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RESEARCH

Effects of caffeine on accelerometer measured sleep and physical activity among older adults under free-living conditions

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Abstract

Background Adequate sleep and physical activity promote longevity among older adults. Caffeine supplementation could be used to increase activity levels, but its effects have not been examined in real-world settings where potential trade-offs regarding sleep quality are also considered. This study sought to examine associations between caffeine intake and accelerometer-derived sleep and activity among older adults under free-living conditions.

Methods Cross-sectional data were gathered from older adults aged 65+ in the 2011-14 National Health and Nutrition Examination Surveys (NHANES). Sleep parameters were derived from accelerometer data using a data-driven machine learning approach. Caffeine consumption was categorized based on weight (in mg/kg: 0, >0 to 1, >1 to 2, >2 to 3, >3) and absolute consumption (in mg: 0, >0 to 100, >100 to 200, >200 to 300, >300). Multivariable survey weighted regression models were used to examine associations between caffeine with average total daytime activity, highly active minutes, sleep duration, and sleep efficiency. Covariate adjustments included demographics, body mass index, smoking, alcohol, sleep disorders, sleep parameters (for activity outcomes), and daytime activity (for sleep outcomes).

Results *N* = 1,629 NHANES participants were included. Caffeine consumption was highest in the morning. In adjusted models, older adults who consumed > 3 mg/kg were 16.5% more active during the day (95% CI: 9.0, 24.4) and were highly active for 42.8 additional minutes (95% CI: 20.3, 65.4) compared to non-consumers. Similar results were observed for absolute consumption (mg), and significant but lower magnitude effects were observed for lower levels of consumption. Caffeine showed no association with sleep efficiency, while low levels of consumption (≤ 1 mg/kg, ≤ 200 mg) were associated with longer sleep duration.

Conclusions Under free-living dietary, sleep, and activity patterns, this study found older adults who consumed caffeine were more active than non-consumers. Overall consumption was not associated with sleep efficiency but was associated with longer sleep duration at ≤ 1 mg/kg and ≤ 200 mg. Future causal studies should determine the effectiveness of caffeine for promoting higher activity in older adult populations.

Keywords Older adults, Caffeine, Accelerometer, Actigraphy, Physical activity, Sleep, Sleep duration, Sleep efficiency, NHANES, Machine learning

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Background

Sleep and physical activity are crucial for protecting against aging-related decline in health and wellbeing [1, 2]. Sleep quality naturally worsens with age, but maintaining high quality sleep is critical for reducing individual risk of adverse health outcomes. Older adults with poor sleep quality are at higher risk of depression [3], cognitive-decline [4], and hypertension [5]. Like sleep, physical activity levels also decline with age [6], but highly active older adults are at a lower risk health conditions relating to cardiovascular complications [7] and cognitive impairments [8]. Given the importance of sleep and physical activity for promoting longevity in older populations, there is increasing interest in identifying modifiable factors that promote physical activity and high-quality sleep.

Caffeine is a psychoactive stimulant that reduces tiredness by antagonizing adenosine receptors in the brain [9, 10]. Caffeine is commonly used for its ergogenic effects on physical performance in younger populations [11], among which studies have found positive effects on anaerobic power [12], aerobic endurance [13, 14], and reduced perceived exertion [15]. Studies on older adults have largely mirrored methodological approaches taken in younger cohorts where caffeine is acutely consumed in a controlled setting prior to specific physical tasks. Previous studies have found that older adults performed better on arm-curl tests [16], walking tests [16–18], up and go tests [16], cycling endurance [19], and isometric arm flexion endurance tests [19] following acute caffeine consumption. Nevertheless, studies under free living conditions are lacking, and it is unclear whether caffeine consumed under real-world dietary habits is associated with greater total daytime activity. Given the protective effects of physical activity, particularly moderate-to-vigorous activity, studies are needed to determine if higher caffeine consumption correlates with greater activity levels in free living environments.

Studies on the effects of caffeine on sleep have produced varied conclusions based on the timing, amount, and setting in which caffeine is consumed. Many have posited that caffeine's stimulant properties negatively influence sleep quality, and such hypotheses have been observed in controlled experiments where caffeine reduced sleep duration and sleep efficiency [20, 21]. However, such studies were largely conducted in younger populations where caffeine was acutely consumed before sleep in a lab-based setting. By contrast, studies by Hu and Linden found no significant effects of caffeine on objectively and subjectively assessed sleep among older adults in naturalistic settings [22]. Conflicting conclusions have led to speculation that caffeine consumed in controlled studies deviates too far from everyday consumption habits and results in findings that are not generalizable [23]. While the biological mechanisms underpinning caffeine's sleep disruptive properties are relatively well understood, what is unclear is whether caffeine consumption under normal dietary habits negatively influences sleep among older adults. An additional limitation of existing studies is that none examined the effects of caffeine on both sleep and physical activity simultaneously. Caffeine's fatigue-reducing effects make it a potential candidate to promote higher activity levels, however, it is unclear if any potential benefits for stimulating physical activity come with an inherent tradeoff regarding sleep quality when caffeine consumption, activity levels, and sleep are all freely determined.

