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Lifestyle factors as mediators in the relationship between depression, obesity, and blood pressure in the post-pandemic era

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Abstract

Aim: The post-COVID-19 pandemic era has witnessed changes in psychological states and lifestyles. This study aims to explore the associations between depression, obesity, and hypertension, and further assess the mediating effects of lifestyle factors such as sleep duration, working hours, and physical activity on these disease relationships.

Methods: Using data from the National Health and Nutrition Examination Survey (NHANES) from 2005 to 2023, we calculated long-term trends in depression, sleep duration, working hours, metabolic equivalent of exercise, obesity, and blood pressure. Data from 42,395 (sleep duration), 23,101 (working hours), and 20,435 participants (physical activity) were used to evaluate the relationships between lifestyle factors, depression, obesity, and blood pressure.

Results: Between 2021 and 2023, the average depression score in the U.S. increased to 4.13 (4.74), with prevalence rising to 13.2%. Over the past 18 years, national body mass index (BMI), waist circumference (WC),



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waist-to-height ratio (WHtR), and sleep duration increased ($P < 0.001$), while working hours decreased ($P < 0.001$) and physical activity declined post-pandemic ($P < 0.001$). Depression was positively correlated with BMI, WC, WHtR, and diastolic blood pressure (DBP) ($P < 0.0001$), and negatively correlated with systolic blood pressure, sleep duration, and physical activity ($P < 0.0001$). Sleep duration and physical activity mediated 1.72%-4.52% and 9.28%-14.79%, respectively, of the positive correlation between depression and obesity. Physical activity mediated 5.49%-9.96% of the positive correlation between depression and DBP. No mediating effect of working hours was found between depression and obesity or blood pressure ($P = 0.500-0.936$).

Conclusion: In the post-COVID-19 pandemic era, this study advocates for increased attention to lifestyle factors. Moderate extensions in sleep duration, reductions in working hours, and increased physical activity may help alleviate the burdens of depression, obesity, and blood pressure.

Keywords: Depression, lifestyle, sleep duration, worktime, physical activity, obesity, blood pressure, COVID-19

INTRODUCTION

Depression has emerged as a major global health challenge. Over the past decade, the burden of depression has increased rapidly, significantly contributing to the global health burden. By 2021, approximately 332 million people worldwide were affected by depression, with this number continuing to rise^[1]. The COVID-19 pandemic has further exacerbated the prevalence of depression^[2-5]. During the pandemic, the prevalence of depression in the United States was more than three times higher than pre-pandemic levels^[6]. Moreover, many COVID-19 survivors continue to face persistent mental health issues. A recent meta-analysis indicates that the prevalence of depression remains as high as 18% within two years post-COVID-19 infection^[7]. Therefore, addressing the epidemic of depression and preventing the development of adverse psychological and physiological conditions is crucial, necessitating a multifaceted evaluation of feasible interventions.

Obesity and hypertension are significant chronic non-communicable diseases globally, affecting approximately 1 billion^[8,9] and 1.28 billion^[10,11] people, respectively. These conditions not only independently increase the risk of cardiovascular disease (CVD) but also frequently co-occur with depression^[12,13]. The comorbidity of hypertension and depression, in particular, has been associated with increased cardiovascular mortality^[14]. However, research has identified sleep disorders as a mediating factor between depression and obesity^[15], while physical activity plays a crucial bridging role between depression and overweight/obesity^[16,17]. Post-COVID-19 pandemic lifestyle changes may have profound implications for the onset and progression of mental health issues, obesity, and metabolic diseases such as hypertension^[18-21]. Despite the significant economic and interventional potential in this field, related research remains relatively scarce.

This study aims to explore the mediating role of lifestyle factors in the relationship between depression, obesity, and blood pressure-related indicators in the post-COVID-19 pandemic context, utilizing National Health and Nutrition Examination Survey (NHANES) data from 2005 to 2023. Through this research, we hope to elucidate the potential of lifestyle factors in improving the interplay between mental health and metabolic diseases, providing a theoretical basis for clinical interventions and public health policies.

METHODS

Study design and study population

The NHANES is a nationally representative, long-term survey conducted over a two-year cycle for over 50 years to assess the physical health status of the U.S. population. The NHANES protocol was approved by the Ethics Review Board of the National Center for Health Statistics at the Centers for Disease Control and

