MVPA and MSE are associated with improved depression and anxiety symptoms,[41-43] which are also associated with sleep, and some evidence exists of added mental health benefits to these outcomes when engaging in both aerobic MVPA and MSE.[17,19,44] To further establish how combined MVPA-MSE is related to sleep health, it is recommended that future experimental studies are encouraged to compare the effects of the discrete grouping of physical activity modes (i.e. control vs. aerobic MVPA vs. MSE vs. combined aerobic MVPA-MSE) on components of sleep health, and also examine cardiometabolic and mental health as potential mediators of change.

A unique aspect of the current study was the assessment of multiple detrimental sleep health components simultaneously among a large community-based sample. This facilitated novel insights into a range of detrimental sleep health components, and their associations with different combinations of physical activity modalities. Overall, for both age groups, similar patterns were observed, with meeting both guidelines, associated with the lowest prevalence for most of the assessed detrimental sleep health components. Hence, suggesting that increasing engagement in combined MVPA-MSE is likely to have sleep health benefits irrespective of age. Of note was the finding that compared to the APRs for 'short sleep', being physically active was linked to a lower prevalence for 'long sleep' for both age groups. This finding is potentially important because, in comparison to short sleep, long sleep has received less attention in sleep health literature.[45] However, meta-analyses suggest that both shorter and longer sleep durations are likely to negatively influence health, including increased risk of

diabetes, cardiovascular diseases, coronary heart diseases and obesity. [4,5] Indeed, for all-cause mortality, compared to short sleep, long sleep has been linked to higher risk (Risk ratio, 1.39 vs 1.12).[4,5] While cognisant of the limitations of cross-sectional analysis used in the present study, our data suggest that physical activity, and especially the combination of aerobic MVPA and MSE, may be particularly effective lifestyle modification strategies to specifically target those who habitually engage in long sleep as it may benefit their sleep and also cardiometabolic health.

Our study is supportive of recent epidemiological studies involving large community-based samples, that show that a combination of both aerobic MVPA and MSE has beneficial associations with cardiometabolic health,[15] depression/depressive symptom severity[17,19,44] and obesity.[46] However, the fact that ~80% of the sample in the current study did not meet both aerobic and MSE guidelines is concerning from a public health perspective. These low prevalence estimates, in combination with the established multiple health benefits of combined MVPA-MSE, warrant immediate public health action to support and promote the uptake and adherence of both physical activity modes.

Despite well-established sex differences in aerobic MVPA,[47] MSE[28,30] and sleep,[2,48] the prevalence of detrimental sleep components by physical activity levels was mostly concordant between females and males. If confirmed in future prospective studies, this may suggest that sex-specific physical activity-related interventions to enhance sleep health may not be warranted. The results of the depression stratified analysis showed that across both age groups, compared to those with depression, the APRs were mostly concordant. However, since the indicator of depression used in the present study does not account for if the symptoms are

current or not, or the duration and/or severity of this mental health-related outcome, we urge caution in drawing strong inferences from this outcome.

Strengths of the current study include the recruitment of a large sample of adults, and the use of a valid and reliable standardised instrument to assess physical activity.[21] The inclusion of a measure of MSE is also an additional strength, which despite being in the global physical activity recommendations for over a decade,[29] is still rarely assessed in health surveillance.[49] A further strength was the inclusion of multiple sociodemographic (education income, employment etc.) and lifestyle-related variables (alcohol, smoking, BMI etc.), that is likely to confound associations between physical activity and sleep.

A key limitation of the current study is that the cross-sectional design limits interpretations of causality for the main outcomes. It is correspondingly conceivable that those who frequently experience short or long sleep are less likely to participate in physical activity because of their poor sleep health. Hence, the key findings of the current study now need to be replicated by data from prospective cohort and intervention studies. A further key limitation was that the BRFSS 2017 Sleep Disorder Module only accounts for some of the many possible components of sleep health. There is evidence to suggest that other constructs, such as sleep efficiency (sleep latency, wake after sleep onset), alertness/sleepiness/napping, environmental and genetic factors are likely to play a key role in sleep health.[1] Future studies should include assessments of a broader range of sleep health components to provide a more nuanced understanding of the determinants of sleep health. A further limitation was the use of self-report assessments of aerobic MVPA, MSE and sleep health, which may have resulted in recall bias (e.g. under/over-reporting or social desirability). Moreover, there is some concern that the BRFSS Sleep Disorder Module might be limited in its ability to accurately assess sleep disorders, even though