In this study we sought to understand the effects of caffeine consumption on total daytime activity, time spent highly active per day, sleep duration, and sleep efficiency among older adults using accelerometer data from the 2011–2014 National Health and Nutrition Examination Survey (NHANES). Sleep parameters were derived using a machine learning-based Hidden Markov-Model while caffeine consumption was quantified based on dietary recall questionnaires. Hourly activity analyses were additionally conducted to determine if caffeine users exhibited different temporal activity patterns throughout the day compared to non-users.

Methods

Study sample

The data in this study was taken from the 2011–2012 and 2013–2014 waves of the National Health and Nutrition Examination Survey (NHANES): a nationally representative survey of non-institutionalized Americans gathered using multi-staged probability sampling [24]. Participants provided demographics, lifestyle, medical, and dietary information during visits to Mobile Examination Centers. Afterwards, consenting individuals were instructed to wear an ActiGraph GT3X+triaxial accelerometer on their non-dominant wrist for seven consecutive days immediately after leaving the Mobile Examination Center. Participants were further instructed to wear the device continuously and not to remove it for the entire wear period. Raw accelerometer data were pre-processed by the NHANES and made publicly available as minute-level averages in Monitor-Independent Movement Summary (MIMS [25]) units. Data aggregated across 2011-14 for use in this study were consistent in their content and data collection procedures. Ethics approval for the NHANES was given by the National Center for Health Statistics Ethics Review Board and all participants provided their informed consent.

Caffeine consumption

During visits to the Mobile Examination Centers NHANES participants were asked to recall their diet from the day prior. The US Department of Agriculture Food Surveys Research Group processed the dietary recall data before making the timing, type, and nutrient values of every reported food and beverage publicly available. For this study, caffeine consumption in milligrams (mg) was divided into five groups: no caffeine, >0 to 100mg, >100 to 200 mg, and >200 to 300 mg, and >300 mg. A secondary caffeine exposure variable was derived based on mg of caffeine consumed per kilogram (kg) of body weight using the following categorizations: no caffeine, >0 to 1 mg/kg, >1 to 2 mg/kg, >2 to 3 mg/kg, and >3 mg/kg. Cutoffs were chosen following those used in prior controlled studies [11]. We further gathered the timing of caffeine consumption for each participant as well as the amount of caffeine consumed at each time.

Sleep parameters

Objectively measured sleep duration and efficiency were derived from the NHANES accelerometer data using a publicly available, unsupervised, Hidden Markov Model-based (HMM) sleep-wake identification algorithm [26]. The HMM identifies sleep and wake states by distinguishing between movement patterns based on accelerometer data. Acceleration recordings during sleep are largely near-zero, with some nonzero values that indicate movement during sleep. Wake-state acceleration is often at higher intensities due to active movements. The HMM defines sleep onset as the first timepoint of nighttime acceleration data identified as a sleep state. Subsequently, sleep offset is defined by the final timepoint identified as a sleep state. Sleep duration represents the total time between sleep onset and offset whereas wake time after sleep onset (WASO) is defined by summing the time spent in wake states between sleep onset and offset. Sleep efficiency, which represents the proportion of time between sleep onset and offset spent asleep, is therefore calculated by taking the difference between sleep duration and WASO then dividing by sleep duration. Sleep efficiency ranges from zero to one with higher values indicating better sleep. The HMM was developed and validated against gold-standard polysomnography and has been used in prior studies to assess sleep parameters among older adults [26–28].

A night of valid sleep data was defined as a night where the accelerometer data was sufficient in quality and quantity for the HMM to return sleep parameter estimates. Across all nights of valid sleep data, we calculated each participant's average sleep duration and sleep efficiency.

Physical activity

We first calculated each participant's average daytime activity by summing non-sleep activity within each day before taking the average across the days. Prior studies have determined that a cutoff of 19.6 MIMS can be used to classify activity levels as moderate-to-vigorous among older adults [29]. In this study we elected to use "highly active" instead of "moderate-to-vigorous" when describing activity levels. This decision was made to avoid confusion surrounding the equivalence of our categorizations with those in World Health Organization (WHO) public health guidance. Moderate-to-vigorous activity in the WHO activity guidelines [30] are not based on accelerometer cut-points, but rather based on Metabolic Equivalent Tasks (METs) and perceived exertion scales. Thus, alternative terminology was deemed necessary. In accordance with a cutoff of 19.6 MIMS, we calculated each person's number of highly active minutes between every sleep offset and onset time, after which the average was taken across the days. The resulting measure represented each participant's average number of highly active minutes during wake periods. We defined a valid day (non-sleep period) of accelerometer data as at least 90% wear time between sleep offset and sleep onset. Non-wear flags provided by the NHANES were used to identify valid days of accelerometer data. Only daytime activity and minutes of high activity from valid days were considered. In cases where a day was valid but non-wear time was present, we excluded activity counts during minutes of non-wear when deriving all activity metrics.