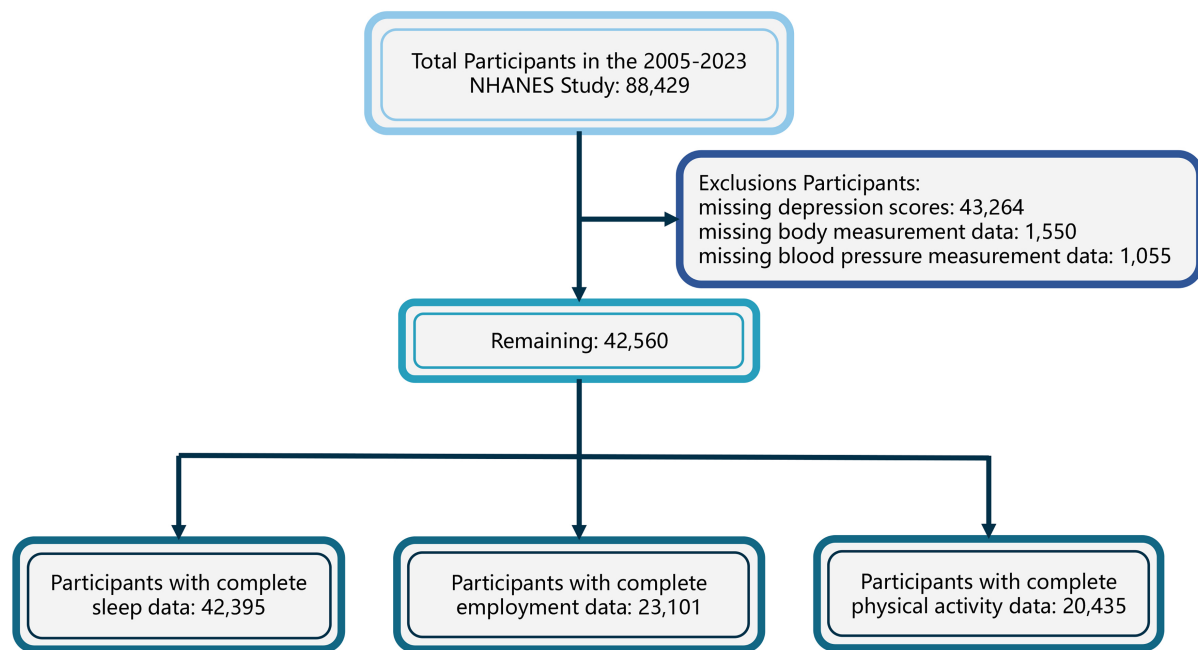


Figure 1. Study population recruitment and discharge flow diagram. NHANES: National Health and Nutrition Examination Survey.

Prevention (CDC), and all participants provided written informed consent. Detailed methods of the NHANES design and data collection have been published elsewhere^[22]. The study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline. Since 2005, NHANES has included data on depression. A total of 88,429 participants were enrolled from 2005 to 2023. After excluding 43,264 participants with missing depression data, 1,550 participants with missing anthropometric data, and 1,055 participants with missing blood pressure data, 42,560 participants remained. To ensure adequate sample sizes, further exclusions for missing data on sleep, work, or physical activity resulted in three independent samples: 42,395, 23,101, and 20,435 participants, respectively [Figure 1].

Assessment of depression, lifestyle factors, obesity, and blood pressure

Depression severity was assessed using the Patient Health Questionnaire (PHQ-9), which evaluates depressive symptoms over the past two weeks [Supplementary Materials]. Scores range from 0 to 27, with scores ≤ 9 indicating no depression and > 9 indicating depression^[23]. Lifestyles were assessed via questionnaires. Sleep duration was defined as the number of hours of sleep on weekdays, calculated as the difference between wake-up and bedtime when necessary. Work hours were defined as weekly hours worked, with a minimum of 5 h for those working < 5 h and a maximum of 80 h for those working > 80 h. Physical activity was calculated using the International Physical Activity Questionnaire Short Form (IPAQ) and metabolic equivalent (MET), quantifying moderate- and vigorous-intensity physical activity per week^[24,25]. We defined 1 min of moderate-intensity activity as 10/3 METs and 1 min of vigorous-intensity activity as 20/3 METs. Anthropometric data were obtained from the Mobile Examination Center (MEC), including height, weight, body mass index (BMI), and waist circumference (WC). The waist-to-height ratio (WHtR) was calculated by dividing WC (cm) by height (cm). Blood pressure measurements were taken at multiple time points by MEC staff, with participants having at least three readings. Systolic (SBP) and diastolic blood pressure (DBP) were defined as the average of these readings. Finally, BMI, WC, WHtR, SBP, and DBP were used to assess obesity and blood pressure status.

Assessment of covariates

Covariate selection was guided by prior studies, logical reasoning, and directed acyclic graph (DAG) modeling [Supplementary Figure 1]. Distal confounders, including age (< 40, 40-60, $\geq$ 60), sex, and race/ethnicity (non-Hispanic Black, non-Hispanic White, Mexican American, other), were included. Socioeconomic variables, such as family income-to-poverty ratio ($\leq$ 1, 1-3, > 3) and marital status (cohabiting or living alone), were considered potential influences on mood and lifestyle. Diabetes (yes/no) was included due to its potential impact on both mood and metabolism. Chronic diseases (yes/no), which can affect mood, were also considered as confounders. Smoking status (never, former, current) was included as a potential confounder for hypertension, and alcohol consumption (never/almost never, former, current) for metabolic outcomes. Hypertension was defined as SBP > 140 mmHg, DBP > 90 mmHg, a prior diagnosis, or current antihypertensive use. Diabetes was defined as fasting blood glucose > 7.0 mmol/L, HbA1c > 6.5%, a previous diagnosis, or current use of antidiabetic medications. Comorbidities, including coronary artery disease, heart failure, poorly controlled asthma, arthritis, stroke, liver disease, and cancer, were included as comorbidity variables for analysis.

Statistical analysis

We accounted for the complex survey design of NHANES, including sample weights, clustering, and stratification. Continuous variables were summarized by means and standard deviations (SD), while categorical variables were reported as counts and percentages (weighted percentages). Missing data were imputed using the random forest (RF) algorithm. All statistical analyses were conducted using R software (version 4.3.2), and a two-sided *P*-value < 0.05 was considered statistically significant.

Weighted analyses were used to examine trends in depression, lifestyle factors, obesity, and blood pressure over the past decade, with results displayed in line graphs. Due to its skewed distribution, physical activity MET values were log-transformed. Group comparisons were made using Kruskal-Wallis, Analysis of Variance (ANOVA), or chi-square tests. In the largest sleep sample ($N = 42,395$), generalized linear models (GLMs) were used to estimate effect sizes and standard errors between depression scores, lifestyle factors, and five obesity or blood pressure indicators. Mediation analysis was performed using the “mediation” package in R, accounting for NHANES complex survey design (including sample weights, clustering, and stratification). A bootstrap method with 1,000 iterations was applied to calculate the total, direct, and indirect mediation effects of depression on obesity and blood pressure, including 95% confidence intervals (CIs) and proportions of mediation.

In sensitivity analysis, structural equation modeling (SEM) was conducted using the “lavaan” package to assess mediation effects of depression through lifestyle factors on obesity and blood pressure, estimating total, direct, and indirect effects with 95%CIs. All model parameters were optimized using Nonlinear Minimization (NLMINB), considering sample weights but not clustering or stratification. Standardized coefficients on the Latent Variable Scale (Std.lv) and All Variables Scale (Std.all) were used to assess result robustness. Consistency between Std.lv and Std.all coefficients indicated model robustness across different scales. Results from primary and sensitivity analyses were considered robust when consistent.

