Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

Accelerometer-measured physical activity and sedentary behaviour are associated with C-reactive protein in US adults who get insufficient sleep: A threshold and isotemporal substitution effect analysis

Yanwei You

To cite this article: Yanwei You (2024) Accelerometer-measured physical activity and sedentary behaviour are associated with C-reactive protein in US adults who get insufficient sleep: A threshold and isotemporal substitution effect analysis, Journal of Sports Sciences, 42:6, 527-536, DOI: 10.1080/02640414.2024.2348906

To link to this article: https://doi.org/10.1080/02640414.2024.2348906

JOURNAL OF SPORTS SCIENCES
2024, VOL. 42, NO. 6, 527–536
https://doi.org/10.1080/02640414.2024.2348906

Routledge
Taylor & Francis Group

PHYSICAL ACTIVITY, HEALTH AND EXERCISE

Accelerometer-measured physical activity and sedentary behaviour are associated with C-reactive protein in US adults who get insufficient sleep: A threshold and isotemporal substitution effect analysis

Yanwei You [a,b]

[a]Division of Sports Science & Physical Education, Tsinghua University, Beijing, China; [b]School of Social Sciences, Tsinghua University, Beijing, China

ABSTRACT

This study aimed to investigate the association between physical activity, sedentary behaviour and chronic inflammation in short sleep adults. The study included 2,113 NHANES participants with self-reported insufficient sleep. C-reactive protein (CRP) was used as the inflammatory biomarker. Physical activity and sedentary behaviour were objectively measured by accelerometers. Weighted regression model, two – piecewise linear regression model, and restricted cubic splines were applied to evaluate associations mentioned above. An isotemporal substitution model was used to assess the modelled effects of replacing sedentary time (ST) with moderate-to-vigorous levels of physical activity (MVPA) or light physical activity (LPA). After adjusting for potential confounding factors, higher levels of ST and lower levels of LPA or MVPA were associated with higher CRP levels. Isotemporal substitution analysis indicated that replacing 30 minutes of ST with 30 minutes of MVPA was associated with a significant decrease in CRP levels. Saturation analysis suggested that the association between MVPA and CRP may plateau at over 20 minutes of MVPA per day. Findings of this study provides insight into the potential benefits of replacing ST with MVPA. This study also suggests that increasing MVPA beyond a certain point may not provide additional anti-inflammatory benefits in a short sleep population.

ARTICLE HISTORY
Received 6 July 2023
Accepted 22 April 2024

KEYWORDS
Short sleep; C-reactive protein; inflammation; physical activity patterns; population-based study

1. Introduction

Over the last three decades, there has been a significant decrease in sleep duration, leading to a rising prevalence of insufficient sleep (Ford et al., 2015; Keyes et al., 2015). It is estimated that in the near future, the price of insufficient sleep will culminate upward to $467.7 billion, predominantly attributable to reduced work productivity and increased risk of mortality linked to insufficient sleep (Hafner et al., 2017). As a means of promoting optimal well-being for adults aged 18–60, the American Academy of Sleep Medicine (AASM) Society suggests at least 7 hours of regular, daily sleep (Watson et al., 2015). Nonetheless, 1/3 of Americans fail to meet this recommendation, necessitating a comprehensive investigation into the health implications experienced by those who experience inadequate sleep.

An abundance of evidence has demonstrated that insufficient sleep represents a considerable factor in the development of inflammation (Atrooz & Salim, 2020; Park et al., 2016; Simpson & Dinges, 2007). C-reactive protein (CRP), acknowledged as a non-specific inflammatory marker, is synthesized in the liver and fundamentally triggers immune responses within the body. This vital protein manifests itself as an autonomous prognosticator of a variety of health outcomes, including obesity (Visser et al., 1999), diabetes (King et al., 2003), cardiovascular diseases (Nocon et al., 2008), stroke (Ford & Giles, 2000), cancer (Allin & Nordestgaard, 2011), and affective disorders (Howren et al., 2009; Pitharouli et al., 2021). CRP is released in response to inflammation, increasing when there is an acute or chronic inflammatory condition present within the physiological system (Ablij & Meinders, 2002). Multiple studies have illustrated that individuals experiencing short sleep duration exhibit elevated CRP rates, indicating an increased risk of inflammation (Holingue et al., 2018; Richardson & Churilla, 2017; Rico-Rosillo & Vega-Robledo, 2018).

In addition to the link between short sleep duration and inflammation, the evidence also suggests that physical activity and sedentary behaviour may play a role in inflammation and CRP levels (Parsons et al., 2017; Pryzbek et al., 2019; You et al., 2022). However, the intensity of physical activity in relation to CRP is unknown, especially among those experiencing insufficient sleep. In the short-sleep population, the positive effects of physical activity are not consistent (Stefan et al., 2018; You et al., 2023, You et al., 2024). There has been abundant evidence that high intensity exercise can bring multiple positive effects on inflammation (Edwards & Loprinzi, 2018; You et al., 2021; You et al., 2023). However, it seems that varying levels of activity intensity might be the reason behind the different impacts of physical activity on biomarkers of systemic inflammation (Nilsson et al., 2018). Based on the above findings, we propose that there is a "sweet spot" in terms of exercise intensity that is optimal for reducing inflammation in the short-sleep population.

Cumulatively, existing research has elucidated that physical activity exerts anti-inflammatory effects, including the attenuation of C-reactive protein (CRP) levels, whereas insufficient

CONTACT Yanwei You yyw22@mails.tsinghua.edu.cn Division of Sports Science & Physical Education, Tsinghua University, Beijing 100084, China
Supplemental data for this article can be accessed online https://doi.org/10.1080/02640414.2024.2348906

sleep appears deleterious in this regard. Research on the associations between varying intensities of physical activity and CRP levels among individuals experiencing short sleep, as well as whether substituting sedentary time with moderate-to-vigorous physical activity (MVPA) or light physical activity (LPA) can have a beneficial effect on inflammation in this population, remains unknown. Although some studies have shown associations between physical activity or exercise participation in different forms and decreased inflammation (Z. Liu et al., 2018; Paolucci et al., 2018), the study populations were small and non-representative of the US population. Additionally, evidence regarding the impact of different physical activity intensities on inflammation was inconsistent (Ding & Xu, 2022; Metsios et al., 2020). Therefore, exploring the dose-response relationship may provide a more comprehensive understanding of the impact of MVPA on CRP levels in individuals with short sleep. The present study endeavours to address these limitations in evidence and provide insights to help develop targeted interventions aimed at mitigating inflammation in individuals with inadequate sleep, thereby improving health outcomes.

To our knowledge, no prior empirical investigation has examined the impact of sedentary behaviour and physical activity on inflammation among adults who get insufficient sleep. Drawing upon data from the National Health and Nutrition Examination Survey (NHANES), we sought to investigate this research gap. The objective of this study was to (i) explore associations between physical activity patterns and CRP levels in individuals with insufficient sleep; (ii) utilize an isochronous substitution model and examine the impact of physical activity replacing sedentary behaviour on CRP levels; (iii) perform a dose-response analysis and determine whether there is a threshold for physical activity intensity that may provide a significant reduction in CRP levels.

2. Methods

2.1. Design and participants

Data from the cross-sectional National Health and Nutrition Examination Survey (NHANES) were analysed. NHANES is a health and nutrition examination survey designed to assess Americans' health and nutritional status. Briefly, this survey contains a multistage probability-clustered, nationally representative sample with stratification at different levels of complexity from various states of the country. Since NHANES introduced its first sleep questionnaire in 2005 and 24-hour waist-worn accelerometer data was available on 2003–2004 and 2005–2006 cycles, we selected the cycle of NHANES 2005–2006. The NCHS Research Ethics Review Board approved the survey protocol and each participant provided written consent to participate in NHANES.