Covariates

To account for potential confounding, we further gathered each person's age, sex, education, race, marital status, income to poverty ratio, body mass index (BMI), alcohol consumption habits, smoking habits, and the presence or absence of sleep disorders. Education categorizations were made based on if an individual's highest level of education was less than higher school, high school or equivalent, some college or associate degree, and college or above. Marital status was defined as married or living with a partner, divorced or separated, widowed, or never married. Individuals who reported currently using cigarettes "every day" or "some days" were categorized as smokers. Individuals who had at least 12 drinks in the last year and reported non-zero values for the frequency they drank over the last 12 months were categorized as drinkers.

Statistical analysis

NHANES participants were excluded if they were less than 65 years old, without dietary recall data, did not have at least five days of accelerometer wear time, or if they did not have at least five nights of accelerometer-derived sleep information, or had missing values in their covariates. All analyses were conducted in accordance with the NHANES Analytic Guidelines using the dietary recall survey weights [31] to account for non-response bias and discrepancies in selection probabilities.

Cohort characteristics were reported as population means and proportions. We additionally derived each participant's average acceleration within each hour across the wear period. Confidence intervals were then calculated for each hour after which spline interpolation was used, and the results were plotted.

Survey-weighted generalized linear models (GLMs) were used to examine associations between absolute (mg) and weight-adjusted (mg/kg) caffeine consumption with average overall daytime activity, minutes of high activity, sleep duration, and sleep efficiency. No caffeine consumption was the reference group in all models. Total daytime activity was modelled on the log scale and coefficients in the corresponding models were reported as a percent change relative to no caffeine consumption. Univariable models, demographic models adjusted for age, sex, race, education, marital status, and income to poverty ratio, as well as full models further adjusting for BMI, smoking, drinking, and sleep disorders, were considered. Full models with activity outcomes were additionally adjusted for sleep duration and efficiency while full models with sleep outcomes were additionally adjusted for total daytime activity. A sensitivity analysis was conducted on a subsample of older adults without sleep disorders (Supplementary Tables S5 and S6, Additional file 1).

An additional exploratory analysis among caffeine users was undertaken to examine whether consumption timing is associated with sleep. Caffeine consumption was summed within the morning (5am – noon), afternoon (noon – 7pm), and evening to overnight (7pm – 5am) for each participant. Two survey-weighted GLMs were fit: one to examine associations with sleep efficiency and another with sleep duration. Each model included caffeine consumed during the morning, afternoon, and evening to overnight as well as age, sex, race, education, marital status, income to poverty ratio, BMI, smoking, drinking, and sleep disorders.

All analyses in this study were undertaken using R version 4.3.3 and significance was set at 0.05.

Results

A total of $N=1{,}629$ NHANES participants were included in the analysis (Fig. 1). The average age was 72.7 (SD: 5.4) and 45% were male (Table 1). Caffeine consumption was most frequent and at the highest intensities during the