RESULTS

Baseline characteristics

The findings of this study represent 241,746,897 U.S. adults, with an overall depression prevalence of 8.62%. Table 1 presents the characteristics of participants. Individuals with depression were younger, more likely to be female, non-Hispanic Black, have lower educational attainment, live alone, and report poorer economic status. Participants with depression were also more likely to smoke, have shorter sleep durations, work fewer hours, and engage in lower levels of physical activity. Additionally, individuals with depression had higher BMI, DBP, and a higher prevalence of comorbidities such as hypertension, diabetes, and hyperlipidemia.

Table 1. Baseline characteristics of NHANES participants from 2005-2023 grouped by depression status^a

Characters	Overall	No depression ^c	Depression ^c	P
Weighted number ^b	241,746,897	220,906,519	20,840,378	
Unweighted number ^b	50,255	45,386	4,869	
Age, years	46.85 (17.60)	46.94 (17.65)	45.86 (17.11)	0.004
Age group (%)				
< 40	17,992 (38.1)	16,325 (38.0)	1,667 (39.4)	0.001
40-60	15,261 (35.3)	13,583 (35.1)	1,678 (37.3)	
≥ 60	17,002 (26.6)	15,478 (26.9)	1,524 (23.3)	
Sex (%)				
Male	24,520 (48.8)	22,685 (49.9)	1,835 (37.3)	< 0.001
Female	25,735 (51.2)	22,701 (50.1)	3,034 (62.7)	
Race/Ethnicity (%)				
Non-hispanic black	10,796 (11.1)	9,754 (10.9)	1,042 (13.0)	< 0.001
Non-hispanic white	21,539 (66.2)	19,446 (66.5)	2,093 (62.4)	
Mexican American	7,263 (8.4)	6,582 (8.4)	681 (8.2)	
Others	10,657 (14.4)	9,604 (14.1)	1,053 (16.5)	
Education (%)				
Less than high school	13,136 (16.8)	11,410 (16.0)	1,726 (25.2)	< 0.001
High school or equivalent	25,349 (53.7)	22,772 (53.2)	2,577 (59.2)	
College or above	11,770 (29.5)	11,204 (30.8)	566 (15.6)	
Marital status (%)				
Living with partner	25,082 (55.2)	23,358 (56.7)	1,724 (38.5)	< 0.001
Living alone	25,173 (44.8)	22,028 (43.3)	3,145 (61.5)	
Family income-to-poverty ratio (%)				
≤ 1.0	9,549 (14.2)	8,005 (12.9)	1,544 (28.1)	< 0.001
1.0-3.0	18,677 (35.4)	16,722 (34.6)	1,955 (43.8)	
> 3.0	17,136 (50.5)	16,298 (52.6)	838 (28.1)	
Smoking (%)				
Never	27,756 (56.6)	25,654 (57.9)	2,102 (42.6)	< 0.001
Former	11,739 (24.6)	10,640 (24.8)	1,099 (22.6)	
Current	9,403 (18.8)	7,826 (17.3)	1,577 (34.8)	
Drinking (%)				
Never/Almost never	6,641 (10.9)	6,045 (11.0)	596 (10.4)	< 0.001
Former	5,629 (10.2)	4,970 (9.9)	659 (13.5)	
Current	33,450 (78.9)	30,386 (79.1)	3,064 (76.1)	
PHQ-9 scores	3.22 (4.31)	2.19 (2.43)	14.15 (4.76)	< 0.001
Sleep duration, hours/day	7.27 (1.47)	7.29 (1.41)	7.05 (2.01)	< 0.001
Work time, hours/week	40.55 (14.30)	40.69 (14.25)	38.41 (14.96)	< 0.001
Moderate PA, hours/week	3.73 (4.83)	3.72 (4.80)	3.79 (5.26)	0.707
Vigorous PA, hours/week	3.79 (4.22)	3.81 (4.17)	3.36 (5.13)	0.043
Log-transformed MET-mins/week	6.73 (1.09)	6.75 (1.08)	6.47 (1.22)	< 0.001
Height, cm	168.54 (10.02)	168.75 (10.00)	166.37 (9.90)	< 0.001
Weight, cm	83.11 (22.03)	82.95 (21.80)	84.88 (24.25)	< 0.001
BMI, kg/m ²	29.17 (7.03)	29.04 (6.89)	30.64 (8.29)	< 0.001
WC, cm	99.28 (16.83)	99.03 (16.67)	101.92 (18.31)	< 0.001
WHtR	0.59 (0.10)	0.59 (0.10)	0.61 (0.11)	< 0.001
High WHtR level (%)	41,518 (81.2)	37,349 (80.9)	4,169 (84.2)	< 0.001
SBP, mmHg	121.80 (17.13)	121.87 (17.08)	121.06 (17.74)	0.026
DBP, mmHg	71.36 (11.95)	71.30 (11.92)	72.04 (12.24)	0.002
Hypertension (%)	20,834 (37.1)	18,387 (36.3)	2,447 (45.9)	< 0.001

Diabetes (%)	8,748 (13.4)	7,528 (12.8)	1,220 (19.8)	< 0.001
Hyperlipidemia (%)	34,021 (67.3)	30,453 (66.9)	3,568 (71.5)	< 0.001
Comorbidity model (%) ^d	20,612 (39.5)	17,767 (38.0)	2,845 (56.2)	< 0.001
Coronary heart disease (%)	3,565 (5.9)	2,949 (5.5)	616 (10.4)	< 0.001
Congestive heart failure (%)	1,631 (2.4)	1,301 (2.1)	330 (5.5)	< 0.001
Stroke (%)	1,913 (2.9)	1,520 (2.6)	393 (6.8)	< 0.001
Poorly controlled asthma (%)	4,559 (8.9)	3,717 (8.1)	842 (17.7)	< 0.001
Liver disease (%)	1,153 (2.1)	892 (1.9)	261 (5.0)	< 0.001
Arthritis (%)	4,966 (25.8)	4,405 (24.4)	561 (40.4)	< 0.001
Cancer (%)	13,694 (10.3)	11,608 (10.1)	2,086 (11.6)	0.074