A flowchart illustrating the inclusion and exclusion process is shown in Figure 1. A total of 9,950 participants were initially included in the study and 4,773 participants were left after excluding those under the age of 20 years ($n = 5,177$). Following this, participants without sleep information or sleeping for more than 7 hours were excluded ($n = 1,791$). Participants with missing CRP information reflecting inflammation were excluded ($n = 191$). Further exclusions were made for participants who lacked accelerometer measurement data ($n = 588$). Participants who were pregnant ($n = 92$) and those with missing covariate data ($n = 88$) were also eliminated. Finally, the study population consisted of 2,113 NHANES participants with short sleep durations and completed accelerometer and CRP data.

2.2. Measurement of sleep

Participants were asked to provide information on their typical sleep length in response to a prompt asking about their routine

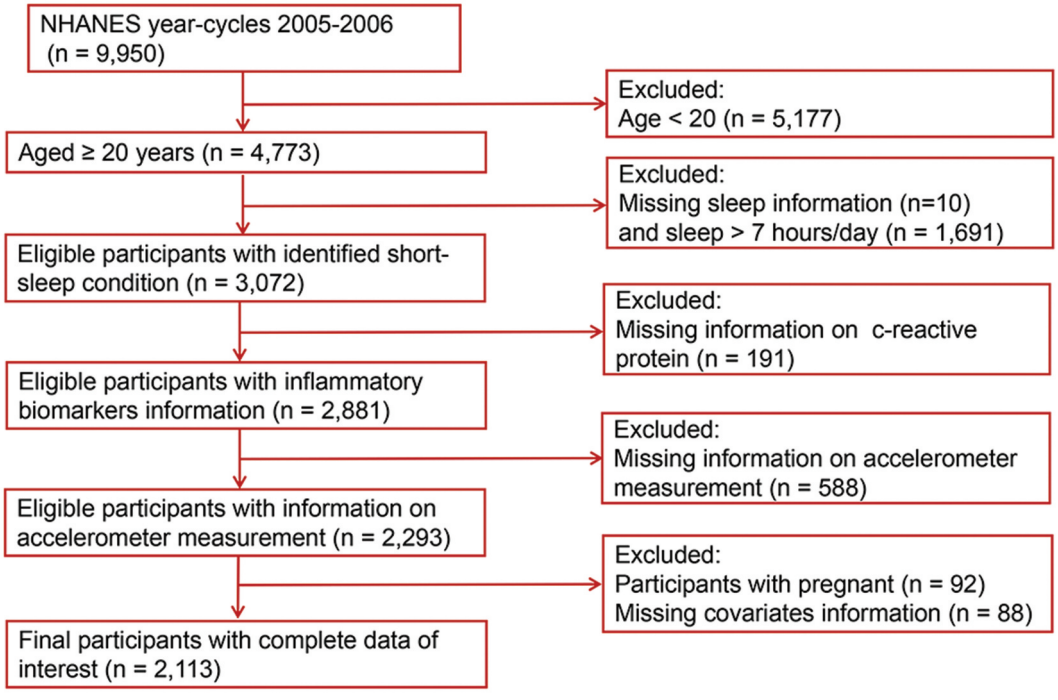

Figure 1. Flowchart illustrating the inclusion and exclusion process.

sleep hours: "How much sleep do you get (hours)?" Data was then compiled accordingly from participant responses recorded typically in whole numbers and according to the hours slept in a 24-hour cycle. National Sleep Foundation's recommended sleep duration in the general population (including young adults, adults and older adults) was at least 7 hours per night (Hirshkowitz et al., 2015; Hirshkowitz et al., 2015). Hence, the cut-off value of short-sleep in this study was set at 7 hours (Y. Liu et al., 2016; You et al., 2023; You et al., 2024).

2.3. Measurement of physical activity

The characterization of physical activity in this study was delimited by the measurement of time participants spent engaged in three daily behaviours: sedentary time (ST), MVPA or LPA. These intensities were calculated using data obtained from a minute-by-minute activity counts recorded via an ActiGraph AM-7164 accelerometer. Participants were required to wear the accelerometer on their waist with the exception of water-based activities and sleep. To ensure the integrity of the physical activity data, we established a criterion where participant records needed a minimum of 10 hours of valid wear time data to be deemed reliable. Days falling below this threshold, with less than 10 hours (600 minutes) of wear time data, were deemed insufficient and thus excluded from our analytical assessments. Notably, in the present investigation, minutes recorded as sedentary were defined as intervals where activity counts fell below 100 counts per minute (CPM) while active minutes indicated those where counts exceeded this threshold. Additionally, LPA minutes were coded as values between 100 and 2020 CPM while MVPA measurements were identified as > 2020 CPM (Troiano et al., 2008; Tudor-Locke et al., 2015). Methodology and procedures associated with the collection of data for the NHANES accelerometer studies have been detailed previously and are available online on public platforms (Cdc/National Center for Health Statistics). These details have been discussed comprehensively in previous works catalogued elsewhere (Tudor-Locke et al., 2012).

2.4. Measurement of CRP

NHANES conducted physical examinations of participants at a mobile examination centre (MEC) during which blood samples were extracted for the purpose of assessing CRP. CRP levels were determined via latex-enhanced nephelometry (Dade Behring, Deerfield, IL). This assay was performed using a calibration curve to enable precise CRP concentration calculations while data signal reduction was achieved through implementation of a storable logit-log function. Quantitative CRP determination assays were conducted using a Behring Nephelometer in order to obtain reliable results with a high level of precision. Complete details on blood sample collection procedures and the analytical techniques utilized are available for review on the NHANES website (Cdc/National Center for Health Statistics, 2023).

2.5. Assessment of covariates

Referring to several previous publications based on the NHANES (You et al., 2023; You et al., 2022; You et al., 2023), this study incorporated a range of covariates to assess the relationship between physical activity patterns and CRP in the short sleep population. Specifically, we included variables such as age, gender, race/ethnicity (non-Hispanic white, non-Hispanic black, Mexican American, and other race), marital status, education, poverty-to-income ratio (PIR), body mass index (BMI), smoking, and alcohol use status. As an indicator of socioeconomic status, we assessed PIR, designating a value less than 1 as below the poverty threshold (Lee et al., 2012). BMI was determined by weight in kilograms divided by height in metres squared (kg/m^2). Smoking status information was obtained from responses to a questionnaire regarding cigarette use, with classification based on never, former, or current smoker. We also assessed alcohol intake status and distinguished between non-drinkers, moderate alcohol users, and high alcohol users. These measures were critical for understanding the influence of sociodemographic characteristics and lifestyle factors on our results.

2.6. Statistical analyses

To accomplish nationally representative estimates, survey analysis procedures were applied to account for sample weights (mobile examination centre exam weight), stratification, and clustering of the complex sampling design (You et al., 2024 You et al., 2024). Weighted means and standard errors (SEs) were calculated for continuous variables, while weighted proportions were determined for categorical variables. Weighted linear regression models using a 30-minute change as the unit for ST, LPA, and MVPA were carried out to pinpoint associations with CRP levels. Quartiles of ST, LPA, and MVPA were also computed as categorical variables for regression analysis to better reflect the trend between physical activity patterns and CRP levels.

To control for covariates, unadjusted and multivariate adjusted models were employed in the analysis. Three models were generated: a crude model without any covariates, Model 1 with covariate adjustments for age, sex, and race, and Model 2 with additional covariates such as marital status, education, PIR, BMI, smoking, and alcohol use status. Regression results were presented as β values with their respective 95% confidence intervals (95% CIs). Stratified analyses were carried out using the crude model to evaluate the effects of different subgroups.