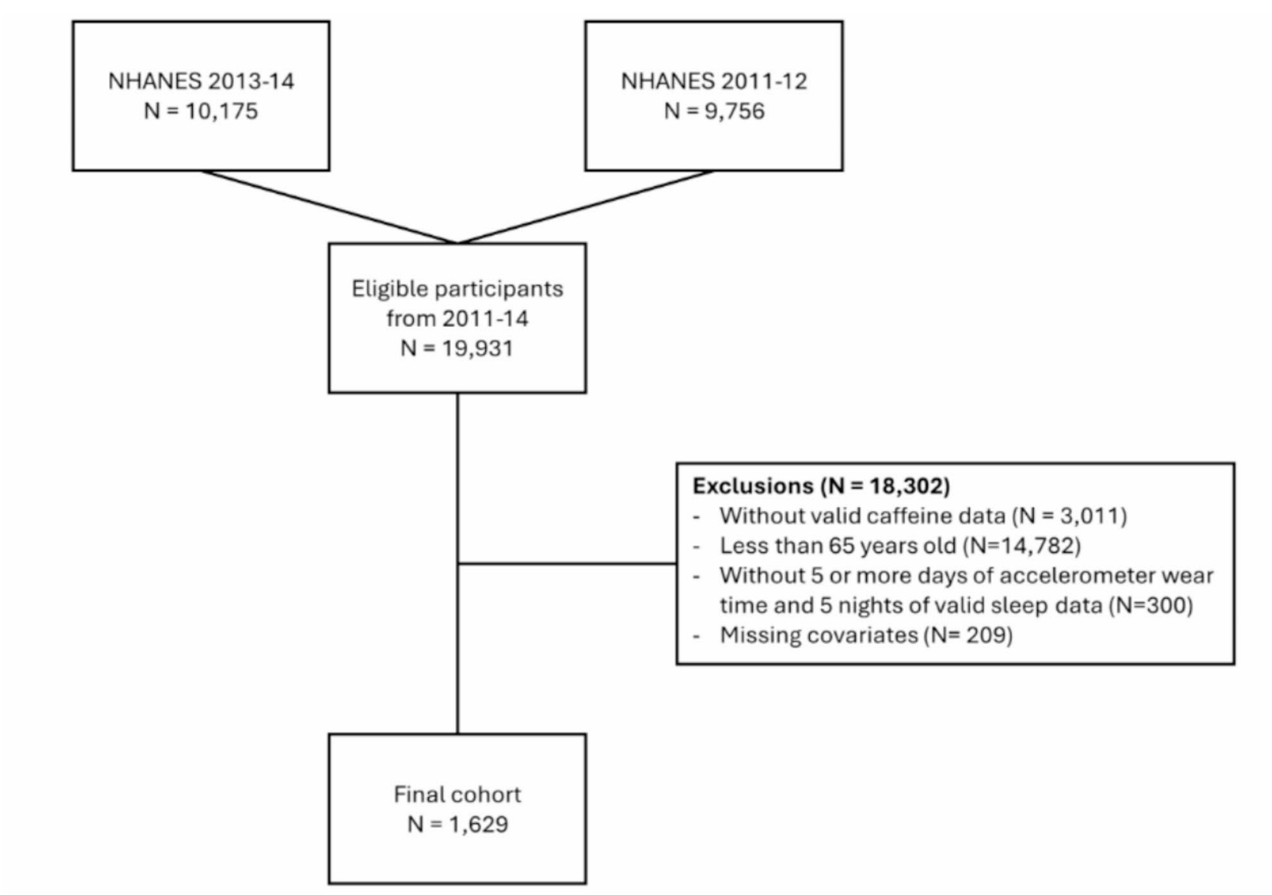

Fig. 1 Participant inclusion flowchart

Table 1 Cohort characteristics

Characteristic	Mean (SD) or %
Age, **mean (SD)**	72.66 (5.37)
Race, %	
Mexican American	2.76
Other Hispanic	3.64
Non-Hispanic White	79.83
Non-Hispanic Black	8.19
Non-Hispanic Asian	3.28
Other race or multi-racial	2.3
Sex – Male, %	45
Education, %	
Less than high school	19.06
High school or equivalent	21.95
Some college or AA degree	30.39
College or above	28.6
Marital status, %	
Married or living with a partner	62.84
Divorced or separated	12.02
Widowed	21.88
Never married	3.25
Smokes, %	8.25
Drinks, %	52.56
Sleep disorder, %	12.21
Income poverty ratio, **mean (SD)**	2.92 (1.55)
BMI, **mean (SD)**	28.77 (6)
Highly active minutes, **mean (SD)**	192.21 (100.95)
Total activity (MIMS), **mean (SD)**	10206.96 (3229.82)
Sleep duration (hours), **mean (SD)**	9.4 (1.64)
Sleep efficiency, **mean (SD)**	0.94 (0.04)
Caffeine consumption in mg, %	
0	8.13
>0 to 100	34.67
>100 to 200	24.22
>200 to 300	14.8
>300	18.18
Caffeine consumption in mg/kg, %	
0	8.13
>0 to 1	29.22
>1 to 2	21.2
>2 to 3	15.34
>3	26.11

morning (Fig. 2). The average BMI was 28.8 (SD: 6.0), 8% were smokers, and 53% were drinkers. Approximately 8% of older adults did not consume caffeine, whereas 18% consumed > 300 mg and 26% consumed > 3 mg/kg.

Raw distributions of caffeine consumption timing (x-axis) versus intensity (y-axis). A total of 18 outliers where consumption was > 750 were removed. The orange curve represents smoothed estimates.

In the hourly activity analyses older adults across all levels of caffeine consumption were largely more active on an hour-by-hour basis than those who did not consume caffeine (Fig. 3). Participants in the highest absolute consumption (> 300 mg) and weight adjusted consumption (> 3 mg/kg) categories were significantly more active than the non-caffeine consumption group for 10 of 24 h and 14 of 24 h respectively (based on average hourly activity and corresponding 95% CIs, Fig. 3). Those who consumed > 300 mg were more active from 6-8am and from 10am-6pm while those who consumed > 3 mg/kg were more active from 6am-8pm. Older adults who consumed caffeine were also generally less active in the late-evening to early-morning hours (9pm-6am) than those who did not consume caffeine, though the differences were not significant. Figures showing hourly-activity