the questions were developed after a recent study suggested that the previous sleep-related BRFSS questions required refinement to increase their sensitivity and specificity.[50,] A further limitation included the fact that 87% of the original sample did not complete the Sleep Disorder Module. It is possible that respondents who chose to complete this module might be more concerned about their sleep health. Other limitations include the use of a crude proxy measure of depression, non-assessment of sedentary behavior/use of sleep medication, and the possibility that other unaccounted factors may have influenced results. Since the overall prevalence of long sleep was lower than that observed in other studies, particularly among adults aged 18-64, these results should be interpreted with some caution.[51,52] Last, there may be limitations with regards to the generalizability of the findings from the current study beyond the US population. For example, compared to other countries, the US has a higher prevalence of those who are overweight/obese[53]. Therefore, until more research is conducted across different countries/regions, we urge caution in assuming that the key findings presented in the current study apply to those from outside the US.

CONCLUSION

This is the first study to describe the associations between aerobic MVPA and MSE with several sleep health components among a large sample of adults. Compared to meeting the MSE and MVPA guidelines only, meeting both guidelines was generally associated with the lowest prevalence of most of the detrimental sleep health components. Longitudinal studies are needed to confirm the temporal associations between physical activity and sleep health.

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Figure 1: BRFSS 2017 participant flow diagram.

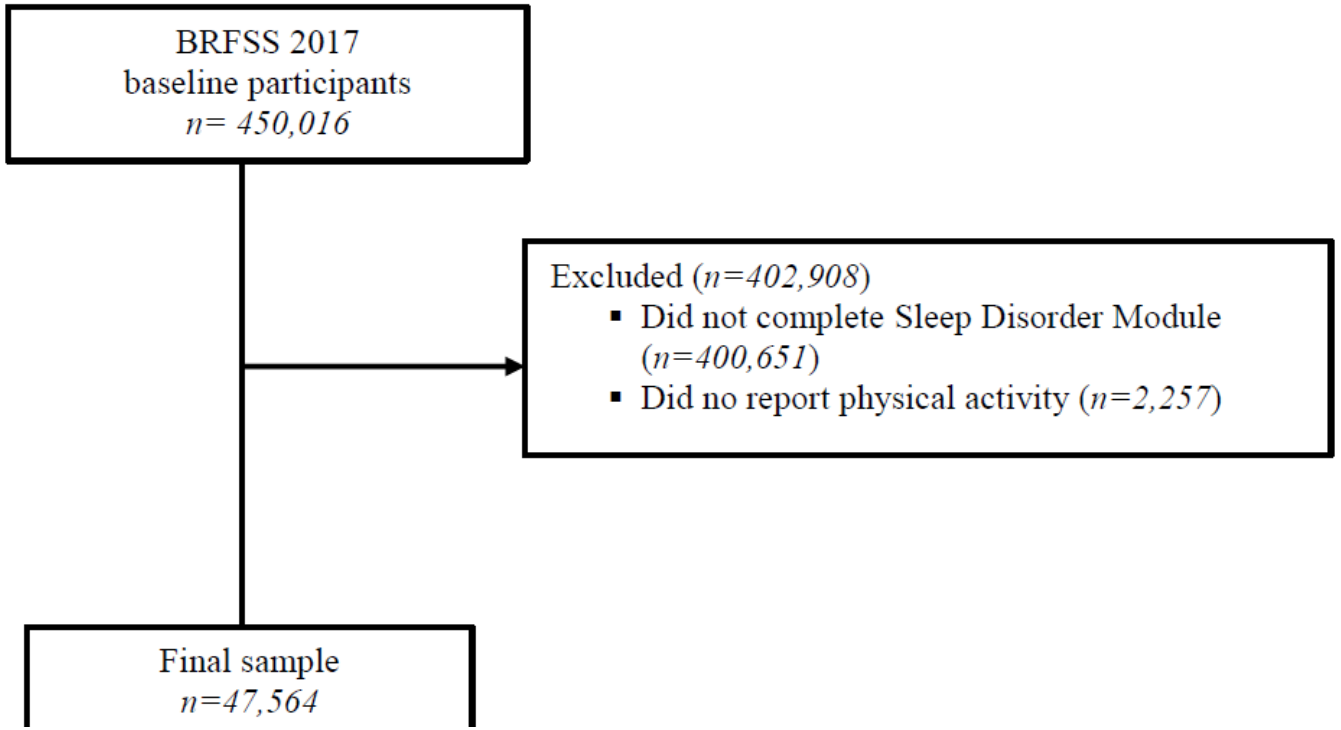

Table 1: Sample characteristics, categories of physical activity guideline adherence[a], sleep health indicators and sleep duration (*n*=47,564).