Isotemporal substitution analysis was implemented to investigate the modelled effects of different physical activity patterns on CRP levels. The isotemporal substitution model was chosen due to its increasing usage in physical activity and health research (Buman et al., 2014; Mekary & Ding, 2019; Nagai et al., 2018). It estimates the effect of changing the amount or type of physical activity on a health outcome while maintaining the total amount of physical activity constant. Under the assumption that the individual's total amount of physical activity remained unchanged and that any change in physical activity was due to a substitution of one type of

physical activity for another, the model was performed to discern the influence of different physical activities on health indicators (such as CRP in this study) by quantifying how replacing a given amount of time spent in one type of activity intensity with an equivalent duration allocated to other intensities (Mekary et al., 2009).

In compliance with prevailing methodologies, we divided all activity intensities (i.e., sedentary behaviour, LPA, and MVPA) by a constant of 30. This approach ensured that each unit represented an exchange of 30 minutes of these behaviours per day and allowed for equivalence to physical activity guidelines (Galmes-Panades et al., 2019). To facilitate a time-substitution model, the author created a variable by adding together sedentary behaviour, LPA, and MVPA. The equation used in the time-substitution model is illustrated as follows: Model = (β1) Total Time + (β2) LPA + (β3) MVPA + (β4) covariates. Notably, the variable to be substituted was not included in the formula. In this regard, β1 – β4 represent the coefficients of different activities on health outcomes without sedentary time.

To investigate the threshold effect and control for any confounding variables, a two-piecewise linear regression model was employed (Xiao et al., 2022; Zhu et al., 2020). Specifically, employing the recurrence method enabled us to identify inflection points occurring over a predefined interval, aiding in the determination of threshold levels of sedentary time, LPA, and MVPA (minutes/day). Comparing the log-likelihood ratio test results for the two-piecewise linear regression model to the one-line linear regression model, the non-linear relationship was also evaluated using restricted cubic splines (optimal knots = 3, the fully adjusted model was used). All analyses were conducted using R and R Studio as the programming environment. The determination of statistical significance in the present investigation was based on a p-value of less than 0.05.

3. Results

The final analysis included a total of 2,113 participants who reported short-sleep duration, with an average sleep of 6.2 hours, representative of a population of 50,386,356 non-institutionalized residents. Among this cohort, 48.81% were male and 51.19% were female. The mean CRP level identified was noted to be 0.42 ± 0.02 mg/dL, reflecting a sensitive indicator for identifying low-grade inflammation indicative of various morbidities. The average time spent sedentary was 479.52 ± 2.97 minutes per day, with an average of 258.86 ± 1.90 minutes per day spent in LPA and 24.05 ± 0.75 minutes per day in MVPA. More demographic information about the study participants is illustrated in Table 1.

After controlling for potential confounding factors and using the continuous measures (represented by 30 minutes of change), the fully adjusted model revealed that higher levels of sedentary time were marginally associated with higher CRP levels [β (95% CI): 0.008(−0.001, 0.017), $p = 0.076$], while higher levels of LPA [β (95% CI): −0.015(−0.030, −0.001), $p = 0.048$] and MVPA [β (95% CI): −0.116(−0.180, −0.051), $p = 0.002$] were associated with lower CRP levels. Moreover, as shown in Table 2, these findings were consistent in the crude model and partially adjusted model (Model 1).

In terms of segmented quartile measures, consistent results were identified with the utilization of either the crude or different adjusted models, as reported in Table 2. When referencing

Table 1. The demographic characteristics of NHANES participants in this study.

Variable	(%)*	Variable	(%/Mean)*
Age		Smokers	
<40	34.83	Never smoker	51.54
[40, 60)	45.36	Former smoker	24.38
≥60	19.81	Current smoker	24.08
Sex		Alcohol drinkers	
Male	48.81	Nondrinker	32.00
Female	51.19	Moderate alcohol use	49.68
Race/ethnicity		High alcohol use	18.32
Non-hispanic White	70.85	Sedentary behaviour (as category)	
Non-hispanic Black	12.43	Q1	23.70
Mexican American	7.76	Q2	26.72
Other Race/ethnicity	8.96	Q3	25.33
Marital status		Q4	24.25
Never married	12.78	LPA (as category)	
Married/living with partner	68.65	Q1	24.14
Widowed/divorced	18.58	Q2	25.43
Education		Q3	25.84
Below high school	5.44	Q4	24.59
High school	36.61	MVPA (as category)	
College or above	57.95	Q1	20.62
Poverty income ratio		Q2	24.22
<1	9.29	Q3	27.49
[1,3)	35.14	Q4	27.68
≥3	55.57	C-reactive protein (mg/dL)	0.42 ± 0.02
BMI (kg/m^2)		Sleep duration (hours/day)	6.18 ± 0.03
<25	30.61	Sedentary behaviour (minutes/day)	479.52 ± 2.97
[25, 30)	32.40	LPA (minutes/day)	258.86 ± 1.90
≥30	36.99	MVPA (minutes/day)	24.05 ± 0.75

*Weighted percentage for category variables and weighted Mean ± SE for continuous variables: NHANES, National Health and Nutrition Examination Survey; BMI, body mass index; LPA, light-level physical activity; MVPA, moderate-to-vigorous level of physical activity.

Table 2. Associations between accelerometer-measured sedentary behaviour, LPA and MVPA with c-reactive protein.

	Crude model[a]		Model 1[b]		Model 2[c]	
	β (95% CI)	*p-value*	β (95% CI)	*p-value*	β (95% CI)	*p-value*
Sedentary behaviour (30 * minutes/day)	0.012(0.004,0.021)	0.008	0.009(0.000, 0.018)	0.042	0.008(−0.001, 0.017)	0.076
Sedentary behaviour (as category)						
Q1	Reference		Reference		Reference	
Q2	0.105(−0.072,0.283)	0.219	0.080(−0.121,0.280)	0.368	0.097(−0.055, 0.249)	0.195
Q3	0.137(0.021,0.252)	0.024	0.104(−0.031,0.238)	0.109	0.106(−0.019, 0.232)	0.090
Q4	0.137(0.034,0.240)	0.013	0.102(−0.015,0.218)	0.077	0.097(−0.014, 0.207)	0.082
LPA (30 * minutes/day)	−0.020(−0.033,-0.006)	0.007	−0.020(−0.034,-0.006)	0.011	−0.015(−0.030, −0.001)	0.048
LPA (as category)						
Q1	Reference		Reference		Reference	
Q2	−0.145(−0.249,-0.041)	0.011	−0.135(−0.251,-0.019)	0.029	−0.112(−0.211,-0.014)	0.028
Q3	−0.078(−0.237, 0.080)	0.302	−0.066(−0.256, 0.124)	0.427	−0.016(−0.200, 0.168)	0.857
Q4	−0.123(−0.234,-0.011)	0.033	−0.122(−0.238,-0.006)	0.043	−0.104(−0.216, 0.007)	0.065
MVPA (30 * minutes/day)	−0.177(−0.218,-0.135)	<0.001	−0.163(−0.229,-0.096)	<0.001	−0.116(−0.180,-0.051)	0.002
MVPA (as category)						
Q1	Reference		Reference		Reference	
Q2	−0.160(−0.341, 0.022)	0.079	−0.178(−0.395, 0.038)	0.090	−0.134(−0.322, 0.055)	0.153
Q3	−0.383(−0.525,-0.241)	<0.001	−0.403(−0.616,-0.190)	0.004	−0.324(−0.512,-0.135)	0.002
Q4	−0.441(−0.566,-0.316)	<0.001	−0.458(−0.671,-0.246)	0.002	−0.350(−0.544,-0.155)	0.002

[a]Crude model, no covariate was adjusted. [b]Model 1, age, sex, race were adjusted. [c]Model 2, age, sex, race, marital status, education, poverty status, body mass index, smokers, and alcohol drinkers were adjusted. CI, confidence interval; LPA, light-level physical activity; MVPA, moderate-to-vigorous level of physical activity.

the first quartile, the fourth quartile of sedentary behaviour displayed marginally positive associations with incremental increases of 0.097 mg/dL in CRP levels [β (95% CI): 0.097 (−0.014, 0.207), $p = 0.082$]. In contrast, when participants possessing the fourth measurement quartile of LPA and MVPA were compared against those belonging to the first measurement level, significant declines in CRP levels by 0.104 and 0.350 mg/dL were detected, respectively [β (95% CI): −0.104 (−0.216, 0.007), $p = 0.065$; β (95% CI): −0.350(−0.544, −0.155), $p = 0.002$]. These outcomes highlighted the potential preventive benefits of LPA and MVPA in reducing low-grade inflammation risk among the study participants.