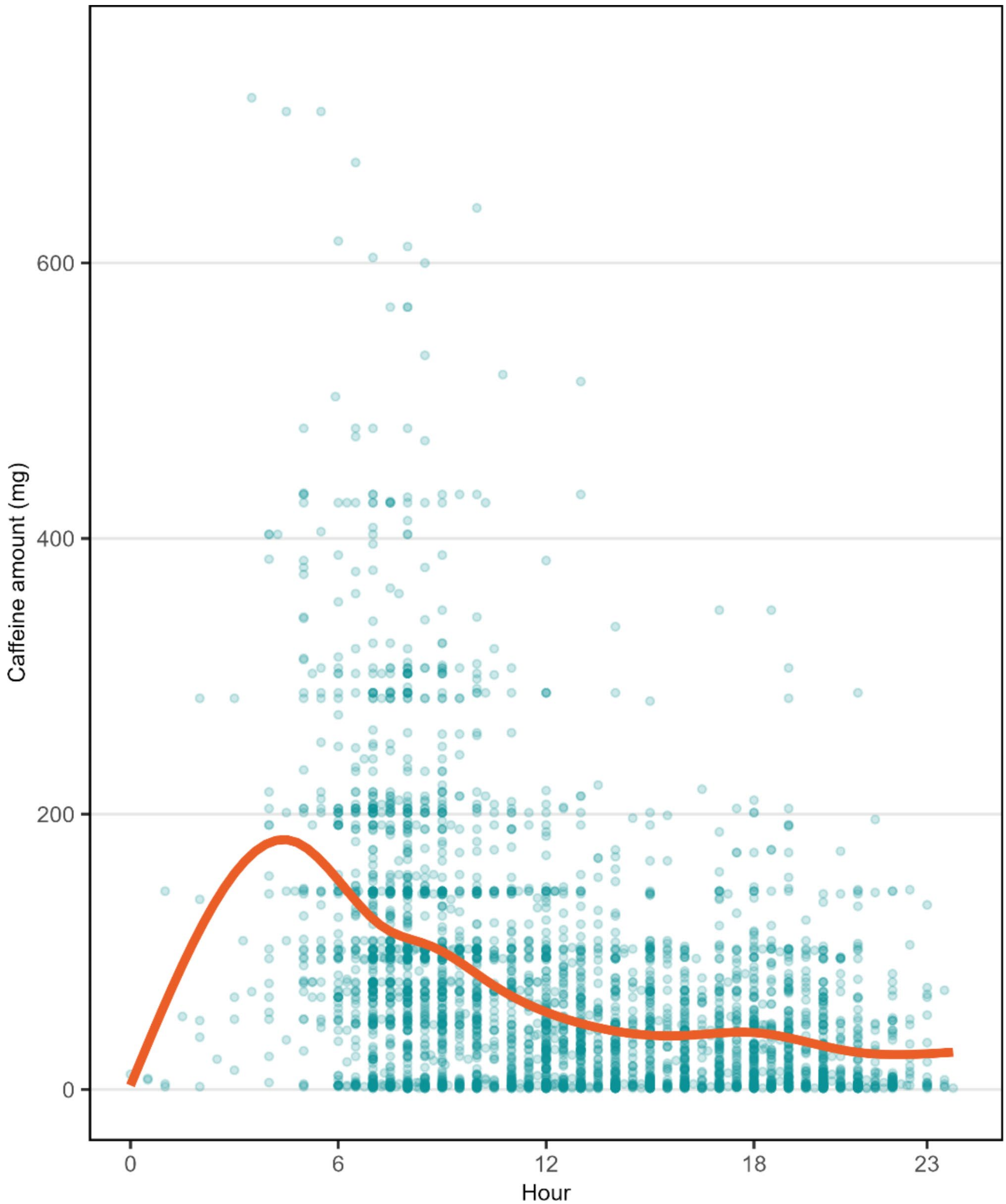

Fig. 2 Caffeine consumption timing versus intensity

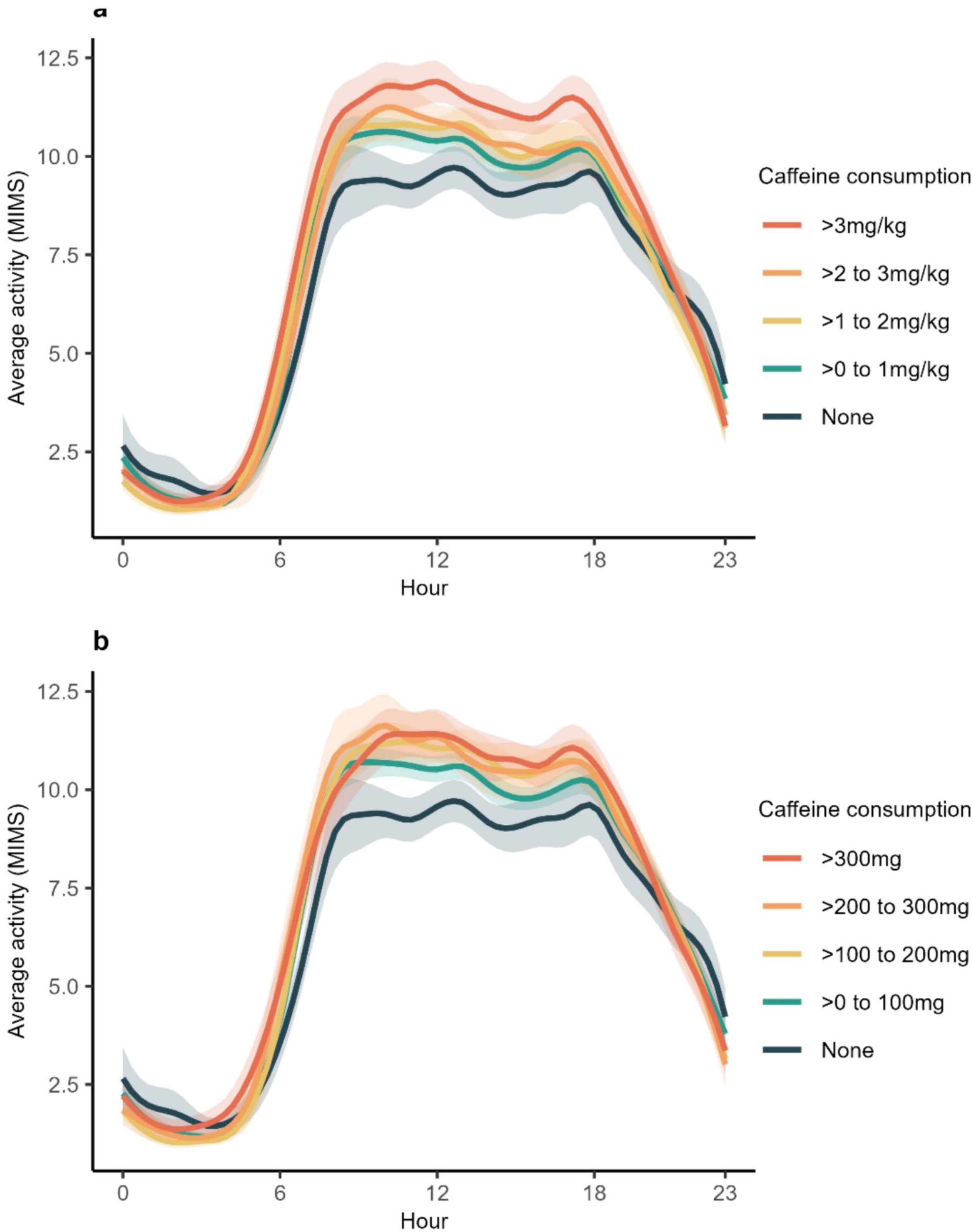

Fig. 3 Hourly daily activity stratified by caffeine consumption

Table 2 Effects of caffeine on physical activity parameters – full models

Covariate[a]	Total activity (MIMs)		Highly active time (mins/day)	
	% change (95% CI)	*p*	Difference (95% CI)	*p*
Caffeine (mg)				
None	Ref.	Ref.	Ref.	Ref.
>0 to 100	11.0 (4.2, 18.3)	0.0051	24.3 (2.3, 46.2)	0.0343
>100 to 200	12.2 (4.7, 20.3)	0.005	29.2 (7.1, 51.3)	0.0158
>200 to 300	14.2 (6.1, 22.8)	0.003	35.8 (11.4, 60.2)	0.0095
>300	13.8 (6.4, 21.8)	0.0022	36.5 (13.0, 59.9)	0.0071
Caffeine (mg/kg)				
0	Ref.	Ref.	Ref.	Ref.
>0 to 1	11.4 (4.3, 19.0)	0.0052	25.5 (2.8, 48.2)	0.0319
>1 to 2	10.2 (3.2, 17.7)	0.0091	21.2 (0.1, 42.2)	0.0492
>2 to 3	11.5 (3.5, 20.1)	0.0096	30.7 (6.1, 55.4)	0.0207
>3	16.5 (9.0, 24.4)	< 0.001	42.8 (20.3, 65.4)	0.0024

[a]Adjusted for age, sex, education, race, body mass index (BMI), income-to-poverty ratio, alcohol consumption, smoking, sleep disorders, sleep duration, and sleep efficiency