Characteristics	**Weighted[b] % (95% CI), M ± SD**
Female	51.6 (50.9-52.4)
Age (years)	48.4 ± 1.4
Black, non-Hispanic	7.6 (7.1-8.1)
Unemployed	5.0 (4.7-5.3)
<High school (lowest)	12.1 (11.6-12.8)
Income <$15,000 (lowest)	9.2 (8.7-9.7)
Body Mass Index (kg/m^2)	28.1 ± 0.5
Poor self-rated health[c]	5.0 (4.7-5.3)
Current smoker	17.2 (16.6-17.8)
Heavy alcohol consumption[d]	6.1 (5.7-6.4)
Previous diagnoses of depression	20.7 (20.1-21.3)
Comorbidities[e]	1.6 ± 0.02
Physical activity guideline adherence	
Meet neither	39.6 (38.9-40.3)
Meet muscle strengthening only	9.6 (9.2-10.1)
Meet MVPA only	30.6 (30.0-31.3)
Meet both	20.1 (19.6-20.7)
Sleep health indicators	
Sleeping difficulties[f]	22.6 (22.0-23.3)
Observed snoring	40.6 (39.9-41.3)
Observed stopping breathing	14.0 (13.5-14.5)
Sleep duration	
Adults (18-64 years) (n=30,739)	
Shorter than recommended sleep (4-6 hours)	36.5 (35.6-37.3)
Recommended sleep (7-9 hours)	60.8 (59.9-61.7)
Longer than recommended sleep' (10-12 hours)	2.8 (2.4-3.1)
Older adults (≥65 years) (n=16,825)	
Shorter than recommended sleep (4-6 hours)	26.6 (23.6-25.7)
Recommended sleep (7-8 hours)	63.1 (62.0-64.3)
Longer than recommended sleep' (9-12 hours)	12.2 (11.5-13.0)

[a] Physical activity guideline adherence = 'Meet neither' defined as moderate-to-vigorous physical activity (MVPA) = 0-149 minutes/week & muscle strengthening exercise (MSE) = 0-1 sessions/week: 'Meet muscle strengthening exercise only' defined as MSE = ≥2 sessions/week & MVPA = 0-149 minutes/week: 'Meet MVPA only' defined as MVPA = ≥150 minutes/week & MSE = 0-1 sessions/week: 'Meet both' defined as MVPA = ≥150 minutes/week & MSE = ≥2 sessions/week.

[b] Data weighted using stratum weight provided by the Centers for Disease Control and Prevention (CDC).

[c] Self-rated health assessed on a 5 point-scale: 1 'Excellent' to 5 'Poor'.

[d] To be classified as a heavy drinker an adult men had to consume ≥14 drinks/week and adult women ≥7 drinks per week.
[e] Comorbidities are self-reported hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer (non-skin) or arthritis/rheumatoid arthritis.
[f] To be classified as experiencing sleep difficulties, a respondent had to report 6 or more days in the last two weeks of trouble falling asleep or staying asleep or sleeping too much.

Table 3: Prevalence ratios[a] and their 95% confidence intervals (PR 95%CI) for detrimental sleep duration[b]/quality[c] categories according to levels of physical activity guideline adherence[d]: for adults aged ≥65 years (*n*=16,151).