Additionally, demographics and lifestyle were notable influencing variables. As depicted in Supplementary Figure S1, our findings found groups with elevated BMI [β (95% CI): 0.021 (0.002,0.040), $p = 0.030$], current smokers [β (95% CI): 0.023 (0.005,0.040), $p = 0.014$] or high alcohol users [β (95% CI): −0.032(0.006,0.059), $p = 0.021$] exhibited corresponding increased CRP levels with every 30-minute increment of sedentary behaviour over time. Additionally, concerning gender disparities, females appeared to reap greater benefits from LPA [β (95% CI): −0.040(−0.057, −0.023), $p < 0.001$] and MVPA [β (95% CI): −0.220(−0.309, −0.132), $p < 0.001$], leading to decreased CRP levels with each 30-minute increase of physical activity. Among different age groups, older participants aged 60 years and above benefited most in the associations between LPA and CRP levels [β (95% CI): −0.037(−0.070, −0.004), $p = 0.031$], however, middle-aged participants between ages 40 to 60 appeared to undergo notable decreases in CRP levels associated with increments of MVPA engagement [β (95% CI): −0.223(−0.315, −0.131), $p < 0.001$]. To provide further details on these associations across different subgroups, a stratified analysis was conducted utilizing the quartiles of sedentary time (Table S1), LPA (Table S2), and MVPA (Table S3).

Table 3 demonstrates that the substitution of 30 minutes of sedentary time with LPA was not found to be significantly associated with CRP levels [β (95% CI): −0.010(−0.032, 0.011), $p = 0.309$]. However, it was discovered that replacing 30 minutes of sedentary time with MVPA engendered a notable decrease in CRP levels [β (95% CI): −0.111(−0.174, −0.048), $p = 0.002$]. Substitution of 30 min of LPA with MVPA was associated with decreases in CRP levels [β (95% CI): −0.091(−0.171, −0.010), $p = 0.003$], while replacing 30 minutes of MVPA with analogous temporal segments of sedentary time [β (95% CI): 0.040(0.016, 0.065), $p = 0.003$] or LPA [β (95% CI): 0.042(−0.004, 0.089), $p = 0.073$] were associated with increases in CRP levels. These findings suggested that even a slight increase in MVPA could offer anti-inflammatory benefits in the short sleep population.

Furthermore, the saturation analysis (Table 4) using two – piecewise linear regression models indicated that there may be a plateau effect of MVPA on CRP levels, where increasing

Table 3. Isotemporal substitution model evaluation of 30 minutes/day replacement of sedentary behaviour and physical activity on c-reactive protein.

	Sedentary behaviour		LPA		MVPA	
	β (95% CI)	*p-value*	β (95% CI)	*p-value*	β (95% CI)	*p-value*
Sedentary behaviour (30 * minutes/day)	Dropped		−0.010(−0.032, 0.011)	0.309	−0.111(−0.174,-0.048)	0.002
LPA (30 * minutes/day)	0.010(−0.004, 0.023)	0.158	Dropped		−0.091(−0.171,-0.010)	0.003
MVPA (30 * minutes/day)	0.040(0.016, 0.065)	0.003	0.042(−0.004, 0.089)	0.073	Dropped	

Fully adjusted model (Model 2) was used. Age, sex, race, marital status, education, poverty status, body mass index, smokers, and alcohol drinkers were adjusted. CI, confidence interval; LPA, light-level physical activity; MVPA, moderate-to-vigorous level of physical activity.

Table 4. Threshold effect analysis of associations between accelerometer-measured sedentary behaviour, LPA and MVPA with c-reactive protein.

	β (95% CI)	*p-value*
Sedentary behaviour (minutes/day)		
One – line linear regression model	0.000 (0.000, 0.001)	0.095
Two – piecewise linear regression model		
Sedentary time < 480	0.000 (0.000, 0.001)	0.123
Sedentary time ≥ 480	0.000 (−0.001, 0.001)	0.791
Log – likelihood ratio test		0.439
LPA (minutes/day)		
One – line linear regression model	−0.001 (−0.001, 0.000)	0.056
Two – piecewise linear regression model		
LPA <280	−0.001 (−0.002, 0.000)	0.074
LPA ≥280	−0.000 (−0.001, 0.001)	0.854
Log – likelihood ratio test		0.431
MVPA (minutes/day)		
One – line linear regression model	−0.004 (−0.006, −0.002)	<0.001
Two – piecewise linear regression model		
MVPA <20	−0.016 (−0.023, −0.010)	<0.001
MVPA ≥20	−0.001 (−0.003, 0.001)	0.276
Log – likelihood ratio test		<0.001

Age, sex, race, marital status, education, poverty status, body mass index, smokers, and alcohol drinkers were adjusted. CI, confidence interval; LPA, light-level physical activity; MVPA, moderate-to-vigorous level of physical activity.

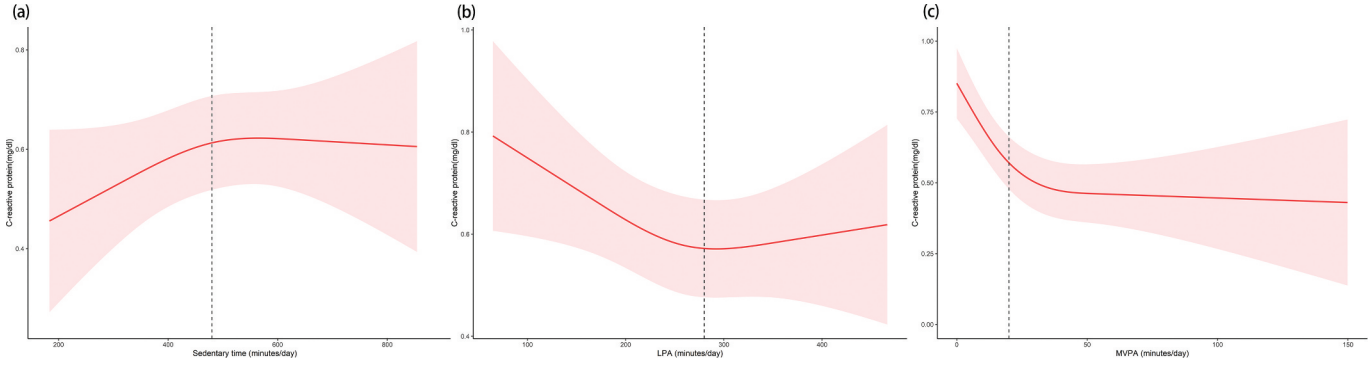

Figure 2. The dose-response relationship between sedentary time (a), LPA (b), MVPA (c) and c-reactive protein.