^aBaseline characteristics were calculated using the NHANES complex weighted design; no data imputation was performed; ^bData from 50,255 participants with complete depression information were analyzed, representing 241,746,897 Americans; ^cDepression was defined as a PHQ-9 score > 9; scores ≤ 9 were considered as no depression; ^dThe comorbidity model includes the presence of one or more of the following conditions: coronary heart disease, congestive heart failure, stroke, poorly controlled asthma, liver disease, arthritis, or cancer. NHANES: National Health and Nutrition Examination Survey; PA: physical activity; MET: metabolic equivalent; BMI: body mass index; WC: waist circumference; WHtR: waist-to-height ratio; SBP: systolic blood pressure; DBP: diastolic blood pressure; PHQ-9: patient health questionnaire-9.

Long-term trends in depression, lifestyle, obesity, and blood pressure

Among participants from 2021 to 2023, the mean depression score was 4.13 (SD = 4.74), with a prevalence of 13.2%, marking a significant increase compared to the lower, fluctuating levels observed over the past 18 years [Figure 2 and Supplementary Table 1]. Over the past 18 years, BMI, WC, and WHtR have shown upward trends [Supplementary Figures 2-6 and Supplementary Tables 2-6]. Compared to 2015, the 2023 SBP decreased from 120.76 mmHg (SD = 17.35) to 118.46 mmHg (SD = 17.13), while DBP increased from 67.95 mmHg (SD = 12.80) to 72.67 mmHg (SD = 11.37). The average nightly sleep duration increased from 6.93 h (SD = 1.39) in 2015 to 7.74 h (SD = 1.55) in 2023. Weekly working hours for employed individuals decreased from 41.99 h (SD = 14.81) to 39.54 h (SD = 13.93). Physical activity (measured in weekly MET-minutes) increased from 1,469.31 (SD = 1648.18) in 2017 to 1,566.61 (SD = 2,618.95) in 2023; however, its natural logarithmic value decreased from 6.79 (SD = 1.04) to 6.61 (SD = 1.32).

Associations between depression, lifestyle, obesity, and blood pressure

After adjusting for gender, age, race/ethnicity, marital status, education level, poverty-income ratio, smoking, alcohol consumption, hypertension, diabetes, dyslipidemia, and comorbidities, depression scores were significantly positively correlated with BMI ($\beta = 0.099$, SE = 0.011), WC ($\beta = 0.246$, SE = 0.026), WHtR ($\beta = 0.00153$, SE = 0.00016), and DBP ($\beta = 0.088$, SE = 0.017), and negatively correlated with SBP ($\beta = -0.120$, SE = 0.024) [Supplementary Table 7]. Sleep duration and physical activity were negatively associated with depression ($P < 0.0001$) [Supplementary Table 8]. Both sleep duration and physical activity were negatively correlated with obesity ($P < 0.0001$ to $P = 0.0027$). Weekly working hours were positively correlated with obesity ($P < 0.0001$) and DBP ($P = 0.0002$), but no significant correlation with SBP ($P = 0.9$) [Supplementary Table 9].

Mediating effects of lifestyle factors in the relationship between depression, obesity, and blood pressure

Table 2 presents the results of the mediation analysis using bootstrap resampling, accounting for NHANES complex survey weights, clustering, and stratification. Depression scores were positively correlated with BMI, WC, WHtR, and DBP in all three samples, and negatively correlated with SBP. Sleep duration mediated 3.09%, 1.78%, and -2.42% of the associations between depression and BMI, WHtR, and DBP,

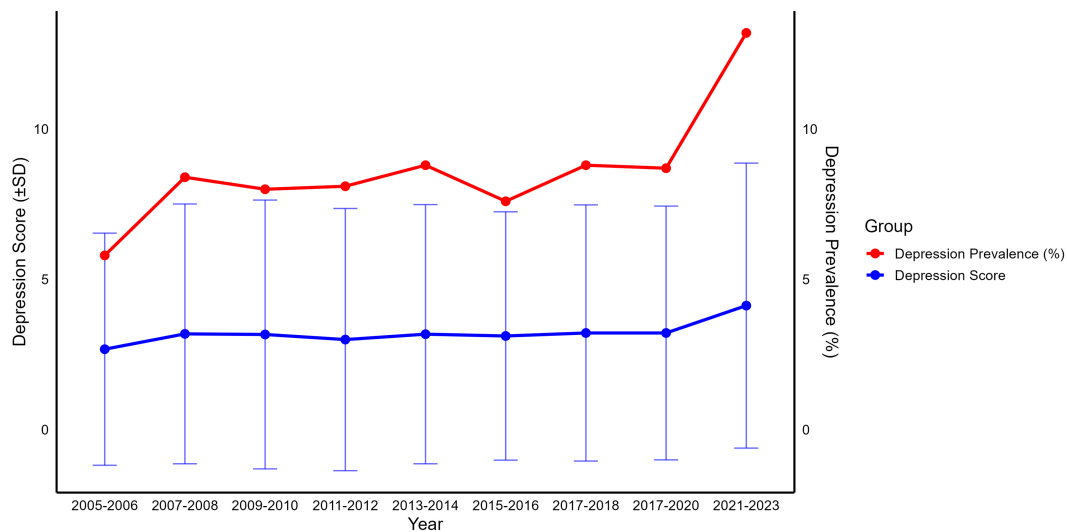


Figure 2. Trends in depression prevalence and scores among Americans from 2005 to 2023. Based on complex sampling weighted analysis, the study used the weights from each interview period, representing a total of 1,818,136,185 Americans. Due to the COVID-19 pandemic, sampling was paused in 2019-2020, resulting in a small sample size. As a result, the 2019-2020 period was combined with the 2017-2018 period into a single group. Participants in the 2017-2018 and 2017-2020 periods theoretically overlap.

respectively. The mediation effect between depression and WC was weaker (1.82%, $P = 0.11$), while no mediation effect was observed between depression and SBP ($P = 0.86$). Physical activity significantly mediated 11.72%, 15.42%, 14.79%, and 9.96% of the associations between depression and BMI, WC, WHtR, and DBP, respectively. Working hours did not mediate the relationship between depression and obesity or blood pressure.