Detrimental sleep duration[b]/quality[c] categories (≥65 years)	Physical activity guideline adherence[d]	Model 1[e] PR (95% CI)	Model 2[f] APR (95% CI)	Model 3[g] APR (95% CI)	Model 4[h] APR (95% CI)
Recommend sleep/poor quality[i]	Meet neither	1 (reference)	1 (reference)	1 (reference)	1 (reference)
	MSE only	0.94 (0.73-1.19)	1.01 (0.77-1.30)	1.02 (0.78-1.33)	1.02 (0.78-1.33)
	Aerobic MVPA only	0.74 (0.65-0.85)	0.75 (0.65-0.88)	0.75 (0.64-0.87)	0.75 (0.64-0.87)
	Meet both	0.72 (0.61-0.85)	0.71 (0.59-0.84)	0.70 (0.59-0.84)	0.71 (0.59-0.85)
Short sleep/good quality[i]	Meet neither	1 (reference)	1 (reference)	1 (reference)	1 (reference)
	MSE only	0.95 (0.80-1.12)	1.02 (0.84-1.22)	1.03 (0.85-1.25)	1.04 (0.85-1.25)
	Aerobic MVPA only	0.81 (0.75-0.89)	0.83 (0.75-0.92)	0.83 (0.75-0.92)	0.83 (0.75-0.93)
	Meet both	0.73 (0.65-0.82)	0.73 (0.65-0.83)	0.74 (0.65-0.84)	0.74 (0.65-0.84)
Short sleep/poor quality[i]	Meet neither	1 (reference)	1 (reference)	1 (reference)	1 (reference)
	Muscle strengthening only	0.88 (0.71-1.08)	0.89 (0.69-1.12)	0.88 (0.68-1.11)	0.88 (0.68-1.11)
	Aerobic MVPA only	0.58 (0.52-0.66)	0.63 (0.55-0.72)	0.61 (0.53-0.70)	0.61 (0.53-0.70)
	Meet both	0.53 (0.45-0.62)	0.51 (0.43-0.61)	0.52 (0.43-0.62)	0.51 (0.43-0.62)
Long sleep/good quality[i]	Meet neither	1 (reference)	1 (reference)	1 (reference)	1 (reference)
	Muscle strengthening only	0.95 (0.78-1.16)	1.00 (0.80-1.25)	1.02 (0.81-1.27)	1.02 (0.81-1.27)
	Aerobic MVPA only	0.77 (0.69-0.86)	0.80 (0.71-0.91)	0.79 (0.69-0.89)	0.79 (0.70-0.90)
	Meet both	0.65 (0.56-0.74)	0.65 (0.55-0.91)	0.64 (0.55-0.75)	0.64 (0.55-0.75)
Long sleep/poor quality[i]	Meet neither	1 (reference)	1 (reference)	1 (reference)	1 (reference)
	Muscle strengthening only	0.74 (0.44-1.18)	0.87 (0.48-1.44)	0.88 (0.50-1.45)	0.87 (0.48-1.44)
	Aerobic MVPA only	0.38 (0.28-0.51)	0.40 (0.28-0.56)	0.40 (0.28-0.57)	0.40 (0.28-0.56)
	Meet both	0.37 (0.25-0.53)	0.37 (0.23-0.56)	0.40 (0.26-0.60)	0.37 (0.23-0.56)

[a] Prevalence ratio calculated using Poisson regression with a robust error variance.

[b] Short sleep = 4-6 hours; Recommended sleep = 7-9 hours; and long sleep =10-12 hours.

[c] To be classified as experiencing 'poor sleep quality', a respondent had to report 6 or more days in the last two weeks of trouble falling asleep or staying asleep or sleeping too much..

[d] Physical activity levels: 'Meet neither': MVPA= 0-149 MSE= 0-1 sessions/week; 'MSE only'; MSE= ≥2 sessions/week & MVPA= 0-149 minutes/week); 'MVPA only' MVPA= ≥150 minutes/week & MSE= 0-1 sessions/week; and 'Meet both': MVPA= ≥150 minutes /week & MSE= ≥2 sessions/week.

[e] Model 1: unadjusted PR.

[f] Model 2: adjusted PR: age, sex, race/ethnicity, employment, education, income.

[g] Model 3: adjusted for Model 2 + self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression, and comorbidities (hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer [non-skin], arthritis/rheumatoid arthritis).

[h] Model 4: adjusted for Model 3 + observed snoring and stopping breathing during sleep.

[i] Reference category for adults aged 18-64 years = recommended sleep (7-9 hours)/good quality.

Supplementary Table 2: Adjusted prevalence ratios[a] and their 95% confidence intervals (APR 95% CI) for short or longer than recommended sleep according to levels of physical activity guideline adherence[b]: stratified by sex, age and previous diagnosis of depression for adults aged 18-64 years.