MVPA beyond 20 minutes per day may not provide additional anti-inflammatory benefits [β (95% CI): −0.001 (−0.003, 0.001), $p = 0.276$]. Similar plateaus were also identified in the associations between sedentary behaviour, LPA and CRP levels. These dose-response relationships are described in Figure 2

4. Discussions

The role of physical activity and sedentary behaviour in relation to inflammation has been the subject of several studies in recent years (Edwards & Loprinzi, 2018; Parsons et al., 2017; Pryzbek et al., 2019). This study sought to investigate the relationship between accelerometer-measured physical activity and sedentary time and CRP levels in a population of adults who reported short sleep duration. The study utilized data from the National Health and Nutrition Examination Survey (NHANES) and found a significant association between physical activity, sedentary behaviour and CRP levels.

This study found that more time spent sedentary was associated with increased CRP levels in the short sleep population. This finding aligned with previous research that confirmed the pro-inflammatory impact of extended sedentariness (Falconer et al., 2014; Haapala et al., 2022; Henson et al., 2013), hence providing further evidence in support of the proposition that even among people who lacked sleep, greater periods of inactivity were linked to amplified markers of chronic inflammation. The implications of such a relationship may be particularly concerning for those in occupations that entail both sleep insufficiency and extensive sitting, including office workers and long-distance drivers. While not explored in the present study, prior investigations have also demonstrated that brief interruptions in sedentary behaviour can elicit favourable effects on inflammation levels (Benatti & Ried-Larsen, 2015; Chandrasekaran et al., 2021), underscoring the importance not just of total physical activity amounts but also that of breaks from sedentary bouts. Furthermore, it's suggested that prioritizing physical activity over sedentary habits could bring about beneficial changes in systemic inflammation and reduce the risk of chronic diseases, considering that sedentary behaviour serves as a pivotal contributor to an increase in various metabolic and cardiovascular diseases (Wilmot et al., 2012).

An isochronous substitution model was employed to examine the effect of physical activity replacing sedentary behaviour on CRP levels among individuals with insufficient sleep. Our results showed that substituting sedentary time with MVPA was

associated with lower CRP levels, while substituting with LPA had no significant effect. One recent study in children shared similar findings with us, suggesting that utilizing MVPA to replace sedentary time can influence specific inflammatory biomarkers favourably, but found no such relationship between substitutions of other intensity levels and these biomarkers (Verswijveren et al., 2021). Another population-based, cross-sectional survey conducted in Ireland also identified that redirecting 30 minutes of sedentary time towards MVPA yielded an even more favourable inflammatory profile (Phillips et al., 2017). However, one study in a middle-aged population found that substituting LPA for sedentary time may be linked with favourable changes in methylation of apoptosis-associated speck-like protein, a potential inflammatory biomarker, while MVPA had little effect (Nishida et al., 2019). Differences in outcomes between studies may be explained by inconsistencies in inflammatory marker measurement times and different sample sizes. Based on our current findings, individuals who lack sufficient sleep should be encouraged to engage in MVPA, rather than LPA, to substitute for sedentariness, thus potentially improving chronic inflammation levels.

Furthermore, a dose-response analysis was conducted to determine if there exists an optimal threshold for MVPA that maximizes the reduction in CRP levels. Prior research indicated that people engaging in physical activity comprising a duration of roughly 150 minutes per week, or approximately 30 minutes daily (if conducted five days per week) experienced reduced serum inflammatory biomarker levels (Smith et al., 2019). Another previous study among the general population proposed that engaging in over 30 minutes of daily MVPA was associated with significantly lower CRP levels (Loprinzi, 2015). Interestingly, this study identified that for the short-sleep population, doing 20 minutes of MVPA daily may provide anti-inflammatory effects, beyond which increased quantities of MVPA confer marginal benefits. It may be that those who get short-sleep are more prone to fatigue and that greater MVPA amounts can produce stress and increasing inflammatory markers (Magherini et al., 2019; Pedersen & Hoffman-Goetz, 2000). Additional exploration is warranted to test the aforementioned conjectures.

Analyzing 24-hour movement behaviour is another perspective to explore the relationship between ST, LPA, MVPA and inflammation. The potential impact of reallocating time from sedentary behaviour to sleep for short sleepers is interesting. This raises a pertinent question: could reallocating time to additional sleep potentially confer similar benefits as seen with MVPA in terms of inflammation reduction? This aspect could indeed contribute to the observed MVPA threshold, suggesting that beyond a certain point, further allocation to MVPA might not yield additional benefits for inflammation. Redirecting time to prioritize adequate sleep might emerge as a more beneficial strategy. However, it's important to note that objectively measured sleep data was not available in the 2005–2006 NHANES dataset, which limited our ability to directly explore this aspect. Thus, we encourage further studies to obtain objectively-measured sleep and physical activity data to verify our findings.

Notable strengths in this study include examining the novel question of exploring the relationship between physical activity patterns in the short-sleep population. Secondly, large nationally representative samples are employed, which enhances the generalizability of the study findings. The inclusion and exclusion criteria highlight the rigorous and comprehensive procedures undertaken to obtain a focused and representative sample size for the current research investigation. Thirdly, accelerometry data are utilized to provide a more accurate assessment of physical activity and sedentary behaviour compared to self-report measures. Last but not least, isotemporal substitution models and threshold effect analysis methods are used to explore the detailed relationship between physical activity and inflammation, which enhances our understanding of the benefits of PA in populations with insufficient sleep.

However, there are also limitations to the study that should be considered. Firstly, the study used a cross-sectional design, which limited the ability to establish causality. As these data are cross-sectional, future studies, particularly longitudinal ones, are warranted. It is also important to note that this study focuses on individuals who report short sleep durations, which might not be representative of the general population. It could be another topic to look at populations who are getting the recommended amount of sleep each night. Secondly, in our analysis, we utilized the Troiano cut-points to establish ST, LPA, and MVPA. While these cut-points are commonly used and validated for adults, there are concerns about their application to special groups such as older adults. There is a lack of consensus on applicable cut-points to delineate PA intensity, particularly for older adults. Age-related changes in physical capabilities may affect the interpretation of activity levels. Thirdly, considering that time is finite, ST, LPA, MVPA are usually highly correlated with each other. Using an isotemporal substitution model may have the statistical limitations of multicollinearity. The emerging method of Isometric Log Ratio (ILR) analysis (involving time data of various activities using isometric log ratio transformation) can more precisely assess the impact of different physical activity behaviours on health indicators.

5. Conclusions

As a final note, in a nationwide short-sleep population, the findings of this study provided evidence of the importance of reducing sedentary behaviour and increasing MVPA to mitigate inflammation. The study highlighted the need for interventions such as MVPA aimed at reducing sedentary time in individuals who report short sleep durations. Moreover, a threshold effect was identified that more MVPA was not always better. There was a negative correlation between MVPA of no more than 20 minutes per day and inflammation levels in short sleep individuals. Future research should investigate the long-term impact of reducing sedentary behaviour and increasing physical activity on inflammation levels as well as the in-depth biological mechanisms.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Yanwei You http://orcid.org/0000-0001-8367-4980

Ethics approval and consent to participate

The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). All information from the NHANES program is available and free for public, so the agreement of the medical ethics committee board was not necessary.