Sensitivity analysis

Table 3 presents the sensitivity analysis results within the SEM framework, which only accounts for sampling weights. In all three samples, depression scores were positively correlated with BMI, WC, WHtR, and DBP ($P < 0.001$), and negatively correlated with SBP ($P < 0.001$). Sleep duration mediated 4.52%, 2.29%, 1.72%, and 1.62% of the associations between depression and BMI, WC, WHtR, and SBP, respectively. No mediation effect was observed between depression and DBP ($P = 0.441$). Physical activity mediated 9.28%, 14.10%, 14.69%, 5.49%, and -2.59% of the associations between depression and BMI, WC, WHtR, SBP, and DBP, respectively. No mediation effect by work hours was found between depression and obesity or blood pressure. Consistency across effect sizes, Std.lv, and Std.all coefficients supported the robustness of the findings. Results are considered robust when P -values < 0.05 and standardized coefficients are consistent across both analyses [Figure 3]. Sleep duration mediated 1.72%-4.52% of the association between depression and obesity, and physical activity mediated 9.28%-14.79% of the association between depression and obesity. Physical activity also mediated 5.49%-9.96% of the positive association between depression and DBP.

DISCUSSION

This study is the first to examine the trends of depression and lifestyle factors in the United States' post-pandemic era using nationally representative data. Findings reveal a significant increase in depression prevalence post-pandemic, rising from 8.7% pre-pandemic to 13.2%. This increase is accompanied by longer sleep durations, reduced working hours, and a slight decline in physical activity levels. Additionally, depression severity is positively correlated with BMI, WC, WHtR, and DBP, and negatively correlated with

Table 2. Mediator analysis of depression, lifestyle, obesity, and blood pressure with weights, clustering, and stratification^a

	TE		ADE		ACME		PM		
	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Proportion
Sleep duration (h/date)									
BMI	0.099 (0.093, 0.105)	< 0.0001	0.096 (0.090, 0.102)	< 0.0001	0.003 (0.003, 0.003)	< 0.0001	0.031 (0.027, 0.036)	< 0.0001	3.09%
WC	0.247 (0.173, 0.323)	< 0.0001	0.242 (0.169, 0.318)	< 0.0001	0.005 (-0.001, 0.010)	0.110	0.018 (-0.004, 0.046)	0.110	1.82%
WhtR ^b	0.002 (0.002, 0.002)	< 0.0001	0.002 (0.002, 0.002)	< 0.0001	0.000 (0.000, 0.000)	< 0.0001	0.018 (0.018, 0.018)	< 0.0001	1.78%
SBP	-0.120 (-0.176, -0.054)	0.002	-0.119 (-0.175, -0.052)	0.002	-0.000 (-0.003, 0.003)	0.858	0.003 (-0.020, 0.037)	0.860	0.25%
DBP	0.088 (0.066, 0.111)	< 0.0001	0.090 (0.068, 0.112)	< 0.0001	-0.002 (-0.004, -0.000)	0.012	-0.024 (-0.044, -0.005)	0.012	-2.42%
Working hours (h/week)									
BMI	0.107 (0.091, 0.124)	< 0.0001	0.108 (0.093, 0.125)	< 0.0001	-0.001 (-0.005, 0.002)	0.550	-0.011 (-0.046, 0.021)	0.550	-1.07%
WC	0.247 (0.009, 0.497)	0.060	0.250 (0.007, 0.502)	0.058	-0.003 (-0.012, 0.005)	0.480	-0.009 (-0.083, 0.051)	0.508	-0.91%
WhtR ^b	0.002 (0.002, 0.002)	< 0.0001	0.002 (0.002, 0.002)	< 0.0001	-0.000 (-0.000, 0.000)	0.500	-0.010 (-0.038, 0.019)	0.500	-0.97%
SBP	-0.092 (-0.186, -0.000)	0.054	-0.092 (-0.185, 0.001)	0.054	0.000 (-0.002, 0.002)	0.950	-0.000 (-0.050, 0.041)	0.936	-0.03%
DBP	0.103 (0.052, 0.155)	< 0.0001	0.104 (0.053, 0.156)	< 0.0001	-0.001 (-0.004, 0.002)	0.520	-0.009 (-0.047, 0.021)	0.520	-0.86%
Physical activity (MET-mins/week)									
BMI	0.120 (0.105, 0.135)	< 0.0001	0.106 (0.091, 0.121)	< 0.0001	0.014 (0.013, 0.015)	< 0.0001	0.117 (0.104, 0.135)	< 0.0001	11.72%
WC	0.292 (0.100, 0.495)	< 0.0001	0.247 (0.060, 0.444)	0.010	0.045 (0.030, 0.060)	< 0.0001	0.154 (0.089, 0.411)	< 0.0001	15.42%
WhtR ^b	0.002 (0.002, 0.002)	< 0.0001	0.002 (0.002, 0.002)	< 0.0001	0.000 (0.000, 0.000)	< 0.0001	0.148 (0.148, 0.148)	< 0.0001	14.79%
SBP	-0.144 (-0.264, -0.027)	0.016	-0.148 (-0.270, -0.030)	0.018	0.004 (-0.005, 0.013)	0.400	-0.027 (-0.149, 0.061)	0.388	-2.70%
DBP	0.114 (0.043, 0.181)	< 0.0001	0.103 (0.034, 0.169)	< 0.0001	0.012 (0.007, 0.016)	< 0.0001	0.100 (0.059, 0.238)	< 0.0001	9.96%

^aAdjusted for age group, sex, race/ethnicity, education, marital status, family income-to-poverty ratio, smoking, drinking, hypertension, diabetes, and comorbidities. Analyses of Sleep duration, Working hours, and Physical activity included 42,395, 23,101, and 20,435 participants, respectively. Simulations were performed 1,000 times to calculate these statistics; ^bEffect estimates for WhtR showed a concentrated distribution. TE: Total effect; ADE: average direct effect; ACME: average causal mediation effect; PM: proportion mediated; CI: confidence interval; P: P-value; BMI: body mass index; WC: waist circumference; WhtR: waist-to-height ratio; SBP: systolic blood pressure; DBP: diastolic blood pressure; MET: metabolic equivalent.