Table 3 Effects of caffeine consumption timing on sleep parameters – full models

Covariate[a]	Sleep duration (mins)		Sleep efficiency	
	Difference (95% CI)	*p*	Difference (95% CI)	*p*
Caffeine (mg)				
None	Ref.	Ref.	Ref.	Ref.
>0 to 100	22.1 (5.1, 39.0)	0.0164	-0.000 (-0.008, 0.008)	0.9948
>100 to 200	24.4 (6.7, 42.1)	0.0122	0.002 (-0.007, 0.010)	0.6944
>200 to 300	7.7 (-18.0, 33.4)	0.5158	0.001 (-0.010, 0.012)	0.8729
>300	15.1 (-14.0, 44.2)	0.2716	-0.004 (-0.021, 0.014)	0.6577
Caffeine (mg/kg)				
0	Ref.	Ref.	Ref.	Ref.
>0 to 1	26.0 (8.0, 44.0)	0.0096	-0.001 (-0.010, 0.008)	0.7885
>1 to 2	17.7 (-0.8, 36.3)	0.0589	0.003 (-0.006, 0.012)	0.4964
>2 to 3	14.7 (-12.0, 41.4)	0.244	-0.001 (-0.011, 0.008)	0.747
>3	13.9 (-11.9, 39.7)	0.2538	-0.001 (-0.015, 0.014)	0.9218

[a]Adjusted for age, sex, education, race, body mass index (BMI), income-to-poverty ratio, alcohol consumption, smoking, sleep disorders, and total daytime activity

differences between each consumption category relative to the no consumption can be found in Additional File Figs. 1 and 2.