Availability of data and material (ADM)

The datasets generated and analysed for the current study are available in the NHANES repository. These data can be accessed using the following link: https://wwwn.cdc.gov/nchs/nhanes/Default.aspx

References

Ablij, H., & Meinders, A. (2002). C-reactive protein: History and revival. *European Journal of Internal Medicine*, *13*(7), 412. https://doi.org/10.1016/s0953-6205(02)00132-2

Allin, K. H., & Nordestgaard, B. G. (2011). Elevated C-reactive protein in the diagnosis, prognosis, and cause of cancer. *Critical Reviews in Clinical Laboratory Sciences*, *48*(4), 155–170. https://doi.org/10.3109/10408363.2011.599831

Atrooz, F., & Salim, S. (2020). Sleep deprivation, oxidative stress and inflammation. *Advances in Protein Chemistry and Structural Biology*, *119*, 309–336. Advance online publication. https://doi.org/10.1016/bs.apcsb.2019.03.001

Benatti, F. B., & Ried-Larsen, M. (2015). The effects of breaking up prolonged sitting time: A review of experimental studies. *Medicine and Science in Sports and Exercise*, *47*(10), 2053–2061. https://doi.org/10.1249/MSS.0000000000000654

Buman, M. P., Winkler, E. A., Kurka, J. M., Hekler, E. B., Baldwin, C. M., Owen, N., Ainsworth, B. E., Healy, G. N., & Gardiner, P. A. (2014). Reallocating time to sleep, sedentary behaviors, or active behaviors: Associations with cardiovascular disease risk biomarkers, NHANES 2005–2006. *American Journal of Epidemiology*, *179*(3), 323–334. https://doi.org/10.1093/aje/kwt292

Cdc/National Center for Health Statistics. *National health and nutrition examination survey 2005–2006. Anthropometry and physical activity monitor procedures* manual. Retrieved April 7, 2023 from http://www.cdc.gov/nchs/data/nhanes/nhanes_05_06/BM.pdf

Cdc/National Center for Health Statistics. *National health and nutrition examination survey 2005–2006. Data documentation, codebook, and frequencies C-Reactive protein (crp)*. Retrieved April 7, 2023 from. https://wwwn.cdc.gov/Nchs/Nhanes/2005-2006/CRP_D.htm#LBXCRP

Chandrasekaran, B., Pesola, A. J., Rao, C. R., & Arumugam, A. (2021). Does breaking up prolonged sitting improve cognitive functions in sedentary adults? A mapping review and hypothesis formulation on the potential physiological mechanisms. *BMC musculoskeletal disorders*, *22*(1), 274. https://doi.org/10.1186/s12891-021-04136-5

Ding, Y., & Xu, X. (2022). Dose- and intensity-response associations between leisure-time physical activity and markers of inflammation and oxidative stress in older adults. *Journal of Aging and Physical Activity*, *30*(6), 950–962. https://doi.org/10.1123/japa.2021-0219

Edwards, M. K., & Loprinzi, P. D. (2018). Systemic inflammation as a function of the individual and combined associations of sedentary behaviour, physical activity and cardiorespiratory fitness. *Clinical Physiology and Functional Imaging*, *38*(1), 93–99. https://doi.org/10.1111/cpf.12388

Falconer, C. L., Cooper, A. R., Walhin, J. P., Thompson, D., Page, A. S., Peters, T. J., Montgomery, A. A., Sharp, D. J., Dayan, C. M., & Andrews, R. C. (2014). Sedentary time and markers of inflammation in people with newly diagnosed type 2 diabetes. *Nutrition, metabolism, and cardiovascular diseases : NMCD*, *24*(9), 956–962. https://doi.org/10.1016/j.numecd.2014.03.009

Ford, E. S., Cunningham, T. J., & Croft, J. B. (2015). Trends in self-reported sleep duration among us adults from 1985 to 2012. *Sleep*, *38*(5), 829–832. https://doi.org/10.5665/sleep.4684

Ford, E. S., & Giles, W. H. (2000). Serum C-Reactive protein and self-reported stroke: Findings from the third national health and nutrition examination survey. *Arteriosclerosis, Thrombosis, and Vascular Biology*, *20*(4), 1052–1056. https://doi.org/10.1161/01.atv.20.4.1052

Galmes-Panades, A. M., Varela-Mato, V., Konieczna, J., Warnberg, J., Martinez-Gonzalez, M. Á., Salas-Salvado, J., Corella, D., Schröder, H., Vioque, J., Alonso-Gómez, Á. M., Martínez, J. A., Serra-Majem, L., Estruch, R., Tinahones, F. J., Lapetra, J., Pintó, X., Tur, J. A., Garcia-Rios, A., … Fitó, M. (2019). Isotemporal substitution of inactive time with physical activity and time in bed: Cross-sectional associations with cardiometabolic health in the predimed-plus study. *The International Journal of Behavioral Nutrition and Physical Activity*, *16*(1), 137. https://doi.org/10.1186/s12966-019-0892-4

Haapala, E. A., Vaisto, J., Ihalainen, J. K., Gonzalez, C. T., Leppanen, M. H., Veijalainen, A., Sallinen, T., Eloranta, A.-M., Ekelund, U., Schwab, U., Brage, S., Atalay, M., & Lakka, T. A. (2022). Associations of physical activity, sedentary time, and diet quality with biomarkers of inflammation in children. *European Journal of Sport Science*, *22*(6), 906–915. https://doi.org/10.1080/17461391.2021.1892830

Hafner, M., Stepanek, M., Taylor, J., Troxel, W. M., & van Stolk, C. (2017). Why sleep matters-the economic costs of insufficient sleep: A cross-country comparative analysis. *Rand Health Quarterly*, *6*(4), 11.

Henson, J., Yates, T., Edwardson, C. L., Khunti, K., Talbot, D., Gray, L. J., Leigh, T. M., Carter, P., & Davies, M. J. (2013). Sedentary time and markers of chronic low-grade inflammation in a high risk population. *Public Library of Science ONE*, *8*(10), e78350. https://doi.org/10.1371/journal.pone.0078350

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Adams Hillard, P. J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., & Ware, J. C. (2015). National sleep foundation's updated sleep duration recommendations: Final report. *Sleep Health*, *1*(4), 233–243. https://doi.org/10.1016/j.sleh.2015.10.004

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., Ware, J. C., & Adams Hillard, P. J. (2015). National sleep foundation's sleep time duration recommendations: Methodology and results summary. *Sleep Health*, *1*(1), 40–43. https://doi.org/10.1016/j.sleh.2014.12.010

Holingue, C., Owusu, J. T., Feder, K. A., & Spira, A. P. (2018). Sleep duration and C-reactive protein: Associations among pregnant and non-pregnant women. *Journal of Reproductive Immunology*, *128*, 9–15. https://doi.org/10.1016/j.jri.2018.05.003

Howren, M. B., Lamkin, D. M., & Suls, J. (2009). Associations of depression with C-Reactive protein, il-1, and il-6: A meta-analysis. *Psychosomatic Medicine*, *71*(2), 171–186. https://doi.org/10.1097/PSY.0b013e3181907c1b

Keyes, K. M., Maslowsky, J., Hamilton, A., & Schulenberg, J. (2015). The great sleep recession: Changes in sleep duration among us adolescents, 1991-2012. *Pediatrics*, *135*(3), 460–468. https://doi.org/10.1542/peds.2014-2707

King, D. E., Mainous, A. G., 3rd, Buchanan, T. A., & Pearson, W. S. (2003). C-Reactive protein and glycemic control in adults with diabetes. *Diabetes Care*, *26*(5), 1535–1539. https://doi.org/10.2337/diacare.26.5.1535

Lee, H., Cardinal, B. J., & Loprinzi, P. D. (2012). Effects of socioeconomic status and acculturation on accelerometer-measured moderate-to-vigorous physical activity among Mexican American adolescents: Findings from

NHANES 2003-2004. *Journal of Physical Activity & Health*, *9*(8), 1155–1162. https://doi.org/10.1123/jpah.9.8.1155