SBP. Further analysis suggests that lifestyle factors may mediate the relationship between depression, obesity, and blood pressure. Specifically, sleep duration and physical activity, but not working hours, serve as key behavioral pathways through which depressive symptoms affect metabolic health. These results provide valuable insights for managing depression, obesity, and blood pressure in the post-COVID-19 era and support the development of relevant public health policies.

Individuals who have experienced COVID-19 are more likely to develop severe depression and anxiety compared to the general population^[5]. In the post-pandemic period, these psychological disorders have led to a sustained increase in the burden of sleep disturbances^[26,27]. Recent studies corroborate our findings, showing slight increases in sleep duration, more frequent napping, and reduced physical activity levels following the pandemic^[28,29]. A multi-national and multi-cohort study has demonstrated a significant

Table 3. Structural equation model of depression, lifestyle, obesity, and blood pressure with weights^a

	TE					ADE					ACME					PM
	β	SE	P	Std.lv	Std.all	β	SE	P	Std.lv	Std.all	β	SE	P	Std.lv	Std.all	Proportion
Sleep duration (h/date)																
BMI	0.107	0.010	< 0.001	0.107	0.067	0.102	0.010	< 0.001	0.102	0.064	0.005	0.001	< 0.001	0.005	0.003	4.52%
WC	0.240	0.024	< 0.001	0.240	0.061	0.234	0.024	< 0.001	0.234	0.060	0.005	0.002	0.003	0.005	0.001	2.29%
WHtR	0.001	0.000	< 0.001	0.001	0.059	0.001	0.000	< 0.001	0.001	0.058	0.000	0.000	0.029	0.000	0.001	1.72%
SBP	-0.212	0.022	< 0.001	-0.212	-0.053	-0.209	0.022	< 0.001	-0.209	-0.052	-0.003	0.002	0.046	-0.003	-0.001	1.62%
DBP	0.144	0.016	< 0.001	0.144	0.051	0.143	0.016	< 0.001	0.143	0.051	0.001	0.001	0.441	0.001	0.000	0.71%
Working hours (h/week)																
BMI	0.107	0.016	< 0.001	0.107	0.058	0.107	0.016	< 0.001	0.107	0.058	0.000	0.001	0.964	0.000	0.000	0.05%
WC	0.236	0.037	< 0.001	0.236	0.052	0.236	0.037	< 0.001	0.236	0.052	0.000	0.002	0.964	0.000	0.000	0.05%
WHtR	0.001	0.000	< 0.001	0.001	0.054	0.001	0.000	< 0.001	0.001	0.054	0.000	0.000	0.964	0.000	0.000	0.04%
SBP	-0.139	0.030	< 0.001	-0.139	-0.034	-0.139	0.030	< 0.001	-0.139	-0.034	-0.000	0.001	0.964	-0.000	-0.000	0.02%
DBP	0.119	0.023	< 0.001	0.119	0.038	0.119	0.023	< 0.001	0.119	0.038	0.000	0.001	0.964	0.000	0.000	0.05%
Physical activity (MET-mins/week)																
BMI	0.133	0.016	< 0.001	0.133	0.078	0.121	0.016	< 0.001	0.121	0.071	0.012	0.002	< 0.001	0.012	0.007	9.28%
WC	0.298	0.037	< 0.001	0.298	0.070	0.256	0.037	< 0.001	0.256	0.060	0.042	0.006	< 0.001	0.042	0.010	14.10%
WHtR	0.002	0.000	< 0.001	0.002	0.071	0.002	0.000	< 0.001	0.002	0.061	0.000	0.000	< 0.001	0.000	0.010	14.69%
SBP	-0.218	0.032	< 0.001	-0.218	-0.053	-0.223	0.032	< 0.001	-0.223	-0.054	0.006	0.002	0.020	0.006	0.001	-2.59%
DBP	0.163	0.026	< 0.001	0.163	0.055	0.154	0.025	< 0.001	0.154	0.052	0.009	0.002	< 0.001	0.009	0.003	5.49%

^aAdjusted for age group, sex, race/ethnicity, education, marital status, family income-to-poverty ratio, hypertension, diabetes, and comorbidity status. Analyses for Sleep duration, Working hours, and Physical activity included 42,395, 23,101, and 20,435 participants, respectively. SEM: Structural equation modeling; TE: total effect; ADE: average direct effect; ACME: average causal mediation effect; PM: proportion mediated; SE: standard error; P: P-value; Std.lv: standardized estimate for latent variables; Std.all: standardized estimate for all variables; BMI: body mass index; WC: waist circumference; WHtR: waist-to-height ratio; SBP: systolic blood pressure; DBP: diastolic blood pressure; MET: metabolic equivalent.

bidirectional association between depression and cardiometabolic diseases^[30]. Therefore, although no significant changes in BMI, WC, and WHtR were observed before and after the pandemic, the potential long-term impacts of mental health and lifestyle changes, along with resulting metabolic comorbidities, highlight the importance of raising public awareness and implementing measures to mitigate these effects.