After adjusting for demographics, BMI, smoking, drinking, sleep disorders, sleep duration, and sleep efficiency, caffeine consumption was significantly associated with higher levels of overall daily activity and more highly active time per day compared to non-consumption (Table 2). All levels of absolute and weight adjusted caffeine consumption were associated with at least a 10% increase in overall daytime activity levels compared to consuming no caffeine. Older adults who consumed > 300 mg were 13.8% more active (95% CI: 6.4, 21.8) than those who did not consume caffeine whereas those who consumed > 3 mg/kg were 16.5% more active (95% CI: 9.0, 24.4). Daily consumption > 3 mg/kg or > 300 mg was associated with 42.8 (95% CI: 20.3, 65.4) and 36.5 (95% CI: 13.0, 59.9) additional minutes of high activity relative to consuming no caffeine. Similar but lower magnitude effects were observed at lower levels of caffeine consumption. Demographic and univariable models can be found in Supplementary Tables S1 and S2 (Additional file 1).

Compared to consuming no caffeine, caffeine consumption was not associated with differences in sleep efficiency across all levels of consumption after accounting for total daytime activity, sleep disorders, smoking, drinking, BMI, and demographics ($p > 0.4$ for all consumption categories). Associations with sleep duration were varied. Consuming > 0 to 100 mg was associated with 22.1 additional minutes of sleep (95% CI: 5.1, 39.0) whereas consuming > 100 to 200 mg was associated with 24.4 additional minutes (95% CI: 6.7, 42.1) compared to consuming no caffeine. Consuming > 200 to 300 mg and > 300 mg had no significant associations with sleep duration (7.7, 95% CI: -18.0, 33.4 and 15.1, 95% CI: -14.0, 44.2 respectively). For weight-adjusted consumption only consuming > 0 to 1 mg/kg had a significant effect on sleep duration (26.0, 95% CI: 8.0, 44.0). Complete results from the full models can be found in Table 3 while demographic and univariable model results can be found in Supplementary Tables S3 and S4 (Additional file 1).

Discussion

This study found that older adult caffeine users were more active overall, were highly active for more minutes per day, but did not exhibit differences in sleep efficiency compared to older adults who did not consume caffeine when consumption, sleep, and physical activity were objectively measured under real-world conditions in a nationally representative cohort. Our study provides cross-sectional evidence supporting the need for causal studies that determine the effectiveness of caffeine-based dietary interventions for stimulating daytime activity. The findings presented herein additionally support prior hypotheses that the effects of caffeine on sleep measured in laboratory settings may not generalize when caffeine and activity levels are freely determined under natural living conditions.

Our study provides preliminary evidence that caffeine supplementation could be used as a catalyst to promote higher activity levels among older adults. Prior studies examining the effects of caffeine on physical activity have been conducted in controlled settings using specific physical tasks. The most common form of physical activity among older adults is walking [32], which may be distributed unevenly throughout the day. As such, existing studies are not well suited to draw conclusions about how caffeine influences overall daytime activity. We found that caffeine consumption > 300 mg or > 3 mg/kg was associated with more than 36 min of additional highly active time per day in real-world settings compared to consuming no caffeine. While the effects of caffeine on time spent highly active were strongest at high levels of caffeine consumption, the effects of caffeine on overall activity were strong across all levels of consumption. Existing evidence suggests that replacing sedentary behavior with higher intensity activities can result in reduced mortality risk [33], lower levels of frailty [34], faster gait speeds [35], reduced risk of depression [36], and better overall health-related quality of life [37, 38]. While additional studies are needed to confirm that caffeine is causally linked to higher activity levels, the benefits of greater activity among older adults are clear, and potential downstream effects of caffeine supplementation on physical activity could contribute to reducing individual risk of adverse health outcomes.

This study additionally found that caffeine consumed under free-living conditions had no effect on sleep efficiency, which is contrary to findings from controlled studies [20, 21]. Timing likely explains the opposing results. We found consumption to be highest in the morning (Fig. 2), meaning caffeine's ability to impact sleep was severely diminished by the time of sleep onset among older adults in our cohort. Conversely, controlled studies largely required participants to consume caffeine within a few hours of bedtime [20, 21]. Sleep efficiency may also adapt to caffeine consumption among habitual users [39, 40]. Such adaptations could further help explain the null effects on sleep efficiency observed in this study. However, it is unclear why low caffeine consumption (≤200 mg or ≤1 mg/kg) was nevertheless associated with longer sleep duration compared to no-consumption. The clinical relevance of such findings is also unclear. Uncertainty estimates (95% CIs) ranged from 5 additional minutes, which under most sleep habits would be a negligible difference, to 44 min, which is substantial. Previous work by Hu et al. also found that caffeine did not significantly influence the sleep duration among older adults in free living conditions [23]. Our work partially supports their conclusions at higher levels of caffeine consumption. Additional studies are therefore needed to determine if caffeine exhibits non-uniform effects across different sleep parameters.