Liu, Z., Hsu, F. C., Trombetti, A., King, A. C., Liu, C. K., Manini, T. M., Fielding, R. A., Pahor, M., Newman, A. B., Kritchevsky, S., & Gill, T. M. (2018). Effect of 24-month physical activity on cognitive frailty and the role of inflammation: The life randomized clinical trial. *BMC Medicine*, *16* (1), 185. https://doi.org/10.1186/s12916-018-1174-8

Liu, Y., Wheaton, A. G., Chapman, D. P., Cunningham, T. J., Lu, H., & Croft, J. B. (2016). Prevalence of healthy sleep duration among adults–United States, 2014. *MMWR Morbidity and Mortality Weekly Report*, *65*(6), 137–141. https://doi.org/10.15585/mmwr.mm6506a1

Loprinzi, P. D. (2015). Frequency of moderate-to-vigorous physical activity (MVPA) is a greater predictor of systemic inflammation than total weekly volume of MVPA: Implications for physical activity promotion. *Physiology & Behavior*, *141*, 46–50. https://doi.org/10.1016/j.physbeh.2015.01.002

Magherini, F., Fiaschi, T., Marzocchini, R., Mannelli, M., Gamberi, T., Modesti, P. A., & Modesti, A. (2019). Oxidative stress in exercise training: The involvement of inflammation and peripheral signals. *Free Radical Research*, *53*(11–12), 1155–1165. https://doi.org/10.1080/10715762.2019.1697438

Mekary, R. A., & Ding, E. L. (2019). Isotemporal substitution as the gold standard model for physical activity epidemiology: Why it is the most appropriate for activity time research. *International Journal of Environmental Research and Public Health*, *16*(5). 797. https://doi.org/10.3390/ijerph16050797

Mekary, R. A., Willett, W. C., Hu, F. B., & Ding, E. L. (2009). Isotemporal substitution paradigm for physical activity epidemiology and weight change. *American Journal of Epidemiology*, *170*(4), 519–527. https://doi.org/10.1093/aje/kwp163

Metsios, G. S., Moe, R. H., & Kitas, G. D. (2020). Exercise and Inflammation. *Best Practice and Research Clinical Rheumatology*, *34*(2), 101504. https://doi.org/10.1016/j.berh.2020.101504

Nagai, K., Tamaki, K., Kusunoki, H., Wada, Y., Tsuji, S., Ito, M., Sano, K., Amano, M., Shimomura, S., & Shinmura, K. (2018). Isotemporal substitution of sedentary time with physical activity and its associations with frailty status. *Clinical Interventions in Aging*, *13*, 1831–1836. https://doi.org/10.2147/CIA.S175666

Nilsson, A., Bergens, O., & Kadi, F. (2018). Physical activity alters inflammation in older adults by different intensity levels. *Medicine and Science in Sports and Exercise*, *50*(7), 1502–1507. https://doi.org/10.1249/MSS.0000000000001582

Nishida, Y., Hara, M., Higaki, Y., Taguchi, N., Nakamura, K., Nanri, H., Horita, M., Shimanoe, C., Yasukata, J., Miyoshi, N., Yamada, Y., Higashimoto, K., Soejima, H., & Tanaka, K. (2019). Habitual light-intensity physical activity and asc methylation in a middle-aged population. *International Journal of Sports Medicine*, *40*(10), 670–677. https://doi.org/10.1055/a-0965-1374

Nocon, M., Hiemann, T., Muller-Riemenschneider, F., Thalau, F., Roll, S., & Willich, S. N. (2008). Association of physical activity with all-cause and cardiovascular mortality: A systematic review and meta-analysis. *European Journal of Cardiovascular Prevention & Rehabilitation: Official Journal of the European Society of Cardiology, Working Groups on Epidemiology & Prevention & Cardiac Rehabilitation & Exercise Physiology*, *15*(3), 239–246. https://doi.org/10.1097/HJR.0b013e3282f55e09

Paolucci, E. M., Loukov, D., Bowdish, D. M. E., & Heisz, J. J. (2018). Exercise reduces depression and inflammation but intensity matters. *Biological Psychology*, *133*, 79–84. https://doi.org/10.1016/j.biopsycho.2018.01.015

Park, H., Tsai, K. M., Dahl, R. E., Irwin, M. R., McCreath, H., Seeman, T. E., & Fuligni, A. J. (2016). Sleep and inflammation during adolescence. *Psychosomatic Medicine*, *78*(6), 677–685. https://doi.org/10.1097/PSY.0000000000000340

Parsons, T. J., Sartini, C., Welsh, P., Sattar, N., Ash, S., Lennon, L. T., Wannamethee, S. G., Lee, I. M., Whincup, P. H., & Jefferis, B. J. (2017). Physical activity, sedentary behavior, and inflammatory and hemostatic markers in men. *Medicine and Science in Sports and Exercise*, *49*(3), 459–465. https://doi.org/10.1249/MSS.0000000000001113

Pedersen, B. K., & Hoffman-Goetz, L. (2000). Exercise and the immune system: Regulation, integration, and adaptation. *Physiological Reviews*, *80*(3), 1055–1081. https://doi.org/10.1152/physrev.2000.80.3.1055

Phillips, C. M., Dillon, C. B., & Perry, I. J. (2017). Does replacing sedentary behaviour with light or moderate to vigorous physical activity modulate inflammatory status in adults? *The International Journal of Behavioral Nutrition and Physical Activity*, *14*(1), 138. https://doi.org/10.1186/s12966-017-0594-8

Pitharouli, M. C., Hagenaars, S. P., Glanville, K. P., Coleman, J. R. I., Hotopf, M., Lewis, C. M., & Pariante, C. M. (2021). Elevated C-Reactive protein in patients with depression, independent of genetic, health, and psychosocial factors: Results from the UK biobank. *The American Journal of Psychiatry*, *178*(6), 522–529. https://doi.org/10.1176/appi.ajp.2020.20060947

Pryzbek, M., Richardson, J., Thabane, L., & Tang, A. (2019). Exploring the association between physical activity, sedentary behavior, and high-sensitivity C-Reactive protein among stroke survivors. *Journal of Aging and Physical Activity*, *27*(3), 360–366. https://doi.org/10.1123/japa.2018-0080

Richardson, M. R., & Churilla, J. R. (2017). Sleep duration and C-Reactive protein in us adults. *Southern Medical Journal*, *110*(4), 314–317. https://doi.org/10.14423/SMJ.0000000000000632

Rico-Rosillo, M. G., & Vega-Robledo, G. B. (2018). Sleep and immune System. *Revista alergia Mexico*, *65*(2), 160–170. https://doi.org/10.29262/ram.v65i2.359

Simpson, N., & Dinges, D. F. (2007). Sleep and inflammation. *Nutrition Reviews*, *65*(12 Pt 2), S244–52. https://doi.org/10.1301/nr.2007.dec.S244-S252

Smith, L., Stubbs, B., Hu, L., Veronese, N., Vancampfort, D., Williams, G., Vicinanza, D., Jackson, S. E., Ying, L., López-Sánchez, G. F., & Yang, L. (2019). Is active transport and leisure-time physical activity associated with inflammatory markers in us adults? A cross-sectional analyses from Nhanes. *Journal of Physical Activity & Health*, *16*(7), 540–546. https://doi.org/10.1123/jpah.2018-0423

Stefan, L., Vrgoc, G., Rupcic, T., Sporis, G., & Sekulic, D. (2018). Sleep duration and sleep quality are associated with physical activity in elderly people living in nursing homes. *International Journal of Environmental Research and Public Health*, *15*(11). 2512. https://doi.org/10.3390/ijerph15112512