Existing research indicates a complex interplay between mental and metabolic health. Substantial evidence from Europe and North America shows a positive correlation between overweight/obesity and depression, with overweight or obese individuals being more susceptible to mood disorders^[31-33]. In contrast, many

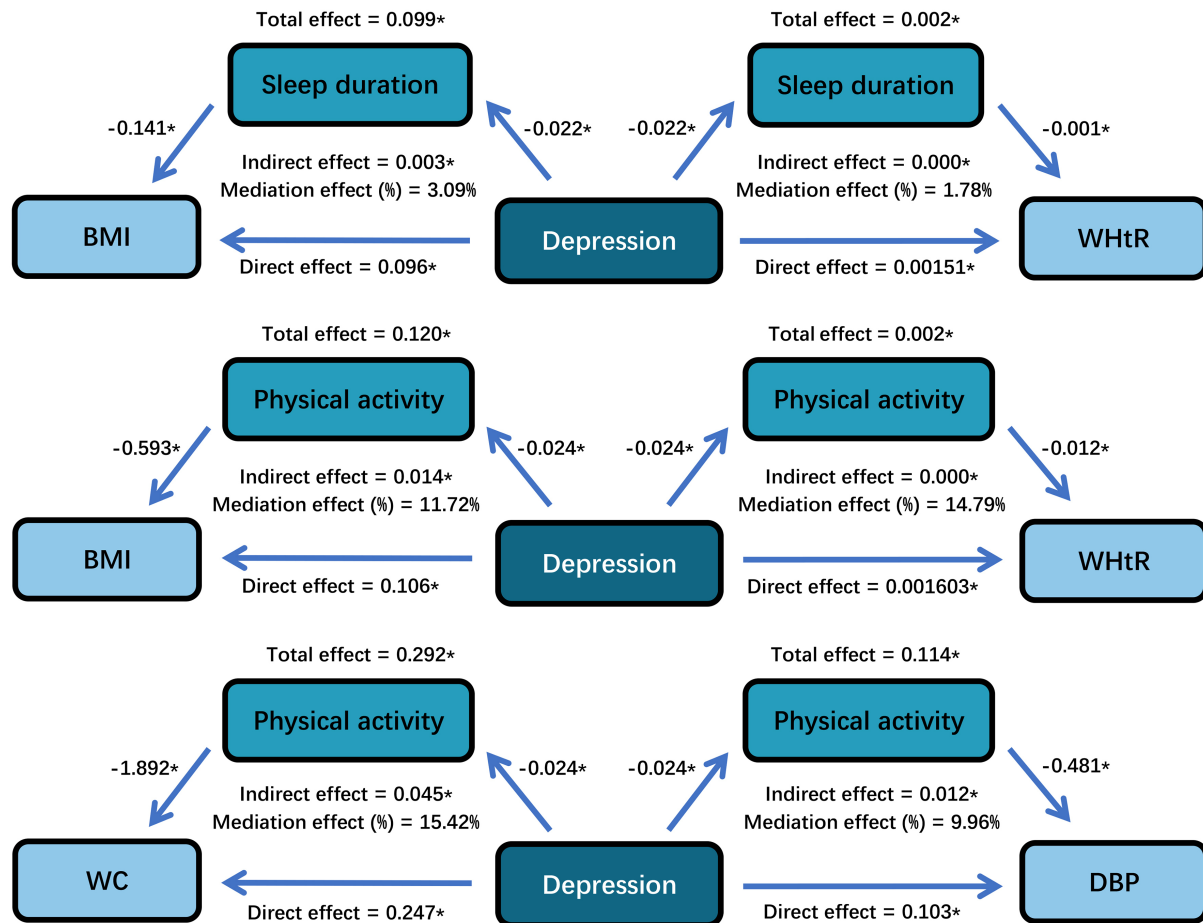


Figure 3. The mediating role of lifestyle in the relationship between depression, obesity, and blood pressure^{a,b}. ^aThe mediating factors with P -values < 0.05 in both mediation analysis and structural equation modeling. Presented as the results of the mediation analysis; ^bAdjusted for age group, sex, race/ethnicity, education, marital status, family income-to-poverty ratio, smoking, drinking, hypertension, diabetes, and comorbidity model. BMI: Body mass index; WC: waist circumference; WHtR: waist-to-height ratio; DBP: diastolic blood pressure. * $P < 0.0001$.

Asian studies suggest that obesity is not an independent risk predictor for depression, and some even find a negative correlation between the two^[34-37]. The association between depression and obesity may share pathophysiological mechanisms such as inflammatory responses, gut dysbiosis, and neurotransmitter imbalances^[38-41]. However, these significant regional differences suggest that sociocultural factors, dietary habits, body image perceptions, social stress structures, and the accessibility of mental health resources play crucial roles in shaping the relationship between depression and obesity. For example, in East Asia, a larger body size is often viewed as a symbol of prosperity and good health, reflecting collectivist cultural values historically associated with group survival. In contrast, Western regions often uphold the value that “self-discipline is a virtue”, attributing obesity primarily to a lack of self-control and emphasizing individual body regulation. Additionally, in academic circles, obesity is classified as a chronic disease. However, current definitions of overweight and obesity are predominantly based on BMI and its derived metrics. While BMI serves as an epidemiological indicator of population-level obesity, it has limitations and risks when applied to individual assessments^[42]. This study not only demonstrates that, within the U.S. population, depression levels are positively correlated with BMI and WC but also identifies a positive correlation between WHtR and depression. Moreover, the relationship between depression and blood pressure is complex. Previous studies have shown that depression may be negatively correlated^[43-48] or unrelated^[49] to SBP and may be

positively^[50-53], negatively^[44-46], or not significantly^[43,49] related to DBP. However, these studies were primarily conducted in Europe, Asia, and Australia, with a lack of large-scale data from the U.S. This study found that depression levels were negatively correlated with SBP and positively correlated with DBP. This seemingly paradoxical relationship underscores the multidimensional impact of depression as a systemic disorder on the cardiovascular system. Although the underlying mechanisms remain unclear, depression may influence blood pressure levels not only through biological and neuroendocrine pathways but also via emotional and behavioral changes at a macro level^[54,55].