This study is the first to provide real-world evidence regarding caffeine's effects on both sleep and physical activity in a single cohort of older adults. Prior findings led to hypotheses that a trade-off may exist between caffeine's beneficial effects on physical activity versus its negative effects on sleep. However, studies were lacking in real-world settings. Our findings suggest that no such tradeoff exists among older adults who consume caffeine most frequently and intensely in the morning. As such, this study provides foundational evidence for future causal studies seeking to examine the effectiveness of caffeine-based interventions for increasing activity levels among older adults. Such supplementation may be particularly beneficial for passively increasing activity levels among older adults who otherwise would refuse traditional physical training programs. However, causal studies are still needed, and any future supplementation programs will necessarily need to be personalized. Tolerance to caffeine's fatigue-reducing properties, either due to genetics or built-up from chronic consumption, can vary considerably between individuals [10, 41]. Negative side effects of caffeine will also need to be weighed against the positive effect on daytime activity. Negative side effects from caffeine can include increased blood pressure [42], anxiety [43], and indigestion [44]. Older adults may have a greater sensitivity to caffeine's side effects than younger adults [45], meaning caution will be necessary in any caffeine-based interventions to increase daytime activity. Caffeine's effects, both positive and negative, may also vary between habitual users and those who previously abstained from caffeine consumption. Longitudinal studies are therefore needed to untangle the complexities of designing caffeine-based interventions to provide dose-response evidence pertaining to negative side effects and to provide evidence on the efficacy of interventions relative to individual tolerance.

Another central component of future interventions will be the timing of caffeine consumption. In our preliminary analysis we found that higher consumption during the evening and overnight (7pm – 5am) to be associated with shorter sleep duration (Additional File Table 7). Such results are consistent with prior meta-analytic findings [20]. Administering caffeine during the morning appears to be the most intuitive candidate for optimal timing as it aligns closely with natural consumption habits (Fig. 2), allows sufficient time for caffeine to exit the bloodstream before sleep, and allows more daytime hours for caffeine's stimulatory effects to potentially increase daytime activity. Prior work also suggests that higher activity in the midday-afternoon (11am-5pm) is associated with the greatest reduction in mortality risk compared to other timeframes [46]. Such evidence further supports morning consumption as an optimal candidate. However, as mentioned previously, additional studies are needed to support or content any hypotheses regarding optimal timing.

The primary strengths of this study include using objective measures of both sleep and physical activity in a naturally representative cohort of older adults in real-world settings. Absolute and weight-adjusted caffeine derived from dietary questionnaires further allowed us to segment caffeine intake into specific categories similar to those used in lab settings. Compared to other observational studies that measured caffeine intake in cups of coffee or tea, the exposures used herein more precisely captured individual intake levels. The use of accelerometer data further allowed us to examine temporal hour-by-hour activity differences across different levels of caffeine consumption.

This study is not without limitations. First, caffeine consumption was measured using dietary data from a single day immediately preceding the wearable device wear period, meaning this study implicitly assumed that reported caffeine consumption was consistent during the device wear period. Second, causal effects of caffeine on physical activity and sleep could not be examined due to the cross-sectional nature of the data. The possibility of reverse causation cannot be overlooked. Differences in activity across caffeine consumption categorizations may be due to highly active individuals supplementing their diet with caffeine to maintain their energy levels. Future studies are therefore needed to support or contest the hypotheses generated based on our study. Third, as has been reported previously, the sleep-wake algorithm used herein may have overestimated sleep duration and efficiency due to difficulties differentiating sedentary and sleep states using minute-level acceleration data compared to more granular activity summaries [47–49]. Lastly, though this study was conducted in a nationally representative cohort from the United States, it is unclear whether the findings generalize across countries and cultures outside of the US.

Conclusion

Compared to not consuming caffeine, this study found that high consumption was associated with greater overall activity and more "highly active" time per day, but not associated with changes in sleep efficiency, among older adults under natural dietary and activity habits. Pending causal studies, caffeine supplementation could be used as a catalyst to promote physical activity among older adults without significantly impacting sleep quality if consumption is appropriately timed.

Abbreviations

BMI	Body mass index
HMM	Hidden Markov Model
kg	Kilograms
mg	Milligrams
MIMS	Motor Independent Movement Summary
NHANES	National Health and Nutrition Examination Survey

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-024-20115-6.

Supplementary Material 1

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None.

Author contributions

CS, WZ, and XL conceptualized and designed the study. CS and WX conducted statistical analyses. All authors were involved in the interpretation of the results as well as revising the manuscript. The final paper was read and approved by all authors.

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None.

Data availability

The National Health and Nutrition Examination Survey (NHANES) is publicly available through the National Center for Health Statistics.

Declarations

Ethics approval and consent to participate

All NHANES participants provided informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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