Troiano, R. P., Berrigan, D., Dodd, K. W., Masse, L. C., Tilert, T., & McDowell, M. (2008). Physical activity in the United States measured by accelerometer. *Medicine and Science in Sports and Exercise*, *40*(1), 181–188. https://doi.org/10.1249/mss.0b013e31815a51b3

Tudor-Locke, C., Barreira, T. V., Schuna, J. M., Jr., Mire, E. F., Chaput, J. P., Fogelholm, M., Hu, G., Kuriyan, R., Kurpad, A., Lambert, E. V., Maher, C., Maia, J., Matsudo, V., Olds, T., Onywera, V., Sarmiento, O. L., Standage, M., Tremblay, M. S., . . . Church, T. S. (2015). Improving wear time compliance with a 24-hour waist-worn accelerometer protocol in the international study of childhood obesity, lifestyle and the environment (iscole). *The International Journal of Behavioral Nutrition and Physical Activity*, *12*(1), 11. https://doi.org/10.1186/s12966-015-0172-x

Tudor-Locke, C., Camhi, S. M., & Troiano, R. P. (2012). A catalog of rules, variables, and definitions applied to accelerometer data in the national health and nutrition examination survey, 2003-2006. *Preventing Chronic Disease*, *9*, E113. Advance online publication. https://doi.org/10.5888/pcd9.110332

Verswijveren, S., Salmon, J., Daly, R. M., Della Gatta, P. A., Arundell, L., Dunstan, D. W., Hesketh, K. D., Cerin, E., & Ridgers, N. D. (2021). Is replacing sedentary time with bouts of physical activity associated with inflammatory biomarkers in children? *Scandinavian Journal of Medicine & Science in Sports*, *31*(3), 733–741. https://doi.org/10.1111/sms.13879

Visser, M., Bouter, L. M., GM, M., Wener, M. H., & Harris, T. B. (1999). Elevated C-Reactive protein levels in overweight and obese adults. *JAMA*, *282*(22), 2131–2135. https://doi.org/10.1001/jama.282.22.2131

Watson, N. F., Badr, M. S., Belenky, G., Bliwise, D. L., Buxton, O. M., Buysse, D., Dinges, D. F., Gangwisch, J., Grandner, M. A., Kushida, C., Malhotra, R. K., Martin, J. L., Patel, S. R., Quan, S., & Tasali, E. (2015). Recommended amount of sleep for a healthy adult: A joint consensus statement of the American Academy of sleep medicine and sleep research society. *Sleep*, *38*(6), 843–844. https://doi.org/10.5665/sleep.4716

Wilmot, E. G., Edwardson, C. L., Achana, F. A., Davies, M. J., Gorely, T., Gray, L. J., Khunti, K., Yates, T., & Biddle, S. J. H. (2012). Sedentary time in adults and the association with diabetes, cardiovascular disease and

death: Systematic review and meta-analysis. *Diabetologia*, *55*(11), 2895–2905. https://doi.org/10.1007/s00125-012-2677-z

Xiao, Q., Cai, B., Yin, A., Huo, H., Lan, K., Zhou, G., Shen, L., & He, B. (2022). L-Shaped association of serum 25-hydroxyvitamin D concentrations with cardiovascular and all-cause mortality in individuals with osteoarthritis: Results from the NHANES database prospective cohort study. *BMC Medicine*, *20*(1), 308. https://doi.org/10.1186/s12916-022-02510-1

You, Y., Chen, Y., Fang, W., Li, X., Wang, R., Liu, J., & Ma, X. (2022). The association between sedentary behavior, exercise, and sleep disturbance: A mediation analysis of inflammatory biomarkers. *Frontiers in immunology*, *13*, 1080782. https://doi.org/10.3389/fimmu.2022.1080782

You, Y., Chen, Y., Liu, R., Zhang, Y., Wang, M., Yang, Z., Liu, J., & Ma, X. (2024). Inverted U-shaped relationship between sleep duration and phenotypic age in US adults: a population-based study. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-56316-7

You, Y., Chen, Y., Li, J., Zhang, Q., Zhang, Y., Yang, P., & Cao, Q. (2023). Physical activity mitigates the influence of blood cadmium on memory function: A cross-sectional analysis in us elderly population. *Environmental Science and Pollution Research International*, *30*(26), 68809–68820. https://doi.org/10.1007/s11356-023-27053-7

You, Y., Chen, Y., Wei, M., Tang, M., Lu, Y., Zhang, Q., & Cao, Q. (2024). Mediation Role of Recreational Physical Activity in the Relationship between the Dietary Intake of Live Microbes and the Systemic Immune-Inflammation Index: A Real-World Cross-Sectional Study. *Nutrients*, *16*(6). https://doi.org/10.3390/nu16060777

You, Y., Chen, Y., Yin, J., Zhang, Z., Zhang, K., Zhou, J., & Jin, S. (2022). Relationship between leisure-time physical activity and depressive symptoms under different levels of dietary inflammatory index. *Frontiers in Nutrition*, *9*, 983511. https://doi.org/10.3389/fnut.2022.983511

You, Y., Chen, Y., Zhang, Q., Yan, N., Ning, Y., & Cao, Q. (2023). Muscle quality index is associated with trouble sleeping: A cross-sectional population based study. *BMC Public Health*, *23*(1), 489. https://doi.org/10.1186/s12889-023-15411-6

You, Y., Chen, Y., Zhang, Y., Zhang, Q., Yu, Y., & Cao, Q. (2023). Mitigation role of physical exercise participation in the relationship between blood cadmium and sleep disturbance: A cross-sectional study. *BMC Public Health*, *23*(1), 1465. https://doi.org/10.1186/s12889-023-16358-4

You, Y., Li, W., Liu, J., Li, X., Fu, Y., & Ma, X. (2021). Bibliometric review to explore emerging high-intensity interval training in health promotion: A new century picture. *Frontiers in Public Health*, *9*, 697633. Advance online publication. https://doi.org/10.3389/fpubh.2021.697633

You, Y., Liu, J., Wang, D., Fu, Y., Liu, R., & Ma, X. (2023). Cognitive performance in short sleep young adults with different physical activity levels: A cross-sectional fnirs study. *Brain Sciences*, *13*(2). https://doi.org/10.3390/brainsci13020171

You, Y., Mo, L., Tong, J., Chen, X., & You, Y. (2024). The role of education attainment on 24-hour movement behavior in emerging adults: evidence from a population-based studyTable_1.docx. *Frontier Public Health*, *12*. https://doi.org/10.3389/fpubh.2024.119715010.3389/fpubh.2024.1197150.s001

You, Y., Wang, R., Li, J., Cao, F., Zhang, Y., & Ma, X. (2024). The Role of Dietary Intake of Live Microbes in the Association Between Leisure-Time Physical Activity and Depressive Symptoms: A Population-based Study. *Applied Physiology, Nutrition, and Metabolism*. https://doi.org/10.1139/apnm-2023-0550

You, Y., Wei, M., Chen, Y., Fu, Y., Ablitip, A., Liu, J., & Ma, X. (2023). The association between recreational physical activity and depression in the short sleep population: A cross-sectional study. *Frontiers in Neuroscience*, *17*, 17. https://doi.org/10.3389/fnins.2023.1016619

Zhu, F., Chen, C., Zhang, Y., Chen, S., Huang, X., Li, J., Wang, Y., Liu, X., Deng, G., & Gao, J. (2020). Elevated blood mercury level has a nonlinear association with infertility in U.S. women: Data from the NHANES 2013–2016. *Reproductive Toxicology (Elmsford, NY)*, *91*, 53–58. https://doi.org/10.1016/j.reprotox.2019.11.005