		Sex-stratified	
		Male	**Female**
	Physical activity guideline adherence[b]	**APR[d](95% CI)**	**APR[d] (95% CI)**
Shorter than recommended sleep (4-6 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.90 (0.82-1.00)	0.88 (0.79-0.99)
	Aerobic MVPA only	0.87 (0.80-0.93)	0.84 (0.78-0.90)
	Meet both	0.91 (0.84-0.98)	0.81 (0.74-0.88)
Longer than recommended sleep' (10-12 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.68 (0.44-1.02)	0.50 (0.31-0.76)
	Aerobic MVPA only	0.58 (0.42-0.79)	0.42 (0.32-0.56)
	Meet both	0.50 (0.34-0.71)	0.34 (0.24-0.49)
		Previous diagnosis of depression	
		Yes	**No**
		APR[f] (95% CI)	**APR[f] (95% CI)**
Shorter than recommended sleep (4-6 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.96 (0.83-1.10)	0.94 (0.84-1.10)
	Aerobic MVPA only	0.86 (0.79-0.65)	0.82 (0.78-0.87)
	Meet both	0.94 (0.85-1.05)	0.82 (0.77-0.87)
Longer than recommended sleep' (10-12 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.43 (0.24-0.72)	0.79 (0.54-1.13)
	Aerobic MVPA only	0.50 (0.36-0.68)	0.56 (0.42-0.74)
	Meet both	0.47 (0.30-0.71)	0.50 (0.35-0.68)

[a] Prevalence ratio calculated using Poisson regression with a robust error variance and adjusted for sex, age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and comorbidities (hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer [non-skin], arthritis/rheumatoid arthritis.

[b] Physical activity levels: 'Meet neither': MVPA= 0-149 MSE= 0-1 sessions/week; 'MSE only'; MSE= ≥2 sessions/week & MVPA= 0-149 minutes/week); 'MVPA only' MVPA= ≥150 minutes/week & MSE= 0-1 sessions/week; and 'Meet both': MVPA= ≥150 minutes /week & MSE= ≥2 sessions/week.

[c] Reference category = Recommended sleep (7-9 hours).

[d] adjusted for age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis.

[e] adjusted for sex, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis.

[f] adjusted for sex, age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis

Supplementary Table 3: Adjusted prevalence ratios[a] and their 95% confidence intervals (APR 95% CI) for short or longer than recommended sleep according to levels of physical activity guideline adherence[b]: stratified by sex, age and previous diagnosis of depression for adults aged ≥65 years.

		Sex-stratified	
		Male	**Female**
	Physical activity guideline adherence[b]	**APR[d](95% CI)**	**APR[d] (95% CI)**
Shorter than recommended sleep (4-6 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.96 (0.75-1.22)	0.98 (0.81-1.18)
	Aerobic MVPA only	0.75 (0.66-0.86)	0.82 (0.74-0.92)
	Meet both	0.71 (0.61-0.83)	0.71 (0.61-0.81)
Longer than recommended sleep' (9-12 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	1.09 (0.79-1.48)	0.93 (0.70-1.21)
	Aerobic MVPA only	0.82 (0.69-0.98)	0.72 (0.61-0.84)
	Meet both	0.73 (0.59-0.90	0.54 (0.44-0.67)
		Previous diagnosis of depression	
		Yes	**No**
		APR[f] (95% CI)	**APR[f] (95% CI)**
Shorter than recommended sleep (4-6 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.98(0.83-1.16)	0.95 (0.67-1.32)
	Aerobic MVPA only	0.80 (0.73-0.88)	0.82 (0.67-1.01)
	Meet both	0.70 (0.63-0.79)	0.79 (0.61-1.03)
Longer than recommended sleep' (9-12 hours)[c]	Meet neither	1 (reference)	1 (reference)
	Muscle strengthening only	0.94 (0.60-1.39)	1.03 (0.81-1.30)
	Aerobic MVPA only	0.57 (0.72-1.16)	0.76 (0.67-0.87)
	Meet both	0.76 (0.55-1.05)	0.64 (0.54-0.76)

[a] Prevalence ratio calculated using Poisson regression with a robust error variance and adjusted for sex, age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and comorbidities (hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer [non-skin], arthritis/rheumatoid arthritis.

[b] Physical activity levels: 'Meet neither': MVPA= 0-149 MSE= 0-1 sessions/week; 'MSE only'; MSE= ≥2 sessions/week & MVPA= 0-149 minutes/week); 'MVPA only' MVPA= ≥150 minutes/week & MSE= 0-1 sessions/week; and 'Meet both': MVPA= ≥150 minutes /week & MSE= ≥2 sessions/week.

[c] Reference category = Recommended sleep (7-8 hours).

[d] adjusted for age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis.

[e] adjusted for sex, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption, previous diagnosis of depression and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis.

[f] adjusted for sex, age, race/ethnicity, employment, education, income, self-rated health, BMI, smoking, heavy alcohol consumption and self-reported comorbidities: hypertension, high cholesterol, myocardial infarction, coronary heart disease, stroke, diabetes, chronic obstructive pulmonary disease, asthma, kidney disease, cancer non-skin and arthritis/rheumatoid arthritis