Lifestyle factors may be a critical link in the interplay between mental and CVDs, as they are both manifestations of psychological and cardiovascular states and independent risk factors affecting both health domains. Additionally, sleep, work, and physical activity - three time-consuming lifestyle factors - significantly impact health. For instance, insufficient sleep duration is closely related to obesity and cardiovascular risk^[56], prolonged working hours are associated with hypertension^[57,58] and obesity^[59], and engaging in more than 300 min of physical activity per week significantly reduces the risk of depression^[60].

In this study, extended sleep duration and increased physical activity were associated with improved depression scores and lower obesity-related indicators. Working hours were not related to depression levels; however, increased working hours were linked to higher obesity-related indicators. Therefore, we emphasize that appropriately extending sleep duration and increasing physical activity are associated with concurrent improvements in psychological and metabolic health. Nevertheless, due to limited daily time, balancing increased sleep and exercise with other major commitments, such as work schedules, remains a challenge. Future research should comprehensively integrate the interrelationships among multiple lifestyle factors.

The key findings of this study indicate that lifestyle factors partially mediate the relationships between depression, obesity, and blood pressure. Specifically, sleep duration and physical activity mediate the relationship between depression and obesity by 1.72%-4.52% and 9.28%-14.79%, respectively, while physical activity mediates the relationship between depression and DBP by 5.49%-9.96%. These results highlight the potential importance of lifestyle interventions in reducing the risks of depression, obesity, and hypertension. Supporting evidence from related studies includes Nathalie's research, which demonstrates a positive correlation between poor mental health and overweight, with physical activity accounting for 20% of this relationship^[16]. Additionally, Yu *et al.* identified sleep disorders as key independent mediators between depression and obesity^[15]. Unlike their questionnaire-based approaches, our study strengthens these conclusions by quantifying sleep duration. However, we did not find a mediating effect of working hours on the relationships between depression and obesity or blood pressure. Nonetheless, working hours were positively correlated with obesity and DBP, suggesting that long working hours may increase the risk of obesity and hypertension. Extended working hours may also exacerbate the comorbidity of depression and obesity by impairing sleep quality and reducing physical activity time. The relationship between depression and metabolic factors is influenced not only by individual behaviors but also by external factors such as the social environment and workplace. To better address these health challenges, we recommend integrating mental health assessments into primary care screening protocols, with a particular emphasis on mental health and lifestyle factors in the post-pandemic period. Additionally, workplace health policies should incorporate increased mental health support and resources to encourage physical activity, thereby addressing the interconnected challenges of mental and metabolic health.

This study utilized a nationally representative large sample, ensuring scientific rigor and nationwide generalizability. To minimize the impact of confounding factors, we employed a DAG model. By

accounting for different sampling weights, we validated the robustness of our results. However, several limitations remain. First, the cross-sectional design restricts causal inferences, as correlation does not equate to causation. Consequently, we cannot determine the causal direction between variables, assert that changes in psychological states and lifestyles are entirely attributable to COVID-19, or clarify the causal relationships among depression, lifestyle, and metabolic factors. Second, this study focused solely on depression within the realm of mental health; future research should encompass a broader evaluation of mental health changes before and after the pandemic. Third, although we analyzed lifestyle factors such as sleep duration, working hours, and physical activity, other factors like diet and social activities may also influence the outcomes and warrant further investigation. Fourth, the results primarily reflect the cultural and social context of the American population, necessitating caution when generalizing to other cultural backgrounds. Fifth, our analysis of working hours included only employed individuals, which may not fully represent the mental health and lifestyle conditions of the unemployed, thereby limiting the applicability of our conclusions.

Conclusions

In conclusion, this study indicates that depression may become a significant public health challenge in the future. Sleep duration and physical activity, rather than working hours, play crucial mediating roles in the relationships among depression, obesity, and blood pressure. Policy interventions should promote healthy lifestyles, particularly in the post-pandemic era, by implementing targeted strategies such as moderately increasing sleep duration, reducing working hours, and enhancing physical activity to alleviate the burdens of mental and metabolic diseases.

DECLARATIONS

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Authors' contributions

Made substantial contributions to conception and design of the study: Zuo SH, Liu CY, Wang RY, Wang Y, Mu JJ

Performed data curation: Zuo SH, Liu CY, Wang RY

Performed formal analysis: Zuo SH

Performed investigation: Zuo SH, Liu CY, Wang RY

Performed methodology: Zuo SH, Liu CY, Wang RY, Hu GL, Wang Y, Mu JJ

Performed project administration: Zuo SH

Performed software work: Zuo SH, Liu CY, Wang RY

Performed validation: Zuo SH, Liu CY, Wang RY

Performed visualization: Zuo SH

Performed writing - original draft: Zuo SH

Performed writing - review and editing: Zuo SH, Hu GL, Sun Y, Chang MK, Man ZY, Jia H, Zhang T, Du MF, Zhang X, Wang Y, Mu JJ

Obtained funding: Wang Y, Mu JJ

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All authors have read and approved the final manuscript.

Availability of data and materials

The datasets analyzed in this study are available in the NHANES repository (<https://www.cdc.gov/nchs/nhanes/index.htm>). Additional data generated during the analysis are available from the corresponding authors upon reasonable request.

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Conflicts of interest

Wang Y is a Junior Editorial Board member of the journal *Metabolism and Target Organ Damage*. Wang Y was not involved in any steps of the editorial process, including reviewer selection, manuscript handling, or decision making. The other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

This study utilized de-identified data from the National Health and Nutrition Examination Survey (NHANES) database (2005–2023), which is publicly accessible. The original data collection and release were approved by the National Center for Health Statistics (NCHS) Research Ethics Review Board, in compliance with relevant ethical guidelines and privacy regulations. Therefore, no additional ethics approval was required for the secondary analysis of these publicly available, de-identified data.

Consent for publication

Not applicable.

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